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Hybrid strengthening of steel-concrete composite beam, part 1: Experimental investigation

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ABSTRACT

Due to the partial interaction between steel beam and concrete slab, two neutral axes in a steel-concrete composite beam are formed, sometimes even at low load. As a result, both the soffit of the slab and beam can be in tension if slip is allowed in the composite beam which is a common case for numerous composite beams. While most the previous studies emphasised on the strengthening of the steel beam only, this study investigates the effect of strengthening both the concrete slab and steel beam. To perform this, two commonly used materials, carbon fibre reinforced polymer (CFRP) and steel plates, are implemented in different combination. The arrangements include CFRP on both the slab and beam, steel plate on both concrete and steel, CFRP on concrete and steel beam separately, steel beam on the slab and beam separately and the hybrid technique which is the combination of both CFRP and steel plate. In addition, the techniques are also compared against the beams where almost full interactions are achieved to explore the suitability of the proposed scheme if partial interaction is absent. It is found that the hybrid strengthening can enhance the maximum load carrying capacity, stiffness and ductility of a steel-concrete composite beams when partial interaction is present between the concrete slab and the steel beam.

1. Introduction

Steel-concrete composite beams, widely used for bridge construction, is a common structural element. At present, a number of these composite beams require strengthening due to various reasons, such as, deterioration of one or more structural component, increased number of traffic on the structure and reaching at the end of the their design life. Therefore, various materials and composites along with different strengthening scheme can be found in the literature. This includes the application of steel plate [1,2], carbon fibre reinforced polymer (CFRP) laminates [3,4], CFRP sheet [5–7], glass fibre reinforced polymer (GFRP), etc. To attach the CFRP, adhesives (mainly epoxy) are used, whereas both adhesive and welding techniques have been implemented to apply steel plates.

The application of CFRP on concrete beam or slab is well established. Externally bonded CFRP can significantly enhance the strength and stiffness of concrete beam [8,9]. For one way slab, CFRP is applied in a similar manner as practiced for the beams, while bi-directional CFRP should be adopted for two way slab [10]. The widely accepted means to attach the CFRP on concrete surface are adhesives. The most common type failure modes for CFRP-concrete composite beams are reported as follows: intermediate crack induced debonding, concrete cover separation, plate end interfacial debonding, critical diagonal crack and combination of any two [11].

To strengthen the steel beam, the classical approach was to attach steel plate on the soffit of a steel beam by welding or adhesive. Welded steel plate for repair were reported in [1,2], and epoxy bonded steel plate on steel beam for the strengthening purpose was also investigated in [12–14]. Apart from the steel plate, following the success of CFRP on concrete for retrofitting, this composite has been used on steel beam as well. However, the material properties or strength of FRP is more important when it is applied on steel in contrast to concrete. Since the strength of concrete is very low compared to CFRP, low strength CFRP is equally effective as high strength CFRP. This is due to the fact that the failure usually occurs at the concrete or at the interface. Nevertheless, different strength of CFRP, named as standard modulus (SM), high modulus (HM) and ultra-high modulus (UHM), contributes at different extent in terms of improving the strength of the steel beam. Strengthening using SM-CFRP can be found in [15,7] and using HM-CFRP are reported in [15–17,7]. It is reported that a major improvement can be achieved by using UHM-CFRP [18,16]. The predominant failure modes of CFRP-steel composite beam are found to be either the yielding of steel flange or the failure at the bonding surface as plate end debonding.

For the steel-concrete composite beams, strengthening is achieved by applying steel plate or CFRP at the soffit of the bottom flange of steel beam. To repair a composite beam member, Sen et al. [4] applied CFRP plates on the bottom flange of six steel beams with various

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thickness. The beams were initially loaded to yield the steel flange and then repaired using CFRP plates. The strength gain corresponding to 2 and 5 mm thick CFRP plates were 9 and 32%, respectively, for 370 MPa steel beam. Miller et al. [19] also used 5.3 mm thick CFRP plates on an existing steel girder in order to retrofit the structure in the field. An increase of 11.6% flexural stiffness was achieved in the study. Tavakkholizadeh and Saadatmanesh [6] applied CFRP sheet of one, three and five layers on the tension flange of steel beam. Addtionally, three artifical damages as loss of cross-section to various extent were incorporated. The ultimate load carrying capacity of the beams with 25, 50 and 100% loss of cross-sectional area of the bottom flange was improved by 20, 80 and 10%, respectively. On a different study, Tavakkholizadeh and Saadatmanesh [7] explored the suitability of using pultruted SM-CFRP and HM-CFRP on the girder with varrying layers as adopted in their previous study. The ultimate load was increased by 44, 51 and 76% for one, three and five layers of CFRP, respectively. Fam et al. [16] investigated the application of SM, HM and UHM CFRPs on undamaged composite beams and on notched steel beams as well. The flexural strength and stiffness of the undamaged composite beams were increased by 51 and 19%, respectively. It was also concluded that the thickness and type of CFRP affects the improvement to a different degree due to the difference in failure modes of CFRP enhanced composite beams.

While the aforementioned studies strengthened the steel flange only to improve the structural properties of the composite beam, strengthening other components of the composite girders are also reported in some literature. Al-Saidy et al. [20] introduced damage in a composite girder as different degree of cross-sectional loss and repaired using CFRP sheet by retrofitting both the steel web and flange separately and combined. The latter was found to be more effective in terms of strength gain. Sallam et al. [21] suggested the application of steel plate welded to the compression flange of the steel girder as well. In addition, another study of the same authors [22] compared three different strengthening technique that included the application of CFRP plate on the tension flange only, CFRP plates on tension flange and steel plate on the compression flange and steel plates on both flanges. The conclusions of this study include, CFRP sheet is more effective than CFRP plates (one layer) in terms of improvement in ultimate load and bonded or welded steel plates performed better for load transfer. Moreover, Sallam et al. [23] compared between the strengthening of the steel I-beam by CFRP and steel plates. Three types of bonding techniques (discontinuous, U-shape on both ends and bonding with adhesive) were implemented for steel plates, whereas the the CFRP was applied using adhesive only. Also, the CFRP was applied on both steel flange and web separately and combined. It was found that the ultimate load carrying capacity of a steel beam strengthened with welded steel plate show higher increase compared to the same of CFRP strengthened steel beam.

Al-Saidy et al. [24] conducted a parametric study on the behaviour of composite bridge girders when strengthened by CFRP plates following an experimental investigation in their earlier work [15]. The study explored the effect of the compressive strength of concrete, the cross-sectional area of the bottom flange of the steel beam and the stiffness, thickness and ultimate strain of the CFRP. It was concluded that ductility decreased in the strengthened section, but increase with the higher compressive strength of concrete. In addition, the modulus of elasticity of CFRP should be same or higher than the same of steel to obtain reasonable gain in ultimate load. Further, the CFRP is more effective for steel beams with lower yield stress.

In the previous studies, the focus was made on the strengthening of steel beam only. However, the partial interaction exists between the steel beam and concrete from the beginning of the load-deflection curve [25] that leads to dual neutral axes in composite beams resulting in development of tension at the bottom of steel beam and concrete slab as well. Therefore, this study investigates the effect of strengthening both the concrete slab and steel beam. Two mostly used materials, CFRP and steel plate, are used for the strengthening purpose with different combination in order to determine the suitable and effective techniques. In this paper, the experimental results are reported while the companion paper outlines the design guideline for these types of strengthening schemes.

2. Experimental program

In this study, high strength bolts are used to provide shear connection between steel beam and concrete slab. Therefore, push-out tests were conducted first in order to determine the shear capacity of each bolt. Then, nine composite beams were constructed with different number of shear connectors and various strengthening schemes.

2.1. Push-out test samples

To analyse the capacity of high strength bolts as shear connectors, three samples were prepared. The thickness of the concrete slab was set to 50 mm which is essentially the thickness of the concrete slab used for the construction of the composite beam. Instead of steel I beam, a square hollow section (SHS) with the similar material properties of the I-beam was used to connect the concrete slab. The thickness of the SHS (10 mm) was selected similar to the thickness of the flange of the steel I beam. Since the load per shear connector depends mainly on the properties of concrete and not on the steel, theoretically, the use of SHS should not affect the result. Fig. 1(a) shows the cross-section of the push-out test samples. The details of the material and geometrical properties of the materials used for the push-out tests are described below.

2.1.1. Materials

2.1.1.1. Steel beam. The SHS used for the push-out test was the 100 × 100 × 10 SHS. The height of the steel SHS was 300 mm, and the centroid of the SHS was 50 mm above the centroids of the concrete slabs. The modulus of elasticity, yield stress and tensile strength of the SHS is 200 GPa, 450 MPa and 500 MPa, respectively.

2.1.1.2. Concrete. Obviously, the concrete slab for the push-out test was constructed similarly as the concrete slab used for the composite beams. Accordingly, the thickness of the concrete slab was set at 50 mm. Due to the small thickness of the concrete slab, maximum size of the coarse aggregates was selected as 7 mm. The water cement ratio for the concrete was 0.38. Both the height and width of the concrete slab were 300 mm. The concrete slab was cured for 28 days by covering with wet hessian. Also, three concrete cylinders were casted to determine the compressive strength of the concrete.

2.1.1.3. Steel reinforcement. SL81 steel mesh was used for the reinforced concrete to provide longitudinal and transverse reinforcement as in the composite beams. Within the 300 × 300 mm concrete slab, two longitudinal and two transverse reinforcement were placed. The clear cover of the steel reinforcement was 10 mm. The diameter of the SL81 mesh is 8 mm with a centre to centre distance of 100 mm. The characteristic yield stress of the steel reinforcement is 600 MPa.

2.1.1.4. Shear connector. M8 high strength (grade 8.8) bolts were used to provide connection between the steel beam and concrete. The length of the bolt was 40 mm which enables a clear concrete cover of 10 mm. One bolt was used on both sides of the steel beam (Fig. 1a). Therefore, the bolt was placed at the centre of the concrete slab. The yield stress and tensile strength of the shear connector are 660 and 830 MPa, respectively.

2.1.2. Test set-up

The push-out specimens were tested using hydraulic testing machine with a capacity of 500 kN. The relative slip was measured