APPLICATION OF STEEL-GFRP HYBRID COMPOSITE TO ASYMMETRIC CABLE-STAYED BRIDGE FOR EMERGENCY DISASTER RELIEF

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Abstract

This study develops a temporary bridge system by using a self-weight balance approach and a cantilever incremental launching method. An asymmetric self-anchored cable-stayed bridge is proposed. The structural segments constructed by heavyweight materials (e.g., steel and concrete) are used as counter-weights at the rescue end and the cross-river segments are constructed by lightweight materials (e.g., composite materials) in order to increase the span to easily reach the isolated island end without any supports or foundations. The lightweight temporary composite bridge system includes a weight balance structural module, a bridge tower structural module, a crossing structural module, and connection cables. By combining the great strength and light weight of glass fiber reinforced composite material with the structural features of an asymmetrical cable-stayed bridge, this technology overcomes the time restrictions imposed in the past by the use of temporary roadways made from concrete pipes (which often take from 3 days to a week for construction) and temporary steel bridges (require approximately 1-3 weeks for installation). In contrast, this transportable bridge can be assembled within 6 hours, and possesses the advantages of (1) quick assembly, (2) do-it-yourself use by residents, and (3) reusability.

1. Introduction

Owing to resent extreme climate, typhoons floods and earthquakes have become the largest threat of natural disaster in Taiwan over the years. For example 88 floods were caused by the Typhoon Morakot in 2009, and more than 200 bridges were damaged and more than 100 bridges were washed away (Fig. 1a). Chi-Chi Earthquake in 1999 also caused more than 150 bridges damaged (Fig. 1b), resulting in isolated mountain communities, to which emergency relief supplies could not be easily delivered.

The advanced composite materials have found expanded use in aerospace, marine and automobile industries during the past few years due to their good engineering properties such as high specific strength and stiffness, lower density, high fatigue endurance and high damping, etc. The advantages of fiber reinforced polymer (FRP) composites make them attractive for use in replacement decks or in new bridge systems as well. Such as (1) bridge decks, including FRP rebar reinforced concrete deck systems, FRP grid and grating reinforced concrete deck system, deck system made completely out of FRP composite and hybrid FRP plate reinforced concrete deck systems, (2) FRP composite bridge

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girders and beams, including glass fiber reinforced polymer (GFRP) composite girders, carbon fiber reinforced polymer (CFRP) composite girders and hybrid girders and (3) slab-on-girder bridge systems [1].

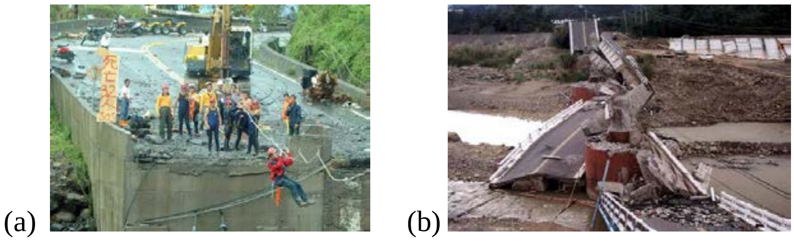

Figure 1. Damage of bridge and disaster relief due to: (a) Typhoon Morakot and (b) Chi-Chi Earthquake.

FRP bridge technology has moved rapidly from laboratory prototypes to actual demonstration projects in this field. Worthy of mentioning, the world's first pedestrian bridge constructed entirely of FRP composites dates back to 1972, and is a single span (span length of 24 m and width of 1.8 m) bridge in Tel Aviv, Israel with total weight 2.5 tons of GFRP [2]. The world's first vehicle bridge, Miyun Traffic Bridge, constructed entirely of FRP dates back to 1982, and is a single span (span length of 20.7 m) two-lane (width of 9.2 m) bridge in Beijing, China with GFRP girders made from hand lay-up process [3]. The bridge was constructed by approximately 20 workers within two weeks assisted only by a light gin pole and capstan winches. Furthermore, the world's first cable-stayed bridge, Aberfeldy Foot-Bridge, is located at Scotland, and is made completely out of composites (GFRP for super-structure, aramid fiber for cable), 113 m long [1].

Nowadays, FRP composite are used mostly in deck systems, footbridges and vehicle bridges. This paper focuses on the advantages of FRP composite in applications for typhoon, flood and earthquake disaster rescue in Taiwan. The objective of this paper is to present: (1) a novel lightweight bridge which is portable, reusable, and transportable by manpower, (2) adjustable structural joints that combine bolts, welding, and adhesive method for easy manufacture and rapid assembly, and (3) effective structural design techniques for increasing the bonding strength of joints and decreasing the deflection-to-span ratio.

2. Conceptual Design and Major Challenges

2.1. Conceptual Design of Temporary Bridge for Disaster Relief

In order to design a lightweight bridge with portable, reusable, and suitable capabilities for transportation, the following design requirements are considered: (1) for the disaster relief and transportation of goods, the design goals for the temporary bridge are set to a span length of 20 m, a width of 3 m, a live load of 5 tons (for transport the rescue goods via truck of 3.5 tons) and a deflection-to-span ratio of L/400 (the design goal may be modified by the actual requirement of a disaster region), (2) for the lightweight requirement, the advantages of composite materials are used for the temporary bridge, (3) for the short to medium span bridge, the beam-type or truss-type bridge is considered, for the medium to long span bridge, the cable-stayed bridge or suspension bridge could be considered, and (4) for the requirement for transportation using manpower, the weight limitations of 20 kg per frame and 250 kg per segment are considered.

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2.2. The Major Challenges

The report-"FRP bridge - technologies and prospects" [4] showed that the drawbacks of a FRP composite bridge includes, (1) the low modulus of materials (comparing with steel) and low stiffness of the FRP components which leads to large deflection of the structure, (2) the joints and connections should be simplified, and (3) the high price of composite materials, the cost-effective problems should be considered.

Base on above literature reviews, the major challenges for the design of a FRP temporary composite bridge to be considered are: (1) the stiffness of the composite frame should be improved to meet the deflection-to-span ratio requirement, (2) the effective and simplified joints and connections of the composite structure should be studied, (3) for light weight, sufficient strength, acceptable stiffness, and reasonable price, the cost-effectiveness of composite materials should be determined their use, and (4) a novel bridge structure for the lightweight bridge with portable, reusable, and suitable capabilities for manual transportation need to be innovatively created.

2.3. Concept and construction sequences

The development of a suitable bridge type with the function of quickly to restoring traffic and providing emergency disaster relief is important. This bridge should be constructed within a short time and limited by few manpower and simple tools and should also be portable and reusable. This study develops a temporary bridge system by using a self-weight balance approach and a cantilever incremental launching method. An asymmetric self-anchored cable-stayed bridge is proposed. The structural segments constructed by heavyweight materials (e.g., steel and concrete) are used as counter-weights at the rescue end and the cross-river segments are constructed by lightweight materials (e.g., composite materials) in order to increase the span to easily reach the isolated island end without any supports or foundations.

The advantages of this composite bridge include the following: (1) during the construction stage, the asymmetric self-anchored cable-stayed bridge is easily constructed from the rescue end to the isolated island end by using the self-weight balance of heavyweight structural segments and lightweight cross-river segments. The wires of the cable-stayed bridge are helpfully for the construction of cross-river segments by using the cantilever incremental launching method; further, (2) during the commissioning completion stage, these wires are effective in reducing the deformation of the bridge caused by live loads from traffic.

The lightweight temporary composite bridge system includes a weight balance structural module, a bridge tower structural module, a crossing structural module, and connection cables. The weight balance structural module and the bridge tower structural module are constructed of steel, concrete, and any other heavyweight materials as structural segments. The crossing structural module is constructed of composites and any other lightweight materials. The construction sequences is as follows: (1) assemble the structural segments to complete the weight balance structural module (Fig. 2a); (2) assemble the structural segments to complete the bridge tower structural module, fix the bottom part to the weight balance structural module, and couple the top part to the weight balance structural module via at least one connection cable (Fig. 2b); and (3) assemble the crossing segments between the rescue end and the isolated island end gap (Fig. 2c) to complete the crossing structural module and couple it to the top part of the bridge tower structural module via at least one connection cable (Fig. 2d).

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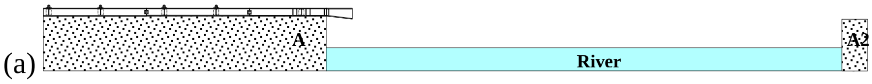

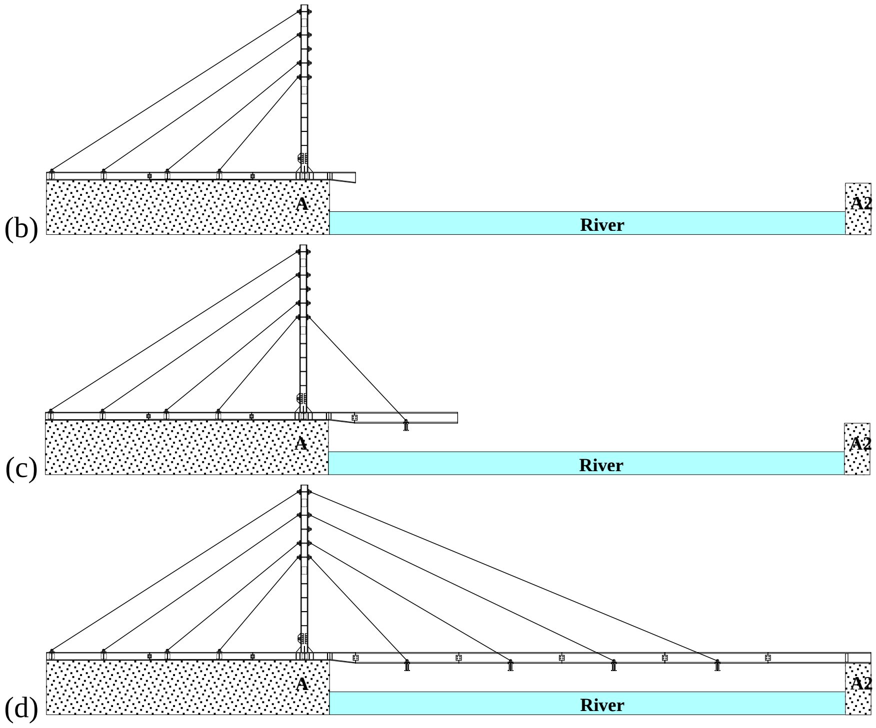

Figure 2. Construction sequences: (a) assemble the weight balance structural module, (b) assemble the bridge tower structural module, (c) assemble the crossing structural module, and (d) complete the construction of the bridge.

3. Material properties and detail design of composite bridge

The pultruded H-shaped GFRP girders, which were produced by a local manufacturer in Taiwan, are shown in Fig. 3. The 410 mm × 20 mm × 200 mm × 18 mm H-shaped composite girders, with a length of 8.0 m, are cut into two parts with lengths of 6.5 m and 1.5 m. The 6.5 m long girder provides moment capacity and bolted connection test for the composite girder as illustrated in the next section. Part of the 1.5 m long girder is cut as specimens for the material property test and as multiple fasteners for the bolted connections test. The experimental results of the material property test for the GFRP girder shows the linear relation of the stress-strain curves for the tensile specimens of the GFRP girder. The elastic moduli can be obtained from the linear regression of the stress-strain curve, which are 12.73 GPa in the web and 28.30 GPa in the flange of the GFRP girder. Table 1 shows the theoretical and experimental results of the material property test for the GFRP girders. The elastic modulus of the theoretical and experimental results on the web of the composite girder is very similar; however the value shows some difference in the flange of the GFRP girder.

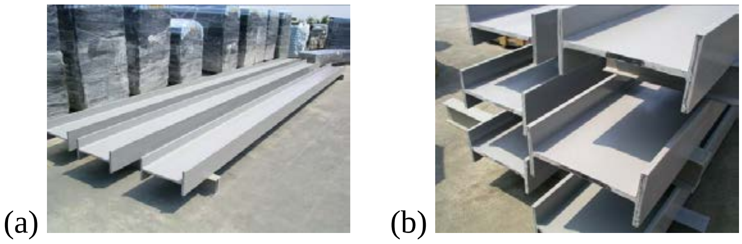

Figure 3. Appearance and cross section of the H-shaped GFRP girder: (a) pultruded H-shaped GFRP girder and (b) the cross section of the GFRP girder.

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Table 1. Material properties of the GFRP girder.

Material type	Position	Elastic modulus E (GPa)	
		Theoretical	Experimental
GFRP	Flange	23.24	28.30
	Web	12.82	12.73

The composite bridge is composed of structural steel and GFRP composite materials. In this paper, steel structural design follows the Taiwan local code of steel building construction [5] and composite structure using the design code proposed by the U.S. Department of Agriculture (USDA) Forest Service [6] and the American Association of State Highway and Transportation Officials (AASHTO) [7]. The following equations are used for the design of the steel components in the temporary composite bridge system:

$$\frac{f_a}{0.6F_a}+\frac{f_{bx}}{F_{bx}}+\frac{f_{by}}{F_{by}}\leq 1.0 \tag{1}$$

$$\frac{f_a}{F_a}+\frac{C_{mx}f_{bx}}{\left(1-\frac{f_a}{F'_{ex}}\right)F_{bx}}+\frac{C_{my}f_{by}}{\left(1-\frac{f_a}{F'_{ey}}\right)F_{by}}\leq 1.0 \tag{2}$$

$$\frac{f_v}{F_v}\leq 1.0 \tag{3}$$

In these equations, the expressions f_a and f_b represent the actual axial and bending stress, respectively; F_a and F_b denote the allowable axial and bending stress, respectively; C_m corresponds to a modification factor; F'_e represents Euler's critical buckling stress; f_v denotes the actual shear stress; and F_v represents the allowable shear stress.

Parallel FRP girder bridge systems are studied to meet the design requirements of a span of 20 m, a width of 3 m, a live load of 5 tons (for transportation of rescue goods via a truck weighing 3.5 tons), and a deflection-to-span ratio of L/400, which is suggested by AASHTO [7]. The 410 mm × 20 mm × 200 mm × 18 mm H-shaped composite girders are used in the bridge system. The material properties of GFRP are as follows: Young's modulus = 20.03 GPa; density = 1.72 g/cm^3; and allowable stress = 207 MPa. We have designed a steel-composite cable-stayed bridge with a span of 20 m, a width of 3 m, and a live load of 5 tons (for transportation of rescue goods via a truck weighing 3.5 tons) and a deflection-to-span ratio of L/400 for the assembled and river-crossing test. Fig. 4 shows the design results of the asymmetric self-anchored cable-stayed bridge. Seven parallel steel girders and H-shape pillars using A572 grade 50 steel with a 294 mm × 200 mm × 8 mm × 12 mm cross section on the A1 side abutment are used as the weight balance structural module, five parallel FRP girders using GFRP with a 410 mm × 200 mm × 18 mm × 20 mm cross section are used as crossing structural module, and double-H-shape steel cross beams are used to aid the crossing of the river (Fig. 4a and 4b). We used a steel frame on the A1 side abutment as a counterweight and a cable-stayed type bridge to quickly assemble the lightweight GFRP temporary bridge via the incremental launching method to cross the river and therefore achieve the goal of providing disaster relief. By using the same capacity for connection design (details of the connection are shown in Fig. 4c), the numerical result shows that connection between the steel girder and the GFRP girder is not the critical connection; instead, the critical connection is located at connection G4 between GFRP segment C and GFRP segment D (Fig. 4d).

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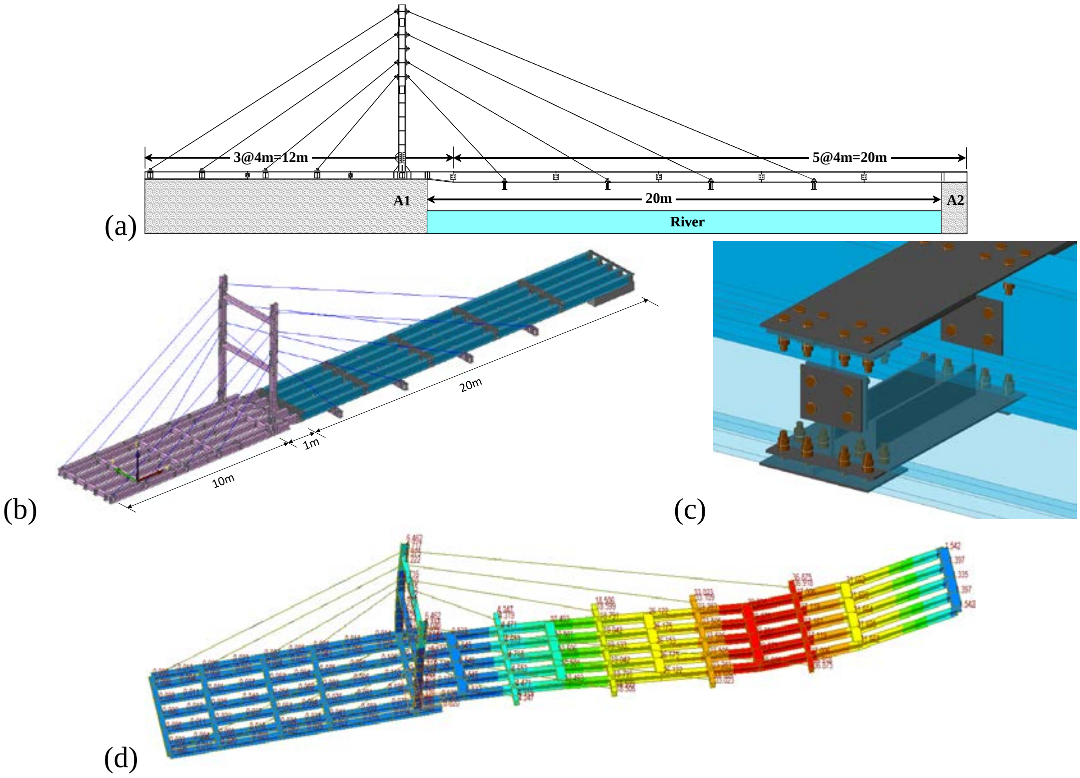

Figure 4. Design results of the 20 m span temporary composite bridge: (a) the front view (b) the 3D view, (c) the bolted connection using bolts and a steel connection plate, and (d) the shape of deformation.

4. Experimental verification of the composite bridge for emergency disaster relief

4.1. Construction sequences and river-crossing tests

The construction sequence is shown in Fig. 5 and is as follows: (1) step 1: assembly of seven parallel steel girders with 294 mm × 200 mm × 8 mm × 12 mm cross sections and a total length of 12 m (3@4m), and a bolted connection at the web of the girder with box cross beams (200 mm × 200 mm × 6 mm) (Fig. 5a); (2) step 2: assembly of H-shape pillars with 18 connection devices for the steel cable, with 294 mm × 200 mm × 8 mm × 12 mm cross sections and a total height of 6.5 m (Fig. 5b), and a bolted connection with the top flange of the outer girders of the seven parallel steel girders at the third segment (Fig. 5c); (3) step 3: assembly of the first segment of the five parallel GFRP girders (Fig. 5d) and then connection to the third segment of the weight balance structural module (Fig. 5e); (4) step 4: assembly of the second segment of the five parallel GFRP girders by using the same sequence as the previous step (Fig. 5f) and then connection to the first segment of the crossing structural module (Fig. 5g); and (5) step 5: assembly of the third to final segment of the five parallel GFRP girders by using the same procedure as the previous step (Fig. 5h) and completion of the construction sequence to cross the river (Fig. 5i). The test results show that the 20 m span temporary composite bridge for emergency disaster relief was constructed by 30 workers within 6 hours via manpower, simple tools, and a small truck with a crane – ultimately meeting the requirements for emergency disaster relief.

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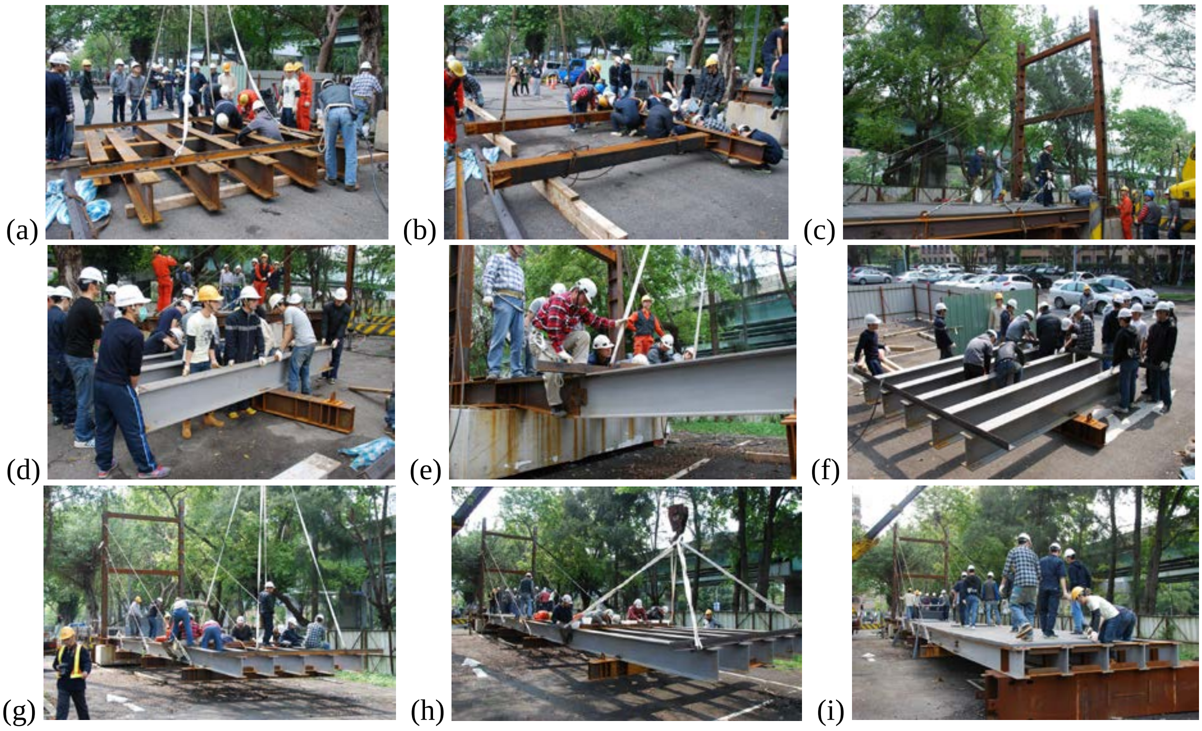

Figure 5. Construction sequence of the 20 m span temporary composite bridge: (a) seven parallel steel girders assembly, (b) connection of the weight balance structural module, (c) the H-shape pillars assembly, (d) connection of the bridge tower structural module, (e) first segment of the GFRP girders assembly, (f) connection of the crossing structural module, (g) second segment of the GFRP girders assembly, (h) and (i) connection of the crossing structural module, and (j) completion of the composite bridge construction.

4.2. Full scale flexural and dynamic tests

The experimental setup of a temporary composite bridge with a span of 20 m is shown in Fig. 6a and the different loading positions of a small truck weighing 3.5 tons (total weight 5 tons) is shown in Fig. 6b. The test program includes a flexural test, an off-axis flexural test, and a dynamic test. The results of the flexural and dynamic tests are shown in Fig. 7. The deformed shapes are shown in Fig. 7a and Fig. 7b. The maximum displacements are 53.41 mm (flexural test) and 56.23 mm (off-axis flexural test) and occurred at connection G4. The maximum longitudinal strains are 5.05×10^{-4} (flexural test) and -5.53×10^{-4} (off-axis flexural test) and occurred on B3 at the left hand side of connection G4 (Fig. 7c). The deflection versus time at connection G4 is shown in Fig. 7d. The flexural and dynamic test results indicate that the deflection-to-span ratio is around L/356, which is very close to the design requirement of L/400, for a live load of 5 tons.

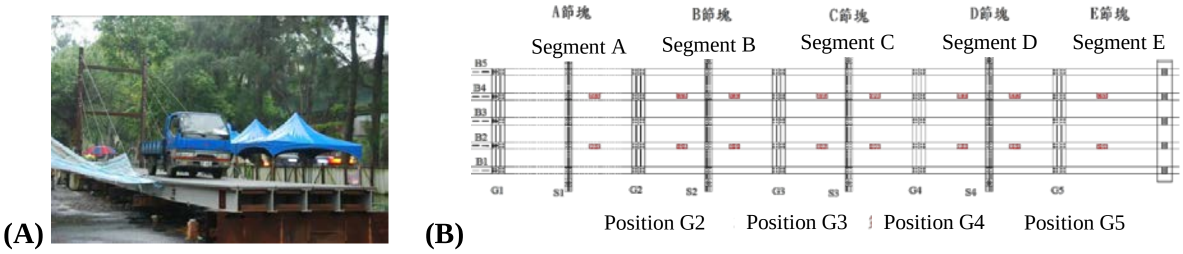

Figure 6. The experimental setup of the 20 m span temporary composite bridge: (a) the test setup and (b) the wheel position of a small truck.

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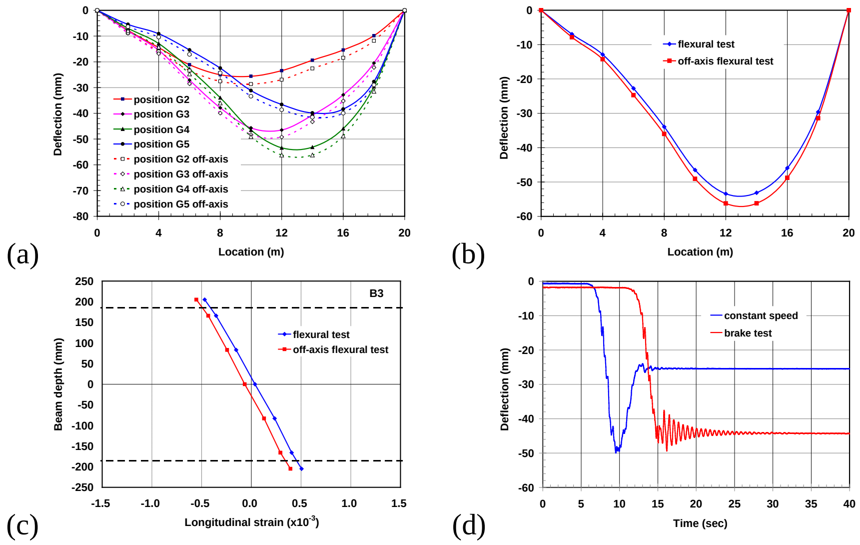

Figure 7. Flexural and dynamic test results of the 20 m span temporary composite bridge: (a) the deformed shape (different loading position), (b) the deformed shape (loading at position G4), (c) the longitudinal strain along the depth of the B3 girder, and (d) deflection versus time at connection G4.

5. Conclusions

This paper developed a lightweight, portable, and reusable temporary composite bridge for emergency disaster relief. This bridge is an asymmetric self-anchored cable-stayed bridge designed using steel-FRP composite materials to improve the stiffness of the composite frame, reduce the deflection of the bridge, and allow easy travel across a river without any supports or foundations. All of these achievements ultimately reach the goal of disaster relief through the use of the concept of weight balance and the incremental launching method. The current research results are summarized as follows: (1) for the in situ test of a 20 m temporary composite bridge for emergency disaster relief, the novel bridge was constructed by 30 workers within 6 hours through the use of manpower, simple tools, and a small truck with a crane to meet the requirements of emergency disaster relief; (2) the flexural and dynamic test results indicate that the deflection-to-span ratio is around L/356, which is very close to the design requirement of L/400, for a live load of 5 tons.

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