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Rehabilitation of notch damaged steel beams using a carbon fiber reinforced hybrid polymeric-matrix composite

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ABSTRACT

The retrofit of notch damaged steel beams is investigated via the experimental testing of nine wide-flange steel beam specimens and finite element simulation. Three notch configurations representing various damage levels were identified, and the beam specimens were retrofitted using carbon fiber reinforced polymer (CFRP) laminates and a recently developed Carbon-fiber Hybrid-polymeric Matrix Composite (CHMC) that has been termed CarbonFlex, and that exhibits superior energy dissipation and ductility properties. The peak-load deflections of the CarbonFlex-retrofitted beams were calculated to be between 67.8% and 73.1% higher than their CFRP-retrofitted counterparts. The results are attributed to the substantially higher damage tolerance of CarbonFlex than conventional carbon-fiber reinforced polymer. Finite element models were developed to investigate the damage mechanism and loading carrying capacities of the beams, and the strain/ stress distributions near the notch tips. The numerical results match closely with the experimentally determined load–deflection curves and the strain fields obtained by the digital imaging correlations (DIC) technique. Both experimental and numerical results clearly indicate the effectiveness of CarbonFlex, as a candidate retrofitting material, for damaged steel structures. Lastly, the micro-mechanisms by which CarbonFlex could sufficiently sustain a significant amount of the peak strength at large deformations are discussed through scanning electron microscopy (SEM) and nano-indentation studies.

1. Introduction

Polymeric matrix composites (PMCs) have been popularly used in infrastructure applications due to their many merits, including high-strength-to-mass ratio, superior durability and easy in situ applications [1,2]. One particular type of PMC that has drawn significant attention is fiber reinforced polymers (FRPs) which combine high-strength high-modulus fibers with low modulus polymer matrices that serve as binding material to ensure stress transfer between the fibers. A number of various fiber types has been used for producing fibrous composites although the particular application of unidirectional weaved continuous carbon fibers or glass fibers are ubiquitous in civil infrastructure applications. Because of the increasing demand of the polymeric matrix composites in the civil infrastructure industry, research efforts on the utilization of FRPs for new constructions [3] and strengthening or retrofitting damaged structures [4,5] have been extensively carried out since the mid- 1980s. FRP materials were initially used as strengthening materials for reinforced concrete (RC) flexural components [6,7] and were used to provide lateral confinement for RC compression members [8]. The applications of FRPs have since been expanded to masonry [9], wood [10], and concrete/steel composite structures [11].

Despite the significant amount of research and applications of FRPs in RC and masonry structures, efforts on using FRP materials to retrofit and strengthen steel structures have been relatively limited [12]. In the mid- 1990s, Mertz and Gillespie [13] tested six 1525 mm long steel beams (W200 × 15 section) strengthened with five different lay-ups. The increases in elastic stiffness of the five strengthened steel beams in comparison to the control beam ranged from 11% to 30%; and the strengths of the members increased by 41–71%. As part of that same study, Mertz and Gillespie retrofitted and tested two full-scale corrosion damaged bridge girders; the test results show that CFRP strengthening significantly increased the stiffness and moment bearing capacity of the corroded girders, where one of the retrofitted girders, the elastic stiffness of which had degraded to approximately 87% of its un-corroded condition, showed full recovery of its flexural stiffness and load capacity. In a more recent study, Linghoff et al. [14] conducted laboratory tests of five un-strengthened and strengthened steel beams retrofitted with CFRPs having various thickness and modulus of elasticity. Their study reported approximately 20% increase in bending

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capacity after applying CFRP laminates to the tension-side flange of the steel beams. Analytically, Deng et al. [15] presented an approach to conduct a stress analysis of steel beams bonded with CFRP laminates, where a finite element (FE) analysis was used to validate the analytical solutions. Besides the aforementioned researchers on the static strengthening and retrofit using FRPs, several studies have focused on extending the fatigue life or on repairing fatigue cracks in steel members. Nozaka et al. [16] compared the test results of various CFRP laminate/adhesive systems that were used to retrofit notched steel beams. A primary focus of the study was to develop a simple analytical approach for estimating the bond length of the various repair schemes; twenty-seven "effective bond length" specimens – having five different retrofitting configurations, two types of CFRP strips, and five types of adhesives – were used in the study. Experimental studies conducted by Tavakkolizadeh and Saadatmanesh [17], Wu et al. [18], and Jiao et al. [19] demonstrated the effectiveness of using a CFRP-retrofit scheme to extend the fatigue life of damaged and intact steel girders. Hmidan et al. [20], Kim and Harries [21], Kim and Brunell [22] on the other hand, investigated the CFRP repair strategies for steel beams having experienced notched damages. The influence of notch configurations was studied using an FE analysis to obtain the *J*-integral versus displacement curves of various repaired and unrepaired beams.

Due to the higher strength and stiffness of steel, the failure modes and mechanisms of FRP-retrofitted steel structural systems are generally different than those of concrete–FRP systems [12]. For example, debonding of the retrofitting laminates, if it occurs, often initiates at the steel–primer interface, thus mandating careful surface preparation prior to applying the laminates [20]. Although the CFRP-retrofit has shown significant merits over traditional retrofitting techniques, such as steel patching, its drawbacks are well documented [23]. The brittle nature of the reinforcing fibers and the binding matrix results in brittle failure of CFRP retrofitted structures, controlled by either laminate rupture or delamination. A study conducted by Hamed and Rabinovitch [24] investigated the damping properties of CFRP retrofitted structural components, showing the presence of minimal damping in CFRP-strengthened RC beams. Studies [25–27] have further validated that insufficient damping may result in: (1) large elastic response and vibrations; (2) minimal ductility in the inelastic range; and (3) potentially high acceleration responses during seismic events.

The present study discusses the experimental test results of nine notch damaged steel beams retrofitted using CFRP and also a new Carbon-fiber Hybrid-polymeric Matrix Composite (CHMC), that has been recently developed by Zhou and Attard [11,28], and Zhou et al. [28]; therefore, the CHMC will herein be interchangeably referred to as CarbonFlex. CarbonFlex (nonprovisional patent on file, M12-023, PCT/US11/63581 High Strength and High Elasticity Composite Materials and Methods of Reinforcing Substrates with the Same) is a carbon fiber-based composite manufactured via a new patented hybrid-matrix system involving amino-based polymeric compounds to provide necessary damping and high strength sustainability of the carbon fibrous component. An earlier study conducted by Zhou and Attard [11,29] indicates the enormous potential of CarbonFlex, as a retrofitting material, to be able to sustain strength of an otherwise brittle carbon fiber-based composite system and to subsequently prevent catastrophic failure of structures. In the study, three unrepaired steel beams with various notch configurations were labeled as the control group and tested under static three-point bending. Three notched (damaged) specimens were retrofitted with CFRP and three other notched specimens were retrofitted using the newly developed CHMC; the six retrofitted beams were then tested under the same static three-point bending configuration. The experimental test results of the nine specimens are subsequently presented, and finite element models were developed to analyze the bending behavior, failure mechanisms, and the stress/strain distributions around critical regions. The computational results are validated by the experiments. Lastly, a fracture surface morphology study was carried out on both CFRP and CarbonFlex (or CHMC), as stand-alone systems, to explore possible mechanisms contributing to the ability of CarbonFlex to stabilize the damage in the laminates and to sustain a significant portion of the large peak strength of the carbon component at higher strains.

2. Experimental program

2.1. Specimen configurations and retrofit schemes

An experimental program was developed to investigate the performances of the notch damaged steel beams with and without the composite laminate retrofits. Three types of notch configurations were used to represent prescriptive damage levels in the steel beams. The three damage levels are (1) total loss of the tension-side flange of the steel beam; (2) total loss of the flange plus 25% web loss; and (3) total loss of flange plus 50% web loss as presented in Fig. 1. Since the fracture and crack propagation of steel can be highly dependent on the sharpness of the crack tip, the width of the notch was controlled to be 1.27 mm (50 mils) in all cases. American Institute of Steel Construction (AISC) W100 × 19 SI (W4 × 13) hot rolled sections were used in the study in order to accommodate the test machine configuration and dimensions. The sections were made of ASTM A992 grade steel having a nominal yield strength of 344.7 MPa (50 ksi). The specimens were subjected to three-point bending under static load conditions and with a span length of 304.8 mm (12 in.). The specimens were categorized into three groups. Specimens NB-1–3 are the non-retrofitted control beams having three different notch configurations (Fig. 1a). Specimens CB-1–3 are retrofitted using conventional CFRP. Specimens CFB-1–3 are the notched beams having been retrofitted using the CHMC laminates externally bonded to the tension-side of the flanges. Preparation of the steel beams included sand-blasting the bottom surfaces of the tension flanges and applying an acetone cleanser to improve the bond strength between the laminates and the substrate steel by removing any rust and residual grease prior to applying the epoxy-based primer. Laminate debonding has been proven to be one of the dominant failure modes of FRP retrofitted/ or strengthened steel structural members [12] even though careful surface preparations may had been performed [20,22]. In addition, the existence of a geometric discontinuity, e.g., at the mid-span notch in this case, would impose significant interfacial shear stress concentrations in this vicinity, which would initiate the progressive laminate debonding at early loading stages. In order to preclude the undesired total detachment of the retrofitting laminates and to maintain the partial function of the laminates following adhesive failure, mechanical anchorages were used, as has been the case in several retrofitting practices [30–32]. In the current experimental program, a mechanical anchorage system, as shown in Fig. 2b, was used to ensure the failure mode of the retrofitted beam are controlled by laminate rupture such that a fair comparison between the performances of CFRP and the newly developed CarbonFlex (or CHMC) was achieved. The CFRP used to retrofit CB-1–3 was the MBrace® CF130 system produced by BASF, having a nominal laminate strength of 3800 MPa [33]. The TORAYCA® unidirectionally weaved carbon fiber having a nominal thickness of 0.165 mm/ply constituted the reinforcing fiber of the CHMC and provided the baseline strength. Different from the conventional CFRP composite, the CarbonFlex (or CHMC) incorporates a multilayered matrix with higher damping and fracture toughness, as aforementioned in the introduction, to provide the load bearing fiber a more stable media for stress transfer, and thus, enhances