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Flexural strength of steel I-beams reinforced with CFRP sheets at tension flange

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ABSTRACT

The use of modern Carbon Fiber Reinforced Polymer (CFRP) to strengthen and repair steel beams in flexure has been rapidly increased within the past few years. This technique benefits from light-weight and extra-strong CFRP material to enhance the flexural capacity of cross section. To study the reinforcing effect of CFRP, one hundred and seventy-eight models were analyzed to cover six variables representing the common problem parameters; the variables were the slenderness ratio of web (h_w/t_w), the mono-symmetric ratio of I-beam (ψ), the area of CFRP (A_{cfrp}), the modulus of elasticity of CFRP (E_{cfrp}), the tensile strength of CFRP (F_{ucfrp}), and the length of CFRP sheet (L_{cfrp}). The adhesive properties used in parametric analysis were determined from experimental tests conducted for double-strap steel-to-CFRP joints with various bond lengths (50 to 200 mm), and the proposed model constructed using the general finite element program, ANSYS 17, was verified with experimental tests of full-scale steel beams reinforced with CFRP. The parametric study revealed that CFRP sheets were very efficient in reinforcing compact mono-symmetric sections, whereas the enhancement in beams with non-compact sections was very small. CFRP sheets were able to reach its ultimate strength provided that enough bond length was ensured. Analytical procedure to calculate the flexural strength of steel I-shaped beams reinforced with CFRP sheets at tension flange was presented.

1. Introduction

The use of modern Carbon Fiber Reinforced Polymer (CFRP) to strengthen and repair steel beams has been rapidly increased within the past few years. This technique benefits from the light-weight and extra-strong CFRP material to enhance the flexural capacity of the cross section. Although CFRP is expensive to produce, it has been commonly adopted where high-strength to light-weight ratio and rigidity are required. CFRP strength can be up to 10 times the strength of mild steel, and approximately 3.5 times the strength of Glass Fiber Reinforced Polymer (GFRP); it is much less in weight compared to mild steel for the same desired tensile capacity. The behavior of steel beams strengthened with CFRP plates in flexure has been subjected to several studies, and the strengthened beams have been reported to undergo various modes of failure such as: bending failure (yielding in beam flanges and web), lateral-torsional buckling (instability in compression flange), CFRP debonding (end and intermediate debonding), delamination or rupture of CFRP, and local bucking of compression flange or web. A flexurally-strengthened steel beams is good example for bond critical applications governed by CFRP debonding [1, 2].

The failure between CFRP and steel is due to the high interfacial shear stresses induced in the contact surfaces. End-debonding is the common mode of failure for beams strengthened for flexural yielding, whereas intermediate-debonding is expected in beams strengthened against local buckling [3, 4]. Various analytical and experimental works on steel and composite beams have been performed to understand the effect of the CFRP sheets on both behavior and strength. CFRP sheets will not only enhance the ultimate flexural capacity of the beams, but they can also delay the yielding of the beam by increasing its flexural stiffness, especially when high modulus CFRP is used Tavakkolizadeh and Saadatmanesh [5, 6]; Schnerch and Rizkalla [7]; Dawood et al. [8].

Compared to other traditional strengthening methods, such as adding steel cover plate to the beam, using CFRP is recommended for many reasons. The strength of CFRP is much higher than steel, using CFRP with high and ultra-high moduli of elasticity can release considerable portion of stresses from the existing structures under service loads, CFRP negligible weight will not penalize the already suffering structure, and the high corrosion resistance for CFRP material will enhance durability of structures suffering from corrosion. Applicability of CFRP sheets is as well simpler and easier compared to welding plates that may require more power effort or preheating to release built-in stresses. Using CFRP will also eliminate the difficult overhead welding. On the

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other hand, welding cover plates can reduce the fatigue life, whereas attaching CFRP sheets can increase the fatigue life of steel beam [8–10].

Tavakkolizadeh and Saadatmanesh [6] discussed the use CFRP for rehabilitation of deteriorating infrastructure. The study focused mainly on using CFRP laminates to upgrade the capacity of composite girders in bridges. The results showed that the retrofitting using CFRP sheets was very promising since the ultimate load carrying capacity for all tested samples was significantly increased. The girders ultimate capacity was increased up to 76% and the yield capacity had been also enhanced. The analytical model also indicated that the ductility of the retrofitted beams had been decreased compared to the un-strengthened girders. Tavakkolizadeh and Saadatmanesh [9] discussed the fatigue strength of steel girders strengthened with CFRP as well. The results showed that the CFRP patch not only extended the fatigue life of a detail more than three times, but also decreases the crack growth rate significantly.

Dawood et al. [8] investigated the behavior of composite girders strengthened with high-modulus CFRP under three experimental phases. The first phase checked the feasibility of using various strengthening systems; the second phase investigated the behavior under overloading conditions; and the third phase checked the fatigue durability. The research findings demonstrated that the high-modulus CFRP was very effective in increasing the girder strength and elastic stiffness. The elastic stiffness, yield load, and ultimate load were increased by 46%, 85%, and 61%, respectively. The research as well demonstrated that using high-modulus CFRP materials was a cost-effective alternative to repair composite girders.

Schnerch and Rizkalla [7] studied the behavior of large-scale composite steel beams, typically used in bridges construction, when strengthened with CFRP sheets. Tests showed that using CFRP increased the stiffness between 10 and 34%, whereas the ultimate strength was enhanced up to 46%. The study also discussed the concept of prestressing the CFRP strips during application using intermediate and high modulus CFRP. The analytical model used in the study was based on strain compatibility and constitutive material properties, and provided reasonable prediction for the stiffness increase, ultimate strength, and modes of failure. It was revealed that the use of high modulus CFRP was necessary to induce significant stiffness increase, whereas the strength of CFRP was the most important parameters for ultimate strength enhancement.

Linghoff et al. [11, 12] investigated the behavior of steel beams reinforced with different configuration of CFRP laminates in service and ultimate states. Laboratory tests and simplified analytical solution were adopted for the parametric study. The laboratory tests and analytical solutions showed that the increase in bending moment capacity reached 20%. Debonding problems have been noticed for only one of the tested beams which was attributed to poor adhesion between CFRP and steel; for other beams, rupture in CFRP laminates controlled the cross-section strength. The strengthening system that produced the most desirable strength and serviceability behaviors was the CFRP laminates with high tensile strength and Young's modulus equivalent to that of steel. The analytical models showed that further increase in moment capacity was not possible since the yielding of top compression flange controlled the section strength.

Shervani-Tabar and Davaran [13] inspected the strengthening of steel girders in aging bridges by using CFRP laminates glued to the damaged tension flange. The debonding problem of CFRP strips was studied and enhancement method was presented; the effect of different bond lengths for CFRP laminates had been also investigated. The experimental results showed that adding small pieces of steel plates (patches) over CFRP laminate and beam flange at the high stress concentration points increased the bonding resistance by about 50%. In comparison with the traditional bonding techniques (without patches and clamps), double-lap shear tests showed also that the method of adding steel patches and mechanical clamping increased the bonding resistance up to 59% and 35%, respectively. The participation of both faces of CFRP laminate encased between the patched and main steel beams was concluded to be the main reason of bond improvement.

Similar to reinforced concrete structures, the applicability of using CFRP sheets to restore the ultimate load-carrying capacity and stiffness of composite girders suffering from damage was investigated by Tavakkolizadeh and Saadatmanesh [5]. Three large-scale girders (W355x13.6 Grade A36) were repaired with CFRP sheets and tested under monotonic loading with few unloading cycles. The tension flanges of the girders were cut with different total depths of 43, 86, and 171 mm to represent three different damage levels and simulate 25, 50, and 100% loss of tension flange. The girders were then strengthened by CFRP sheets attached to the bottom surface of the tension flange and covering 80% of the girder span. The test results showed that epoxy bonded CFRP sheet were able to restore the ultimate load-carrying capacity and stiffness of damaged steel-concrete composite girders.

Shaat and Fam [10] studied the repair of damaged composite beams using CFRP sheets. Experimental tests were conducted on W150×22W150×22 steel sections with top concrete slab. To simulate the fatigue crack or localized corrosion, severe damage was introduced in ten beams by saw cutting the tension flange completely at mid span. Moderate and high modulus CFRP sheets were then used to repair the damaged beams. Although the non-strengthened beams showed reduction in flexural strength and stiffness by 60 and 54%, respectively, CFRP sheets succeeded to attain various levels recovery that exceeded the original undamaged strength and stiffness for some specimens.

The performance of steel and concrete beams strengthened with CFRP sheets under cyclic loading or seismic loads was addressed by many researchers. Tavakkolizadeh and Saadatmanesh [14] investigated steel beams with CFRP sheets under several unloading and reloading cycles. The increases in ultimate load-carrying capacity was 145% and 63% for the beams with 80% and 40% loss of tension flange area, respectively. The stiffness of the damaged beams after strengthening reached 95% of the original stiffness. In another research program, Tavakkolizadeh and Saadatmanesh [9] tested steel beams with CFRP sheets under four-points bending with loading rate between 5 and 10 Hz. Different constant stress ranges between 69 and 379 MPa were considered; however, the length and thickness of CFRP sheets were kept unchanged for all specimens. The number of cycles to failure and beam stiffness were improved with the use of the CFRP sheets. Fernando et al. [15] investigated the behavior and failure mechanism of steel beams reinforced with CFRP sheet under cyclic loading. The study tested four beams with prestressed CFRP sheet and another control beam with unstressed CFRP sheet under four different ranges. The results showed that the debonding of the CFRP sheet had a significant effect on crack propagation, and the crack propagation rate was decreased with the use of prestressed CFRP sheets. Using CFRP sheets to retrofit or strengthen concrete elements under seismic loads was proved efficient in different cases [16–19].

Despite the rapid acceptance gained by CFRP material across the past years, most of CFRP applications were concerned of structures not exposed to fire (such as bridges). With the increasing use of CFRP in buildings, performance under fire is an important property to be considered beside the normal gravity and lateral loads. Compared to more robust concrete and steel elements, CFRP strength and stiffness properties begin to deteriorate faster due to CFRP material composition and tiny thickness. CFRP do not have sufficient documentation of bond properties and mechanical characteristics at elevated temperatures as well. Research work conducted on this issue focused on reinforced concrete elements rather than steel. The behavior of structural members exposed to fire are dependent on the thermal and mechanical properties of the constituent materials (thermal conductivity, specific heat, mass loss in high temperature, thermal expansion, and strength and deformation characteristics under normal and elevated temperatures). Enhanced performance under fire conditions could be gained through insulations schemes, such as fire coatings and insulation boards. While structural steel members require protection to preserve their strength in a fire