A Novel Composite Emergency Bridge for Disaster Rescue

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SUMMARY:
Owing to recent extreme climate, typhoons, floods and earthquakes have become the largest natural disaster threat of natural in Taiwan over the years. Due to the above natural disaster, some bridges were damaged, resulting in isolated mountain residential communities, and the inability to deliver emergency relief supplies. In order to provide quick emergency relief, the simple construction of a temporary bridge becomes critical for the transportation and delivery of food and medical supplies into the emergency disaster area. The objective of this paper is to present, (1) a novel bridge structure for a lightweight bridge with portable, reusable, and suitable capabilities for ease of transportation using manpower, (2) versatile joints that combine bolts, welding, and adhesives 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.

Keywords: Portable and reusable bridge, Hybrid composite, Multiple bolted-connection, Arch effect by steel tie

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 Morakot typhoon in 2009, and more than 200 bridges were damaged and more than 100 bridges were washed away. Chi-Chi earthquake in 1999 also caused more than 150 bridges damaged, resulting in isolated mountain communities, to which emergency relief supplies could not be easily delivered (Fig. 1.1).

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 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 (Cheng and Karbhari, 2006).

Figure 1.1. Damage of bridge and disaster rescue in Morakot typhoon and Chi-Chi Earthquake

FRP bridge technology has moved rapidly from laboratory prototypes to actual demonstration projects in the 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 ton of GFRP (Hollaway, 2001). 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 20.7m) two-lane (width of 9.2m) bridge in Beijing, China with GFRP girders made from hand lay-up process (Seible et. al., 1993). 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 (Cheng and Karbhari, 2006).

Nowadays, FRP composite are used mostly in deck systems, footbridges and vehicle bridges. This paper will focus 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.

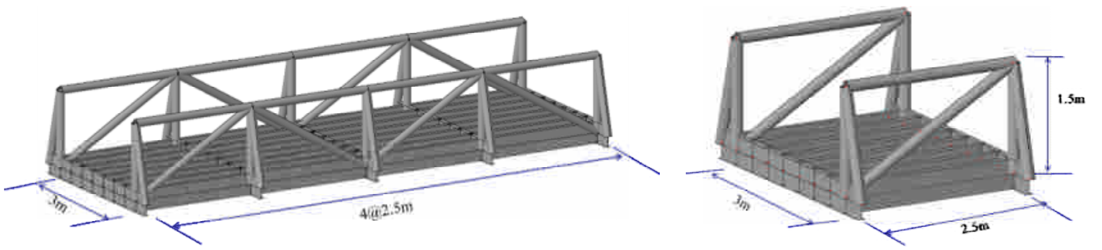
2. CONCEPTUAL AND PRELIMINARY DESIGN

2.1 Conceptual Design of Temporary Bridge for Disaster Rescue

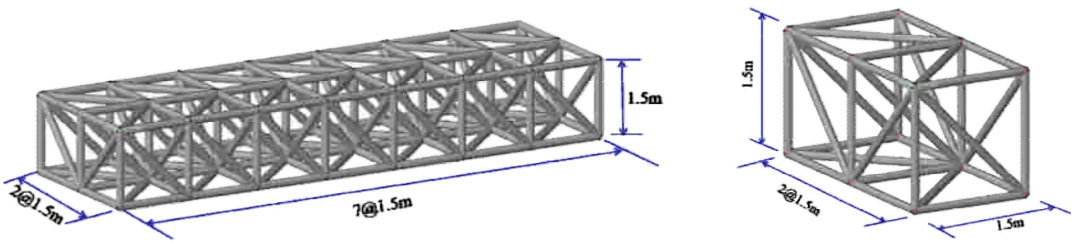
In order to design a lightweight bridge with portable, reusable, and suitable capabilities for transportation, the following design requirements are considered: (1) for the disaster rescue and transportation of goods, in the initial stage, the design goals for the temporary bridge are set to a span length of 20 m, but in the initial year this is limited to 10 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, but is not discussed herein.) and (4) for the requirement for transportation using manpower, the weight limitations of 20 kg per frame and 250 kg per segment are considered.

2.2 Preliminary Design

In the first year of the "Lightweight, Portable and Reusable Composite Bridge Research and Development Project", the design goals for the temporary bridge were initially set to a span length of 10 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. There are two types of bridge, beam-type and truss-type bridges, and two types of material, GFRP and CFRP composites, that are considered in the preliminary design. The bridge will be divided into several segments for the portable requirement as shown in Fig. 2.1.



(a) Beam-type bridge and the typical segment



(b) Truss-type bridge and the typical segment

Figure 2.1. Types of bridge and the typical segments of temporary composite bridge

The composite material used in the temporary bridge design includes pultruded GFRP and CFRP for the trusses. The material properties of the GFRP are: Young's modulus = 17.2 GPa, density = 1.72 g/cm^3, allowable stress = 207 MPa, and the properties of three types of CFRP are: Young's modulus = 50, 100, and 150 GPa, density = 1.5 g/cm^3, allowable stress = 640 MPa. The typical FRP girder in the beam-type bridge has double H-shaped cross section, having the dimensions of 206×10×102×10 mm. The typical FRP girder in the truss-type bridge has circular shaped cross section, and the dimension is ϕ160×10 mm. By using the commercial software, Midas Civil 2011 V2.1, the numerical results are shown in table 2.1 and table 2.2.

Table 2.1. Preliminary design results of the beam-type bridge

Material	E (GPa)	Stress (MPa)	Allowable stress (MPa)	Displacement (cm)	L/800 (cm)	Segment weight (kg)
GFRP	17.2	16.78	207	1.175	1.25	550
CFRP	50	16.78	640	0.412	1.25	220
	100	16.78	640	0.210	1.25	190
	150	16.78	640	0.137	1.25	156

Table 2.2. Preliminary design results of the truss-type bridge

Material	E (GPa)	Stress (MPa)	Allowable stress (MPa)	Displacement (cm)	L/800 (cm)	Segment weight (kg)
GFRP	17.2	9.03	207	0.856	1.25	260
CFRP	50	9.03	640	0.300	1.25	93
	100	9.03	640	0.150	1.25	40
	150	9.03	640	0.100	1.25	28

The results show that the design is controlled by deflection of composite bridge rather than by stress. For a light weight and manually transportable requirements (weight limitations of 20 kg per frame and 250 kg per segment), using CFRP is better than GFRP, and the truss-type is better than the beam-type, for the temporary composite bridge design.

2.3 The Major Challenges

The results of preliminary design and "FRP bridge – technologies and prospects" published by Japan

Society of Civil Engineers (JSCE, 2004) showed that the drawbacks of an FRP composite bridge includes, (1) the low modulus of materials (comparing with steel) and low stiffness of the FRP components which leads to large deflections 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 results and literature reviews, the major challenges for the design of an 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.

3. EXPERIMENTAL AND NUMERICAL INVESTIGATION

3.1 Material Approach to Improve Stiffness of Composite Girder

In 1999 Szak et. al. used deep composite fibreglass I-girders with embedded carbon fibers in the flanges to increase the stiffness of the girders. Similarly, the flexural behaviour of innovative hybrid I-shaped girders consisting of glass fiber reinforced plastics and carbon fiber reinforced plastics were tested by Asamoto et. al., 2008.

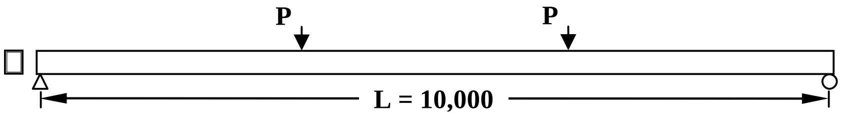
This paper try to find a means of improving the stiffness of composite girder, and the following materials and hybrid sections are prepared for experiments. Three types of 410×20×200×18 mm H-shaped composite sections are shown in Fig. 3.1. All of the three types of composite sections have the same lamination in web and only make some differences in flange. The first one is an all glass fiber section with more than 60% fiber content in weight, for short "GFRP", shown in Fig. 3.1a, the second one has half glass fiber and half carbon fiber of 0^{o} direction in flanges of section with more than 60% fiber content in weight, for short "hybrid GFRP/CFRP", shown in Fig. 3.1b, and the third one has fully carbon fiber of 0^{o} direction in flanges of section with more than 60% fiber content in weight, for short "partial CFRP", shown in Fig. 3.1c.

(a) GFRP (b) Hybrid GFRP/CFRP (c) Partial CFRP

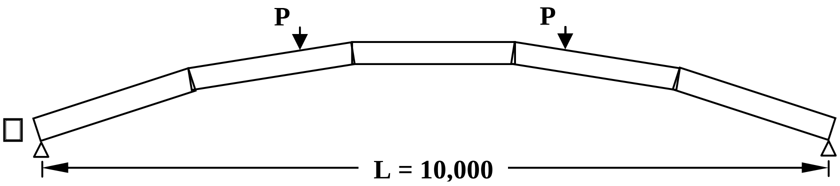
Figure 3.1. Hybrid glass and carbon fibers in flanges to improve stiffness of H-shaped girder

3.2 Arch Effect to Improve Stiffness of Composite Girder

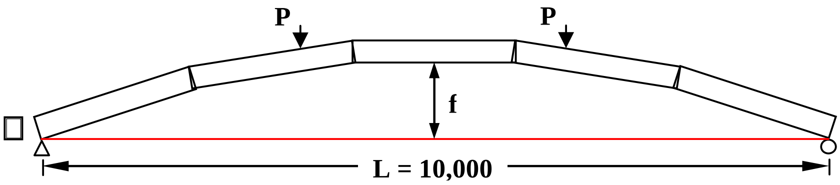
Besides the material approach, the structural effects are considered to improve the stiffness of composite girder. The arch effect is the effective means to improve the stiffness and capacity of medium span bridge. The typical arch effect test setups are shown in Fig. 3.2. The GFRP frame with box-shaped and 134×104×8 mm dimension are separated to three types of numerical test, benchmark composite girder with simple support, arch composite girder with hinge support at both ends, and arch composite girder with steel tie (7×1.6 mm steel wire) and simple support.



(a) Benchmark composite girder (mm)



(b) Arch composite girder (mm)



(c) Arch composite girder with tied (mm)

Figure 3.2. Stiffness test of benchmark and arch girder w & w/o tie

3.3 Moment Capacity and Bolted Connection of Composite Girder

There are many researchers focus on the joints and connections of FRP composite frame (Erki et. al., 2005; Sedlacek and Trumpf, 2002; Nguyen and Hiroshi, 2010). Mechanical connections may be used alone or in combination with other methods of joining composites, either to themselves or to other materials. The literatures review shown, it is very difficult with mechanical fastening to achieve a joint resistance in exceed of the FRP materials being jointed. This article try to use bolted connections with composite and steel fasteners as joints of composite frames of 410×20×200×18 mm H-shaped cross sections with three types of material, GFRP, hybrid GFRP/CFRP and partial CFRP, testing for the three types of multiple fastener connections are shown in Fig. 3.3 and testing for the moment capacity of composite girder are shown in Fig. 3.4.

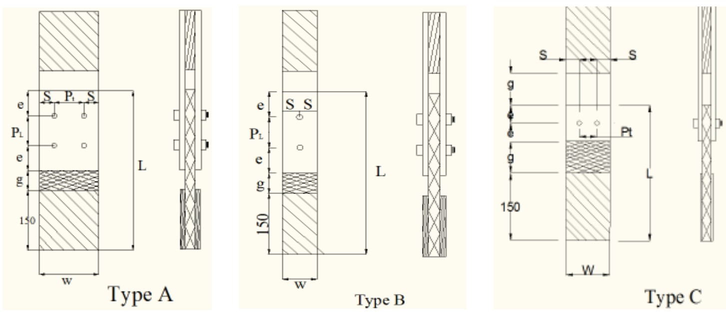
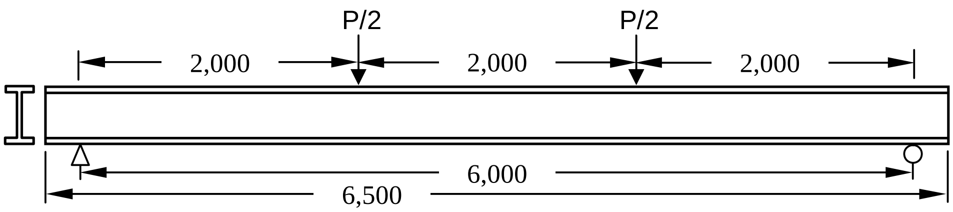
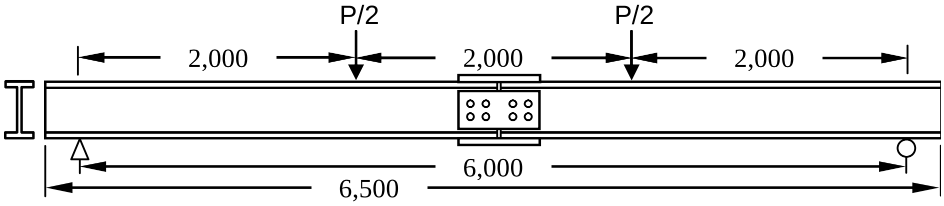


Figure 3.3. Multiple fastener bolted connection of composite plate



(a) Benchmark composite girder (mm)



(b) Bolted connection composite girder (mm)

Figure 3.4. Moment capacity test for benchmark and bolted connection composite girder

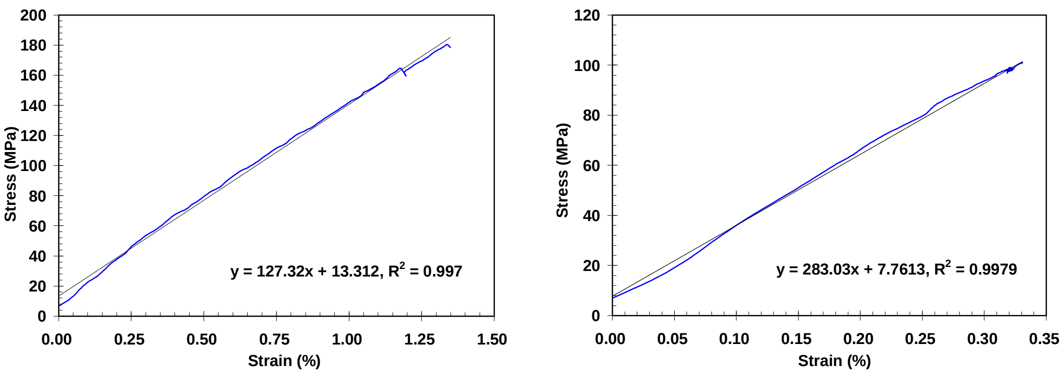
4. RESULTS AND DISCUSSIONS

4.1 Material Approach to Improve Stiffness of Composite Girder

The pultruded H-shaped GFRP hybrid GFRP/CFRP and partial CFRP girders, produced by Taiwan local manufacturer, are shown in Fig. 4.1. The length of the girder is 8.0 m long and will cut to two parts as 6.5 m and 1.5 m long. The 6.5 m long girder will provide for moment capacity and bolted connection test for composite girder, will illustrate in next section. Some part of 1.5 m long girder will cut as specimens for material property test and cut as multiple fasteners for bolted connections test. The experimental results of material property for GFRP girder are shown in Fig. 4.2. It shows the linear relation of stress strain curves for tensile specimens of GFRP girder and the elastic modulus can be obtained from the linear regression of stress strain curve, the values are 12.73 GPa in web and 28.30 GPa in flange of GFRP girder. Table 4.1 shows the theoretical and experimental results of material property for three type composite girders. The elastic modulus of theoretical and experimental results of composite girder's web are very similar, the value are some difference in flange of hybrid GFRP/CFRP girder but the value are quite difference in the flange of partial CFRP girder.

(a) Pultruded H-shaped composite girder, (b) Cross section of composite girder

Figure 4.1. Three types of H-shaped composite girder (GFRP, hybrid GFRP/CFRP and partial CFRP)



(a) Web of GFRP girder (b) Flange of GFRP girder

Figure 4.2. Stress strain relation of tensile specimens for GFRP girder

Table 4.1. Material properties of three type composite girders

Material type	Position	Elastic modulus E (GPa)	
		Theoretical	Experimental
GFRP girder	Flange	23.24	28.30
	Web	12.82	12.73
Hybrid GFRP/CFRP girder	Flange	25.79	33.59
	Web	12.82	12.73
Partial CFRP girder	Flange	35.15	62.91
	Web	12.82	12.73

4.2 Arch Effect to Improve Stiffness of Composite Girder

The arch effect of GFRP girder is considered by using the commercial software, SAP 2000 2007 V11.0.8. The material properties of GFRP are Young's modulus = 17.2 GPa, density = 1.72 g/cm^3, allowable stress = 207 MPa. The numerical results for arch height of 0.2 times span are shown in table 4.2, the central deflection and stiffness of girder are normalized by benchmark girder, the normalized central deflection decreases from 1.0 to 0.061 for simple support arch girder with steel tie (7×1.6 mm steel wire) and decreases from 1.0 to 0.015 for hinge support arch girder. The normalized frame stiffness increases from 1.0 to 16.535 for simple support arch girder with steel tie and increases from 1.0 to 65.869 for hinge support arch girder. Obviously, the arch effect can increase the stiffness of composite frame by hinge support arch girder and simple support arch girder with steel tie.

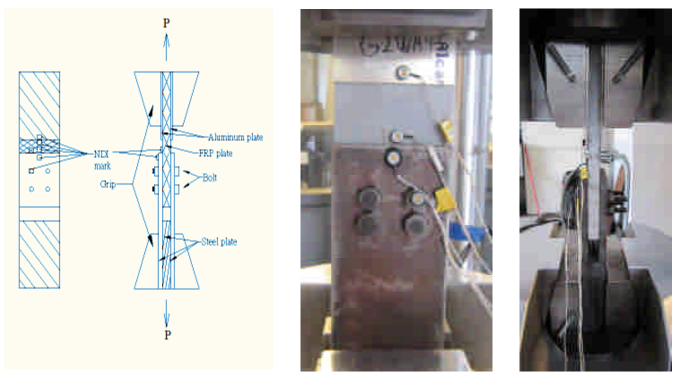
Table 4.2. Numerical results for arch effect of GFRP girders

	Support	Normalized central deflection	Normalized frame stiffness
Benchmark girder	SS*	1.000	1.000
Arch girder with steel tie	SS*	0.061	16.535
Arch girder	HS**	0.015	65.869

Note: SS* = simple support, HS** = hinge support

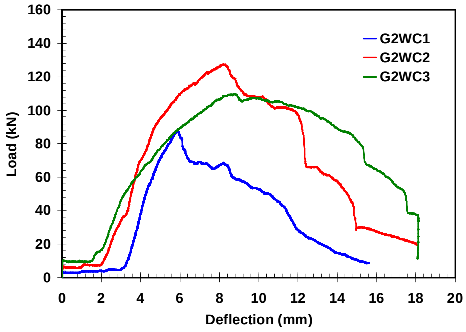
4.3 Bolted Connection of Composite Plate

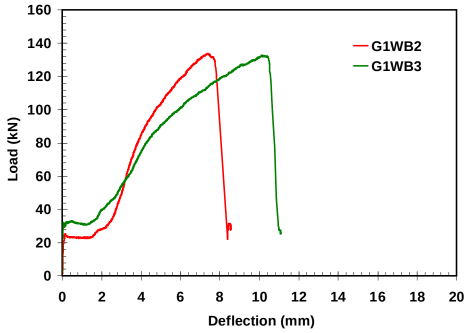
The test setup of bolted connection specimens of composite plate cut from GFRP girders are shown in Fig. 4.3. The test results are shown in Fig. 4.4 and table 4.3. Figure 4.4 shows the typical load deflection curves and failure modes of bolted connection FRP plate. There are two types of failure modes occurred in this test, (1) bearing failure mode: the behaviours are ductile and some contact failures are shown in Fig 4.4a and Fig. 4.4c; (2) tensile failure mode: the behaviours are brittle and some cracking failures alone the plate are shown in Fig 4.4b and Fig. 4.4d. Table 4.3 shows the test results of multiple fastener bolted connections of composite plates. Obviously, the longitudinal pitch ≥ 4d and transverse pitch ≥ 4d for web are satisfied, but for flange the bearing failure should be avoided and needs future study.



(a) Experimental setup (b) Front view (c) Side view

Figure 4.3. Bolted connection test of composite plate





(a) Load deflection of type C connection (web) (b) Load deflection of type B connection (web)


(c) Bearing failure (G2WC1) (d) Tensile failure (G1WB2)

Figure 4.4. Load deflection curves and failure modes of bolted connection composite plate

Table 4.3. Test results of multiple fastener bolted connection of composite plate

	Specimen	Type	Location	Width (mm)	PL (mm)	PT (mm)	Predicted Force (kN)	Test Force (kN)	Force/Per bolt (kN)	Failure Mode*
1	G1WA1	A	Web	100	40(4d)	40(4d)	178.6	222.4	55.6	TF
2	G1WA2	A	Web	80	40(4d)	20(2d)	178.6	121.2	30.3	TF
3	G1WA5	A	Web	100	60(6d)	40(4d)	178.6	236.1	59.1	TF
4	G1FB1	B	Flange	60	20(2d)	-	72.3	66.2	33.1	BF
5	G1FB2	B	Flange	60	40(4d)	-	72.3	72.3	36.1	BF
6	G2WC1	C	Web	80	-	20(2d)	87.8	87.8	43.9	BF
7	G2WC2	C	Web	100	-	40(4d)	87.8	127.4	63.7	BF
8	G2WC3	C	Web	120	-	60(6d)	87.8	109.8	54.9	BF
9	G1WB2	B	Web	60	40(4d)	-	132.7	133.8	66.9	TF
10	G1WB3	B	Web	60	60(6d)	-	132.7	132.7	66.3	TF

Note: TF = tensile failure, BF = bearing failure

4.4 Moment Capacity of Composite Girder

The test setups of four point bending test of benchmark composite girders are shown in Fig. 4.5. The test results are shown in Fig. 4.6. It shows the typical load deflection curves of composite girders and the slope (P/δ_{Mid}) can be obtained from the linear regression of the curves, then the effective modulus can be derived from $E_{eff} = 23PL^3/1296I\delta_{Mid} = (23L^3/1296I)\cdot(P/\delta_{Mid})$, the values are 20.03 GPa for GFRP girder, 22.35 GPa for hybrid GFRP/CFRP girder and 28.38 GPa for partial CFRP girder. The theoretical and experimental results of effective modulus are compared in table 4.4. It is clear that added carbon fiber to hybrid FRP and partial CFRP are effective for stiffness improvement. Table 4.5 shows the results of cost-effective analysis for hybrid FRP girder, the performance to cost ratios decrease from 100.15 (GFRP) to 82.78 (hybrid GFRP/CFRP) and 81.09 (partial CFRP).

Figure 4.5. Four point bending test setup of benchmark composite girder

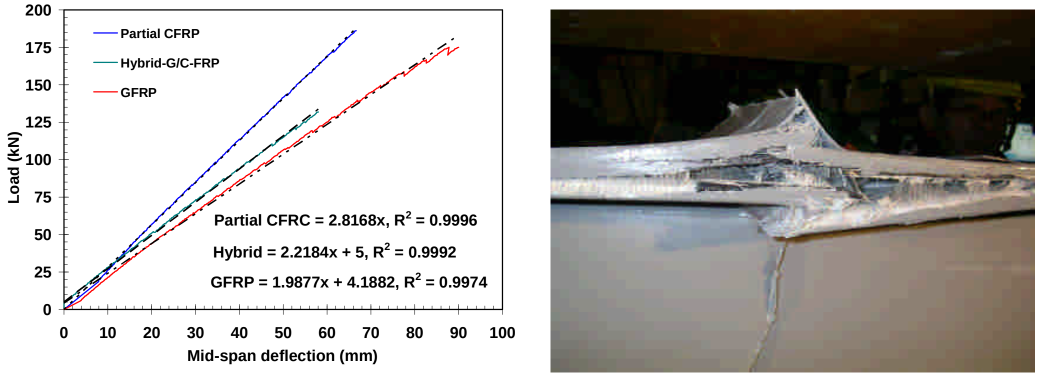


Figure 4.6. Load deflection curves and failure mode of GFRP, hybrid GFRP/CFRP and partial CFRP girders

Table 4.4. Effective modulus of three type composite girders (GFRP, hybrid GFRP/VFRP and partial CFRP)

Material type	Position	Elastic modulus E (GPa)	Effective modulus E_{eff} (GPa)	
		Theoretical	Theoretical	Experimental
GFRP girder	Flange	23.24	21.16	20.03
	Web	12.82		
Hybrid GFRP/CFRP girder	Flange	25.79	23.20	22.35
	Web	12.82		
Partial CFRP girder	Flange	35.15	30.69	28.38
	Web	12.82		

Table 4.5. Cost-effective analysis of hybrid FRP girder

Material type	Experimental E_{eff} (GPa)	Price (US$/m)	Performance to cost ratio (P/C) (MPa/(NT$/m))
GFRP girder	20.03	200	100.15
Hybrid-GFRP/CFRP girder	22.35	270	82.78
Partial CFRP girder	28.38	350	81.09

5. RESULTS OF DETAIL DESIGN

The parallel-FRP-girder bridge systems are studied to meet the special design requirement. The 410×20×200×18 mm H-shaped composite girders are used in the bridge system (Fig. 5.1). The material properties of GFRP are Young's modulus = 20.03 GPa, density = 1.72 g/cm^3, allowable stress = 207 MPa, and the properties of partial CFRP are Young's modulus = 28.38 GPa, density = 1.5 g/cm^3, allowable stress = 640 MPa. The numerical results for number of parallel girders and deflection-to-span ratios are shown in table 5.1. The results shows 5 GFRP girders bridge system could meet the requirement for deflection-to-span ratio of L/230 and 5 partial CFRP girders bridge system could meet the requirement for deflection-to-span ratio of L/320.

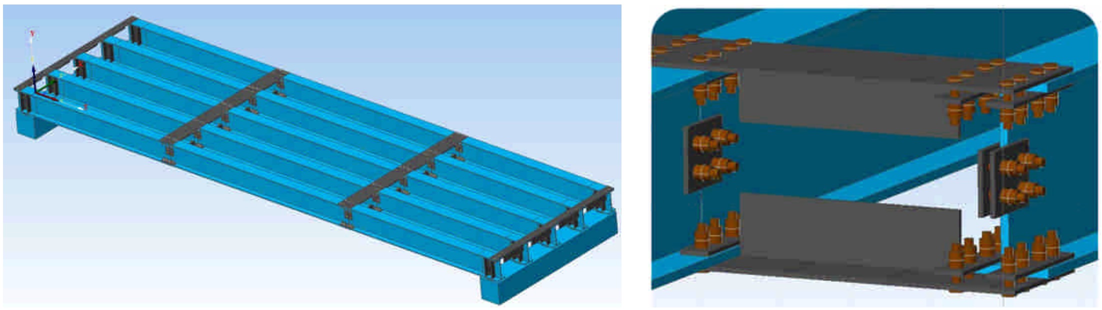
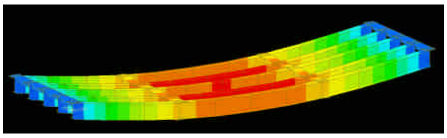
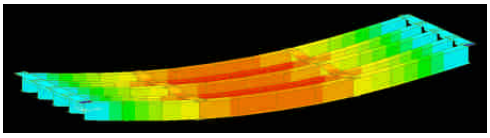


Figure 5.1. The parallel-girder composite bridge system and typical bolted connection detail



(a) 5-parallel GFRP girder bridge



(b) 5-parallel partial CFRP girder bridge

Figure 5.2. Deformation of parallel-girder bridge system under specific design loading

Table 5.1. Numerical results of parallel-girder composite bridge systems

Material	E_{eff} (GPa)	No. of parallel girders	Deflection (cm)	L/230 (cm)	L/320 (cm)	No. of bolts
GFRP	20.03	5	4.34	4.348	3.125	240
Partial CFRP	28.35	5	3.11	4.348	3.125	240

6. SUMMARY AND DISCUSSION

The current research results are summary as, (1) the design of temporary composite bridge is dominated by deflection rather than by strength, and the truss-type has better deflection behaviour than the beam-type design, but the corresponding joints problems of multi-connection truss structure needs further study, (2) in material approach, added carbon fiber in hybrid FRP girder is effective for stiffness improvement, but not cost-effective for performance to cost ratio, (3) the arch effect can increase the stiffness of composite frame by 16.535 times for arch girder with steel tie and simple support, furthermore by 65.869 times for arch girder with a hinge support at both ends, (4) in multiple bolted connection, the longitudinal pitch ≥ 4d and transverse pitch ≥ 4d for web are satisfied, but for flange the bearing failure should be avoided and needs future study and (5) 5-GFRP-girder bridge system could meet the requirement for deflection-to-span ratio of L/230 and 5-partial CFRP-girder bridge system could meet the higher requirement of L/320.

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