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FRP-steel bond study of IM and UHM CFRP strips

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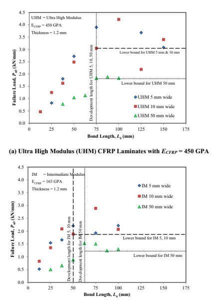
HIGHLIGHTS

- Ultra High Modulus (UHM) CFRP laminate strips have a bond strength of 3.0 kN/mm.
- Intermediate Modulus (IM) CFRP laminate strips have a bond strength of 1.9 kN/mm.
- UHM CFRP laminate strips have a development length of 75 mm.
- IM CFRP laminate strips have a development length of 50 mm.
- CFRP strips have higher bond strength per unit width than 50 mm wide laminates.

GRAPHICAL ABSTRACT



(a) Ultra High Modulus (UHM) CFRP Laminates with E_{CFRP} = 450 GPA
(b) Intermediate Modulus (IM) CFRP laminates with E_{CFRP} = 165 GPA

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ABSTRACT

Prior research has highlighted the premature debonding failure in spliced Ultra High Modulus (UHM) CFRP laminates. This study is the initial step in developing an alternate to spliced laminates by introducing CFRP strip panels that provide continuity through a finger joint between two consecutive panels. The panels are fabricated using narrow CFRP strips (e.g., 5 mm) mounted on a fabric mesh designed to preserve the required clear spacing between individual strips. The objective herein is the determination of the bond strength and development length for the individual strips in the finger joint. Initially, an estimate of the development length for both Intermediate Modulus (IM) and UHM CFRP laminates is derived from tests conducted on steel plate specimens doubly reinforced with CFRP laminates. Tests on double lap shear specimens, for both IM and UHM CFRP, were carried out to derive the bond characteristics for the 50 mm wide laminates and the 5 mm and 10 mm wide CFRP strips. The laminates and the strips have the same thickness. The development length was 50 mm and 75 mm, and the bond strength was 1.9 kN/mm and 3.0 kN/mm for the IM and UHM CFRP strips (both 5 mm and 10 mm), respectively. These findings will be used in future studies to develop a "finger joint" that connects the CFRP strip panels to form a continuous externally bonded reinforcement. The experimental results showed that CFRP strips having a low CFRP strip to steel width ratio have higher bond strength per unit width when compared to both IM and UHM CFRP and 50 mm wide laminates.

1. Introduction

Over the past twenty years, composites have become one of the most popular methods of repairing and/or strengthening civil infrastructure. The use of Fiber Reinforced Polymer (FRP) laminates/plates and fabric/sheets to repair and strengthen reinforced concrete structures is well established. On the otherhand, the application of FRP composites to steel structures remains understudied while over half of the structurally deficient bridges listed in the Federal Highway Administration's (FHWA) National Bridge Inventory (NBI) have steel superstructures [1].

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Due to higher relative stiffness, and the many benefits they offer over traditional methods of bolting or welding of steel plates, Carbon FRPs (CFRPs) is being studied for strengthening of steel structures. The elastic modulus of commonly used CFRP plates varies from 150 to 450 GPa [2]. Often, ambiguities and uncertainties arise if researchers use inconsistent terminology to describe different CFRP materials. To avoid these issues, the authors proposed [3] — and adopted for this study — a classification scheme based on the modulus of steel (Table 1).

Previous research on the strengthening of steel structures has focused mainly on the more common Intermediate Modulus (IM) CFRP with an elastic modulus <200 GPa. In numerous laboratory experiments IM CFRP plates have been used with success to strengthen concrete/steel-steel composite girders [4–7]. Applications involving wide flange beams have been limited due to negligible increases in elastic stiffness. For a significant amount of load transfer to occur, and for the effective use of CFRP material, the steel must yield in compression, the thickness of the CFRP plates need to be significantly increased, or the distance between the bottom flange and CFRP plate should be increased by inserting additional material [8]. Given the difficulties of achieving these behaviors using IM CFRP laminates, limited research has been carried out on strengthening of steel structures with CFRP compared to CFRP strengthening of concrete structures. Hollaway and Cadei [9] reviewed some key issues regarding the use of FRP in strengthening steel structures such as adhesive bond with reference to surface preparation and durability, force transfer between adherents and adhesive, in-service properties of FRP, and impact damage. They also presented several case studies of FRP used to strengthen steel structures. A review by Zhao and Zhang [2] on FRP-strengthened steel structures covered topics such as bond between the steel and CFRP, strengthening of steel hollow section members, and fatigue crack propagation in FRP-steel members. A recent study by Liu and Dawood [10] studied the reliability of bonded CFRP-steel joints. Design guidelines for the use of FRP in strengthening steel have been introduced in the United Kingdom [11], Italy [12], and the United States [13]. With an elastic modulus higher than that of steel, high modulus (HM) and ultra-high modulus (UHM) CFRP plates provide substantial load transfer in steel beams prior to steel yield. Previous work has shown the primary failure mode for HM and UHM CFRP bonded steel systems to be CFRP rupture [2,8]. This has been attributed to the lower rupture strains of higher modulus CFRP as well as reduced normal (or peeling) stresses on the adhesive at the ends due to thinner CFRP plates required for a particular strengthening level. Compared to the failure modes for IM CFRP, which include failure at the steel/CFRP-adhesive interface, cohesive failure of adhesive, CFRP delamination and CFRP rupture [2], the use of HM and UHM CFRP uses the laminate's full capacity. Dawood et al. [14] and Schnerch and Rizkalla [8] carried out full-scale beam tests and found that significant increases in service level stiffness and service load can be achieved by using UHM CFRP. Peiris and Harik [3] successfully carried out field deployment of UHM CFRP laminates to increase the load carrying capacity of a steel girder bridge; load tests validated the results.

Table 1
Classification of CFRP.

Laminate Category	Modulus Relative to Steel	Modulus
Low Modulus	$E_{CFRP} \leq 0.5E_{Steel}$	<100 GPa
Intermediate Modulus	$0.5E_{Steel} \leq E_{CFRP} \leq E_{Steel}$	100–200 GPa
High Modulus	$E_{Steel} \leq E_{CFRP} \leq 2E_{Steel}$	200–400 GPa
Ultra-High Modulus	$E_{CFRP} \geq 2E_{Steel}$	greater than 400 GPa

When using CFRP laminates for flexural strengthening of long spans, applying a single continuous CFRP plate requires significant labor and equipment, and the difficulty of application increases in proportion to bridge length as well as the degree of accessibility to the bridge superstructure's underside. Complications multiply when working over waterways or multi-lane roadways. Splicing of CFRP plates is a more economical alternative, where fewer workers can carry out the strengthening, which significantly reduces labor and equipment costs. Some studies have reported on the viability of lap splicing of CFRP plates for concrete beams [15,16]. Schnerch and Rizkalla [8] evaluated the effectiveness of lap splices for composite concrete deck-steel girders strengthened with UHM CFRP. While splicing of adjacent CFRP laminates can be executed with a splice plate, UHM CFRP laminate splice plates can be susceptible to debonding due to their higher modulus. Dawood et al.'s [17] investigation of splice lengths and different end geometries for UHM CFRP laminates found that the typical square plate-ended splice plates debonded at 55% of the unstrengthened beam yield load.

Previous research on FRP-concrete bond behavior found that the width ratio between the FRP laminate and concrete influenced the ultimate bond strength [18]. It was found that a smaller FRP laminate width, when compared to the width of the bonded concrete surface, leads to higher shear stress in the adhesive at failure. This study examines the effect of the FRP laminate to steel width ratio on FRP-steel bond strength utilizing both IM and UHM CFRP laminates, with the primary goal of developing a novel method of externally reinforcing steel beams with CFRP strip panels. As the initial phase of the project (Phase I), the bond characteristics of CFRP strips for the development of the CFRP strip panels is evaluated. The modular construction of the strip panels is expected to eliminate the need for splice plates, particularly when using HM and UHM laminates to strengthen steel bridge girders. The CFRP strips in the strip panel are mounted on a fabric mesh designed to preserve the required spacing between the strips while facilitating the handling and transportation of the panels (Fig. 1). The length of each panel, which can vary, is set at 1.2 m. This lets individual workers handle and mount sections to girder bottoms. Fig. 1 details the proposed CFRP strip panels, utilizing 10 mm wide strips, and overlap using a finger joint. The modular nature of the construction — one panel applied to the beam at a time — also diminishes the need for extensive scaffolding and multiple personnel. The current study evaluated, experimentally and analytically, the bond behavior between both IM and UHM CFRP strips and steel, the required development length for each strip (i.e. the 'finger joint' between panels), and the bond strength. In the next phase of the project (Phase II), beam tests will be conducted to evaluate the effectiveness of UHM CFRP strip panels in strengthening steel beams, and the results will be reported elsewhere.

The bond characteristics of UHM CFRP strengthened steel are not fully understood. Recently Wu et al. [19] conducted one of the first experimental and analytical studies on the bond between UHM CFRP and steel. The authors are unaware of any research carried out evaluating the width effect on FRP-steel bond, especially when utilizing UHM CFRP laminates. In the present study, both IM and UHM CFRP strips bonded to steel plates were tested in double lap shear to evaluate and compare the bond behavior. The authors also examined debonding under tensile loads for IM and UHM CFRP strengthened steel plates to identify the lower limits of the bond strength due to laminate discontinuity close to maximum moment regions. Additional details regarding the testing and results of the beam tests conducted based on the developed CFRP strip panels can be found within the first authors dissertation [20] and will be reported in a subsequent paper.