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Dynamics of the scissors-type Mobile Bridge

Yuki Chikahiro[a], Ichiro Ario[b,*], Piotr Pawlowski[c], Cezary Graczykowski[c], Masatoshi Nakazawa[d], Jan Holnicki-Szulc[c], Syuichi Ono[e]

[a]*Shinshu University, 4-17-1 Wakasato, Nagano 380-8553, Japan*
[b]*Hiroshima University, 1-4-1 Kagamiyama, Higashi-hiroshima 739-8527, Japan*
[c]*Institute of Fundamental Technological Research, Polish Academy of Sciences, ul. Pawinskiego 5B, Warszawa 02-106, Poland*
[d]*Tohoku Gakuin University, 13-1 Chuou 1, Tagajo 985-8537, Japan*
[e]*Japan Construction Method and Machinery Research Institute, Fuji 417-0801, Japan*

Abstract

We have experienced many times a phenomenon in which a bridge is washed away due to a typhoon, heavy rain in the rainy season, localized torrential rain, tsunami, and other flood disasters, or in which a bridge is damaged by an earthquake or a tremor. There is accordingly increasing demand for new technology and science to restore bridges that have been washed away or damaged. The paper presents a new type of emergency bridge, called Mobile Bridge^{TM}(MB), which can be quickly constructed in case of damages after a natural disaster. The concept of the bridge is based on the application of scissor-type mechanism, which provides its rapid deployment. Up to now several experimental MBs of different size were constructed and tested. The presented research reviews fundamental numerical and experimental results for the MB version 4.0 (MB4.0). Experimental testing included strain and acceleration measurements in free and forced loading conditions. From these results, it was possible to estimate basic dynamic characteristics of the bridge. Besides, in order to provide a basis for development of new construction methods for structural reinforcement and suppression of vibrations, various numerical analyses were conducted. The conducted research allows for a better and safer design of the movable and foldable full-scale bridge, the MB.

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Keywords: Deployable bridge; Scissors-type bridge; Emergency bridge; Light-weight structure; Temporary bridge

1. Introduction

We have many kinds of natural disasters such as earthquakes, floods, tsunamis, and landslides. Japan has a long history of devastating disasters, which have killed thousands of people and heavily destroyed infrastructure. In 1995, the great Hanshin-Awaji earthquake took place destroying many buildings and infrastructure. Portions of the country are still recovering from the Tohoku earthquake and tsunami in 2011. In recent years, there were many damaged bridges by several typhoons in local areas of Japan, Hokkaido, Tohoku and Kagoshima. Natural disasters can occur anywhere in the world and pose a threat to our lives. In the aftermath of a natural disaster, rapid restoration of the infrastructure is required. Repairing the damaged infrastructure is of the utmost importance, because this not only aids evacuation but also allows relief to be provided to local communities.

However, many risks and restrictions are present within the disaster zones. Even if a prefabricated bridge is used in an emergency, it takes a week or more until it is in a usable state. Because heavy machinery and emergency vehicles may be unable to access the site, recovery work may be delayed. In certain situations, the emergency bridge may be needed even where no professional structural engineers are available. Besides, new secondary hazards caused by localized damage are likely to impede any rescue operations. These situations raise the question of "what useful activities can be performed in the immediate aftermath of a natural disaster".

* Corresponding author. Tel.& fax: +81-82-424-7792
E-mail address: mario@hiroshima-u.ac.jp

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In the field of bridge engineering several studies have discussed the merits of modular bridges [1] and the use of lightweight materials, such as FRP [2] or air tubes [3]. Although these propositions allow the rapid construction of bridges, there remain various problems regarding the creation of large construction yards and the use of heavy industrial machines. However, any rescue technology should have a low level of complexity and high degree of resilience to enable its deployment by unqualified personnel. Hence, up to now, we propose a new type of foldable and deployable bridge called the Mobile Bridge (MB) (Japan Patent No.2006-037668 [4], PCT WO2015/193930A1 [5] as shown in **Fig. 1**). The MB can be deployed and folded quickly owing to a scissor mechanism [1], and it therefore provides highly efficient construction and easy transportation. The idea for this new bridge comes from academic studies on buckling based on Origami (Japanese traditional paper craft) [6], [7].

In previous studies of the MB [8] - [10], the mechanism and design concept were evaluated by numerical FE analysis followed by a fundamental static-loading test using a small experimental bridge. Now, the current research reviews field testing of the latest MB during real river crossing and its fundamental experimental and numerical results for the full-scale MB. Experimental testing included strain and acceleration measurements in free and forced loading conditions. From these results, it was possible to estimate basic dynamic characteristics of the bridge. Besides, in order to provide a basis for development of new methods for structural reinforcement and suppression of vibrations, various numerical models were created. The conducted research allows for a better and safer design of the MB.

2. MB based on Origami and Multi-Folding Technology

The scissors mechanism in its most basic form consists of two linear elements joined at their centres by a pivot providing a hinge-connection. In the fully deployed state the two members are in the shape of the character ‘X’ creating the deployed single scissor unit. This basic scissor unit is connected to the next unit by two hinges as shown in **Fig. 1**. The structure is deployable and has a large ratio of length of change from the fully extended state to the folded state. In the non-deployed or compact state the structure can be easily transported or stored for future reuse.

This concept of a scissor type mechanism was suggested by E. P. Pinero, an architect from Spain [11]. He applied this idea to a deployable roof structure and obtained a patent in 1961. After this successful application, T. R. Zeigler and F. Escring focused on the geometric layout design of the scissor units and put forward deployable domes using the mechanism [12], [13]. Recently M. Saito [14] has analyzed the strength and stability of scissor structures reinforced with a string system. Indeed, scissor type structures are increasingly used in a wide range of mechanical and space engineering fields [15].

Our current study for the MB plays an important role as an innovative product in the bridge engineering field. The scissors mechanism enables the MB to be constructed and easily transported because of the compact pre-assemble configuration. These fundamental concepts of the design of the MB result in following advantages:

1. The MB uses the patented technology [4], [5] based on a scissor mechanism for deploying an emergency bridge system set within a modular and pre-assembling or less-assembling design.
2. The MB is a compact transportable bridge system, *robotic bridge*, which is suitable for transportation on a car trailer or lorry.
3. The MB system has a completely novel design and offers extraordinary performance that cannot be matched by the older block assembly approach.

In addition, the MB can be deployed in a wide range of areas not only in emergency situation but also for normal operation. For example, many existing old bridges are in a poor technical state due to improper maintenance or overloading. Smaller bridges can be kept operational using the MB serving as temporary bridge. This provides the advantage of keeping bridges operational without interrupting traffic and increasing further damage to the existing bridge.

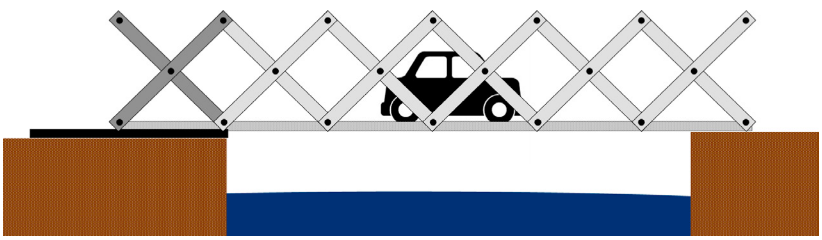


Fig. 1. New concept of a scissor bridge based on Origami-folding idea.

[1] Although the upper and lower chords are the main elements that resist sectional forces in an ordinary truss bridge, the MB lacks chords but can be transported and constructed quickly using a scissor mechanism.

(a) Expansion process of the MB4.0 (b) First test of the MB4.0

Fig. 2. Tests of foldable, movable and deployable bridge “Mobile bridge^{TM}” at 24th March 2015.

Table 1. Configurations under a car loading for the MB4.0

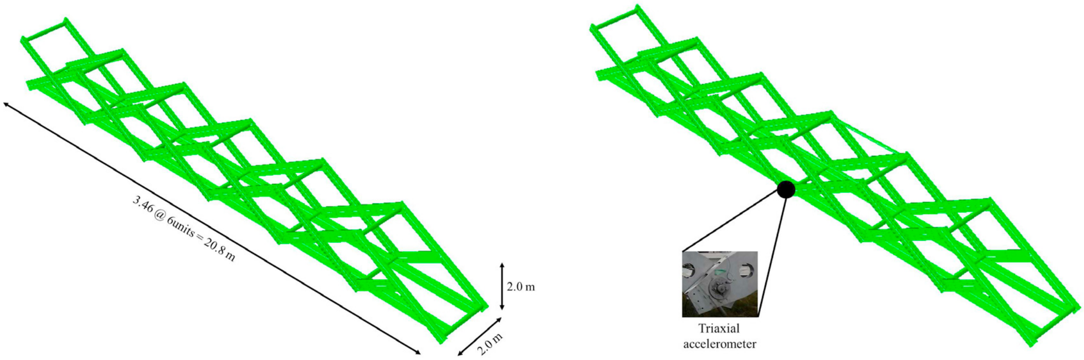
Item	Details	Remarks
Length	3 m ∼ 20.8 m	6 units
Span	0 m ∼ 17. 3 m	5 units
Load for the deck	40 kN per a unit	For a car
Width	Outside: 2.5 m ∼ 3.0 m	Inside: 2 m
Height	Standing: 5 m	Carrying: 3.1 m, inside: 2 m
Weight	About 130 kN	-
Workers	2-3 persons	-
Expanding time	5-10 min.	-
Construction time	1 hour	-
Appear	Hiroshima	25th April 2013
Test place	Hongo river at Fukuyama	24th March 2015

3. First test of crossing a river

We review the release of the first test of full-scale of novel scissor-like bridge structure, “Mobile bridge version 4.0 (MB4.0)” [16] - [18] inspired by *traditional Japanese origami*. A research team at Hiroshima University’s Institute of Engineering, carried out a field test in conditions resembling real situation of deployment of the bridge. The test of the MB4.0 over a real river named Hongo river demonstrated its capability for practical use on 24th April 2015 in Fukuyama in Japan. The width of Hongo river was surveyed approximately 17m.

During the test the MB4.0 arrived to one side of the river carried by a heavy trailer. The bridge is equipped with a out-rigger system, which enables automatic removal from the transport trailer after connecting to a hydraulic pump. In the next step, the bridge, which is transported in the horizontal position is rotated by 90 degrees to the pre-deployment state. The expansion process can be easily controlled and it took only five minutes for the bridge to be fully deployed. The MB4.0 reached safely the other side of the Hongo river without any technical problems and was operated by a very limited technical crew, as shown in **Fig. 2**. The total time from the arrival of the MB4.0 on site to its full expansion is approximately one hour. No works, including preparation of foundations on the other side of the river were carried out during the test. The deployment of the bridge also did not involve use of a crane or any other construction machines, which are typically involved in such situations. This is especially important for time-sensitive situations such as natural disasters.

In the current research, we developed the MB4.0 as a type of *robotic bridge* by improving its mobility and functionality and decreasing its weight. Thus, the MB4.0 has become more transportable and easier to set up at temporary construction sites without any foundation, construction works or heavy machine operations. As a result, it is also much more cost efficient. The current model, the MB4.0, has the length of about 20 m and the height of 2 m, as shown in **Table 1**. Main structural members of the bridge are made of extruded aluminum alloy while the frame for the hydraulic deployment system is constructed of steel SS400.



(a) The MB4.0 without reinforcement (b) The MB4.0 with reinforcement

Fig. 3. FE numerical model and experimental setup of the MB4.0.

Table 2. Numerical and experimental results for frequency analysis of the MB4.0.

Case	Boundary condition	Horizontal direction(Hz)		Vertical direction(Hz)	
		Numerical analysis	Experimental testing	Numerical analysis	Experimental testing
1	Cantilever condition	0.6	-	0.9	-
2	Both-ends supported condition	1.2	1.6	4.6	3.7
3	Both-ends supported condition with reinforcement	2.1	-	6.1	-

4. Fundamental dynamics of MB4.0

4.1. Numerical and experimental conditions

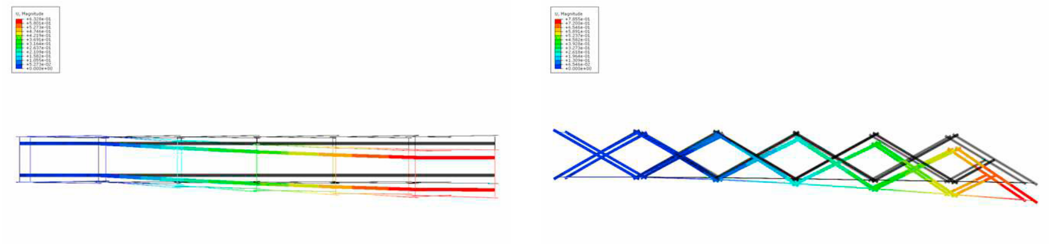
In case of the deployable structures, apart from static analysis of different configurations of expansion, it is very important to investigate the dynamic behavior of the system. High compliance and flexibility of the scissors-type bridge may influence user's comfort and safety in case of heavy dynamic loads such as human induced impacts, wind gusts or earthquakes. Hence, in order to make clear the fundamental dynamics of the MB, that is natural frequency and vibration mode, we carried out numerical simulation and experimental testing for the MB4.0.

In the numerical simulation, FE numerical model is set up by numerical software of ABAQUS 6.12 as shown in **Fig. 3** (a) and (b). The model is represented in 3D considering folding deck-boards system by use of beam elements. The pivot part which is connecting two components is allowed to rotate without any friction. Detail modeling method can be found in our previous paper[10]. The material of the main frame members are made of combination of the aluminum alloy AN01 and steel SS400. The steel member is set on the leftmost unit of the diagonally right up member. Another member is made of the aluminum alloy. In addition to the fundamental analysis of dynamics of the bridge, we evaluated numerically the effect of reinforcing of the structure by additional strut member. The reinforcing member is applied in the middle of the upper hinge part of the bridge.

In the experimental testing, we measured the acceleration of the MB4.0 under both-ends supported condition using triaxial acceleration sensors, which were positioned on the lower hinge parts in the middle of the MB4.0 as shown in **Fig. 3** (b). Vibrations of the MB4.0 were measured in free and forced loading conditions.

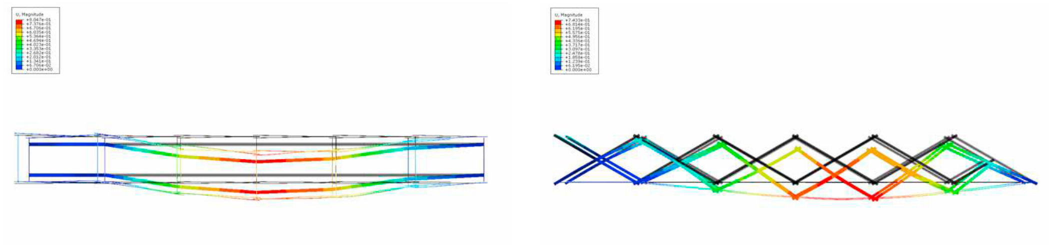
4.2. Numerical and experimental result

The considered problem was eigenvalue analysis aimed at finding natural frequencies of free vibrations and the corresponding vibration modes. Herein, the preliminary results of the eigenvalue analysis of the MB4.0 and its vibration modes are presented as shown in **Table 2** and **Fig. 4** $\sim$ **Fig. 6**. The experimental results were calculated by FFT (Fast Fourier Transformation) using measured accelerations. The eigenvalues for horizontal and vertical direction under both-ends supported condition are 1.6 Hz and 3.7 Hz, respectively. These results indicate that in case of the MB4.0 the vibrations in horizontal direction are stronger than in vertical direction.



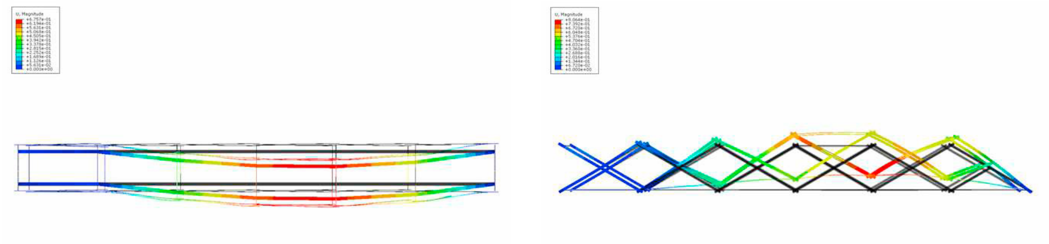
(a) 1^{st} mode for horizontal direction (b) 1^{st} mode for vertical direction

Fig. 4. Vibration modes in cantilever condition.



(a) 1^{st} mode for horizontal direction (b) 1^{st} mode for vertical direction

Fig. 5. Vibration modes in both-ends supported condition.



(a) 1^{st} mode for horizontal direction (b) 1^{st} mode for vertical direction

Fig. 6. Vibration modes in both-ends supported condition with reinforcement.

When we compare the experimental results with the numerical results, the frequency in the horizontal direction shows good accuracy, but results in the vertical direction are slightly different. This discrepancy may result from the method of modeling of deck boards. In our simulation, deck boards are positioned on each lower hinge of the bridge as simply supported. However, in reality, deck boards are foldable and connected to the main structure in more complex way to realize the fully automatic deployment of the bridge as shown in **Fig. 2** (a). Therefore it is considered that numerical results show higher values of resonant frequencies due to higher stiffness comparing to experimental values in the vertical direction. It is also found that modeling method of the deck boards does not affect the results in the horizontal direction.

When we apply the reinforcing member at the middle of the top level of the bridge, the eigen-frequencies both in horizontal and vertical direction increase from the non-reinforced state. These results indicate that by applying reinforcing members the stiffness of the MB4.0 is increased due to reduction of the effect of bending moments in the main structural members. Hence by applying the proper reinforcement to the MB after deployment, control of bridge's stability can be improved resulting in a higher level of safety.

5. Conclusions

This paper presented the new design of the full-scale MB4.0 with integrated lower deck boards and field experiment related to crossing of a real river in Japan. After demonstrating structural safety of the bridge, we carried out fundamental numerical simulation and experimental testing to investigate the dynamics of the MB4.0. The results lead to the following conclusions:

- We succeeded to develop the full-scale scissor type bridge for vehicles and demonstrated its usability based on the field experiment over a real river.
- During the test, the robotic bridge was deployed within one hour without any works carried out on foundations, and vehicles could easily travel across it. This was safely achieved with very few people and without any technical problems.
- The eigenvalue analysis and experimental measurements revealed the basic vibration modes of the MB4.0 and indicated that the bridge is prone to vibrations in horizontal direction due to smaller corresponding stiffness in this direction.
- By applying reinforcing member, the stiffness of the MB4.0 was improved for both horizontal and vertical direction due to reduction of the effect of bending moment in the main structural members of the bridge.

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