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Experimental testing and numerical simulation of a temporary rescue bridge using GFRP composite materials

Hsiao-Hui Hung [a], Yu-Chi Sung [a,b,*], Kou-Chun Chang [a,c], Shih-Hsun Yin [b], Fang-Yao Yeh [a]

[a] National Center for Research on Earthquake Engineering (NCREE), 200, Sec. 3, Xinhai Rd., Taipei 10668, Taiwan, ROC
[b] Department of Civil Engineering, National Taipei University of Technology (NTUT), 1, Sec. 3, Chung-Hsiao E. Rd., Taipei 10608, Taiwan, ROC
[c] Department of Civil Engineering, National Taiwan University (NTU), 1, Sec. 4, Roosevelt Rd., Taipei 10617, Taiwan, ROC

HIGHLIGHTS

- A temporary rescue bridge system using GFRP composite materials is developed.
- The ease of erection of the superstructure was validated through a practice assembly.
- Static and fatigue tests were performed under live loads, followed by a strength test.
- Two analysis models of the test configurations were developed.

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ABSTRACT

Typhoons and earthquakes, which occur frequently in Taiwan, often lead to the washout or collapse of cross-river bridges and cause stoppages to traffic. In order to restore traffic as soon as possible and to provide necessary emergency rescue services, a project was conducted at NCREE with the purpose of developing a type of temporary rescue bridge that is portable, reusable, and easily assembled by workers. A simply supported bridge assembled from five H-shaped Glass Fiber Reinforced Polymer (GFRP) girders with a span length of 10 m was developed. To verify the feasibility of the proposed portable GFRP superstructure, the specimen was first erected in a practice assembly performed by unskilled students. In addition, a series of non-destructive tests were performed sequentially to assess its serviceability condition, followed by a destructive test to examine its ultimate capacity. Experimental results indicate that this bridge satisfied the live load deflection recommendation well with a deflection-to-span ratio of about 1/303, and a safety factor of 4 in strength. The assembly practice and the experimental results demonstrated the practicability of the proposed superstructure and showed a good possibility of utilizing this structure as a temporary rescue bridge. Furthermore, two linear finite element models of the laboratory tests were developed. The results from both models showed good correlation with the deflections and longitudinal strains measured during different service loading conditions.

1. Introduction

Due to its unique geographical location and climate, Taiwan frequently suffers from typhoons and earthquakes. Floods brought about by typhoons or ground shaking induced by earthquakes often lead to the washout or collapse of cross-river bridges and cause stoppages to traffic. Traffic cut-offs may isolate the emergency disaster area from rescue efforts and impede the evacuation of victims and the delivery of food supplies. In order to restore traffic as soon as possible and provide necessary emergency rescue services, a project was conducted at the National Center for Research on Earthquake Engineering (NCREE) with the purpose of developing a type of temporary rescue bridge that is portable, reusable, and easily assembled by workers. To meet these requirements, the material of the bridge should have a high strength-to-weight ratio and excellent durability against corrosion. Fiber Reinforced Polymer (FRP) has advantages of high strength, lightweight, and superb durability compared to traditional materials. Therefore, it was considered a promising material for application to this rescue bridge. The most commonly used FRPs applied in infrastructure include Glass Fiber Reinforced Polymer (GFRP),

* Corresponding author at: National Center for Research on Earthquake Engineering (NCREE), 200, Sec. 3, Xinhai Rd., Taipei 10668, Taiwan, ROC.
E-mail addresses: hhung@narlabs.org.tw (H.-H. Hung), sungyc@ntut.edu.tw (Y.-C. Sung).

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Carbon Fiber Reinforced Polymer (CFRP), and their hybrid. Due to cost effectiveness considerations, GFRP was chosen as the major material for the temporary bridge developed in the current project.

FRP composites were first adopted as structural materials after World War II and were applied in the boating and aerospace industries [1]. In the following years, the advantage of lightweight, high strength, and corrosion resistant composite materials gradually gained the attention of the civil engineering community. Aided by a growth in research and demonstration projects funded by industries and governments, the application of FRP structures in civil engineering has progressed substantially around the world since the late 1980s [2]. Most direct applications of FRP composite materials in bridge infrastructure for vehicular traffic were FRP composite decks, such as those works performed by Hayes et al. [3], Alampalli and Kunin [4], Keller [5], and Zhou et al. [6], among others. On the other hand, due to the absence of appropriate guidelines and codes for the application of FRP on bridges, there were relatively few uses of all-composite FRP girders as the main load-carrying members for highway bridges. Most were constructed for demonstration purposes, such as the Tom's Creek Bridge constructed in Virginia, USA [7,8], and an FRP composite highway bridge in Ohio, USA, which was officially named "Tech 21" to represent materials technology for the 21st century [9]. In addition, because FRP materials are brittle in the sense of being linear elastic to failure, several researchers proposed hybrid girder systems combining FRP composites with traditional materials such as concrete and steel to overcome this shortcoming [10–14]. Other major applications of FRP materials in bridge infrastructure are footbridges and trail bridges for pedestrian traffic. Since the first FRP pedestrian bridge was constructed in Israel in 1975, many FRP pedestrian bridges have been constructed in several countries [15]. A milestone in the development of FRP pedestrian bridges is the cable-stayed Aberfeldy footbridge completed in 1992 in Scotland with a main span of 63 m [16]. In the United States in 2003, there were already more than one hundred constructed FRP pedestrian bridges [15]. Thereafter, a guide concerning FRP trail bridges was written by the U.S. Department of Agriculture (USDA) [15] and guide specifications for the design of FRP pedestrian bridges were published by the American Association of State Highway and Transportation Officials (AASHTO) [17].

According to above literature reviews, composite material bridges for vehicular traffic and pedestrian applications have been increasingly used worldwide, but requirements of rapid assemblage, portability, and reusability were rarely taken into account in those designs until very recently. Since the 1990s, the United States Army has been interested in developing new polymeric-composite mobile army bridges to replace existing heavier metallic bridging systems. A bridging system technology named the Composite Army Bridge (CAB) was developed and proved to be a lighter alternative to existing bridging systems of the same load class [18]. In Canada, a glass FRP bridge system that is rapidly deployable with a high load-carrying capacity was designed by the Canadian Forces [19]. In Malaysia, a portable bridge using FRP composite material was designed for defense and disaster relief operations. A 20% scaled-down model was also constructed for performance testing [20,21]. For the current project conducted at NCREE in Taiwan, to reach the requirements for emergency rescue bridges, this project aims at utilizing FRP composite materials to develop a lightweight temporary rescue bridge that can be easily transported and erected in a short time only by workers with minimal equipment. In addition, despite some field applications and laboratory research related to FRP composite bridge systems has been conducted by many researchers, appropriate design specifications are not currently available and material specifications can only be obtained from manufacturers of FRP materials. Therefore, to validate the information supplied by manufacturers and to clarify any uncertainty in design for the developing bridge, full-scale performance tests were conducted. The testing and evaluation of the composite bridge structure can provide the information necessary to characterize its performance with respect to design predictions and loads.

This project was separated into two stages. The purposes of the first and second stages were to complete a one-lane bridge to cross a river with a span 10 m and 20 m, respectively, with a target service load of 50 kN [22]. This paper will focus on the research performed at the first stage. For this stage, a single-span one-lane GFRP bridge superstructure with a target service load of 50 kN was designed and assembled at NCREE. The superstructure with a span length of 10 m and a width of 3 m was comprised of five pultruded H-shaped GFRP girders manufactured in Taiwan and several GFRP grating decks imported from China. In addition, to make each component of the bridge portable and to ensure its reusability afterwards, each H-shaped girder was separated into three segments and assembled with bolted connections using steel splice plates and high strength bolts. To stiffen the structure to allow higher torsional rigidity, steel transverse cross girders were also provided at the locations of support and at two intermediate locations within the span. Furthermore, to ensure that the developed system could be practically implemented, the feasibility of the proposed portable GFRP superstructure was investigated experimentally. The ease of erection of the superstructure was first validated through a practice assembly performed by unskilled students using standard hand tools. Subsequently, the model was tested under different loading conditions including flexural loading, off-axis flexural loading, and fatigue loading, and its behavior was thoroughly examined. After the fatigue test was completed, the model was loaded in flexure until failure to examine its residual strength and failure modes.

To establish a proper design and analysis procedure for such a GFRP bridge system, two finite element models of the proposed specimen were also generated. One was a sophisticated finite-element model using solid and shell elements, and the other was a simple analytical model for which the main girder and cross beam were simulated with beam elements. Both analytical results were compared with the experimental measurements.

2. Proposed GFRP bridge superstructure

2.1. Test specimen

The proposed composite bridge was constructed with GFRP composite materials and traditional steel materials. The design of the steel members followed the Taiwan local code of steel highway bridges [23] and composite members used the design codes proposed by the USDA Forest Service [15] and the AASHTO [17]. The design process and formula can be found in a previous paper [22] and will not be recapitulated herein.

Due to the relatively low elastic modulus value, the design of FRP components is generally governed by deflection limitations rather than by strength requirements. However, the criterion for deflection is currently somewhat arbitrary. In the U.S., AASHTO Guide specifications for design of FRP pedestrian bridges [17] recommends that the deflection of members be less than the length of the supporting span L divided by 500 (L/500). FRP manufacturers and designers recommend L/400, which would allow more deflection [15]. The CSI Specifications for FRP Pedestrian Bridges set the minimum deflection-to-span ratio as 1/240 [15]. In the United Kingdom, Design of FRP Bridges and Highway Structures limits the deflection of FRP components under a live load to L/300, including shear deformation [24]. In Taiwan, design and material specifications for FRP bridges are not available. By considering that