Application, Development and Challenges of Deployable Structures in Bridge Engineering

Yuchen Zou*

School of Civil Engineering, Southwest Jiaotong University, Chengdu, 610031, China

*Corresponding author: zyc2024117071@my.swjtu.edu.cn

Abstract. Deployable structures are highly promising structures based on the principles of mechanism theory, combining traditional structures with movable mechanisms. Driven by manual, mechanical, or smart material means, they can achieve folding and deployment. Focusing on the applications, development prospects, and challenges of deployable structures in bridge engineering, this paper first elaborates on their mechanism theory, motion principles, and classifications, then analyzes their applications in three scenarios — emergency military bridges, temporary and construction auxiliary bridges, and special intelligent bridges—combined with practical application cases. Finally, it points out future directions such as the integration of deployable structures with smart materials, indicating that they provide key support for the high efficiency, lightweight, and sustainable development of bridge engineering with broad prospects.

Keywords: Deployable Structure, Principles of Mechanism Theory, Driving Method, Application in Bridge Engineering, Smart Materials and Structures.

1. Introduction

Bridges have long been regarded as structures that connect two places, traverse natural barriers, and provide convenience for travel, with their characteristics often embodied by sturdiness, stability, and durability. However, with ongoing progress and development, engineering demands have become increasingly complex, particularly in fields such as emergency disaster relief, modern urban construction, and military operations. In these complex scenarios, the requirements for bridges have surpassed traditional paradigms. It is no longer sufficient to prioritize only "sturdiness, stability, and durability." In specific contexts, qualities like "instant deployment, portability, and reusability" are equally important. It is against this backdrop that deployable structures, an emerging interdisciplinary field, have infused bridge engineering with unprecedented dynamism and intelligence, ushering in a new era of possibilities.

The core principle of deployable structures lies in breaking away from the traditional perception of structures as static load-bearing systems. Instead, based on mechanism theory, they are designed as controllable, movable mechanisms. A research team from North Carolina State University noted in Nature Communications that deployable structures are essentially "dynamic systems achieving controllable deformation through hierarchical closed-loop mechanisms and hinge connections, capable of orderly transitioning from a compact folded state to a functional deployed state with low actuation degrees of freedom" [1]. The Swedish Defence Materiel Administration further specified in its equipment technical standards that deployable structures in engineering must meet three core characteristics: "deployment efficiency, morphological controllability, and functional reusability, achieved through modular design for rapid assembly and folded storage" [2]. By responding to specific actuation methods (such as smart materials), these structures undergo orderly transformation from a folded state to a predetermined deployed form, thereby enabling rapid deployment, functional transformation, or spatial adaptation.

Building upon this core principle, deployable structures have given rise to diverse application systems within the field of bridge engineering. First, there are rapidly deployable bridges for extreme emergency response and military use, whose core value lies in "speed," providing critical technical support for reopening lifelines and ensuring military mobility. Second, there are temporary and construction-assist bridges used during the construction process, which emphasize "reusability" and

"rapid assembly and disassembly," significantly enhancing construction efficiency and aligning with the concept of green building. Third, there are special-function and intelligent bridges, which represent future development trends. Examples include traditional movable bridges and more forward-thinking intelligent bridge systems equipped with capabilities such as self-sensing, self-decision-making, and even self-repair. These endow bridges with the "intelligence" to dynamically adapt to environmental and operational demands.

When bridges need to "appear" or "disappear" on demand, the integration of deployable structures with bridge engineering has emerged as the optimal solution. Leveraging the principles of mechanism theory, deployable structures transform "construction" into "deployment" and simplify "dismantling" into "folding," offering unprecedented spatiotemporal flexibility for emergency response, construction, and military applications. This paper will systematically elaborate on their structural foundations, operational principles, and specific application forms.

2. Principles and Classification of Deployable Structures

2.1. Structural Basis and Motion Principles

The functional transformation between storage and deployment through the geometric transformation of movable mechanisms. Such structures are designed logic of deployable structures originates from mechanism theory, and their essence lies in realizing the ally designed based on the integration of deployable surfaces and multi-body mechanisms. The deployable laminated emergent array technology proposed by Nelson et al. aligns the laminated emergent joint network with the generatrix of the deployable surface, enabling two-dimensionally manufactured structures to acquire large-curvature elastic motion capability while ensuring the determinism of the deployment path [3].

2.2. Classification of Deployable Structures

The classification system of deployable structures also influences their functions and applications. The deployable mechanism classification system proposed by Howell's team divides them into four categories: planar, cylindrical, conical, and tangential deployable mechanisms. Among these, cylindrical and conical deployable mechanisms evolve from planar and spherical mechanisms, respectively [4], while the Bennett 7R mechanism and other similar mechanisms provide an implementation path for tangential deployable structures. This classification offers a theoretical framework for structural design in different scenarios.

The driving methods of deployable structures are evolving from manual and traditional mechanical/fluid-driven systems toward intelligent driving. Manual driving is gradually being phased out, while mechanical and hydraulic driving methods are still used in heavy-load scenarios, with intelligent driving emerging as the core of research [5]. Deployable structures have been further advanced and become an irreplaceable component in fields such as bridge engineering and aerospace, with particularly prominent applications in bridge engineering.

3. Applications of Deployable Structures in Bridge Engineering

3.1. Emergency and Military Rapidly Deployable Bridges

The core principles of deployable structures—including geometric transformation in mechanism theory and multi-source driving—are highly aligned with the demands of bridge engineering for temporariness, maintenance convenience, and emergency response efficiency. Intelligent driving further enhances their advantages, and their technical system can be integrated into bridge engineering practices from three key dimensions: temporary bridges, bridge operation and maintenance, and bridges for special scenarios.

In temporary bridges, emergency and military scenarios are the top priorities for their application. These scenarios impose stringent requirements on bridges in terms of rapid deployment capability,

terrain adaptability, and portability. Through mechanism optimization and driving technology innovation, deployable structures have become a core solution for crossing obstacles such as rivers and gullies, with their application forms focusing on two major directions: emergency response in earthquake relief and military mobility support.

In emergency earthquake relief scenarios, deployable structures emphasize the characteristics of "lightweight + manual deployment" to adapt to complex terrain after road damage. The EASIBridge system developed by Bright Structures (UK) adopts aluminum alloy and carbon fiber composite materials to construct spatial frame-type deployable units. Each component weighs less than 15 kilograms, and a 4-person team can build an 18-meter span bridge within 30 minutes without heavy machinery, capable of supporting the passage of 12-ton rescue vehicles. When folded, its volume is only 1/20 that of traditional Bailey bridges, and it can be airdropped by helicopter to earthquake ruins or mountain breakpoints [6]. Through the structural design of "tool-free splicing + tension self-locking", the system solves the pain points of insufficient equipment and limited operating space at disaster relief sites, and has completed field verification in the post-earthquake reconstruction of Turkey.

In military rapid mobility scenarios, deployable structures adopt the core design logic of "modular folding + mechanized driving" to realize efficient passage support for heavy equipment. The U.S. M1074 Wolverine Heavy Assault Bridge (HAB) utilizes a hydraulically driven folding truss structure, mounted on a tank chassis. It can deploy a 26-meter span bridge deck in only 5 minutes with a load-bearing capacity of 63 tons, playing a key mobility support role in the Iraq War [7]. The modular military bridge system developed by Mabey (UK) connects truss units via mechanical hinges, which are quickly locked with bolts. A 3-4 person team with small machinery can complete the construction of a 30-meter span within 1 hour, and its folded volume is only 1/5 of the deployed state, suitable for airdrop by transport aircraft and truck transportation. Through simplifying deployment steps and optimizing driving efficiency, such designs reduce the erection cycle of traditional bridges from hours to minutes, aligning with the battlefield principle of "time is decisive" [8].

3.2. Temporary and Construction Auxiliary Bridges

During the construction and maintenance phases of bridge engineering, temporary passages and construction work platforms are critical facilities ensuring operational continuity. Deployable structures, with their characteristics of rapid assembly and disassembly, reusability, and strong adaptability, effectively address the pain points of traditional temporary facilities—such as "lengthy setup cycles, significant resource waste, and poor terrain adaptability." Their applications primarily focus on two scenarios: temporary crossings over obstacles and support platforms for construction equipment.

In scenarios involving various on-site obstacles, deployable temporary bridges demonstrate exceptional adaptability and efficiency. They can be quickly erected over foundation pits, watercourses, or existing roads, seamlessly connecting construction zones with external transportation networks. A practical example is the modular deployable temporary bridge introduced by Germany's Waagner-Biro company. In actual operations, a small team of just six workers, assisted by a conventional small crane, can efficiently complete the installation of a stable passage with a span of 24 meters and a deck width of 4 meters within a mere four hours [9]. This bridge possesses strong load-bearing capacity, safely accommodating heavy engineering vehicles with a total weight of up to 25 tons. Its outstanding transport and economic efficiency are particularly notable: when folded, the entire system can be further disassembled into multiple independent units, each with a maximum weight strictly limited to 80 kilograms, greatly facilitating transport via standard trucks. Furthermore, thanks to meticulous component design and connection technology, the system exhibits a material loss rate of less than 5% per cycle of disassembly and installation, achieving high reusability—a characteristic validated across several European highway expansion and renovation projects.

In the application area of elevated work platforms supporting large construction equipment, deployable structures, leveraging their modular and intelligent features, effectively meet the complex

load-bearing requirements of diverse heavy equipment. The innovative deployable construction platform system developed by the UK's Laing O'Rourke construction group is centered around a hydraulically actuated rigid folding frame. When fully deployed, this platform forms a rectangular work surface measuring 12 meters by 8 meters, with a maximum load-bearing capacity of up to 50 tons—sufficient to stably and safely support critical heavy construction equipment such as bridge hanging baskets and large beam launchers [10].

A key technical highlight of this system is the integration of an intelligent monitoring and feedback mechanism. Sensors installed at critical nodes enable real-time monitoring of the platform's overall support stress state. The control system can dynamically and precisely adjust the hydraulic support forces at various locations based on the actual distribution and changes in construction loads, thereby effectively mitigating potential local overload risks and ensuring a high degree of operational safety. This system has been successfully applied in London's Crossrail large-scale railway bridge project, where its efficiency was fully demonstrated: using this platform, the traditional installation cycle for hanging baskets, which typically required seven days, was significantly shortened to just two days, greatly enhancing overall construction efficiency and project schedule reliability.

Whether it's the mechanical quick-connect joints of the German temporary bridge or the hydraulic folding frame of the British work platform, both compress traditional preparation work—which could take days or even weeks—into a timeframe measured in hours. The aim is rapid assembly/disassembly and high reusability. This leap in efficiency not only directly shortens project durations but also holds deeper significance: by enabling the cyclic reuse of a single set of equipment across multiple projects, it drastically reduces material waste and construction debris, achieving a win-win situation for both economic and environmental benefits.

However, the stage for deployable structures extends far beyond these conventional temporary engineering applications. When this "plug-and-play" rapid deployment capability intersects with more diverse and cutting-edge engineering demands, it gives rise to bridge types with even more unique functionalities. Deployable structures can also deeply integrate with bridges possessing special functions and technologies, solving even more challenging problems.

3.3. Special-Function and Intelligent Bridges

In the field of movable and retractable bridges, deployable structures, with their sophisticated mechanism-based designs, excel at balancing the dual demands of land transportation and waterway navigation. The Tower Bridge in London, UK, serves as a classic example in this domain. Its opening system utilizes a hydraulically actuated folding deployable structure. Through symmetrically arranged hydraulic cylinders, the system synchronously drives the rotation of the bridge decks on both sides around preset hinge points. The entire opening process takes only about 10 minutes to achieve a central span opening of 61 meters, ensuring the safe passage of large vessels [11].

In a corresponding approach, the "De Hef" bridge in Rotterdam, Netherlands, demonstrates a different technical pathway. It employs a mechanically driven three-segment folding structure, allowing the entire deck to fold upwards until it becomes parallel with the piers. This operation significantly increases the navigational clearance to 32 meters. To ensure long-term operational reliability, its hinge and transmission system integrates an intelligent monitoring module capable of providing real-time feedback on the structure's operational status, greatly enhancing the precision of the opening/closing actions and the structural safety [12]. This innovative design has been incorporated into the EU's "Smart Infrastructure" pilot project, establishing it as a benchmark for the modernization of movable bridges.

3.4. Future Development Directions of Deployable Structures

Looking ahead, intelligent bridges integrating self-deployment, self-sensing, and self-healing capabilities have become a frontier research focus. The novel combination of deployable structures and new materials has opened a new door for the development of smart bridges. A deployable bridge prototype developed by a research team at the Massachusetts Institute of Technology (MIT) utilizes

shape memory polymers (SMP) as the core material. This material responds to thermal stimuli, enabling the structure to autonomously deploy into a predetermined configuration driven by the material's own phase change, without relying on complex external mechanical devices. The entire process achieves positioning errors of less than 2 millimeters [13]. Simultaneously, a distributed optical fiber sensing network integrated within the structure enables real-time monitoring of stress and deformation during operation.

4. Conclusion

Relying on its unique design rooted in the principles of mechanism theory and the continuous breakthroughs in driving technology, deployable structures are increasingly penetrating into multiple key links of bridge engineering. Specifically, such structures not only effectively address a series of practical dilemmas in specific scenarios—including emergency rescue, construction process assistance, and special traffic support—but also, with their continuously evolving intelligent properties, inject key impetus into the efficient advancement of bridge construction and operation, the implementation of structural lightweight design, and the realization of engineering sustainability. Looking ahead, deployable structures are expected to emerge as an important path to respond to diverse and complex demands and lead engineering and technological innovation in the bridge field. Furthermore, they will play an increasingly crucial role in comprehensively enhancing the functional adaptability of bridges and optimizing the comprehensive benefits throughout their entire life cycle.

References

[1] Li Y, Di Lall A, Zhu J, et al. Adaptive hierarchical origami-based metastructures[J]. Nature Communications, 2024, 15(1): 7892.

[2] Swedish Defence Materiel Administration. Improved Ribbon Bridge (IRB) Technical Specification[R]. Stockholm: Swedish Defence Materiel Administration, 2025.

[3] Nelson T G, et al. "Facilitating Deployable Mechanisms and Structures via Developable Layers"[J]. ASME Journal of Mechanisms and Robotics, 2016, 8(3): 031006.

[4] Howell L L. "A Definition and Demonstration of Developable Mechanisms"[D]. Provo: Brigham Young University, 2018.

[5] Maxiaofei,et al. “China's deployable space structures: progress and trends” [J]. Engineering, 2022, 17(10): 207-219.

[6] Bright Structures Ltd. "EASIBridge: Ultra-Compact Launchable Space-Frame Bridge Prototype Report"[R]. United Kingdom: UK Research and Innovation, 2024.

[7] International Committee on Military Engineering. "Military Bridging: History, Technology and Application"[C]. France: ICME Press, 2021: 145-162.

[8] Mabey Bridge. "Modular Military Bridging Systems Technical Manual"[M]. United Kingdom: Mabey Group, 2022.

[9] Waagner-Biro Bridge Systems. "Modular Deployable Temporary Bridges for Infrastructure Construction"[R]. Vienna: Waagner-Biro Group, 2020.

[10] Laing O'Rourke. "Hydraulic Deployable Work Platforms for Heavy Construction Equipment Support"[J]. Construction Innovation, 2021, 21(3): 452-468.

[11] London Bridge Authority. "The Tower Bridge Lift Mechanism: Design and Operation"[R]. London: London Bridge Authority, 2022.

[12] Rotterdam Municipal Transport. "Technical Renovation Report of Koningshaven Bridge (De Hef)"[R]. Rotterdam: Rotterdam Municipal Transport, 2021.

[13] MIT Department of Civil and Environmental Engineering. "Self-Deploying and Self-Healing Composite Bridges: Prototype Development"[J]. Journal of Intelligent Material Systems and Structures, 2023, 34(8): 1021-1035.