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Repair of damaged end regions of PC beams using externally bonded FRP shear reinforcement

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HIGHLIGHTS

- Mortar repairs for damaged ends of PC bridge girders are structurally insufficient.
- Externally bonded FRP can restore the shear strength of PC beam with localized damaged end regions.
- CFRP is more effective than GFRP in restoring shear strength and stiffness of PC beams with damaged ends.

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ABSTRACT

Fiber reinforced polymer (FRP) composites have emerged as a lightweight and efficient repair and retrofit material for many concrete infrastructure applications. Externally bonded FRP laminates have been shown to be an effective material when used as supplemental flexural and shear reinforcement for reinforced concrete and prestressed concrete beams. One problem afflicting bridge girders is the deterioration of the beam ends due to deicing salt exposure, thus reducing their shear strength. In this study, concrete cover damages are imposed on small scale prestressed concrete beams, which are tested in three-point bending to determine the effect of this type of damage on the shear capacity of the beams. A quick setting mortar repair is used to replace the damaged cover concrete and test its ability to recover the shear strength of the beam. The results show the mortar repair alone is insufficient in regaining the beam's original strength and stiffness. Externally bonded glass and carbon FRP laminates are used as shear reinforcement in conjunction with the mortar repair to recover the strength of the beam. CFRP laminates were superior to GFRP laminates in regaining and exceeding the stiffness and strength of the undamaged beam for this application.

1. Introduction

Much of the existing concrete infrastructure in the United States is near the end of its design life and in need of replacing, rehabilitation, or repair. Over 58,000 bridges have been deemed structurally deficient in 2016 [1]. Many of these structurally deficient bridges are located in the Northeast and Midwest, where harsh climates cause deterioration in concrete structures at an accelerated rate. One specific problem that plagues bridges is the deterioration of the beam's end regions due to failure of expansion joints (see Fig. 1a), which allows water containing deicing salts to flow onto the beam ends. Freezing and thawing cycles of these saturated beam ends cause scaling and spalling of the cover concrete. This can directly expose the steel reinforcement to chlorides, which can lead to severe corrosion and further spalling of concrete. Because of the localized nature of this damage, which may extend only a few feet from the bearing location, the primary concern is shear failure.

Mortar repairs are often used at beam's end regions to replace the damaged cover concrete caused by exposure to deicing salts and freeze/thaw cycling (Fig. 1b). While aesthetically restorative, a mortar repair alone may not be sufficient in restoring the original shear capacity and stiffness at the end of the beam.

Fiber reinforced polymer (FRP) composites have emerged over the past two decades as an effective repair and rehabilitation material for many concrete infrastructure applications. Advantages of FRP materials over conventional steel reinforcement are their high strength to weight ratio and resistance to corrosion. The primary FRP system used for these types of applications are externally bonded FRP sheets or laminates. Externally bonded systems are comprised of a fiber sheet or mat (typically glass or carbon), which is impregnated with a resin to create the composite material. One method of applying the laminates to the concrete surface is

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(a) End damage of girder (b) Typical mortar repair of girder end

Fig. 1. End region damage and mortar repair of concrete bridge girder.

through a wet layup approach [2], in which the resin serves to both saturate the fibers and bind the sheet to the concrete surface at the same time. The flexibility of the fiber sheets makes the wet layup approach an effective option for adding external shear FRP reinforcement to a beam, which requires the wrapping of FRP around the beam's contour.

Externally bonded FRP laminate repair and strengthening systems for concrete bridge infrastructure have been extensively used in flexural applications (e.g. Tedesco et al. [3]; Nanni [4]; Carmichael and Barnes [5]; ElSafty and Graeff [6] among many others). More recently, externally bonded laminates have emerged as an effective means of strengthening beams in shear by way of U-wraps or bonded face plies [7]. However, effectiveness of these systems is limited by a delamination failure mode, which occurs at an effective strain much lower than the ultimate strain achievable by the FRP composite materials themselves [8]. Previous research has concluded that the effectiveness of externally bonded shear FRP reinforcement decreases as shear span-to-depth ratio decreases (Ary and Kang [9], Belarbi et al. [7]), which could further limit the usefulness of shear FRP laminates in this particular application. Additionally, the effectiveness of an FRP repair when combined with a conventional mortar repair should be investigated to determine the material's suitability for this particular application. Research for this specific application has been very limited. Ramseyer and Kang [10] performed shear tests on AASHTO Type II girders that had been damaged and repaired with carbon-FRP and glass-FRP laminates. In these tests, the girders were tested in shear using a shear span-to-depth ratio of 1. Damage was imposed by first loading the beam to its maximum load in shear, which simulated a corrosively failed end region. Post-damage repair consisted of application of rapid set cement, epoxy-injecting cracks (for some tests), and application of externally bonded wet layup CFRP and GFRP U-wraps. This study concluded that CFRP has the greatest amount of stiffness recovery while GFRP has the highest percentage of strength recovery. Only one test, however, was able to recover the original shear strength of the girder (GFRP with epoxy injected cracks).

This paper presents an experimental study on the application of FRP composite materials as a means of repairing and retrofitting damaged ends of prestressed bridge girders. Three-point bending tests were carried out on three small scale prestressed concrete (PC) beams that have been damaged then reinforced with CFRP and GFRP externally bonded laminates. First, the ability of a basic mortar repair to restore the shear strength of the beam was determined through testing. Then, FRP laminate repairs were performed in combination with the mortar repair to investigate their effectiveness for this type of application.

2. Tests description

2.1. Beam specimen design

The goal of the small scale beam design was to emulate the behavior of an AASHTO PC bridge I-girder, but at a scale in which tests could more easily be performed. Three 7 m long small scale PC beams were cast in the laboratory. Fig. 2 shows the cross sectional dimensions of the beam and details of the steel reinforcement. The cross section of the beam was sized approximately as a half-scale AASHTO Type II I-girder. A top flange was added to represent a portion of slab and to give the beam a greater flexural capacity. The bottom flange retained the geometry and proportions of the AASHTO Type II girder. The beam was cast using concrete with a 28 day cylinder compressive strength of 48.1 MPa. The beam was prestressed with three 12.7 mm diameter 7-wire strands with an elastic modulus of 197.9 GPa and ultimate strength of 1862 MPa. The strands were pretensioned to 1234 MPa, or 66% of the ultimate strength. Additional longitudinal mild steel was provided in the form of 6.35 mm diameter bars with a yield strength of 414 MPa. Shear reinforcement consisted of bent 6.35 mm diameter 414 MPa bars in both the web and bottom flange spaced at 88.9 mm over the central portion of the beam.

At the ends of the beams, which were tested in three point bending, stirrup area was reduced to ensure shear failure. To obtain a cross sectional area below that of 6.35 mm rebar and retain a textured surface with good bond characteristics, threaded rod was used for stirrups in the beam ends. 5 mm diameter threaded rod stirrups with a cross sectional area of 14.2 mm^2 were spaced at 127 mm over the first 1130 mm of the beam on one end and 2260 mm on the other end. The spacing was not increased any further in order to ensure shear cracks would still propagate across multiple stirrups. The Grade B7 threaded rod had a minimum tensile strength of 860 MPa as supplied by the manufacturer; thus, the threaded rod was heat treated to achieve a yield strength close to that of 414 MPa mild steel. The heat treatment consisted of raising the temperature to a specified level and heating for one hour, followed by air cooling to room temperature. A range of temperatures (566 – 816 °C) were tested to determine the treatment temperature which would cause yielding closest to 414 MPa. At 760 °C, the yield strength of the threaded rod was reduced to 420 MPa. Fig. 3 shows the stress-strain curves obtained from tensile tests of untreated and heat treated threaded rod. After determining the ideal temperature, the heat treatment was applied to all of the threaded rod used for stirrups in the beam ends.