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DESIGN CONCEPT AND VERIFICATION OF TEMPORARY RESCUE BRIDGE USING LIGHTWEIGHT COMPOSITE MATERIALS

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ABSTRACT: Typhoons and earthquakes, which occur frequently in Taiwan, often lead to the washout or collapse of river bridges, thereby causing traffic interruption. A project was proposed at the National Center for Research on Earthquake Engineering (NCREE) to restore traffic as soon as possible and to provide necessary emergency rescue services in the aftermath of these events. The proposed solution was to develop a type of temporary rescue bridge that was portable, reusable, and easily assembled by unskilled residents. The objective of this paper was to present an emerging design concept and verification of a temporary rescue bridge. An asymmetric, self-anchored, cable-stayed bridge with heavyweight segments used as a counter-weight at the rescue end and river-spanning segments constructed with lightweight materials was proposed. In the design review stage, to verify the design concept and feasibility of the temporary rescue bridge, a simply supported bridge with a span length of 10 m, assembled from five H-shaped glass fiber reinforced polymer (GFRP) segments, was tested in the laboratory. Static, fatigue, and strength tests were performed on the specimen to investigate its performance under live loads, followed by a strength test to examine its ultimate capacity. In the design verification stage, a series of cross-river tests were performed sequentially to assess its adherence to design requirements, followed by in situ, full-scale, flexural and dynamic tests to examine performance and feasibility. The experimental assembly and results demonstrated the feasibility of the proposed design concept, and showed good potential for using an asymmetric self-anchored cable-stayed bridge for temporary rescue operations.

KEYWORDS: Asymmetrical cable-stayed bridges; Design concept and procedure of temporary rescue bridge; Emergency disaster relief; Glass-fiber-reinforced composite; Lightweight, portable, reusable bridge.

1 INTRODUCTION

As a result of recent climate change, typhoons, floods, and earthquakes have become the most common and problematic types of natural disaster in Taiwan. For example, 88 floods were caused by Typhoon Morakot in 2009, during which, more than 200 bridges were damaged [1], and over 100 more were washed away (*Fig. 1a*). The Chi-Chi Earthquake in 1999 [2] also caused more than 150 bridges to be damaged (*Fig. 1b*), isolating mountain communities and interfering with the delivery of emergency relief supplies.

(a) (b)

Figure 1. Damage to bridges and disaster rescue operations following: (a) Typhoon Morakot, and (b) the Chi-Chi Earthquake

The use of advanced composite materials in the aerospace, marine, and automobile industries has expanded over the past few years, due to the ideal engineering properties of these materials. These properties include high specific strength and stiffness, low density, high fatigue endurance, and high damping capability. The characteristics of fiber-reinforced polymer (FRP) composites make them attractive for use in replacement decks or new bridge systems. Examples of their use include the following: (1) bridge decks, including FRP-rebar-reinforced concrete deck systems, FRP-grid-and-grating-reinforced concrete deck systems, deck systems made completely out of FRP composite, and hybrid-FRP-plate-reinforced concrete deck systems; (2) FRP composite bridge 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 [3]. A composite material could be defined as a combination of two or more materials that gave better properties than those of the individual components used alone. In contrast to metallic alloys, each material retained its separate chemical, physical, and mechanical properties. [4].

FRP bridge technology has progressed rapidly from laboratory prototypes to actual demonstration projects in this field. It was noteworthy that the world's first pedestrian bridge constructed entirely of FRP composites was built in 1972, and was a single span (span length of 24 m and a width of 1.8 m) bridge in Tel Aviv, Israel, with a total weight of 2.5 tons of GFRP [5]. The world's first vehicle bridge constructed entirely of FRP, the Miyun Traffic Bridge, was built in 1982, and was 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 a hand lay-up process [6]. 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, the 133 m Aberfeldy Foot-Bridge located in Scotland, was built entirely from composites (GFRP for the super-structure and aramid fiber for the cables) [3].

A movable temporary bridge that was foldable, extendable, and made with aluminum was designed using stress base optimization methods [7]. The prototype bridge had a length of 1 m when folded and a maximum length of 5.2 m when extended. It could bear the weight of three adults. The operating procedure was very simple; a single person could complete the assembly of the whole bridge within two minutes. Meanwhile, a new type of scrolling lightweight arched bridge had being researched in the US [8]. The prototype model had a length of 3 m and a width of 0.25 m. The bridge consisted of a motor and a cable reel that controlled the entire process of retracting, extending, and recovering the spanning segments. The advantage of a temporary bridge was that only one reel motor was required for complete assembly. A deployable lightweight bridge that facilitates transported and reduced assembly and erection time had also been researched. It used GFRP pipe and steel adapters for connecting trusses, as well as pre-stressed steel cable that was placed into GFRP tubing to increase the stiffness of the bridge [9]. The experimental model for this design was 13 m long, and its advantages were primarily seen during the assembly process. Since no bolts were used, there were comparatively fewer assembly steps and parts, which greatly reduced assembly time.

Nowadays, FRP composites are used mainly in deck systems, footbridges, and vehicle bridges [10]. This paper focuses on the advantages of FRP composites in typhoon, flood, and earthquake disaster rescue applications in Taiwan. The objective of this paper was to present an emerging design concept for, and verification of a temporary rescue bridge. It also presented a novel bridge structure for a portable, reusable, and lightweight bridge and experimental verification of the temporary composite bridge for disaster relief.

2 DESIGN CONCEPT FOR TEMPORARY RESCUE BRIDGE

The design process of a bridge could be divided into four basic stages: conceptual design, preliminary design, detailed design and construction design. The purpose of the conceptual design was to come up with various feasible bridge schemes and to decide on one or more final concepts for further consideration. The purpose of the preliminary design was to select the best scheme from these proposed concepts and then to ascertain the feasibility of the selected concept [11, 12]. The procedure for solving the design problem of a temporary rescue bridge incorporates problem-solving strategy and technique. In the bridge design procedure, the problem-solving strategy is used in planning or preliminary design for the initial stages, while the problem-solving technique is used to deal with the detailed design (detailed analysis and calculation of the completion of the drawings). A more complete procedure will include problem-solving at the construction stage. At present, school education and literature are focused on the technical level, such as the establishment of mechanical concepts, component strength calculation and design methodologies, while less research focuses on problem-solving strategy and design concepts for temporary rescue bridges.

2.1 Challenges in emergency bridge design

Natural disasters often lead to the washout or collapse of bridges, thereby causing traffic interruption. In order to restore traffic and to provide necessary emergency rescue services, the most commonly used temporary rescue bridges in Taiwan are temporary roadways made from concrete pipes, which often take from three days to one week to construct (*Fig. 2a*) and temporary steel bridges, which take 1-3 weeks to install (*Fig. 2b*), but the assembly time is often too slow to provide urgently required aid.

The main disadvantage and limitation of the above two types of temporary rescue bridge are the following: (1) construction depends on the water level and associated dangers; (2) they are unable to deliver disaster relief supplies in adequate time. Thus, the challenges and functional requirements for emergency bridges are as follows: (1) easy transportation and quick assembly, since the commonly used temporary rescue bridges take a long time to complete, disaster relief is often delayed in the meantime; (2) reusability, in order to help customers save on costs, a quick assembly and disassembly design for temporary rescue bridges should be adopted, enabling the bridge to be quickly disassembled after use to facilitate repeated usage in the future.

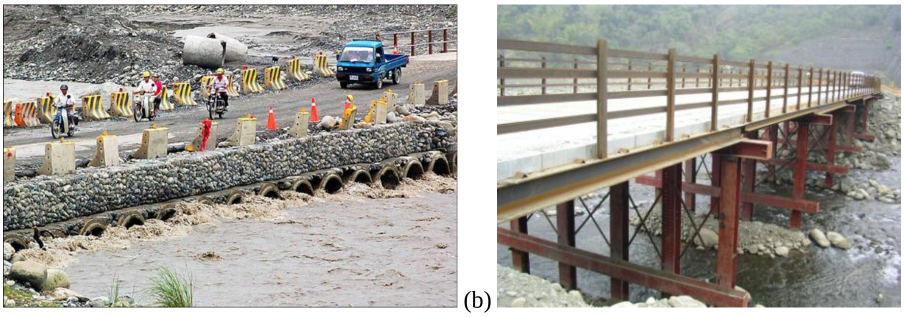
(a)  (b)

Figure 2. The most commonly used temporary rescue bridges in Taiwan, (a) temporary roadways made from concrete pipes, and (b) temporary steel bridges

Temporary rescue bridges should enable disaster relief materials to be shipped into disaster areas and allow victims to be evacuated for medical treatment, effectively reducing loss of lives and property.

2.2 Design concept and procedure

This paper proposes an emerging design concept developed by a logical procedure (*Fig. 3*), to help bridge designers with the problem-solving strategy for temporary rescue bridge design. Furthermore, the procedure considers the design review stage and design verification stage of temporary rescue bridges to ensure that the design output meets the requirements of the design input, a crucial step in the design process.

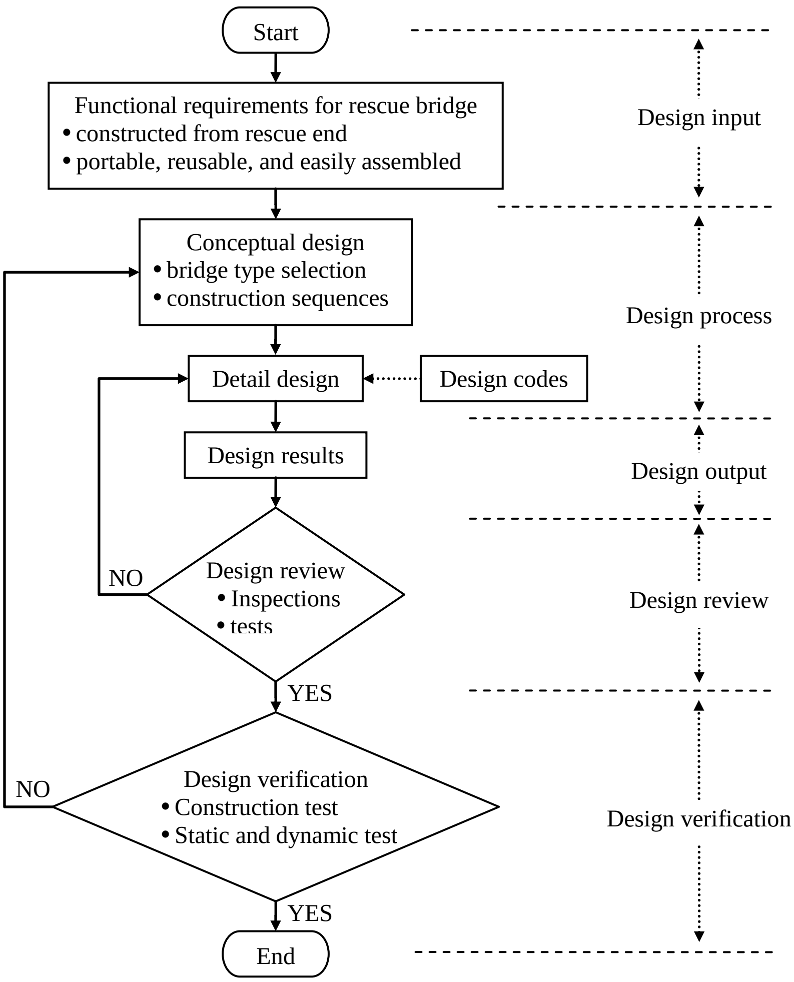


Figure 3. Proposed design concept and procedure for temporary rescue bridges

Figure 3 shows the proposed design concept and procedure for temporary rescue bridges. There are five design stages in the design concept and procedure, including: (1) design input, (2) design process, (3) design output, (4) design review, and (5) design verification.

(a) In the design input stage, functional requirements for temporary rescue bridges may include parameters such as: (1) the bridge should be constructed from the rescue end; and (2) the bridge should be portable, reusable, and easily assembled, etc.
(b) The design process stage begins with conceptual design, and includes the following: (1) bridge type selection to meet the requirements of temporary rescue bridges; and (2) construction sequences, where construction methodologies are considered in order to meet the requirements of temporary rescue bridges. It is then followed by detailed design - different design codes should be considered in this process, corresponding to related construction materials etc.
(c) In the design output stage, design output shall be documented and expressed in terms that can be reviewed and verified against design input requirements. Design output shall: (1) meet the design input requirements; (2) contain or make reference to design codes; (3) identify those characteristics of the design that are crucial to the safe and proper functioning of the temporary rescue bridges (e.g. deflection, strength, operation, etc.).
(d) In the design review stage, at appropriate stages of the design, formal reviews of the design results shall be planned and conducted. Each design review shall include all functions concerned with the design input stage that is being reviewed.
(e) In the design verification stage, at appropriate stages of the design, design verification shall be performed to ensure that the design stage output meets the design stage input requirements. In addition to conducting design reviews, design verification may include activities such as (1) performing alternative calculations, (2) comparing the new design with a similar proven design, if available, and (3) performing inspections, tests and, demonstrations, etc.

3 DESIGN CASE STUDY

3.1 Scenario and design thinking

The design case study looked at communities that were isolated by Typhoon Morakot in 2009. A river bridge with a 20 m span length was washed away by the floods, interrupting traffic travelling to and from surrounding areas. A temporary rescue bridge needed to be completed within 8 hours, so that small trucks of 3.5 tons could access and transport relief materials into the isolated area.

From the proposed design concept and procedure (*Fig. 3*), the design input stage gives the following functional requirements for the temporary rescue bridge: (1) for disaster relief and transportation of goods, the design objectives for the temporary rescue bridge are a span length of 20 m, a width of 3 m, a live load of 5 tons (for transportation of rescue goods by a truck weighing 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) the bridge should be constructed from the rescue end; and (3) the bridge should be portable, reusable, and easily assembled within 8 hours.

3.2 Conceptual design

From the proposed design concept and procedure (*Fig. 3*), for conceptual design in the design process stage, we firstly consider bridge type selection. Table 1 shows the characteristics of different bridge types. Beam, arch, suspension, and cable-stayed bridges, are considered as alternatives for temporary rescue bridges. Beam type bridges have a simple design, and are suitable for short spans; nevertheless, they are not easy to construct from the rescue end, and when the river is wide, they require the installation of supporting piers in the river.

Table 1. Bridge type selection for rescue bridges

Bridge types	Characteristics
Beam	Advantages • Simple design • Good for short spans Disadvantages • When the river is wide, piers must be installed • Not easily constructed from rescue end
Arch	Advantages • Good for medium spans • Natural support system Disadvantages • Requires anchorage at both abutments • Not easily constructed from rescue end
Suspension	Advantages • Good for long spans • Can be built high up over waterways Disadvantages • Requires anchorage at both abutments • Not easily constructed from rescue end
Cable-stayed	Advantages • Good for long spans • Easily constructed from rescue end • Piers not required

These characteristics indicate that beam type bridges are not suitable as rescue bridges. Arch bridges have a natural support system, and are suitable for medium spans; however, they are not easy to construct from the rescue end, and require anchorage at both abutments. These characteristics indicate that arch bridges are not suitable as rescue bridges. Suspension bridges can be built high up over waterways, and are suitable for long spans; however, they are also difficult to construct from the rescue end, and require anchorage at both abutments. These characteristics indicate that suspension bridges are not suitable as rescue bridges. Cable-stayed bridges, unlike the former three alternatives, are easily constructed from the rescue end, do not require the installment of piers in the river, and are suitable for long spans. These characteristics indicate that cable-stayed bridges are suitable for rescue bridges.

The development of a bridge that would allow rapid restoration of access for traffic and emergency disaster relief is very important. It should be possible for this bridge to be constructed within a short time with limited manpower and simple tools. Furthermore, the bridge should be portable and reusable. Lightweight materials (for example composite materials) could be considered and used for the temporary rescue bridge.

This study develops such a bridge system by using a self-balancing approach and a cantilever incremental launching method. An asymmetric self-anchored cable-stayed bridge is proposed. The structural segments are constructed from heavyweight materials (e.g., steel and concrete) that function as counterweights at the rescue end, and the spanning segments are constructed from lightweight materials (e.g., composite materials). This allows the span to be increased so that it can easily reach the isolated island end without any further supports or foundations (*Fig. 4*).

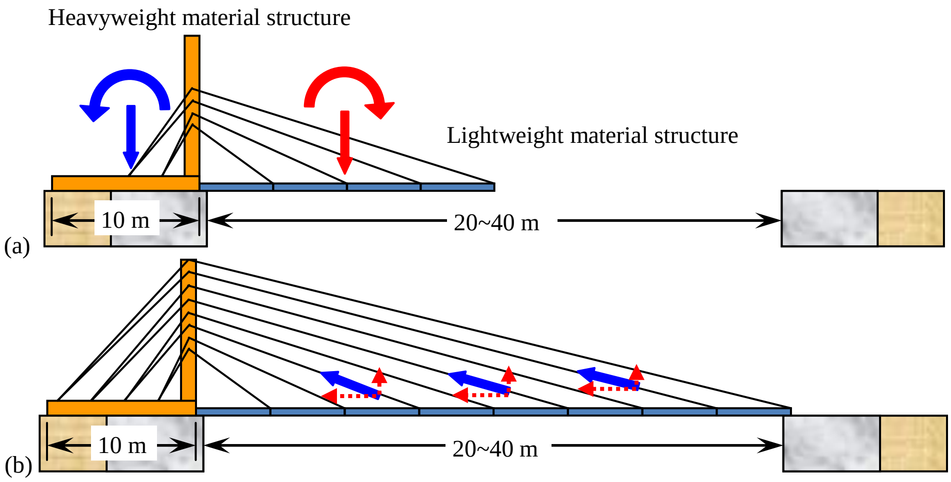


Figure 4. Concept of a temporary composite bridge for emergency disaster relief: (a) the construction stage, and (b) the commissioning and completion stage

There are two main advantages of this temporary rescue bridge design. First, during the construction stage, the asymmetric self-anchored cable-stayed bridge is easily constructed from the rescue end to the isolated island end due to its self-balancing characteristics. The wires of the cable-stayed bridge help with construction of the spanning segments using the cantilever incremental launching method (*Fig. 4a*). Second, when construction is complete, these wires are effective in reducing the deformation of the bridge caused by live loads from traffic (*Fig. 4b*).

For conceptual design in the design process stage (*Fig. 3*), we secondly consider the construction sequence. The lightweight temporary rescue bridge system includes a weight-balance structural module, a bridge-tower structural module, a crossing structural module, and connection cables. The weight-balance and bridge-tower modules are constructed of steel, concrete, and other heavyweight materials, preformed as structural segments.

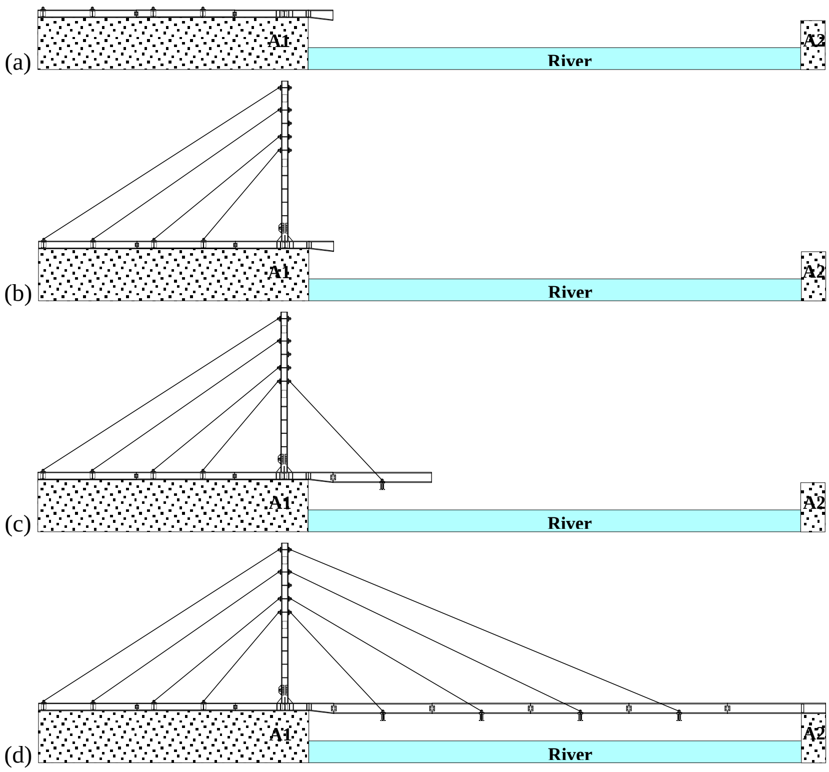


Figure 5. Construction sequences of a temporary rescue bridge: (a) assemble the weight-balance structural module; (b) assemble the bridge-tower structural module; (c) assemble the crossing structural module; and (d) complete the temporary rescue bridge

The crossing module is constructed of composites and other lightweight materials. The construction sequence is as follows: (1) assemble the structural segments that comprise the weight-balance structural module (*Fig. 5a*); (2) assemble the structural segments that comprise the bridge-tower structural module, affix the bottom section to the weight-balance module, and couple the top section with the weight-balance module using at least one connection cable (*Fig. 5b*); (3) assemble the crossing segments over the gap between the rescue end (A1) and the isolated island (A2) end (*Fig. 5c*) to complete the crossing structural module, and couple it to the top section of the bridge-tower structural module with at least one connection cable (*Fig. 5d*).

3.3 Detailed design

The temporary rescue bridge was composed of structural steel and GFRP composite materials. From the detailed design stage of the proposed design concept and procedure (*Fig. 3*), the steel structural design followed the Taiwanese local code of steel highway bridges [13], and the composite structure used the design code proposed by the U.S. Department of Agriculture (USDA) Forest Service [14] and the American Association of State Highway and Transportation Officials (AASHTO) [15]. The following equations [13] were used for the design of the steel components in the temporary composite bridge system:

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

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

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

Where: f_a and f_b represent the actual axial and bending stresses, respectively;

F_a and F_b denote the allowable axial and bending stresses, respectively;

C_m corresponds to a modification factor;

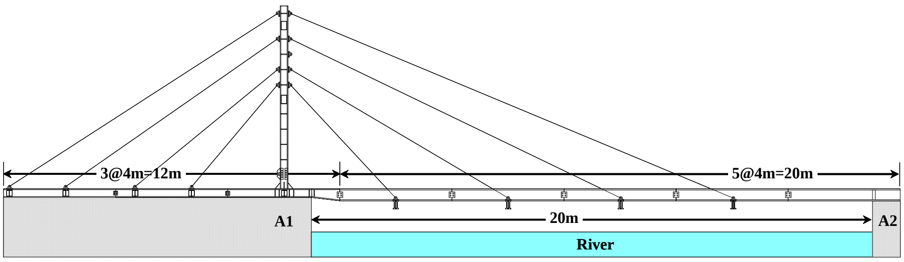
F'_e represents Euler's critical buckling stress;

f_v denotes the actual shear stress;

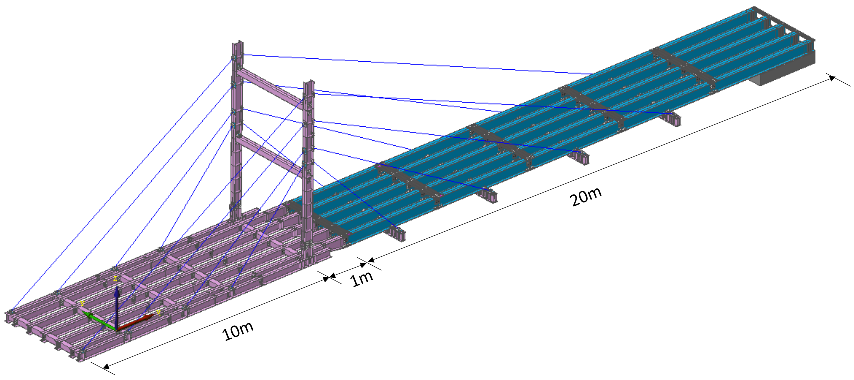
F_v represents the allowable shear stress.

Parallel FRP girder bridge systems were studied to assess the stuructural requirements necessary to meet the following design requirements: 20 m span; 3 m width; 5 ton live load capability (for transportation of rescue goods in a truck weighing 3.5 tons); and a deflection-to-span ratio of L/400, which was recommended by USDA [14]. The bridge system used 410 mm × 20 mm × 200 mm × 18 mm H-shaped composite girders. The material properties of GFRP were as follows: Young's modulus = 20.03 GPa; density = 1.72 g/cm^3; and allowable stress = 207 MPa.

For the design output stage, we designed a steel-and-composite cable-stayed bridge that met all the functional requirements from the design input stage for the assembly and river-crossing objectives. *Figure 6* shows the design results of the asymmetric self-anchored cable-stayed bridge. Seven parallel steel girders and H-shaped pillars formed from A572 grade-50 steel with a 294 mm × 200 mm × 8 mm × 12 mm cross-section on the A1-side abutment, were used for the weight-balance structural module. Five parallel GFRP girders with a 410 mm × 200 mm × 18 mm × 20 mm cross-section were used for the crossing structural module, and double-H-shaped steel crossbeams were used to support the river-crossing segments (*Fig. 6a* and *Fig. 6b*). We used a steel frame on the A1-side abutment as a counterweight, and the incremental launching method to rapidly assemble the lightweight cable-stayed GFRP temporary rescue bridge. We used the same capacity for the connection design (details of the connection were shown in *Fig. 6c*), and the numerical result showed that the connection between the steel and GFRP girders was not the critical one. Instead, the critical connection was that at connection G4, between GFRP segments C and D (*Fig. 6d*).



(a)



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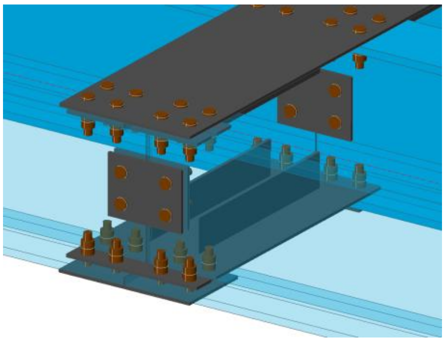

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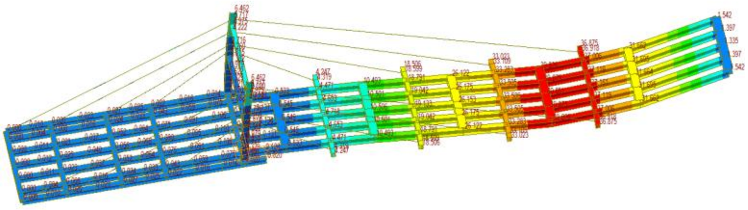


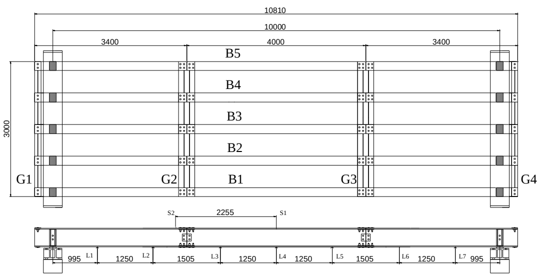
(d)

Figure 6. Design results for the 20-m span temporary rescue composite bridge: (a) front view; (b) 3D view; (c) the bolted connection using bolts and steel connection plates; and (d) the deformation shape

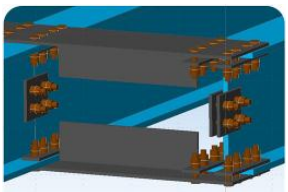
4 LABORATORY TESTS AND DESIGN REVIEW

Inspections in the design review stage were carried out to check that the design output met the requirements of the design input. A GFRP composite bridge spanning 10 m (*Fig. 7*) designed using the outlined procedure, gave test results summarized in the following sections [16].

The experimental setup of the 10-m span GFRP composite bridge was shown in *Fig. 8a* and the loading position simulating a small truck weighing 3.5 tons was shown in *Fig. 8b*. The test program included a flexural test, a fatigue test, and a strength test.



(a)



(b)

Figure 7. Design results of the 10-m span GFRP composite bridge: (a) design drawings, and (b) connection details

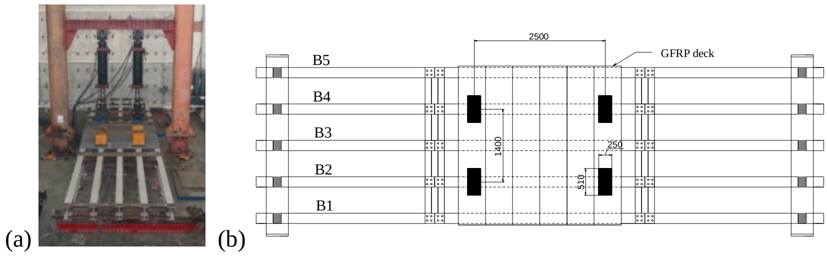


Figure 8. The experimental setup of the 10-m span GFRP composite bridge: (a) the test setup, and (b) the wheel position of a small truck

4.1 Flexural test

The test setup for the flexural test of the 10-m span GFRP composite bridge was identical to that of the previous section and was shown in *Fig. 8*. The results of the flexural test were shown in *Fig. 9*. *Figure 9a* showed the linear relation of the load-deflection curve. The deformed shapes were shown in *Fig. 9b* and *Fig. 9c*. The maximum displacements were 26.58 mm (P = 50 kN) and 52.94 mm (P = 100 kN), which occurred at the middle span of the B4 girder.

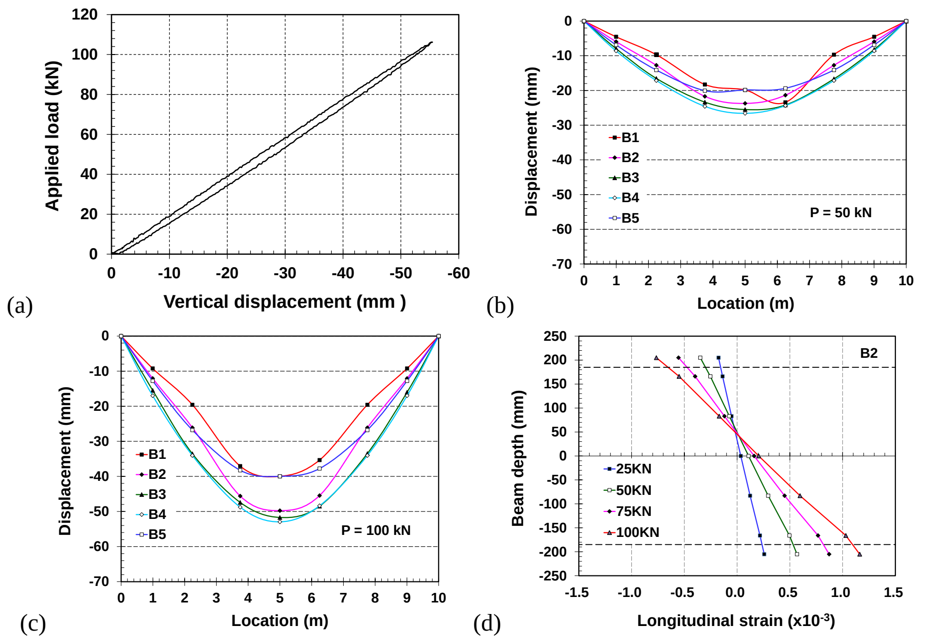


Figure 9. Flexural test results of the 10-m span GFRP composite bridge: (a) applied load versus vertical displacement; (b) deformed shape (P = 50 kN); (c) deformed shape (P = 100 kN); and (d) longitudinal strain along the depth of the B2 girder

The maximum longitudinal strains were 5.681×10^{-4} (P = 50 kN) and 1.162×10^{-3}

(P = 100 kN), which occurred at the bottom flange of the B2 girder (*Fig. 9d*). The flexural test results indicated that the deflection-to-span ratio under a live load of 5 tons was approximately L/376, which was very close to the design requirement of L/400 [14].

4.2 Fatigue test

The test setup for the fatigue test of the 10-m span GFRP composite bridge was identical to that of the flexural test and was shown in *Fig. 8*. The frequency of fatigue loading was 1 Hz, and a total of 2×10^5 cycles of loading with a magnitude of 50 kN (the target design load) were applied to the specimen. Additionally, the specimen was subjected to a static flexural loading after every 1×10^4 cycles to examine the stiffness degradation. The test results were shown in *Fig. 10*. *Figure 10a* showed the linear relation of the load-deflection curve after every 1×10^4 cycles. The stiffness degradation curve was shown in *Fig. 10b*. The stiffness ratio was defined as the ratio of the stiffness measured after every 1×10^4 cycles of loading, to the stiffness measured in the first flexural test. The test results showed that there was no stiffness degradation over 2×10^5 cycles of loading with a magnitude of 50 kN.

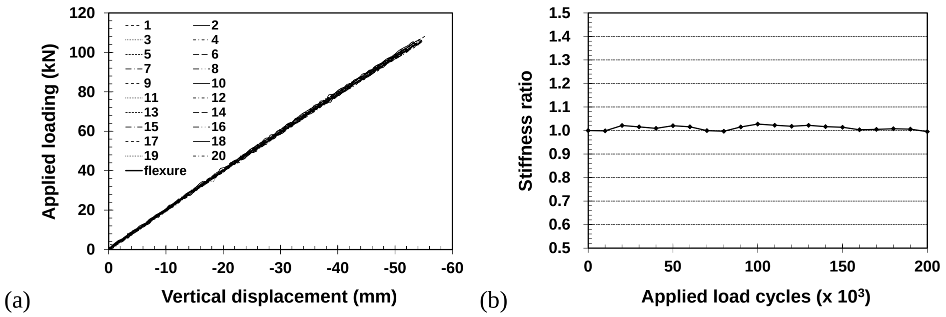


Figure 10. Fatigue test results of the 10-m span GFRP composite bridge: (a) applied load versus vertical displacement, and (b) stiffness degradation

4.3 Strength test

The test setup for the strength test of the GFRP composite bridge was identical to that for the previous tests and was shown in *Fig. 8*. The specimen was tested in flexural loading to failure, to examine its residual strength and failure mode. The test protocol included the displacements, which ranged from 1 cm to 20 cm. Three cycles were applied for each displacement level from 1 cm to 8 cm; two cycles were applied when the displacement amplitude ranged from 10 cm to 16 cm, while only one cycle was applied when the amplitude was 20 cm. The test results were shown in *Fig. 11*. *Figure 11a* showed the load deflection curve at the midspan of the B3 girder; when the displacement was less than 10 cm, the loading and unloading curves were very much linear and elastic, and when the displacement was equal to 20 cm, the maximum load was around 324 kN. The deformed shapes were shown in *Fig. 11b*. The maximum displacements of 207.56 mm, 204.21 mm, and 198.49 mm occurred at the midspan of the B4, B2, and B3 girders, respectively. The maximum longitudinal strains of 3.743×10^{-3} occurred at the bottom flange of the B2 girder (*Fig. 11c*). The failure of the specimen was due to slippage at the connection, but not in the GFRP girder itself (*Fig. 11d*). The strength test results indicated that the design of the proposed composite bridge was deflection-driven, instead of being strength-driven. It also showed that the proposed design had strength higher than was required for a safety factor greater than 4.

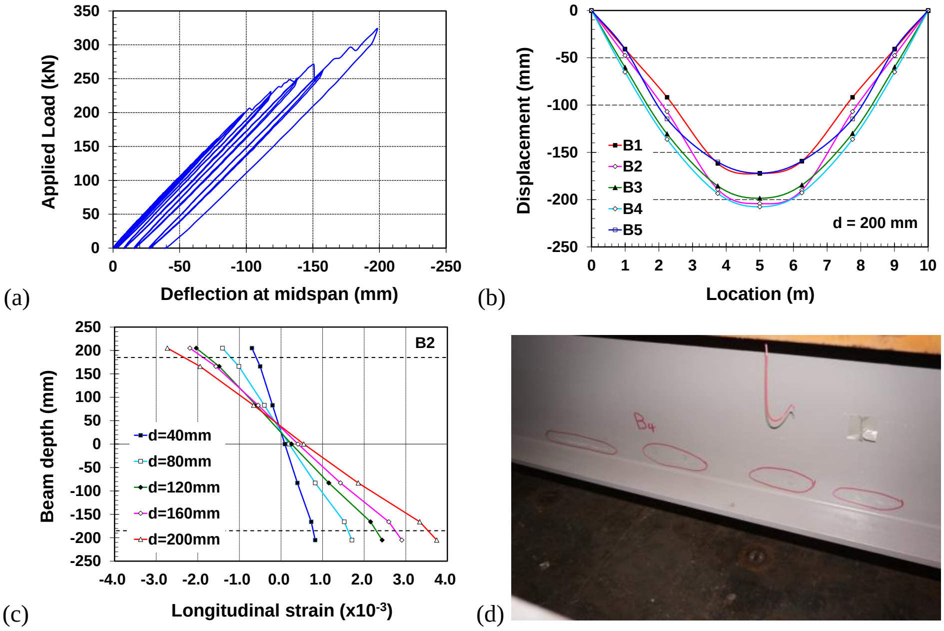


Figure 11. Strength test results of the 10-m span GFRP composite bridge: (a) applied load versus vertical displacement; (b) deformed shape (d = 200 mm); (c) longitudinal strain along the depth of the B2 girder; and (d) failure mode of the girder

5 IN SITU EXPERIMENTS AND DESIGN VERIFICATION

In order to confirm the ease of assembly and feasibility of the lightweight temporary rescue bridge for disaster relief, we designed a steel and composite cable-stayed bridge with a span of 20 m, a width of 3 m, a live load of 5 tons and a deflection-to-span ratio of L/400 for the assembly and river-crossing test. The design results of the asymmetric self-anchored cable-stayed bridge were shown in *Fig. 6*.

5.1 Construction sequences and river-crossing tests

Construction, static and dynamic tests were performed in the design verification stage, and the test results were summarized as follows [17].

The construction sequence was shown in *Fig. 12* and had the following steps. Step 1 was to assemble the seven parallel steel girders (294 mm × 200 mm × 8 mm × 12 mm cross-section) with a combined length of 12 m (3 × 4m), connected with box-girder cross beams (200 mm × 200 mm × 6 mm) via bolts at the webs of the H-shaped girders (*Fig. 12a* and *Fig. 12b*). Step 2 was to assemble the H-shaped pillars (294 mm × 200 mm × 8 mm × 12 mm cross-section) with 18 connection devices for the steel cable, giving a total height of 6.5 m (*Fig. 12c*), and a bolted connection with the top flange of the outer of the seven parallel steel girders in the third segment (*Fig. 12d*). Step 3 was to assemble the first segment of the five parallel GFRP girders (*Fig. 12e*) and connected them to the third segment of the weight-balance structural module (*Fig. 12f*). Step 4 was to assemble the second segment of the five parallel GFRP girders using the same sequence as in the previous step (*Fig. 12g*) and connected it to the first segment of the crossing structural module (*Fig. 12h*). Step 5 was to assemble the third to fifth segments of the five parallel GFRP girders using the same procedure as in the previous step (*Fig. 12i*) and completed the construction sequence to cross the river (*Fig. 12j*).

The 20-m span temporary composite bridge was constructed by 30 unskilled workers within six hours using manpower, simple tools, and a small truck with a crane, thereby meeting the requirements for emergency disaster relief. The temporary rescue composite bridge features three major advantages: quick assembly, DIY applications, and reusability:

(a) Quick assembly: Currently, temporary roadways made from concrete pipes and temporary steel bridges are the most common methods for dealing with collapsed bridges. However, because these take a long time to complete, disaster relief is often delayed in the meantime. At approximately half the weight of temporary steel bridges, the proposed lightweight composite temporary rescue bridge is easy to set up - requiring only six hours - and better able to meet the urgent needs of disaster victims in the midst of an emergency.

(b) DIY applications: Traditional bridges must be set up by professional engineers. By contrast, the proposed composite temporary rescue bridge requires only one professional engineer and a few dozen workers (no experience necessary). The bridge can be set up within six hours using simple tools and a portable assembly workbench. The composite temporary rescue bridges may be preemptively shipped to areas that are prone to floods and landslides so that in the event of a bridge collapse, only one professional engineer will be needed (who can be sent to the disaster area via helicopter or cable car) to free trapped residents and reestablish access to surrounding areas. Rather than passively waiting for outside help, residents can help themselves, which combined with an outside effort, significantly increases the speed of disaster relief.

(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

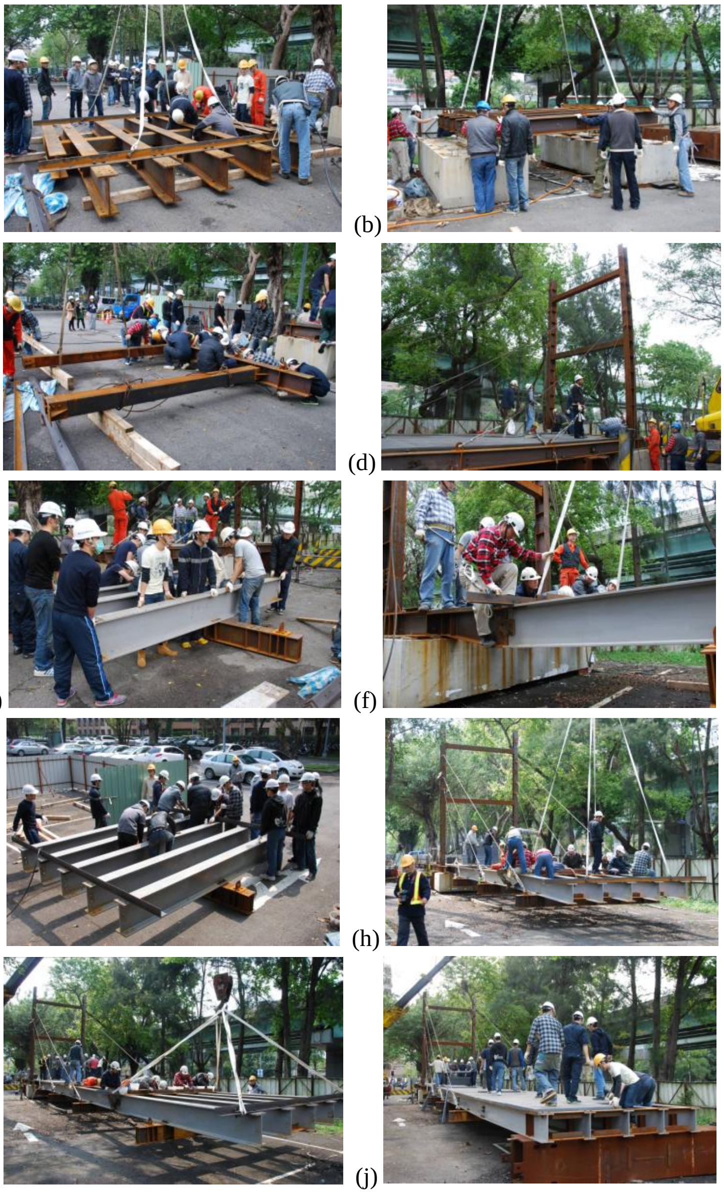


Figure 12. Construction sequence of the 20-m span temporary rescue composite bridge: (a) assembly of seven parallel steel girders; (b) connection of the weight-balance structural module; (c) assembly of the double-H-shaped pillar; (d) connection of the bridge-tower structural module; (e) assembly of the first segment of GFRP girders; (f) connection of the crossing structural module; (g) assembly of the second segment of GFRP girders; (h) and (i) connection of the crossing structural module; and (j) completion of the composite bridge construction

(c) Reusability: Although GFRP composite has a number of advantages, it is twice as expensive as steel. To help our customers save on costs, we have adopted a quick assembly and disassembly design for our composite temporary rescue bridge, enabling it to be quickly disassembled after use to facilitate repeated usage in the future. Laboratory tests have confirmed that our composite bridge can support a 5-ton truck for over 200,000 crossings.

5.2 In situ full scale flexural and dynamic tests

The experimental setup of the proposed composite temporary rescue bridge with a span of 20 m was shown in *Fig. 13a*. The bridge was constructed over the gap between the rescue end (A1) and the isolated island (A2) end. The loading positions of a small truck weighing 3.5 tons (total weight 5 tons) was shown in *Fig. 13b*. The test program included a flexural test, an off-axis flexural test, and a dynamic test. The results of the flexural and dynamic tests were shown in *Fig. 14*. The shape deformation was shown in *Fig. 14a* and *Fig. 14b*. The maximum displacements were 53.41 mm (flexural test) and 56.23 mm (off-axis flexural test); these occurred at connection G4. The maximum longitudinal strains were $5.05\text{x}10^{-4}$ (flexural test) and -5.53×10^{-4} (off-axis flexural test); these occurred in girder B3, on the left side of connection G4 (*Fig. 14c*). Deflection over time at connection G4 was shown in *Fig. 14d*. The flexural and dynamic test results indicated that the deflection-to-span ratio for a live load of 5 tons was around L/356, which was very close to the design requirement of L/400.

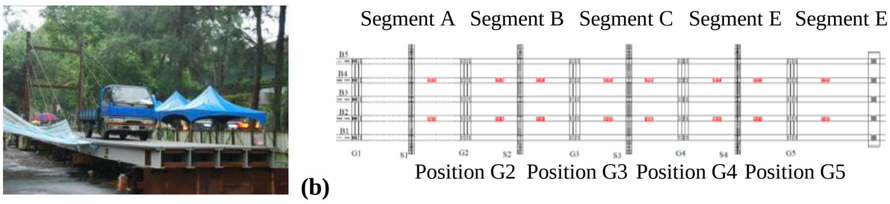
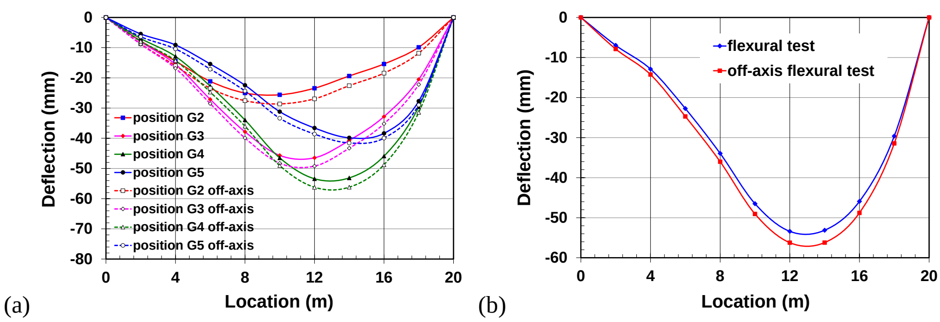


Figure 13. The experimental setup of the 20-m span temporary rescue composite bridge: (a) test setup, and (b) wheel position for a small truck



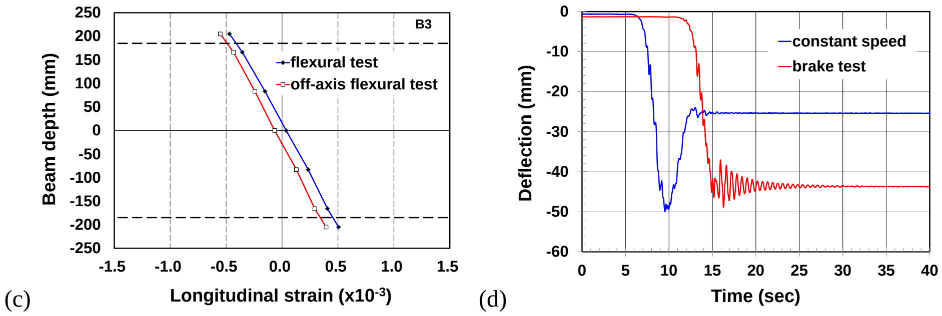


Figure 14. Flexural and dynamic test results of the 20-m span temporary rescue composite bridge: (a) shape deformation (various loading position); (b) shape deformation (loading at position G4); (c) longitudinal strain along the depth of B3 girder; and (d) deflection over time at connection G4

6 CONCLUSIONS

This paper proposes an emerging design concept and procedure for a temporary rescue bridge; and presents a design for a lightweight, portable, and reusable temporary composite bridge for emergency disaster relief. The proposed design concept and procedure for a temporary rescue bridge includes five major design stages: design input, design process, design output, design review, and design verification; which could help bridge designers with problem-solving strategy for temporary rescue bridge design.

The temporary rescue bridge outlined in the paper is an asymmetric self-anchored cable-stayed bridge designed using steel and FRP composite materials to improve the stiffness of the composite frame, reduce the deflection of the bridge, and allow easy spanning of a river without any other supports or foundations. The bridge therefore achieves the goals associated with disaster relief through the use of a self-balanced structure and the incremental launching method. The results of this study are summarized as follows: (1) the proposed design concept and procedure for designing a temporary rescue bridge is helpful for bridge designers in term of problem-solving strategy for temporary rescue bridge design; (2) there is no stiffness degradation of a 10-m span GFRP composite bridge, over 2×10^5 cycles of loading with a target design amplitude of 50 kN; (3) the design of the 10-m span GFRP composite bridge is deflection-driven, instead of being strength-driven, and the strength is higher than is required for a safety factor greater than 4; (4) the 20-m span temporary rescue composite bridge was constructed by 30 unskilled workers within six hours using only manpower, simple tools, and a small truck with a crane, which meets the requirements of emergency disaster relief; (5) the flexural and dynamic test results of the 20-m span temporary rescue composite bridge indicate that the deflection-to-span ratio for a live load of 5 tons is around L/356, which is very close to the design requirement of L/400.

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