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Fatigue behavior of damaged steel beams repaired with CFRP strips

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ABSTRACT

This paper presents the flexural behavior of damaged steel beams repaired with carbon fiber reinforced polymer (CFRP) strips. The damage is intentionally created by notching the tension flange of the beams. Six beams are tested to evaluate the static and fatigue performance of the repaired beams with emphasis on local plasticity and the CFRP–steel interface. A three-dimensional finite element analysis (FEA) is conducted to predict the experimental behavior. A modeling approach is proposed to simulate the fatigue response of the repaired beams, based on the strain-life method and cumulative damage theory. CFRP-repair results in a recovery of static load-carrying capacity of the damaged beam to that of an undamaged beam. The stress range at the damage influences the fatigue life, damage propagation, and plastic strain development of the repaired beams. Fatigue-crack propagation across the web of the beams is not significant up to 50% of their fatigue life, whereas brittle web fracture follows beyond the threshold. A bilinear fatigue response is observed at the CFRP-steel interface, whose magnitudes are dependent upon the number of fatigue cycles and the applied stress range. An empirical model is proposed to predict the fatigue behavior of the interface.

1. Introduction

The issue of infrastructure management and rehabilitation is one of the primary interests in civil engineering community. Constructed bridge members deteriorate because of aging, corrosion, increased service loads and traffic volume, use of deicing salts, and collision of heavy trucks [1–3]. Over $180 billion is required to address structurally deficient or functionally obsolete bridges in the United States [4]. Of particular interest are steel bridges that account for more than 43% of the substandard bridges in the nation [5]. Steel bridges are susceptible to corrosion and fatigue cracks. Structural repair of damaged members provides a viable alternative to replacement, reducing downtime and cost. Traditional repair techniques for steel bridges include use of steel plates bolted or welded to damaged girders. Although the performance of such repaired girders is generally acceptable, the repairs themselves may introduce new potential problems associated with increased dead load, corrosion (crevice and galvanic corrosion), and the introduction of fatigue-sensitive details at the junction of existing and repair materials [6]. The application of carbon fiber reinforced polymer (CFRP) composites is proposed as an alternative to steel-plating repair methods. The advantages of CFRP materials include their non-corrosive characteristics, high stiffness- and strength-to-weight ratios, ease and rapidity of erection, and reduced long-term maintenance expenses [7]. A significant advantage of CFRP systems is that they are typically adhesively bonded, rather than mechanically connected, to the substrate steel, resulting in mitigation of the additional stress raisers associated with bolt holes or welds. Although CFRP composites have been primarily used for repairing concrete structures [8], there are relatively limited data available on strengthening damaged steel members using CFRP [9–15]. Nonetheless, this body of work clearly indicates the promise of this technique for strengthening damaged steel members subject to monotonic loads. Cadei et al. [16] provides significant guidance for such applications.

A number of recent studies have investigated the behavior of steel beams having damaged tension flanges repaired with CFRP patches and subject to fatigue loading [5,11,15,17–19]. Tavakkolizadeh and Saadatmanesh [5] assessed the fatigue behavior of intentionally notched steel beams ($L = 1.3$ m) patched with short CFRP sheets ($L = 0.3$ m). A design curve was generated to estimate the fatigue performance of repaired steel beams. CFRP-patching resulted in improvement in fatigue life of damaged beams of up to 3.4 times over that of unrepaired beams. Nozaka et al. [11] considered the performance of combinations of two CFRP materials and five adhesive systems to enhance the fatigue behavior of steel sections. They reported the greatest increase in fatigue strength resulting from the system combining the CFRP and adhesive having the lowest moduli of elasticity of those considered. O'Neill et al. [20] also report improved fatigue performance when

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