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FLEXURAL STRENGTHENING OF COMPOSITE STEEL-CONCRETE GIRDERS USING ADVANCED COMPOSITE MATERIALS

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ABSTRACT

Composite steel-concrete girders are used widely in bridge and building construction as the main structural elements in flexure. The load-carrying capacity of an under-strength or deficient steel-concrete composite girders can be improved by epoxy bonding fiber reinforced polymers (FRP) laminates to its tension flange. This paper presents the results of an experimental study that investigated the behaviour of steel-concrete composite girders strengthened in flexure using various advanced composite materials tested under static loading. The different strengthening materials used in this investigation included unidirectional intermediate and high modulus Carbon Fiber Reinforced Polymer (CFRP) plates, unidirectional CFRP sheets and the newly developed unidirectional Steel Reinforced Polymer (SRP) sheets. The primary objective of this investigation was to assess the flexural behaviour of the strengthened beams and examine the effectiveness of the different strengthening materials. Test results are very promising and showed that epoxy bonded CFRP sheets or plates and SRP sheets significantly improved the stiffness and increased the ultimate load carrying capacity of the steel-concrete composite girders. The effect of strengthening on the elastic stiffness and ultimate strength was more profound for beam with high modulus CFRP plate.

KEYWORDS

Carbon fiber reinforced polymer, composite, concrete, externally bonded, flexure, high-modulus, sheets, plates, steel

1. INTRODUCTION

Many researchers conducted experimental and analytical studies on concrete beams and slabs strengthened in flexure using externally bonded FRP sheets or strips, however; research on steel-concrete composite girders is limited and only few studies are reported in the literature. Tests conducted by Mertz and Gillespie (1993) on small-scale steel beams strengthened in flexure with CFRP plates showed about 20% increase in the flexural stiffness and more than 50% increase in the ultimate strength. Sen et al., (1994 and 2001) loaded large-scale steel-concrete composite girders past yielding before being repaired using unidirectional CFRP plates and the results showed an increase in the ultimate strength from 11 to 52% depending on the mode of failure, thickness of the CFRP plates, the anchorage at the ends of the plates, and the yield strength of the steel beams. The effect of the number of layers of CFRP sheets on the behaviour of large-scale composite girders has been investigated by Tavakkolizadeh and Saadatmanesh (2003a) and the test results showed an increase in the ultimate strength by 44, 51 and 76% using 1, 3 and 5 layers, respectively. Tests showed that the CFRP sheets not only extended the fatigue life of a steel beam by more than three times, but also decreased the crack growth rate significantly (Tavakkolizadeh and Saadatmanesh, 2003b). To simulate field corrosion, steel composite beams were damaged by removing 50 and 75% of their bottom flange then repaired using CFRP plates to restore their original strength. Test results showed that 50% of the elastic flexural stiffness can be restored and the ultimate strength was fully restored (Al Saidy et al., 2004). Recently, high modulus and ultra-high modulus CFRP strips have been used to strengthen large-scale steel composite girders, and test results showed an increase in the ultimate flexural capacity by 16 and 45%, respectively; however, the flexural stiffness increased only by 10% and 36% due to the high elasticity modulus of the strips (Schnerch et al., 2005).

This paper investigates the feasibility and effectiveness of using various materials including high-modulus FRP to strengthen large-scale steel-concrete composite girders, simulating the majority of the highway bridges, tested under static loading. The structural performance of the strengthened steel beams will be examined and discussed.

2. EXPERIMENTAL INVESTIGATION

2.1 Specimens Details

A total of five 6.2m long steel-concrete composite girders made of steel I-beams and 56 mm thick by 435 mm wide reinforced concrete slabs were fabricated and tested. Shear stud connectors welded to the top flange of the steel beams were used to provide the shear connection between the concrete slab and the steel beams. Two longitudinal rows of shear studs were used with a 90 mm transverse spacing between rows of studs. The studs were spaced at 50 mm apart in the longitudinal direction. Figure 1 shows details of a typical beam specimen.

2.2 Material Properties

Concrete

The specified 28-d compressive strength of the concrete was 40 MPa. The actual concrete strength at the day of testing determined as the average of three standard concrete cylinders was 40.3, 39.1, 37.0, 39.0, and 36.5 MPa for beams B1, B2, B3, B4, and B5, respectively.

Steel

The steel beams were standard W200×19.3 Grade G40.21-M345W hot rolled I-sections with average yield and ultimate tensile strengths obtained from tension tests of 414 MPa and 532 MPa, respectively. The interface shear reinforcement along the top flange of the steel beam and the reinforced concrete slab was provided by shear connector. The shear connectors were 6.0 mm diameter and 28.5mm length with yield and ultimate tensile strengths of 345 MPa and 414 MPa, respectively. The composite concrete deck slab reinforcement consisted of a welded wire fabric steel mesh type 152.4 × 152.4 MW28.3 × MW28.3 with a nominal diameter of 6.0mm.

Strengthening Materials

The externally bonded strengthening systems selected for this study were carbon FRP sheets, carbon FRP plates, and steel-reinforced polymer (SRP) sheets. The material properties of the different systems are given in Table 1. A two-part component epoxy adhesive, the main epoxy resin and the curing agent hardener, was used. Sikadur 330 was used for bonding the SRP and CFRP sheets, and Sikadur 30 was used for bonding the CFRP plates to the bottom flange of the steel girders.

Table 1 – FRP material properties as reported by the manufacturers

FRP products (type)	Dimensions	Elastic Modulus (MPa)	Ultimate Tensile Strength (MPa)
Unidirectional SRP Sheet (Hardwire™ 3×2-23-12)	$0.44 mm^2/mm^{\dagger}$	206000	3170
Pultruded CFRP Plate (Sika Carbodur® type S 812)	$1.2 mm^{\ddagger}$	160000	2800
Unidirectional CFRP Sheet (Sika Wrap® Hex230C)	$0.381 mm^{\ddagger}$	61012	715
Pultruded High Modulus CFRP Plate (Sika Carbodur® type H 514)	$1.4 mm^{\ddagger}$	300000	1300

† Net area per width ‡ Thickness

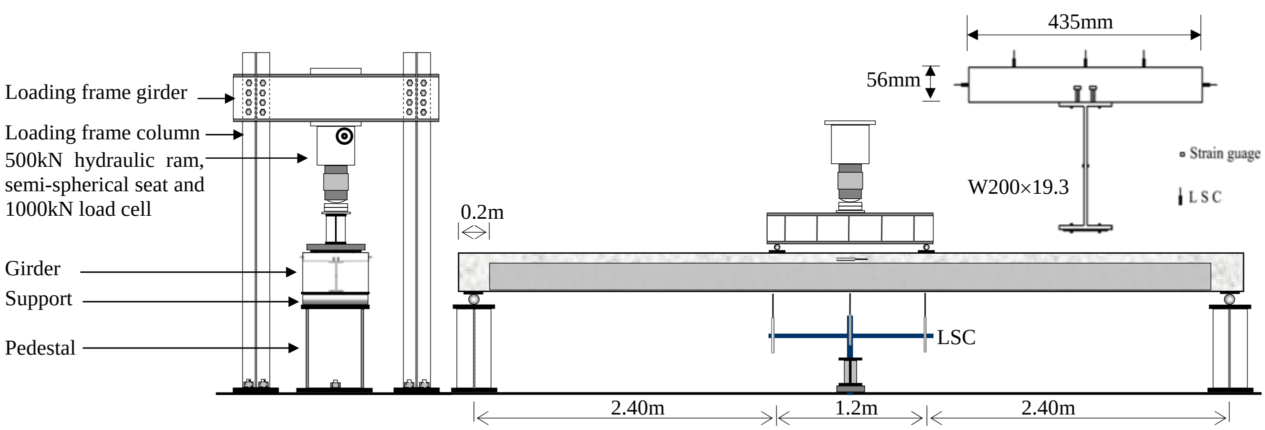

Figure 1: Test set-up and instrumentation of the steel-concrete composite girders

2.3 Test Matrix

One beam (B1) was tested without strengthening and served as unstrengthened control specimen. Four beams (B2, B3, B4, and B5) were strengthened with various systems designed to achieve a 30% increase in the ultimate load carrying capacity over the control beam. Table 2 summarizes the test matrix.

Table 2 – Test matrix for the composite girder specimens

Beam #	Strengthening System
B1	Control beam without strengthening
B2	Beam strengthened using two layers of 82mm wide SRP sheets
B3	Beam strengthened using one layer of 80 mm wide CFRP plate
B4	Beam strengthened using five layers of 98 mm wide CFRP sheets
B5	Beam strengthened using one layer of 25 mm wide HM-CFRP plate

2.4 Surface Preparation of Steel Beam and Installation of the Strengthening Systems

To ensure good and strong bond, the bottom surface of each steel beams was prepared by sand blasting and cleaned by air brushing to remove any dust. Before applying the strengthening materials an organic solvent (acetone) was used to clean the surface from any other bond inhibiting materials. Installation of the strengthening systems followed typical field conditions on the bottom flange beneath the steel I-beams using the dry lay-up technique. The epoxy was allowed to fully cure at room temperature for at least one week before testing the beams. The anchorage system consisted of a steel plate bolted to the bottom flange of the beam at both ends of the strengthening materials.

2.5 Test Setup, Procedure and Instrumentation

The 6.2m long girders were simply supported with a span of 6.0m between supports and tested under four-points bending static loading with 1.2m spacing between the two concentrated point loads. The load was applied using a 500kN capacity actuator through an MTS controller-testing machine operating under displacement control mode. The control beam (B1) was tested under a monotonically increasing load up to failure at a constant loading rate. To study the behavior of the strengthened beams after being loaded to the service condition and past the yield load, the Diagnostic Cyclic Load testing protocol was adopted in beams B2, B3, B4 and B5 (Nanni and Mettemeyer, 2001). All beams were fully instrumented to monitor their behaviour by measuring the deflection at midspan using Linear Strain Conversion devices (LSCs), strains in the concrete in the compression zone, and strain in the steel and in the CFRP and SRP reinforcements using electrical resistance strain gauges. During testing, the data were automatically collected and electronically recorded using a data acquisition system connected to a personal computer. Typical test set-up and instrumentation is shown in Figure 1.

2.6 Test Results and Discussion

The load versus midspan deflection curves comparing the flexural behaviour of the five beams are presented in Figure 2. For beams B2, B3 and B4, the strengthening effect is mainly affecting the post-yielding response since the stresses in the composite materials are less than those in the bottom steel flange due to their lower modulus of elasticity than steel. For the same beams, the improvement in the stiffness in the elastic range prior to yielding of the bottom steel flange is not significant due to the smaller elastic modulus of the strengthening materials compared with the steel section, however; the strengthening effect was more evident for beam B5 strengthened with a high modulus CFRP plate as shown by the significant increase in stiffness in the elastic range and ultimate strength when compared to beams B2, B3 and B4. The effectiveness of the FRP materials was more pronounced after yielding. As expected from the design, the beams achieved the required percentage increase in strength (30%) as can bee seen for beams B2 and B3 the increase in strength was 29%, and 35%, respectively, except for beam B4 the increase in strength was 23% because the applied area of CFRP sheets of 187mm^2 (or 5 layers of 98mm) was less than the required 272mm^2 (8 layers of 89.25mm) in order to achieve 30% increase in strength. The use of higher modulus CFRP plate resulted in the highest stiffness increase. Beam (B5) strengthened with HM-CFRP plate demonstrated strength increases up to 49%. All strengthened beams had minimal losses in ductility compared to the control beam.

The load-deflection behaviour is bilinear until failure. No degradation in the stiffness was noticed due to the unloading/loading cycles which became slightly nonlinear after yielding. As well, after yielding, the strengthened beams continued to resist further increase in the applied load with a more gradual linear slope than the pre-yield portion of the curve. The increase in the load continued until failure. Failure of beams B2, B3 and B4 occurred by crushing of the concrete near one of the load points, while beam B5 strengthened with HM CFRP plate failed by rupture of the plate that occurred within the constant moment region. Ductility is slightly reduced with the addition of composite materials. No debonding or delamination between the FRP and the steel beam was observed in any of the beams, indicating that the surface preparation was adequate and the bonding was strong enough.

3. CONCLUSIONS

On the basis of the experimental study presented, the following conclusions can be made:

- No bond failure was observed between the composite materials and the steel surface in all specimens.
- The effect of FRP bonding on the elastic stiffness was not significant for beams strengthened with intermediate modulus CFRP sheets or plates and SRP sheets.
- Test results showed significant increases in the stiffness prior to yield as well in the ultimate strength for the beam with HM-CFRP plate indicating the possibility to increase service loadings. This is very important when strengthening bridge to meet the more stringent limits imposed on serviceability (live load deflections) and ultimate strength of current codes.
- Crushing of the concrete was the dominating mode of failure except for the beam with HM-CFRP plate it was by rupture of the plate in the constant moment region.
- In general, all strengthened beams failed in a ductile manner accompanied by large deformation; however the beam strengthened with HM-CFRP plates showed less ductile behaviour but higher capacity.

To summarize, this study has confirmed the structural benefits and feasibility of using externally bonded intermediate modulus CFRP plates and sheets and SRP sheets to strengthen steel-concrete composite girder. However, the results indicated that high-modulus CFRP plates are more effective at increasing the strength and stiffness and are well suited for use in the repair and strengthening of steel structures.

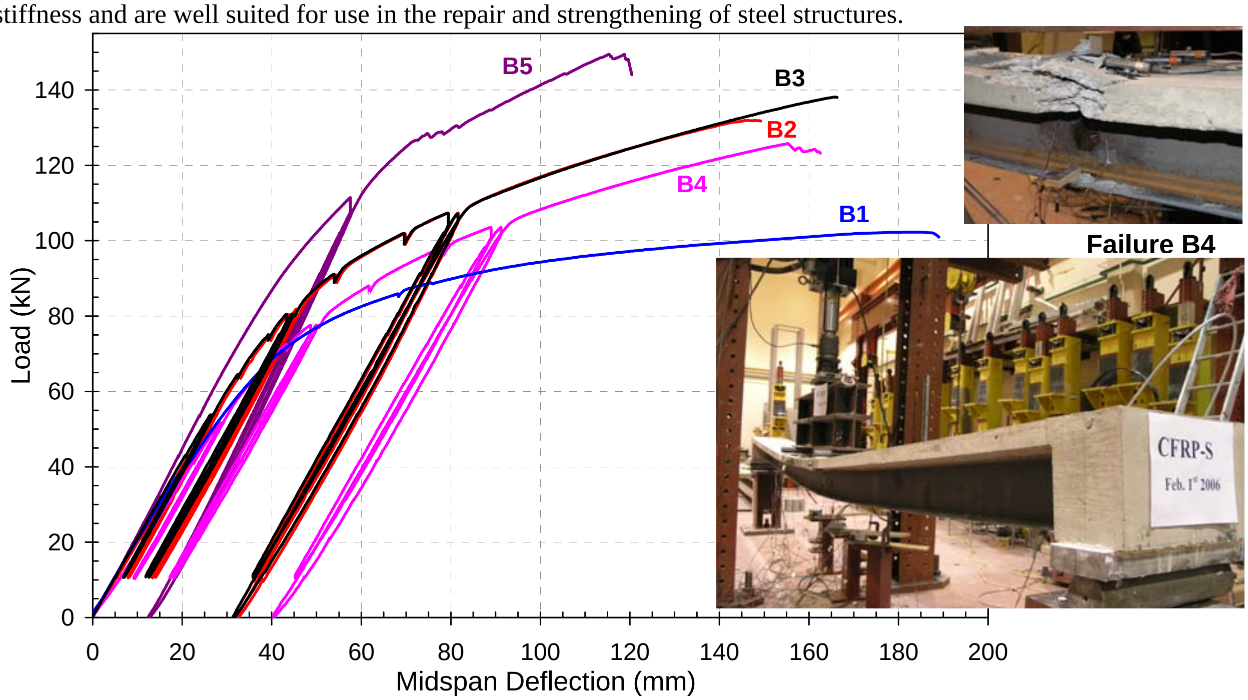

Figure 2 Load-midspan deflection curves for all steel-concrete composite girders

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