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Recent and Future Trends in Deployable Bridges Using Scissor-Like Elements

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Abstract. Within this recent decade, climate change has amplified the effects of natural disasters around the world. It is known that road infrastructure is crucial in post-disaster response operations; however, road infrastructures are also often damaged by the disaster. One of the vital but fragile parts of this infrastructure is bridges; a collapsed or damaged bridge can substantially delay search and rescue operations, as well as delivery of essential humanitarian supplies into the regions affected. This paper provides an overview of the novel use of deployable scissor bridges to rapidly replace functions of affected bridges after a disaster through evaluating the advantages as well as limitations of 6 existing scissor bridge designs compared to existing modular solutions. A particular focus will also be placed on suggesting possible improvements in scissor bridge designs, including the use of composite materials and the implementation of smart bridge health monitoring systems. Most current solutions exist as modular rapid assembly bridges, often designed with a focus on military applications. Deployable scissor bridges offer advantages in civilian applications, including higher portability, shorter construction time and reduced manpower demand. However, current challenges in the design include high deflections and a lower load capacity. Fibre-reinforced polymers (hereafter FRP) can be used in the bridge's main frame to decrease its dead load without sacrificing the structure's strength. At the same time, embedded sensors can feed back to active vibration control systems, damping bridge vibrations

Keywords: emergency deployable bridge, scissors-type bridge, scissor-like elements

1. Introduction

Climate change in Inner Mongolia has altered and accelerated the hydrological cycles, resulting in an increased level of precipitation as well as an increased occurrence of extreme rainfall events [1]. A research paper also suggested a 9-fold increase in flood risks between 2000 and 2018 in areas around the Yellow River basin, which includes central regions in central Inner Mongolia [2]. In July this year, torrential rain triggered flooding in the county, affecting more than 46200 people and resulting in an economic loss of about 203.5 million yuan [3].

Between 2000 and 2020, there were 4623 recorded climate-related disasters globally, affecting 3.9 billion people [4]. This includes 1.2billion people impacted by riverine floods and 501 million people affected by tropical storms [4]. Under an additional global warming of 1.5 degrees, it is

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projected that losses induced by flooding will further increase by 160 to 240% [5]. In 2021, 22 bridges were destroyed when 2 dams collapsed in Hulunbuir during heavy rainfall [6].

Time is critical in emergency aid operations after a natural disaster. A swift deployment of disaster response teams into the affected areas is essential to minimise casualties and financial losses [7]. Connectivity to the area must be reestablished quickly to ensure that medical evacuations can take place and humanitarian aid can be delivered to supply essential assistance such as temporary energy generators, shelter, food and water [8].



Figure 1. Large pieces of debris are accumulating in front of a bridge, obstructing water flow [9]

However, the arrival of rescue and relief services can be delayed due to disruptions in transportation networks connecting the affected regions, as key road infrastructures can be affected by the disaster or from secondary damage [10]. One of the vital parts of the transport infrastructure is bridges, which enable passage over obstacles which would otherwise be difficult or unsafe to traverse. However, post-natural disasters, bridges are also becoming a critical and vulnerable failing point in local transportation networks. One of the leading causes of bridge failure is hydraulic [11-13]. During floods and tsunamis, the high water currents can exert hydrodynamic load on the substructure of a bridge. In addition, the water current can also pick up chunks of large debris (shown in Figure 1), which can cause damage when it collides with the bridge. The accumulation of this debris can further obstruct the flow of floodwater and increase the hydrodynamic forces exerted onto the bridge. The hydraulic load on soil and rocks can also cause sediments around the bridge foundation to wear away, forming scours. Although scours (shown in Figure 2) can also be produced through the natural water currents slowly over time, fast-flowing currents in flooding and tsunamis amplify the erosion of sediments, resulting in more intensive scouring, which can significantly destabilise foundations and affect the bridge's structural integrity [11-14].

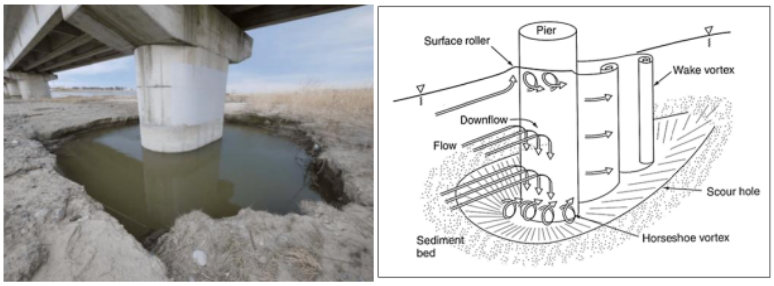

Figure 2. Left figure shows the formation of scours under a bridge [15]. Right figure shows the flow of water currents around the pier of a bridge [16]

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Bridges are also vulnerable in geological disasters, besides causing shear failures and resulting in buckling of the bridge structure [17]. Intensive vibrations in earthquakes can cause soft and saturated soils to behave like liquids. As a result, the settlements lose their strength, reducing their load-carrying capacity. This can prompt the foundations of the bridge to sink or tilt, triggering lateral spreading [18, 19].

2. Past and present rapid bridge construction strategies

2.1. Modular bridges

The Bailey bridge, proposed by Donald Bailey in 1941, is often referred to as the first, widely endorsed modern rapid bridge system. It is a military portable truss bridge originally adopted by the British, Canadian and American military during the Second World War. It consists of prefabricated wood and steel elements, which can then be assembled on site with minimal use of heavy machinery [20].

Military bridging systems, including an improved variation of the Bailey bridge, are often still the most viable solutions for replacing damaged or collapsed bridges. Modern military bridging systems can be classified into assault, tactical and line of communication bridges. Assault bridges are used in active combat environments and require the smallest amount of time as well as resources to deploy. In contrast, tactical and line of communication bridges are designed to be deployed for a longer period of time whilst carrying a higher volume of traffic [21].

Its modern successors, such as the Mabey Logistic support bridge, were proven to be particularly useful for re-establishing temporary civilian connections as a result of extreme weather events through a number of case studies [22-24]. In one of the reports, an LSB was deployed in Switzerland after a bridge was washed away. The report suggests that a team of 20 soldiers was able to construct an LSB with a length of about 40 meters in 4 days [24].

2.2. Deployable bridges using scissor-like elements

2.2.1. Classification of scissor-like elements

Within the recent decade, researchers in mechanical systems and deployable structures have proposed a new rapid bridge design, which consists of scissor-like elements (hereafter SLE). SLE can be classified using the unit-based method, where each scissor unit is defined as a pair of links connected by an intermediate joint. In a scissor chain, each scissor unit is then connected to the others with two additional pairs of hinges known as terminal joints. A line is also imagined to join the two terminal joints; this line is referred to as a unit line. Planar SLE can be categorised into 3 groups: translation units, polar units and angulated units. The scissor linkage used in the Mobile Bridge are translational units; unit lines of translational units are parallel, as they consist of 2 identical links with the intermediate unit position at the middle. Contrarily, the position of the intermediate unit in a polar unit is eccentric, and its unit lines intersect at a centre. In an angulated unit, the links are not straight and have a kink angle less than 180 degrees [25, 26].

2.2.2. Existing deployable scissor bridge designs

The concept of a deployable bridge which utilizes translational scissor-like linkages was first explored by Professor Ichiro Ario at Hiroshima University [27]. The latest version of the patented design developed by the same University, Mobile Bridge 4.0 (MB 4.0), has a total retracted and

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expanded length of 3 meters and 20.8 meters, respectively [28]. Since there are many variations of dimensions and designs published by research investigating different areas of the concept. 6 different deployable scissor bridge models were studied in this paper (summarised in Table 1).

Table 1. Summary of 6 different deployable scissor bridge designs

Deployed Dimensions			Weight	Design	Materials	Reference
Length	Weight	Height				
20.8 m	2.5~3.0 m	3.1 m	130 kN	Full-scale model of Mobile Bridge 4.0,	The main frame of the structure is made with extruded aluminum alloy, the hydraulic deployment system is made using steel SS400	2017 [28]
7 m		2 m	8.6 kN	Full-scale model ofMobile Bridge 1.0	The main frame is made from aluminum alloy A6N01, the deck is made from aluminum alloy A6063	2016 [29]
16 m				Scissor bridge with coupling SLE	Low alloy steel	2021 [30,31]
60.38ft≈18.40 m			11.16ton≈111.20 kN	Optimized scissor bridge design, using a range of polar scissor units	Aluminum B209	2018 [32]
14 m	2.2 m	2 m		Virtual simulation model used for performing stress analysis	A36 Structural Steel	2018 [33]
14 m	2.2 m	2 m		Virtual simulation model with open grid decks to improve to weight-to strength ratio	A36 Structural Steel	2020 [34]

In another paper, a static stress analysis of a similar scissor-like bridge design was done using ANSYS Workbench (shown in Figure 3) [33]. The simulations show that, with fixed supports, the structure of the fully deployed bridge was able to withstand its targeted load of 210070N, which is exerted by 2.6 units of 4x4 pickup trucks. A maximum deformation of 15.741mm is recorded in this configuration, although deformation can be reduced to 13.451mm when only the load of a single truck is applied onto the bridge. In addition, a satisfactory factor of safety of 1.803 was also obtained from the maximum principal stress [33].

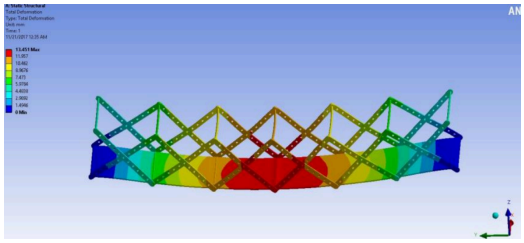

Figure 3. A scissor bridge's total deflection under the load of one 4x4 pickup truck [33]

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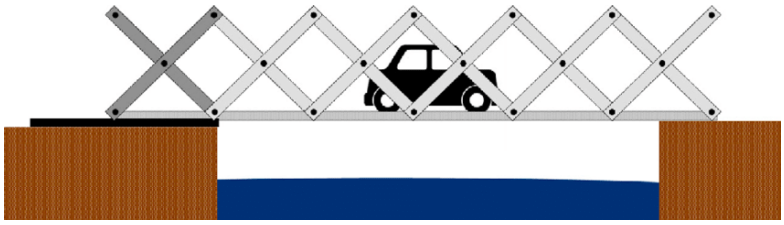

Figure 4. Visual diagram of a fully deployed scissor bridge [28]



Figure 5. Mobile bridge 4.0 in field test [28]

Deployable scissor bridges offer advantages in speed, logistics and manpower over assemblies of modular LSBs. In 2017, the Hiroshima University Institute of Engineering carried out a field test of the latest version of the mobile bridge: MB 4.0 over the Hongo River (shown in Figure 4). The mobile bridge system was successfully deployed without the use of any construction machinery, such as a crane. The report also suggested that only 2-3 workers assisted in the deployment process. The total construction time between the arrival of the structure and its full expansion is 1 hour, while the actual time it takes to expand the scissor mechanism is only 5 minutes [28]. Whereas components of LSBs must be transported individually and reassembled, a scissor bridge consists of a single, one-degree-of-freedom structure that only needs to be expanded on site (shown in Figure 5). As a result, deploying the scissor bridge is less time-consuming and labour-intensive. Activating the actuation system to deploy the scissor bridge is also simple and does not require skilled personnel. This means that the bridge can be used even when no professional engineer can access the area.

3. Future challenges and developments

Current designs of scissor bridges do not offer the same loading capacity as the modular emergency bridge. Numerical analysis of the proposed coupled scissor design has shown that its stress is 10% higher compared to double warren truss structures used in existing modular bridges [30]. In addition, when the existing translational scissor structure design is further optimised by MIT, the weight per foot value is still higher even when compared to common girder bridges [32].

3.1. Materials

It is shown in Table 1 that models of deployable scissor bridges in the studied designs are made using common bridge construction metals, including aluminium and steel. In particular, the

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lightweight, high-strength and corrosion-resistant properties of aluminium make it an attractive material choice; the full-scale prototype of MB 1.0 and MB 4.0 developed by Hiroshima University are both constructed using extruded aluminium alloy scissor members, with researchers citing the material's ability to reduce the dead weight of the structure [28, 29].

3.2. Composite materials

Composites such as Fibre Reinforced Polymer have also been suggested by several researchers as an alternative to the conventional construction materials used in rapid assembly bridges. FRP consists of a polymer matrix and a reinforcing fibre material such as glass, carbon, basalt and aramid. FRP composites have increasingly been utilised in the construction of non-deployable bridges and have also been used to extend the fatigue life of existing bridges due to their high fatigue strength [35]. It is also shown that FRBs have an advantageous strength-to-weight ratio, with the density of FRP being 30% lower compared to aluminium and only a quarter of the density of steel [36]. A scissor bridge that uses FRP as its main frame would have a further reduced dead weight, increasing the bridge's portability. At the same time, due to the complexity of a composite’s material property, further research is needed to investigate the structural performance of a scissor bridge that is primarily made with FRP. This includes numerical analysis of stress distribution and vibrations in the structure. In one of the papers [32], the author has highlighted limitations in the supported materials on their digital simulation software. This may have contributed to the lack of previous work surrounding this scope of research.

The initial cost of material and production can be a significant drawback when using FRP. In a study evaluating uses of FRP in the construction of non-deployable bridges, the researcher has pointed to how individual designs specific to a single bridge may result in a higher FRP manufacturing cost compared to producing a series of repetitive parts in the aviation industry [36]. However, in contrast to conventional bridges, components in a scissor bridge, such as the scissor elements and the deck panels, are highly repetitive. In situations where many identical scissor bridges are needed in response to a disaster or to provide sufficient response capability in preparation for disasters, production of scissor bridge components will resemble mass production as seen in the aviation industry, and is therefore likely to be lower cost compared to a conventional bridge made in FRP.

Another challenge with using FRP for scissor bridges involves access to FRP production capability. FRP production is dominated by countries including China, the USA, Germany and Japan. Low-income countries in disaster-prone regions may not have the capability to produce bridges locally, which means that there may significant delay in the replacement processes if the bridge is required to be shipped from another country. This makes FRP not as accessible as conventional options such as steel.

3.3. Implementation of smart systems in deployable scissor bridges

Maintaining the deployable bridge as well as ensuring its safety is as paramount as maintaining conventional bridges. Although developed bridges have obtained a high factor of safety, deflections and vibrations are another limitation. Researchers at MIT have also added that the current design does not meet deflection regulations set by the American Association of State Highway and Transportation Officials (AASHTO) [32]. A suggested solution is to add reinforcing members to the bridge after it is deployed [28], which will reduce the effect of bending forces. Simulation studies have shown that this is an effective method, with the stress of reinforced coupling scissor bridges

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becoming 2% lower than that of the double warrant truss structure [30]. However, this would also mean an increased construction time when the bridge is deployed during a disaster.

Another possible strategy is to implement active vibration control systems into future deployable bridges. Recent decades have seen the advent of smart bridge structures, where damage detection algorithms and embedded sensors allow the bridge's health to be constantly monitored, as well as to send alerts when its structural safety becomes compromised. Some examples of variables monitored include stress, strain and vibrations, as well as external variables such as humidity and windspeed. Data recorded from these sensors can also allow the bridge to provide automatic actions in response to changes, such as active vibration control systems.

4. Conclusion

Results of the review reinforced key advantages in adapting a deployable bridge in a disaster, but have also highlighted some limitations in the scissor bridge's design. This includes vibrations caused by bending forces as well as a lower loading capacity compared to existing modular solutions. The following conclusion can be drawn:

Existing solutions to rapidly replace collapsed bridges consist of military bridging systems and modular bridges made up of pre-fabricated elements, which have been widely used in past disasters. The load capacity of such bridges is designed focusing on military line of support applications; as a result, the portability of the bridge is limited, and a large amount of manpower is required to construct the bridge. Deployable scissor bridges are made up of multiple units of SLEs, which enables 1 degree of freedom deployability. Scissor bridges are highly portable when compacted and are expanded on site rapidly without requiring foundation works.

Steel and aluminium are used for the main frame of the bridge in current full-scale prototypes as well as in digital simulations. Limitations in the load capacity of the current scissor bridge designs can be addressed through the utilisation of alternative materials such as FRP due to its superior strength-to-weight ratios. In addition, smart monitoring systems can also be implemented to limit deflections through the use of an active vibration control system.

Further work on stress simulation of a scissor bridge made up of FRPs is required to better understand the stress properties of the composite material. Application of topology optimisation to assist future scissor bridge design can also be evaluated to utilise a combination of translational, polar and angular SLE.

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