

Feasibility Study on Increasing Bending Stiffness of FRP Girders by Bonding CFRP Strips and Bonding Girder Sections

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ABSTRACT

Substantial deflection of FRP composite girders when subjected to flexural loading is still a major design challenge that structural engineers are faced with. In this study, a way to increase the bending stiffness of FRP girder is suggested. This study investigated the feasibility of (a) externally bonding CFRP strips of high elastic modulus onto the flanges of FRP girder and (b) stacking one girder on another to form a large-scaled section girder as means of increasing the bending stiffness of FRP girders.

During the research, analytical and experimental studies were conducted to evaluate; the effectiveness of the adhesive layer in holding the CFRP strips to FRP girder and FRP girder to FRP girder, the applicable span length of a footbridge (proposed structure) constructed using FRP girders with CFRP strips bonded on its flanges and stacked girders, and the ultimate bending strength of the FRP composite girder.

It was noted that the bending stiffness of FRP girder can be effectively increased by externally bonding CFRP strips onto its flanges depending on the mechanical properties of the CFRP strips. By stacking one girder on another, the ultimate strength of the girder almost quadrupled as compared to a simple girder.

From this study, the conclusion is that; the adhesive layer effectively provided the bonding strength required to hold the constituent members together thus additional connectors like bolts and rivets are not necessary. The ultimate bending strength of FRP girders can be considerably increased by either using CFRP strips or bonding girder sections.

Therefore, strengthening FRP girder by bonding CFRP strips and bonding girder sections are feasible methods for increasing the bending stiffness of FRP girders and can be useful in the design of FRP footbridges.

KEYWORD

FRP footbridge, bending stiffness, bonding CFRP strip, bonding girder sections

1. INTRODUCTION

Until recent years, a lot of bridges were constructed using steel and concrete. Due to harsh environmental conditions, these bridges have undergone deterioration of various degrees. Some of the main causes of deterioration include; salt attacks resulting into the steel and the rebar inside the concrete corroding, fatigue and carbonation in the case of concrete. These have resulted into enormous amount of resources being spent to ensure the longevity of these structures, hence increase Life Cycle Cost (LCC).

Due to the above mentioned problems, engineers and scientist have continually searched for new alternative environmental resistant construction materials. One of the new construction materials that have seen significant increase in its use over the last decade is Fiber Reinforced Plastic (FRP).

FRP is a composite material and is made by reinforcing polymer matrix with fibers. It has many desirable characteristics such as; being very light (almost 1/5 the density of steel), excellent strength to weight ratio, durable, high resistance to environmental conditions, easy handling, erection and fabrication amongst others [1], [2].

The major drawback in the use of FRP as a construction material includes the high initial cost which pushes the project cost much higher than when steel or concrete were used. In addition unlike in the design of steel or concrete structures where design methods are based mostly on stress, in the design of FRP structures, design method is based on deflection limitation as FRP pultruded profiles are known to deflect considerably under flexural loading. For this reason, different design method is adopted [3], [4].

The objective of this study is to suggest two ways to increase the bending stiffness of FRP girder;
 (a) Externally bonding CFRP strips of high elastic modulus onto the flanges of FRP girder and
 (b) Stacking one girder on another to form a large-scaled section girder as means of increasing the bending stiffness of FRP girders.
 First, in order to ascertain the feasibility to a pedestrian bridge, the trial design was carried out. Next, in order to investigate the increase in bending stiffness and strength of FRP girders, ultimate flexural capacity test was performed using scale-down FRP girders.

2. TRIAL DESIGN AND FEASIBILITY STUDY

2.1 Design Conditions

In this paper, a structure (pedestrian bridge) of effective width 1.5 m to be constructed using two FRP main girders was proposed. A simply supported girder bridge and 2-span continuous girder bridge was the subject of this trial design. All the members of the bridge including the slab, deck floor and handrails are to be made of FRP materials.

The cross section of the main girders used in trial design is shown in Table 1. The main girder is a pultruded I-section GFRP profile of dimensions; $H600 \times B300 \times t_w 12 \times t_f 18$, which is the largest pultruded profile available in Japan. Three types of girders were used in the trial design; a simple GFRP girder (GN), a GFRP girder with CFRP strips bonded on its flanges (GS) and two GFRP girders one bonded over the other (GD)

The material properties of the main girders, CFRP strips and adhesive used are shown in Table 2. The material properties of GFRP girder used in trial design was the same as that of the scale-down GFRP girders used in the experiment described below.

The design specification is as follows;
 The design dead load of 12.19 kN/m obtained by calculating the weights of main girder, floor system, pavement and felloe, and a live load of 3.5 kN/m² [5] was used.

For serviceability, the deflection limit of $L/500$ or less of span length L and vibration frequency limit of 1.5 - 2.3 Hz [5] respectively were used.

Table 1 Sectional property of girders and applicable span

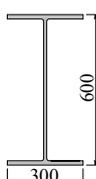
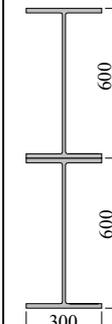
Girder Type	GN	GS	GD
Cross Section			
EI (kN m ²)	37.2×10^3	55.5×10^3	177.8×10^3
GA (kN)	24.7×10^3	24.7×10^3	49.4×10^3
Applicable	1 Span	14.3 m	21.3 m
Span L_{max}	2 Spans	14.5 m+14.5 m	16.5 m+16.5 m
		24.4 m+24.4 m	

Table 2 Material properties

Member	GFRP girder		CFRP strip	Adhesive
	1600 pultruded profile		$B50 \times t2$ mm	Sika dur 30
E (kN/mm ²)	35	28.8	154	1.5
G (kN/mm ²)	-	3.65	-	0.6
σ_{tu} (N/mm ²)	407	253	2466	-
σ_{cu} (N/mm ²)	484	440	-	-

2.2 Bending Stiffness of Girders

Based on the material properties given in Table 2 and the sectional dimension of the girder given in Table 1, the bending stiffness EI and shear stiffness GA of the girders were calculated. The result of calculation is shown in Table 1. The bending stiffness of GFRP girder increased by nearly 50% as a result of bonding CFRP strips onto its flanges. The bending stiffness of stacked GFRP girder is 4.8 times that of a single GFRP girder. On the other hand, the shear stiffness of girder GN was the same as that of girder GS. The shear stiffness of girder GD is twice that of a single GFRP girder, because the effective area for shear was assumed as the area of web.

2.3 Applicable Span Length

Using Timoshenko beam theory, deflection equations were deduced for a simply supported and a 2-span continuous bridge models subjected to live loads applied such that maximum deflection of girder is obtained.

The longest applicable span for which maximum deflection of girder under live load is less than the deflection limit was then calculated. In each case two main girders were considered. Result of the calculation is shown in Table 1.

By bonding CFRP strips onto the flanges of GFRP girder, the applicable span can be increased by about 2 m. Bonding two girders together one over the other results in applicable span of up to about 10 m longer than in case of a simple un-stacked GFRP girder.

3. EXPERIMENTAL STUDY ON FLEXURAL BEHAVIOR

3.1 Materials and Girder Specimens

The GFRP girders used in this experiment were I-section pultruded profiles of cross sectional dimensions; $H300 \times B150 \times t_w14 \times t_f10$ mm. The material properties were obtained from results of coupon test carried out using coupon specimens cut out of the GFRP. An epoxy-resin commercially known as Sidadur 30 was used as adhesive. It is a thixotropic adhesive mortar based on two-

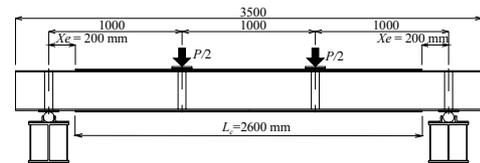
component solvent free epoxy resin. The mixing ratio by weight is 3:1 of component A (resin) and component B (hardener). The mechanical property of the Sikadur 30 was provided by the manufacturers.

The CFRP strips used in the test are of width 50 mm and thickness 2 mm, also pultruded profiles. Tension tests were carried out to determine the material properties of the CFRP strips. Here the CFRP strips and Sikadur 30 used have the same material properties as those used in the trial design. The material properties of the girders used in the test are shown in Table 2.

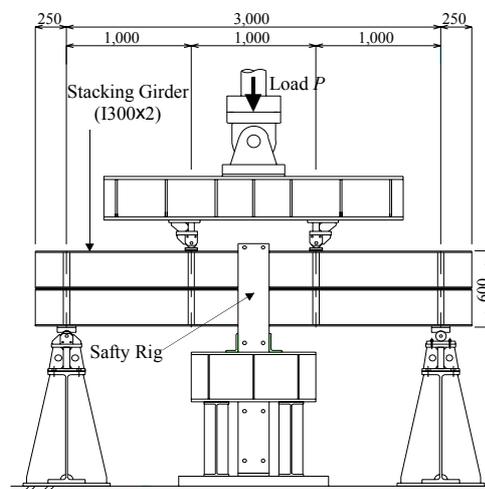
3.2 Instrumentation and Set Up

The schematic view of experimental set up is shown in Figure 1. Girder specimen of total length 3500 mm was set up over two supports one fix and the other movable. The two supports were adjusted such that they are exactly 3000 mm apart (Span $L = 3000$ mm). To prevent local buckling and distribute point load, steel plates of dimensions; $B250 \times L50 \times t12$ mm were placed in between the loading point and the flange of the girder specimen.

To record longitudinal strain due to applied load, strain gauges were embedded at mid-span section and one quarter point section of the girder specimen.



(a) Girder type of GS



(b) Girder type of GD

Figure 1 Schematic view of experimental set up

The deflection at mid-span and displacement at both supports were recorded using highly sensitive displacement sensors. The data from the displacement sensors, strain gauges and load cell were recorded using the static and dynamic data logging systems.

A photographic view of the experimental set up of GS is shown in Photo1.

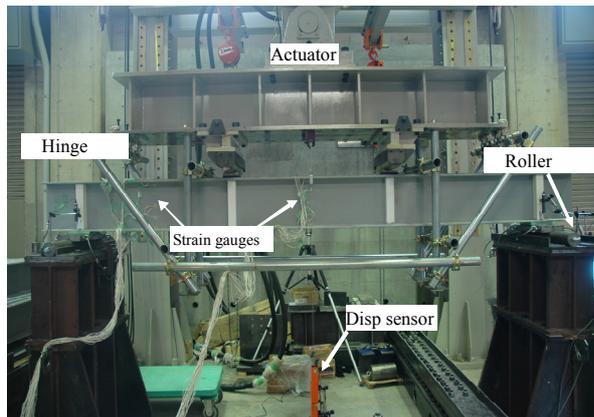


Photo 1 Experimental set up of GS

3.3 Experimental Procedure

Flexural loading tests were performed to evaluate the strength, mode of failure, and the margin of safety of the girders under flexural load. Three specimens; a simple GFRP girder (GN), GFRP girder with CFRP strips bonded onto its flanges (GS) and two GFRP girders bonded one over the other (GD) were used in the flexural loading tests. Flexural loading was applied under four-point bending. The girder specimens were simply supported on two cylindrical metallic supports one fixed and the other movable with span adjusted to 3000 mm apart. The girder specimens were loaded using 1000 kN output hydraulic actuator to which a loading spreader beam is attached. The loading spreader beam was centered above the mid-span and the load cell was adjusted to create a 1000 mm zone with constant bending moment and zero shear. Tests were executed in displacement control with a velocity of 0.05 mm/sec.

Tests on all the girder specimens were performed in two stages. First stage (Stage I), a non-destructive static test to determine the deflection stability of the girder during loading. Applied load during Stage I was up to about 50 kN. In the second stage (Stage II), to measure the ultimate flexural capacity of the girder specimens, load was applied monotonically until the girder specimens failed.

3.4 Experimental results

The result of the flexural loading test were recorded and plotted into graphs. The relationship between displacement at the mid-span of the girder and the applied load is shown in Figure 2. It can be noted from the graph that in all the three cases, the experimental values are almost the same as the analytical values, which are calculated based on Timosenko beam theory and Bernoulli-Euler beam theory.

The deflection at mid-span of GN when a load of 250 kN was applied was 47.8 mm. Those of GS and GD were 30.5 mm and 11.69 mm respectively when subjected to the same flexural load. By bonding CFRP strips onto the flanges of GFRP girder, a 36.2% decrease in deflection was recorded. Stacking a girder over another resulted in a 75.5% decrease in deflection. Moreover, the additional deflection due to shear deformation is considerable large and can not be ignored when examining the increase of the girder stiffness.

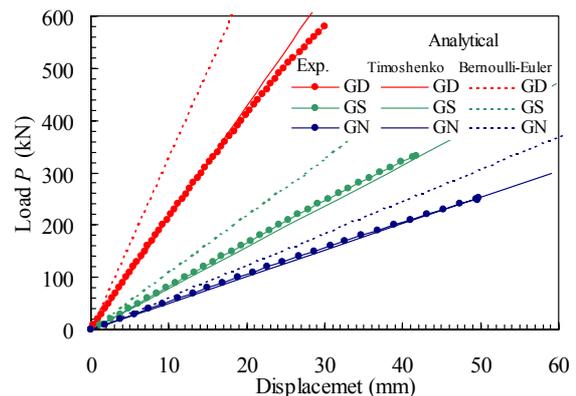


Figure 2 Displacement at mid-span

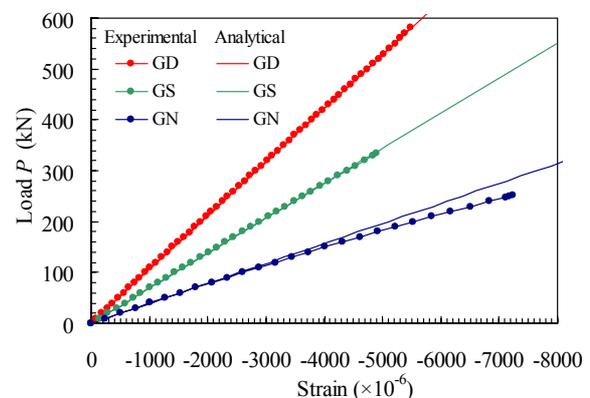


Figure 3 Strain on the upper flange at mid-span

Figure 3 shows the relationship between the applied load and strains on the upper flange at mid-span of the girder specimens. Same as noted

in the case of deflection, the experimental results are identical to the analytical value.

The significant decrease in strain in the girder as the result of bonding CFRP strips (GS) and stacking girders (GD) can be seen from the figure.

To investigate the behavior of the girders and examine the ability of the adhesive layer to hold the constituent member of the girder together as a composite unit, strains along the depth of the girders were measure during the various stages of the loading. The relationship between strain and the distance from the central axis of the girder under various loads for the girder types of GS and GD are shown in Figure 4 and 5 respectively.

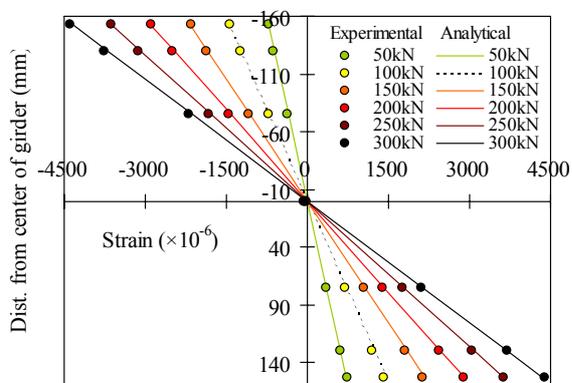


Figure 4 Strain distributions along the depth at mid-span of GS under various loading

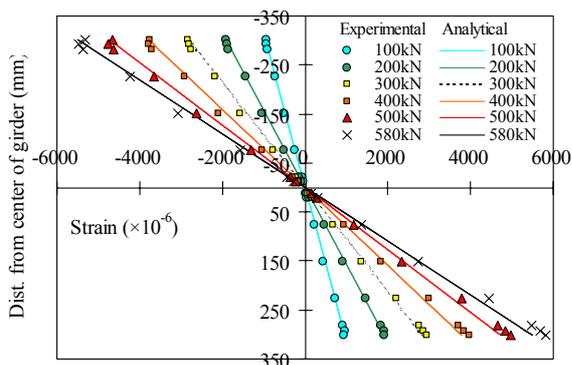


Figure 5 Strain distributions along the depth at mid-span of GD under various loading

The cross section of girders remained in parallel plane to the neutral axis during loading until the point of failure as can be noted from the figures.

When the girders were loaded to failure, the girder types of GN and GS failed at maximum load of 250 kN and 333 kN respectively. The girder type GD had a maximum flexural capacity of 580 kN.

As a result of bonding CFRP strips onto flanges (GS) and stacking two GFRP girders together to form a larger section (GD), the ultimate flexural capacity of the girder type of GN increased by 33.2% and 132% respectively.

Both girder types GN and GS failed after losing their compressive bending resistance. Ruptures in both cases were along the upper flange at mid-span. In the girder type of GS, the CFRP strip on the upper flange first split open along its laminate plane rather than the along the adhesive layer interface between the CFRP strip and the GFRP girder causing the girder to loose its global bending resistance and subsequently failed.

In the case of girder type GD however, failure was by bearing, where the upper flange just below the loading steel plate carved in and collapsed under bearing force from the loading point.

The mode of failure in the girder types of GS and GD is shown in Photos 2 and 3 respectively.

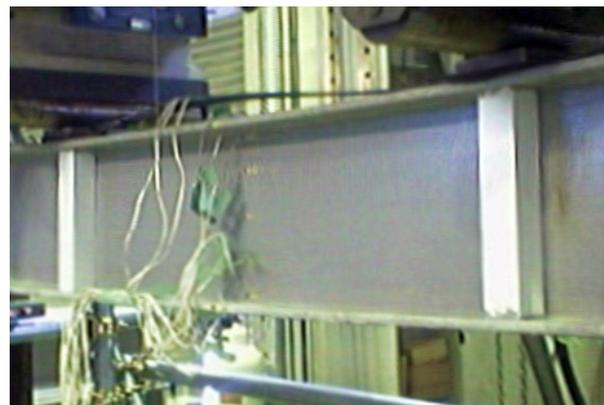


Photo 2 Snap shot showing failure mode in GS

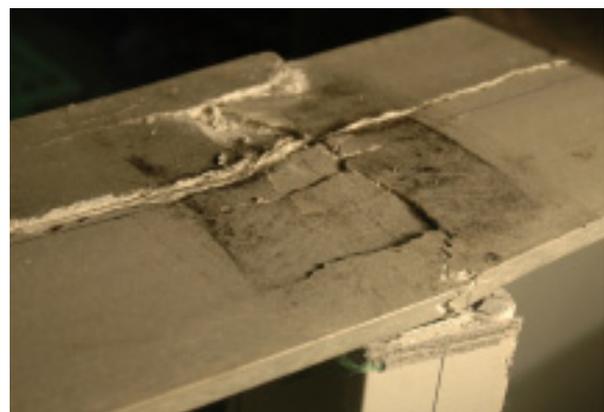


Photo 3 Snap shot showing failure mode in GD

4. CONCLUSIONS

The main objective of this study is to evaluate the feasibility of using CFRP strips and stacking girder to improve the bending stiffness of FRP

girders. The study showed that the bending stiffness of FRP girder can be significantly increased by bonding CFRP strips of higher stiffness on to the girder's flanges and by stacking two girders one over the other form a larger section. The following conclusions were derived from the study:

- (1) When using FRP girder as a flexural member, the additional deflection due to shear deformation cannot be ignored as it constitutes a significant percentage of the total deflection of the girder.
- (2) The adhesive layer is significantly strong enough to hold the structural members together as one composite without the need for additional mechanical connectors.
- (3) The cross section of GFRP girder with CFRP strips bonded onto its flanges and two section girders remain plane and normal to the longitudinal axis until it reaches its point of failure when subjected to flexural loading.
- (4) Where FRP girder is to be use as the prime material in the construction of a pedestrian bridge, increasing the bending stiffness of the girder using CFRP strips and bond girder sections together allows the designer to have some flexibility. For example making the span longer and decreasing the number of main girders.

ACKNOWLEDGEMENT

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