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Experimental and numerical investigation of splicing of concrete-filled fiber-reinforced polymer tubes

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ABSTRACT

The structural performance of spliced, concrete-filled FRP tubes was evaluated. The splices consisted of an internal FRP collar adhesively bonded to the tube segments and a concrete reinforcing cage of carbon fiber composite cable (CFCC). Spliced beams were tested to determine the splice flexural capacity. Adhesive bond strength and CFCC development lengths were experimentally determined. Splice behavior was investigated with 3D finite-element models employing a modified concrete damage plasticity model and cohesive interfaces. Model predictions were in good agreement with the experiments; the predicted capacity was 13.8% greater than the 113.1 kN average failure load of the splice.

1. Introduction

In the past three decades, the use of concrete-filled fiber-reinforced polymer (FRP) tubes (CFFTs) has been explored as an alternative to steel-reinforced concrete structural members. Several infrastructure applications have been investigated, including bridge girders [1,2], marine piles [3], bridge piers [4], deep beams [5], buried arches [6] and bridge columns for multi-hazard resilience [7]. Prior studies were conducted on a range of topics including flexural behavior [8,9], shear behavior [10], fatigue behavior [11,12], the magnitude of strains at rupture [13], and dynamic behavior [14]. In the CFFT system, the FRP tube provides confinement and protection of the concrete core and also serves as the concrete formwork and reinforcement for cast-in-place or precast elements [15]. The concrete core prevents local buckling failure of the FRP and increases the strength and stiffness of the CFFT member [8].

A specific application that has seen significant investigation is the use of CFFT arches for bridge structures [16–19]. Multiple parallel composite arch tubes are placed alongside the roadway and then filled with self-consolidating concrete (SCC) [15]. FRP corrugated decks are fixed on the top side of these CFFT arches to stabilize them prior to concrete filling and to support the granular backfill applied before paving. The buried CFFT arches function as the main structural members of the bridge and are designed according to AASHTO guide specifications [20]. It is important to note that the arches must support the wet weight of the concrete fill and the decking weight prior to curing of the concrete fill, after which the shell serves as tensile, shear and confinement reinforcing for the concrete core. To-date, 23 CFFT arch bridges have been constructed; Fig. 1 illustrates the elements of the buried arch bridge system. These lightweight arches are often shipped to the field by trucks. Shipping long spans of these CFFT arches can be expensive and challenging due to road width, vehicle height limits, and escort cost.

To mitigate the challenges of shipping long spans of arches, splicing two or more smaller segments to form a longer span has been investigated. Relatively few prior studies have been conducted on flexural behavior of spliced CFFTs. Zhu et al. [21] studied splices of CFFT beams in flexure, testing four types of splices, i.e., internal splices with grouted steel bars, grouted FRP bars, unbonded post-tensioned bars, and a fourth splice using an FRP socket similar to that used in the piping industry. The beams were initially stiffer than a control beam that had no splice, but none of the beams was stronger than the control beam, showing that continuity of the FRP provides greater strength than a discontinuous splice. The four beams were tested in flexure, but Zhu et al. [21] noted that adding axial compression would theoretically improve a beam's stiffness and the strength of the joint. As part of a wide study on CFFT piles, Helmi et al. [22] investigated the flexural behavior of three spliced CFFT beams by using a splice consisting of two thick steel circular plates and eight steel bars with threaded

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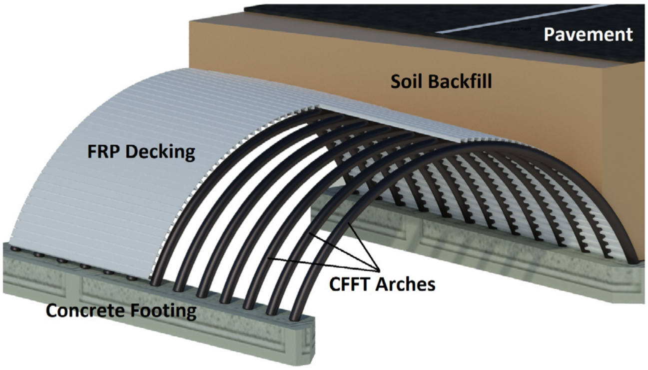

Fig. 1. Main Components of Composite Buried Bridge.

ends screwed into those plates. In general, these spliced specimens were 7% stronger in flexure than the un-spliced tubes that were also tested for comparison.

Parry [23] developed a field splice for the arches that was fabricated from two main parts based on loading type. An external E-glass fiber-reinforced collar was designed to withstand short-term construction and concrete filling loads and held the two arch segments together using mechanical fasteners. The splice also contained conventional steel reinforcing to resist long-term loading that includes forces from the granular backfill, pavement, other superimposed dead loads, and vehicular live loads. The splice proved to be a feasible solution, exhibiting a moment capacity similar to that of a control arch with no splice. The collar developed by Parry [23] successfully carried both short and long-term loads but had a few shortcomings. The external splice was aesthetically unappealing, and the mechanical fasteners proved to be difficult to install on the circular surface of the arch. The steel reinforcing also had the potential to corrode and shorten the lifespan of the CFFT, negating one of its advantages.

The main objective of the study reported in this paper was to develop a steel-free, easily constructed splice and evaluate its structural performance. Experimental and numerical investigations were conducted to investigate the nonlinear flexural response of CFFT beams with and without splices. While similar in concept to the splice of Parry [23], the splice presented here differed in several important ways. It consisted of an internal FRP collar bonded to the FRP shell with a high-strength urethane adhesive to withstand the short-term construction loads and carbon fiber composite cable (CFCC) longitudinal bars and a spiral to withstand permanent and live loads. The CFCC material was produced by Tokyo Rope, Inc. [24] and can be used for concrete tensile and shear reinforcement. Experimental characterization included testing spliced beams in flexure as well as tests to determine the adhesive bond strength and CFCC development lengths. Nonlinear three-dimensional (3D) modeling of spliced and un-spliced (control) CFFT structural beams was completed to enhance our understanding of the splice structural response and failure mechanisms. The modeling was complex due to the need to capture the nonlinear constitutive response of the confined concrete, model the concrete-FRP interaction, and explicitly incorporate the splice including the internal CFCC reinforcement, FRP collar, and the cohesive bond between the collar and shell.

2. CFFT specimen and splice

2.1. CFFT specimen construction

The tubes considered here were fabricated with a combination of an inner layer of E-glass fiber braid and two outer layers of carbon fiber braid to provide confinement, tension, and shear reinforcement with no need for additional steel rebar. The carbon fiber used was Toray T-700 [16,25]. The three fiber layers of the spliced specimens were impregnated with Derakane 610C vinyl ester thermoset resin [26] while the control specimens, tested by Bannon [16], were impregnated with Derakane 8084 vinyl ester thermoset resin using a modified vacuum-assisted resin transfer molding (VARTM) process. These two resins possess similar chemical and mechanical properties, and their use was based on availability at the time of specimen fabrication. This hybrid combination of glass and carbon fiber reinforcement provided an excellent performance while remaining cost-effective, easily fabricated, and lightweight. Table 1 shows the elastic properties of the fiber and matrix materials. The percentage of fiber volume in the entire volume of hybrid braided laminate, fiber volume fraction (V_f), was taken as 50%, according to Bannon [16] and Walton [18]. More details regarding this hybrid FRP tube and the fiber angle, lamina thickness, and sequence are reported in Section 4.2.3.

2.2. Splice description and design

Material cost and availability, fabrication complexity, and collar practicality were considered when developing the splice concept. All materials (FRP collar, adhesive, and self-tapping screws) can be easily procured and installed in the field. Fig. 2 shows the elements of the splice. An FRP arch can be fabricated to be slightly longer than the design length so that the end can be cut off and used as a collar, which maintains the same radius of curvature as the arch. This approach ensured an accurate fit within the arch for any reasonable collar length and evenly distributed the shear stresses on the collar-to-arch adhesive connection. A longitudinal gap in the collar was created by cutting a longitudinal slit down the collar (Fig. 3), which, when closed, gave the splice a slightly smaller diameter and allowed insertion into the end of the CFFT tube being spliced. Self-tapping screws were used to hold the collar tightly against the inside of the CFFT tube to evenly disperse the adhesive and provide clamping pressure while the adhesive cured.

This splice design required analysis for two loading conditions, i.e., short-term construction loads and a design combination of permanent and service live loads. The internal FRP collar bonded to the FRP shell with a high-strength urethane adhesive was designed to withstand the short-term construction loads up to and including decking and concrete filling. The CFCC-reinforced concrete core was designed to withstand the permanent dead load due to soil backfilling, paving, etc. as well as live loads. The splice design assumed a typical buried CFFT bridge geometry, having circular segment arches each with a 305-mm cross-sectional diameter, 9.75-m horizontal span, and 4.87-m radius of curvature. The ultimate design loads were a bending moment of 46.3 kN-m, a shear load of 39 kN, and an axial compression load of 552 kN. The arches were supplied by Advanced Infrastructure Technology, a company located in Orono, Maine, USA that has commercialized the CFFT bridge technology. Short-term concrete filling and construction service loads carried by the FRP shell before the concrete cured were calculated for this case by Parry [23] as a moment of 4.9 kN-m, a shear load of 2.2 kN, and an axial load of 7.1 kN.

Table 1
Fibers and Matrix Parameters of FRP Tube Components.

Material	Elastic Modulus, E (MPa)	Poisson's Ratio υ	Shear Modulus G (MPa)
E-Glass Fiber	72,400	0.230	29,600
T-700 Carbon Fiber	234,000	0.200	27,500
Derakane 8084	2900	0.35	1100
Derakane 610C	3530	0.35	1300