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Experimental study of the flexural response of steel beams strengthened with anchored hybrid composites

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ABSTRACT

This paper proposes an innovative technique for flexural strengthening of steel beams using a special type of drillable fiber reinforced polymer laminates. The utilized laminates are hybrid carbon–glass fiber (CFRP–GRFP) pultruded strips that provide both high tensile and high bearing strengths. The current study explores experimentally the potential enhancement in the flexural capacity of steel beams strengthened with mechanically anchored CFRP–GFRP laminates. The experimental program involves flexural testing of eleven full-scale beams under three-point loading. The influence of various strengthening parameters including length and thickness of FRP laminates, and number of anchoring bolts on the behavior is investigated. The experimental results reveal that increasing length and/or thickness of the FRP laminates improves the ultimate capacity of the strengthened sections. Strengthened beams are shown to exhibit ductile response associated with high deflection if adequate number of anchors is used. Otherwise, a brittle failure takes place because of shear failure in the anchors connecting FRP laminates to the steel beam.

1. Introduction

Rehabilitation of steel structures have gained significant importance due to the highly increasing number of deteriorated steel structures in many places around the globe. In the USA, about 70,000 highway bridges with steel main structural system have been classified as structural deficient or functionally obsolete according to the National Bridge Inventory [1] compiled by the Federal Highway Administration (FHWA) as of December 2011. In general, the overall needs for US infrastructure rehabilitation are estimated to be over 1.6 trillion dollars in the next five years [2]. A similar challenge is faced in Europe. A large number of over 100 years old wrought iron and steel bridges on the British railway and canal network are defective and require remedial work [3]. It is estimated that the UK's infrastructure will need about 60–75 billion dollars every year, between 2012 and 2030 in order to maintain current levels of service [4].

Replacement of deteriorated bridges is not a preferred practical solution due to the involved costs and the associated service interruption. Additionally, deterioration may have affected specific components of the bridge structure which makes it more economical to strengthen (or retrofit) the deteriorated parts only. The conventional strengthening technique is based on attaching additional steel cover plates to the existing structure by welding, bolting or adhesive bonding. These have been shown to be cumbersome, time-consuming methods that require lifting heavy steel items that are corrodible and difficult to fix. Besides, it is highly possible to induce unfavorable residual stresses in the strengthened section when welding is used. Recently, after the introduction of Fiber Reinforced Polymers (FRP) to the structural engineering applications, most of the drawbacks of the conventional strengthening systems can be avoided by using FRP material due to their high strength-to-weight ratio and superior mechanical properties. Furthermore, FRP materials are corrosion resistant, which makes them more durable especially when environmental deterioration is a concern.

1.1. Steel beams strengthened with externally bonded FRP laminates

During the last two decades, many researchers have studied the behavior of steel beams strengthened with FRP laminates that are externally bonded to the tension flange. This allows for utilizing the relatively high tensile strength of FRP laminates to improve the flexural capacity of the strengthened beams. Strengthening of naturally corroded steel girders was explored by Gillespie et al. [5] who reported an increase in the ultimate capacity of beams retrofitted with CFRP strips of about 17% and 25% for severely deteriorated and moderately deteriorated sections, respectively. In

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2001, an experimental study was performed by Sen et al. [6] on six steel beams retrofitted with bonded CFRP laminates. An increase in the ultimate capacity ranging between 21% and 52% was obtained. It was revealed also that specimens retrofitted with thicker CFRP laminates performed better in terms of stiffness gain and reduced deflection. A study by Liu et al. [7] on artificially notched steel girders revealed an increase of 60% and 45% in the ultimate load capacities of the specimens retrofitted with CFRP laminates that extend along the entire span and that cover one quarter of the beam's length, respectively. Lenwari et al. [8] conducted experimental and analytical studies on the flexural performance of steel beams retrofitted with externally bonded CFRP plates. It was reported that as the length of the CFRP plate increased, the ultimate capacity of the strengthened beam increased and the governing failure mode changed from debonding of short laminates to rupture at mid-span for the longer ones. In 2006, Photiou et al. [3] examined the influence of using both ultra-high modulus and high modulus CFRP strips in the strengthening of artificially degraded steel beams of rectangular cross-section. The study showed that attaching U-shaped CFRP units, which extended up the vertical sides of the beam to the neutral axis height, was more efficient than attaching flat CFRP strips to the beam's tension side since it was capable of preventing the severe debonding at higher loading values even after the localized failure of fibers breakage. A comprehensive literature review on steel beams retrofitted with bonded FRP strips was conducted by Buyukozturk et al. [9]. The study summarized the encountered failure modes that control the response of retrofitted beams. These modes included buckling of the compression flange, buckling of the web in shear and rupture or debonding of the FRP strips. Debonding between the steel beam and the FRP strips might occur at the interface between the steel and the adhesive layer, in the adhesive layer itself or by delamination of part of the FRP fibers.

The previously reported research outcomes revealed that steel beams strengthened with externally bonded FRP strips exhibit unfavorable brittle failure mechanism due to debonding of the FRP strips. Therefore, an efficient, practical and cost-effective rehabilitation technique is needed to assist in mitigating such a drawback.

1.2. Steel beams strengthened with mechanically anchored FRP laminates

A recent study by Sweedan et al. [10] investigated the response of mechanically anchored hybrid FRP-steel connections. A total of 24 shear lap connections of different configurations were tested to assess the influence of bolt pattern on the interfacial behavior and the associated failure mechanism. Outcomes of the study revealed a ductile response with high strength of tested connections. The study implied also that the rolled edge distance has insignificant impact on the connection performance. Meanwhile, a sheared edge distance of about six to seven times the bolt hole's diameter is recommended. An introductory investigation was carried out on two I-shaped steel beams strengthened with mechanically anchored FRP laminates. The test results indicated a ductile response along with an improvement in the ultimate capacity of the strengthened beams.

The current paper is motivated by the promising results reported by Sweedan et al. [10] implying the efficiency of the proposed anchoring technique between steel elements and hybrid composite fibers. The paper presents an experimental program that is carried out to investigate the potential gain in the flexural strength of steel beams strengthened with mechanically anchored hybrid FRP laminates. Besides, the experimental program aims at assessing the influence of key design parameters on the efficiency of the proposed strengthening technique. Considered parameters include length of FRP, number of connecting anchors and number of FRP laminates on the behavior and strength of the anchored system.

2. Properties of used materials

The experimental program includes testing of eleven full-scale steel beams with a typical cross section UB203 × 102 × 23 with an overall length of 3.0 m. Three beams are used as control specimens to provide reference response characteristics of unstrengthened steel beams. The remaining eight specimens are used to examine the efficiency of various strengthening configurations as will be discussed in details in Section 3. The mechanical properties of the steel material are identified by tensile testing of six coupons, cut from flanges and web of the steel beams, in accordance with ASTM A370-03a standards [11]. Tested coupons indicate that the steel beams are characterized by average yield stress (F_y) of 335 MPa and tensile strength (F_u) of 429 MPa with a modulus of elasticity (E) of 190 GPa.

The FRP laminates used in this study are SAFSTRIP hybrid carbon–glass fiber (CFRP–GRFP) pultruded strips [12] having 101.6 mm width 3.175 mm thickness. While drilling a hole in an FRP strip manufactured from unidirectional fibers may result in longitudinal splitting of the strip, SAFSTRIP hybrid laminates do not suffer from this drawback because the carbon tows included in the laminates (mainly responsible for carrying the tensile stresses) are sandwiched between layers of fiberglass mats and bonded together by a highly corrosion resistant veinylester resin. As such, the random-direction fibers in the fiberglass mats allow for drilling holes in the SAFSTRIP laminate without splitting it and provide considerable bearing resistance between the anchor and the laminate in typical connections [10]. The mechanical properties of the hybrid laminates, as provided by the manufacturer, are listed in Table 1. The reported tensile strength and elastic modulus are identified according to ASTM D638-10 standards [13] as 852 MPa and 62,190 MPa, respectively. Clamped and unclamped bearing strength values of 351 MPa and 214 MPa, respectively, are reported based on ASTM D-5961 standards [14].

Hexagonal galvanized zinc coated anchors, nuts and washers are employed to fasten the FRP laminates to the tension flange of the strengthened steel beams. M6 × 25 Hilti anchors are used where 6 represents the diameter and 25 stands for the shank length (in millimeters). The anchors are made of high tensile steel of grade 8.8 according to DIN EN ISO 4017 [15] standards with 375 MPa shear strength and 1.0 GPa bearing strength British Standards Institution (BS 5950-1) [16].

3. Test specimens configurations

A schematic presentation of a typical test beam UB203 × 102 × 23 is provided in Fig. 1. For all tested beams, the overall depth d is 203.75 mm. The width of the flange b_f is

Table 1
Mechanical properties of SAFSTRIP hybrid CFRP–GFRP laminates.

Property	Average value (MPa)	Design value (MPa)	ASTM test method
Tensile strength	852	640	D-638
Tensile modulus	62,190	62,190	D-638
Clamped bearing strength	351	279	D-5961
Unclamped bearing strength	214	180	D-5961