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A Study on the Mechanical Behaviour of the BFRP Decks with Fillers

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ABSTRACT

This study presents the mechanical behaviours and the failure modes of Basalt Fiber Reinforced Plastic (BFRP) composite material decks filled with different stuffing materials; and the BFRP decks were tested by using the three-point bending test. In this paper, the study involves the use of a prototype BFRP deck specimen, and BFRP decks filled with Styrofoam concrete, normal-weight concrete (density 2.4 t/m^3, and strength 28 MPa) and epoxy mortar, separately. In the three-point bending test, measurements from a load cell and dial gauges were used to obtain the load-displacement relationship. The stiffness, failure mode and ultimate strength of the BFRP decks in-filled with different fillers will be discussed in this paper.

Keywords. Fiber Reinforced Plastic (FRP), Composite Material, Bridge Deck, Fillers

INTRODUCTION

The subtropical climate of Taiwan, as an island nation, is characterized by hot, humid and rainy weather which accelerates the corrosion of reinforced concrete structures. Two-thirds of the bridges in Taiwan are made of reinforced concrete accounting for about 90% of the country's total bridges. The deterioration phenomenon of current bridge decks has been worsening due to the direct load impact of heavy vehicles and also the chloride attack, making maintenance cost of bridges in Taiwan persistently high.

Therefore, high strength and weather resistant Fiber Reinforced Plastic (FRP) composite material is proposed to apply in the bridge deck. In this study, the FRP bridge deck is intended to improve the deterioration problem of old existing bridge decks. The use of FRP bridge decks has been developed in Europe, United States, Canada and other regions for more than a decade. The relevant information collected from these researches and practical applications of FRP were used as reference in this study.

Zureick (Zureick, 1997) utilized finite element analysis software, ANSYS and GTSTRUDL, to analyze FRP bridge decks of four different cross sections before comparing their results. It was found that after the decks were subjected to the design loads, the maximum stress value was less than the allowable stress, 28 MPa. In addition, from the results of the four different cross sections, it was possible to identify the cross section with the best mechanical behaviour. Keller and Schollmayer (Keller and Schollmayer, 2004) made a study on two-way GFRP deck systems. The study focused on investigating the flexural and mechanical behavior of orthogonal FRP decks. The actual dimension of the FRP deck was used in numerical simulation. In addition, the maximum span between the two main girders of the bridge deck in-cooperated the European Bridge Design Specifications. Experimental results for the study showed that the vertical displacement of the GFRP deck was less than the design deflection. Keller and Schollmayer (Keller and Schollmayer, 2009) used pultruded FRP beam s to form a bridge deck and explored the effect of negative bending moment of the beam. The research pointed out that the properties of a FRP component depends mainly on the material used and production method employed. The study concluded that when the load on the FRP bridge deck exceeds the linear elastic range, the deck will fail locally.

Liu (Liu, 2007) used FRP bridge decks to replace those of an existing steel truss bridge (Hawthorne St. Bridge, Virginia State). The study investigated the strength and fatigue behaviour of the bridge deck on large scale and actual size. Test results showed that FRP bridge deck failed by crushing under the effect of 3 million cycles of loading, while the strength and stiffness had no significant change. It was shown that the overall displacement of the bridge deck is not suitable for design standards reference of the FRP bridge deck without considering local deformation behaviour. Ji *et al.* (Ji, 2010) designed and tested GFRP corrugated-core sandwich in which aluminum sheet was used as the inner core material. The deck was trapezoidal cross section, and it was tested in situ and analyzed by using finite element analysis. It was found from the results of the test that the deck had an enhanced stiffness and strength. Kim *et al.* (Kim, 2011) used 5 hollow square tubes of GFRP deck in a series of three-point bending test, including dynamic loading, static loading and cyclic loading. From the experimental results of the bridge deck it showed that, regardless of which method is used, the ultimate strength design method or working stress design method will meet the required specifications.

RESEARCH CONTENTS

The design of the Basalt Fiber Reinforced Plastics (BFRP) composite material bridge deck and the three-point bending test were presented in this study. The mechanical behavior and failure modes of the BFRP composite material for the bridge deck were investigated. The BFRP bridge deck was designed to meet strength and stiffness requirements.

After completing the production of the BFRP deck specimens, a series of three-point bending tests were carried out on the BFRP deck. The specimens involved are (1) 1 *m* and 2 *m* prototype deck specimens, and (2) three 1 *m* BFRP decks filled with Styrofoam concrete, normal-weight concrete and epoxy mortar, separately. Upon completing the experiments of each BFRP deck group, the stiffness, failure mode and ultimate strength of the BFRP decks of each specimen group were compared and discussed.

EXPERIMENTAL PLANNING AND SETUPS

This study aim s to explore the load-displacement relationships and the failure modes of BFRP bridge decks under the three-point bending tests. In this study, the fillers in the prototype BFRP bridge deck enhanced the stiffness and changed the failure mode of the BFRP deck component.

Experimental planning

Four sets of BFRP bridge deck specimens were tested by three-point bending load experiment. The first set of experiments was the 1 *m* prototype BFRP bridge deck. The main aim of the prototype BFRP bridge deck is to find out the load-displacement relationship and the failure mode of the BFRP deck. Later, the experimental result of the 1 *m* prototype BFRP bridge deck was used as the benchmark. The second set was a BFRP bridge deck filled by Styrofoam concrete to increase the moment of inertia of the BFRP deck. The third set entailed filling the BFRP deck with normal-weight concrete with the intention of enhancing the stiffness, strength and the overall moment of inertia of the BFRP deck. To even enhance the stiffness, strength and also the bondage between the BFRP component and the filler material, the fourth set of experiments was filled by epoxy mortar.

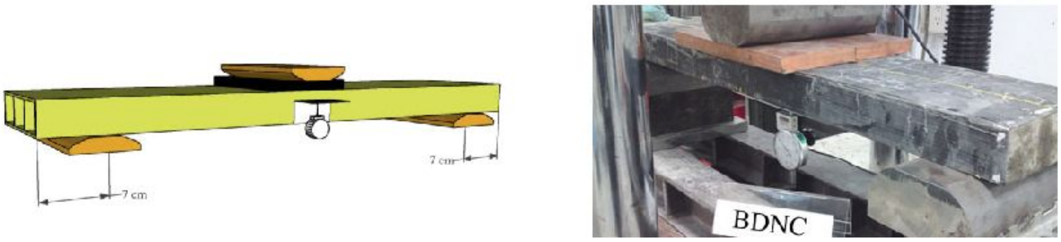
BFRP bridge deck specimens are named according to their lengths and filler material. As seen from Table 1, the first specimen set is a 1 *m* prototype BFRP bridge deck which is named BD1P. The second set of specimens filled by Styrofoam concrete BFRP member is named BDSC. Members of the third set of specimens are named BDNC after normal-weight concrete; and the fourth BFRP specimen set which is filled by epoxy mortar is referred to as BDEM.

Table 1. Naming of BFRP Specimen

Cross-sectional view	Specimen Length (m)	Filler	Specimen name
	1	Nil (Prototype)	BD1P
	1	Styrofoam concrete	BDSC
	1	Normal-weight concrete	BDNC
	1	Epoxy mortar	BDEM

Experimental Setup of Specimens and Instruments

An 100-*ton* universal testing machine was used to conduct the three-point bending test of the simply supported BFRP deck specimens. The supports were placed below the BFRP deck at a clear distance of 7 *cm* from each of the two ends of the deck; and the load was applied directly at the top mid-span of the deck. A dial gauge was mounted below the mid-span of the BFRP deck (which is also directly below the point loading point) to measure the deflection while the specimen is being loaded. The test set up of the BFRP deck specimen is shown in Figure 1. The universal testing machine of this study was a load controlled device, the test stop at at the 80% of the ultimate strength of the BFRP deck. In this paper, the specimens were loaded at a rate of 4.9 *kN* /*min*.



(a) Schematic diagram of BFRP deck (b) Actual setup of BDFP deck

Figure 1. Three-point bending test setup of BFRP components

EXPERIMENTAL RESULTS

For each type of BFRP bridge deck member of this study, the three-point bending test results were used to understand the mechanical behavior and failure mode of the BFRP deck. Details of the experimental results of the various types of BFRP bridge decks are discussed below.

Test Results of Prototype BFRP Deck

Based on the test results of specimen BD1P, the buckling failure mode of the specimen was because the webs of the BRFP deck were too thin, as shown in Figure 2. Nonetheless, the deck as a whole had a flexural behavior during the experiment. The experimental results at failure of specimen BD1P in three-point bending showed that the mid-span deflection at a load of 55.68 kN was 1.42 cm. This was accompanied by a crushing at both webs of the BFRP deck. The top flange also was damaged by crushing just like the webs while no significant damage was seen at the bottom flange. It can be shown that the prototype BFRP specimen was unable to transmit the load to the lower flange leading to its buckling damage mode. The relationship between the load and displacement of the prototype BFRP deck is shown in Figure 3.

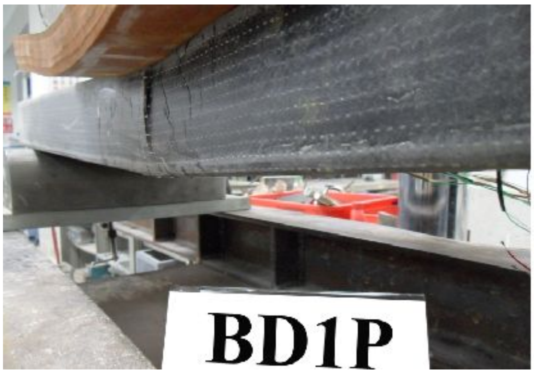


Figure 2. Failure mode of BD1P from three-point bending test at the web

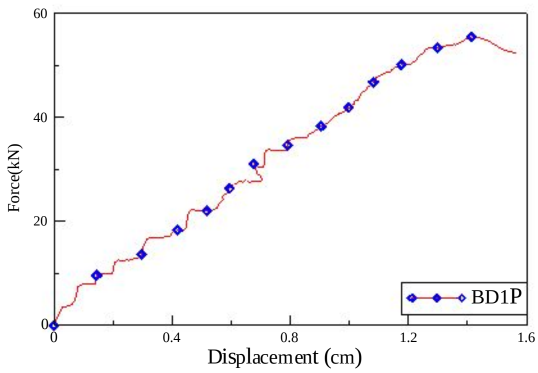


Figure 3. Load-displacement relationship diagram of B D1P specimen

Test Results of BFRP Deck Filled with Styrofoam Concrete

From the experimental results of the BD1P specimen, we learned that because the webs of the BFRP deck were too thin, the deck failed by lateral buckling because the BFRP specimen was unable to effectively transmit the force to the bottom flange. Therefore, in this study, the

BFRP deck was filled with Styrofoam concrete to prevent lateral buckling of the BFRP deck, increase the moment of inertia, enhance the stiffness and reduce the deflection of the deck.

From the experimental results of the BDSC specimen, when specimen BDSC reached its ultimate load of 82.96 kN in the three-point bending test, the corresponding mid-span deflection value was 2.63 cm. The mode of failure observed was a transverse shear failure resulting to crushing of the top flange while the bottom flange had no visible damage, shown in Figure 4. Based on the experimental results, the compressive strength of the BFRP deck is less than the tensile strength. Therefore, when subjected to loading, the infill material and the BFRP deck both failed by crushing. The role of the infill material (Styrofoam concrete) is to effectively transmit the load to the tensile side (bottom flange) of the deck, but because the edges of the deck are too thin, they were unable to withstand the load and failed by shear. The load-displacement diagram of the BFRP deck filled with Styrofoam concrete is shown in Figure 5.

Figure 4. The failure mode of specimen BDSC from three-point bending test

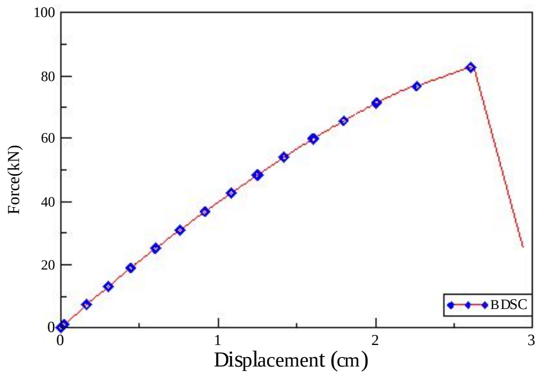


Figure 5. The load-displacement relationship diagram of BDSC specimen

According to experimental results of specimen BDSC, the compressive strength was too small due to the filled Styrofoam concrete. So in the experimental, the tensile side of the BFRP deck wasn't damaged even though the filled Styrofoam concrete was crushed. In this paper, therefore, normal-weight concrete of even higher compressive strength was introduced in order to achieve failure of the deck at the tensile side of the fibers making the deck component fully functional.

Test Results of BFRP Deck Filled with Normal-weight Concrete Mortar

According to the experimental results of specimen BDNC, it was observed that under the three-point bending of the specimen sustained an ultimate load of 131.48 *kN* with a corresponding mid-span displacement of 4.19 *cm* when it was damaged. In addition, the experimental result of BDNC shows that the failure mode of the specimen closely resembles that of specimen BDSC (as shown in Figure 6), which had a buckling of the flanges and transverse shear failure at the webs. And based on the experimental results, it was found that even with the filled material, the compressive strength was still less than the tensile strength of the BFRP deck. This is due to the fibers of the tensile side of the BFRP deck not been damaged yet. The BFRP deck filled with normal-weight concrete helped effectively transmit the load to the tensile side (on the bottom flange) of the BFRP deck, but because the webs of the deck are too thin, they were unable to withstand the load and failed by shear. The load-displacement relationship diagram of the BFRP deck filled with normal-weight concrete is shown in Figure 7.

Figure 6. The failure mode of BDNC from three-point bending test

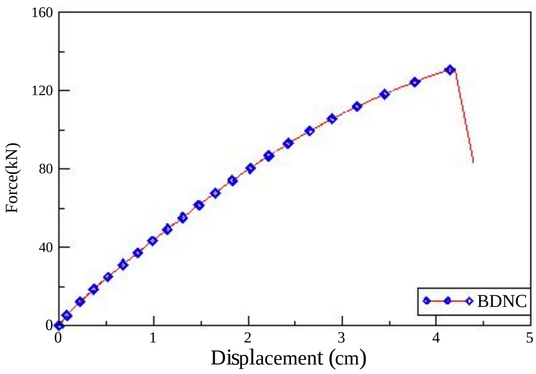


Figure 7. The load-displacement relationship of BDNC specimen

The force-displacement relationship diagram clearly shows a linearly displacement value of 0.5 *cm* which corresponds to a strength of 23.36 *kN* and stiffness of 48.72 *kN* /*cm* of BDNC specimen. Experimental results of the prototype specimen, BD1P, indicated that the BFRP component filled with normal-weight concrete did not significantly increase the stiffness of the BFRP deck. Once again, it was proved that the poor adhesive between the prototype BFRP deck and normal-weight concrete resulted in a no significant increase in the overall stiffness of the BDNC component.

Test Results of BFRP Component Filled with Epoxy Resin Mortar

Experimental results for specimens BDSC and the BDNC showed an interface slippage phenomenon between the BFRP and the filled material resulting in inability to raise the overall stiffness of the component. Therefore, in this study, in order the improve the stiffness of the BFRP deck as well as let the component fail at the tension side, epoxy mortar was adopted separately to enhance the overall effectiveness of the component.

According to the three-point bending test results of the specimen BDEM, it can be seen that specimen BDEM sustained an ultimate bearing capacity of 167.76 kN with a corresponding mid-span displacement of 3.55 cm at failure. The failure mode of the BFRP component was a transverse shear failure along the webs and tensile failure at the bottom flange (as shown in Figure 8). The load-displacement relationship diagram of the BFRP deck filled with epoxy mortar is show n in Figure 9.

As seen from Figure 10, specimen BDEM had a displacement value of 0.5 cm in the linear segment with a corresponding of 36.03 kN, and therefore a stiffness of 72.06 kN/cm. Compared the prototype BFRP deck with the BFRP deck filled with epoxy mortar (BDEM), it was found that the specimen BDEM had a higher stiffness value than the prototype BFRP deck. Consequently, the epoxy mortar can increase the interface adhesive between the BFRP component and the epoxy mortar itself also can improve the overall stiffness and the ultimate strength of the prototype BFRP deck.

Figure 8. The failure mode of specimen BDEM

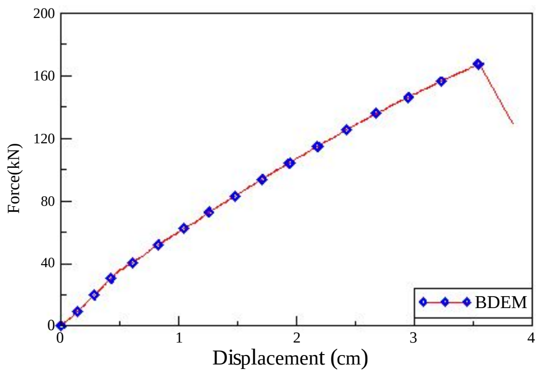


Figure 9. The load-displacement diagram of B DEM specimen

COMPARISON OF THE EXPERIMENTAL RESULTS

In the experimental results of specimen BD1P, since the webs of the BFRP deck is too thin, the deck failed by a lateral buckling phenomenon. Therefore, in this paper, Styrofoam concrete, normal-weight concrete and epoxy mortar were introduced to prevent the lateral buckling of the BFRP deck, increase the moment of inertia and stiffness, and reduce the deflection.

By three-point bending test results it was shown that the filled materials of specimens BDSC and BDNC delayed their failure damage at the compression side but because of the poor adhesive between the filled materials and the BFRP deck causing slippage; the stiffness of the BFRP deck wasn't significantly improved. When specimen BDEM was filled by epoxy mortar, it had a good interface adhesive with the BFRP deck, displayed a non-slip phenomenon in the experimental process, and increased the stiffness by 1.6 folds. A comparison of the displacement trend of the BFRP deck as shown in Figure 10, from the three-point bending, once again proves that the BFRP deck filled with epoxy mortar does, apparently, upgrade the BFRP deck's stiffness and ultimate strength.

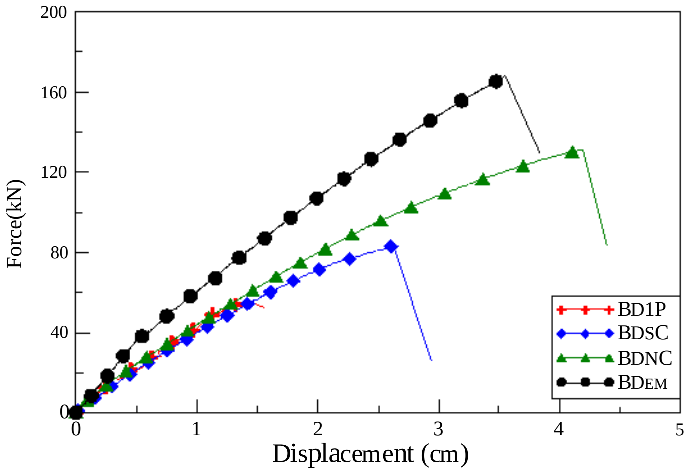


Figure 10. The load-displacement relationship diagram of the BFRP specimens

CONCLUSIONS

A series of three-point bending tests is adopted to understand the force-displacement relationship and failure mode of the BFRP bridge decks which are made of different materials. The following concluding remarks can be addressed.

1. In this study, the three-point bending test experiment of the BFRP bridge deck shows that the BFRP bridge deck failures by lateral shear failure and crushing of the top flange while no flexural failure was observed. To avoid such failure mode, the deck should be filled with a good adhesive resin mortar.

2. Filling the BFRP bridge deck by Styrofoam concrete or normal-weight concrete does not significantly improved the stiffness due to the poor cementation between the filler and the BFRP component. But the ultimate strength and the corresponding mid-span displacement can be enhanced.

3. As seen from the experimental results, the BFRP bridge deck filled with adhesive epoxy mortar that the stiffness and ultimate strength are significantly improved, thus the failure time of the BFRP deck is delayed.

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