EXPLORING FIBER-REINFORCED POLYMER CONCRETE FOR ACCELERATED BRIDGE CONSTRUCTION APPLICATIONS

Quarterly Progress Report
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1. Background and Introduction

The use of precast concrete superstructure elements is a popular strategy for accelerated bridge construction (ABC) and rehabilitation projects. The major advantage is that precast concrete elements can be fabricated before, or in parallel with, on-site activities, thus expediting project delivery. To complete the superstructure, closure joints between adjacent precast superstructure elements are filled with a field-cast material, creating continuity between the concrete elements and splicing steel reinforcement that protrudes from the precast members into the joints. The geometry of the closure joints, the speed at which the connections can be completed, how long before the bridge can be opened to traffic, and the cost of the system are all dependent on the material that is used to fill the gaps between precast elements. The closure joint material must possess strength and durability equal to or better than the adjacent concrete and must be capable of transferring the tensile forces between reinforcement from adjacent elements.

2. Problem Statement

The tension and bond strengths of ultra-high performance concrete (UHPC) make it an excellent closure joint material. However, the time at which UHPC achieves its design strength is directly proportional to the rate of hydration of the cementitious binder. While UHPC may provide the best solution in many instances, alternative joint materials that utilize polymer binders, instead of cementitious ones, may be more suitable if rapid strength gain is needed. This project explores a potential alternative closure joint material, fiber-reinforced polymer concrete (FRPC), which displays levels of the two critical characteristics (bond and tension strength) that are comparable to, or potentially better than, those of UHPC. FRPC has the advantage of requiring shorter closure windows (approximately 4 hours versus 72 hours of UHPC) due to the very rapid strength gain of the polymer, which could be ideal for overnight construction or rehabilitation projects, and provides an additional option to the engineer and contractor when choosing a closure joint material for a particular circumstance.

3. Objectives and Research Approach

The objectives of the proposed research are to review the most promising FRPC materials, assess the temperature dependent properties of FRPC behavior, characterize the mechanical properties (tensile, flexural, and compressive strength) of cast FRPC, and characterize the splice performance of deformed bars embedded in FRPC materials. Based on the results of this experimental investigation, recommendations for the use of FRPC in ABC applications will be developed to maximize the benefit of this relatively new material for different ABC project applications.

4. Description of Research Project Tasks

The following is a description of tasks carried out to date.

Task 1 – Literature Review

This task is complete. Previous research on fiber reinforced polymer concrete has been compiled and separated into areas of interest pertinent to bridge construction applications. A summary of the compiled research can be found in the September 2021 Progress Report.

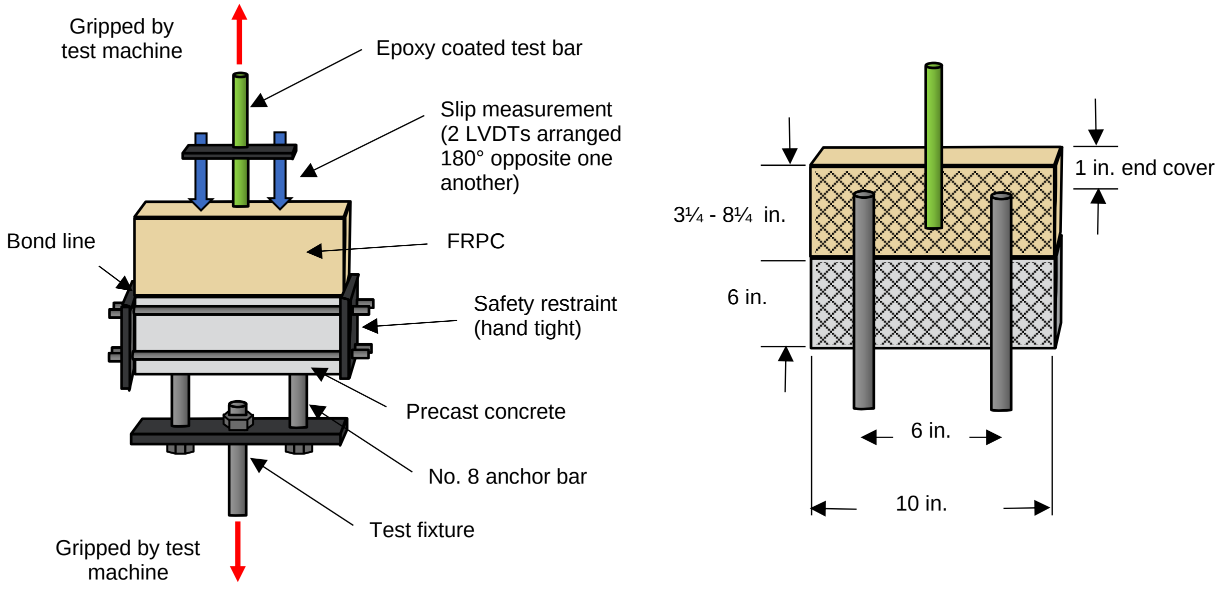
Task 2 – FRPC Material Characterization

This task is complete. The mechanical properties of a commercially available FRPC material, Kwik Bond Hybrid Composite Synthetic Concrete (HCSC), were determined at several test temperatures and ages using standard test methods that would be part of a typical quality control program (i.e. compressive strength, tension strength, and anchorage strength). An overview of the results can be found in the December 2021 Progress Report.

Task 3 – Testing of Splice Specimens

This task is complete. The tests investigated a simplified, non-contact splice configuration that isolates the behavior of reinforcement in a closure joint. The specimen size was selected to allow conditioning the specimens to different temperatures using conventional laboratory equipment and tested using a universal testing machine under precise displacement control. The variables that were investigated include the temperature at time of testing, overlap length between bars, side cover, and bar size. Additional details of the testing plan can be found in the March 2022 Progress Report.

Fig. 1a and Fig. 1b show the simplified non-contact splice configuration that was used in this project. Steel fixtures were used to anchor the reinforcement instead of a slab, similar to the tests performed by Qiao et al. (2016), who investigated the mechanical properties of a non-proprietary UHPC. A precast concrete strip between anchor bars, roughly equal in size to the FRPC strip and below the splice was included to help stiffen the specimen and prevent flexure of the FRPC. An exposed aggregate roughened surface was provided at the concrete-FRPC interface, the surface was primed using a high molecular weight methacrylate (HMWM), and HCSC was cast against it in the horizontal position, mimicking the field orientation of the joint. A preliminary study investigated the influence of the primer on the splice performance in the given test configuration.



(a) (b)

Fig. 1. Splice specimen test details: (a) test setup, (a) specimen geometry

Table 1 summarizes the Task 3 test series, including the testing date of the specimen and failure mode. The test series was developed using a rotatable central composite design (CCD) (Box et al., 2005), with the varied parameters being test temperature, T; splice length, ℓ_s; side cover, c_b; and bar diameter, d_b. The CCD design includes an embedded factorial design, repeated center points to quantify batch-to-batch uncertainty, and additional axial points that allow for the estimation of curvature in the region of interest. The experimental design was centered around the point (T =75 °F, ℓ_s = 3.75 in, c_b = 2.0 in, and d_b = 0.625 in) in the parameter space.The tests were conducted in three sets, or "blocks", comprising 10 specimens apiece. Each block of specimens was made from the same batch of HCSC.

Fig. 2 shows photographs of the three failure modes observed during the test series. The large majority of specimens failed through a bond splitting mechanism (Fig. 2a) as designed. The remainder failed through fracturing of the embedded reinforcement (Fig 2b) or through a pullout mechanism (Fig 2c). Fracture of the reinforcement was observed at the extremities of the experimental design space as expected, at lower test temperatures, longer splice lengths, larger side covers, and smaller bar diameters when compared to the center of the design space

(a) (b) (c)

Fig. 2. Observed failure modes of Task 3 specimens (a) splitting, (b) bar fracture, (c) pullout

Table 1. Task 3 Experimental Matrix

	Run	**Temperature T (°F)**	**Splice length ℓ_s (in)**	**Side Cover c_b (in)**	**Bar diameter d_b (in)**	**Point Description**	**Date Tested**	**Observed Failure**
Batch 0	0-01p	110	2.5	1.375	0.625	Primer	03/04	Splitting
	0-01	110	2.5	1.375	0.625	No primer	03/04	Splitting
	0-02p	40	2.5	2.625	0.625	Primer	03/04	Splitting
	0-02	40	2.5	2.625	0.625	No primer	03/04	Splitting
	0-03p	40	5	1.375	0.625	Primer	03/04	Splitting
	0-03	40	5	1.375	0.625	No primer	03/04	Splitting
	0-04p	110	5	2.625	0.625	Primer	03/04	Splitting
	0-04	110	5	2.625	0.625	No primer	03/04	Splitting
	0-05p	75	3.75	2	0.625	Primer	02/21	Splitting
	0-05	75	3.75	2	0.625	No primer	02/21	Splitting
Block / Batch 1	1-01	40	5	1.375	0.5	Factorial	04/29	Bar Fracture
	1-02	40	2.5	2.625	0.5	Factorial	04/29	Bar Fracture
	1-03	110	2.5	1.375	0.5	Factorial	04/28	Splitting
	1-04	110	5	2.625	0.5	Factorial	04/28	Bar Fracture
	1-05	40	2.5	1.375	0.75	Factorial	04/29	Splitting
	1-06	40	5	2.625	0.75	Factorial	04/29	Splitting
	1-07	110	5	1.375	0.75	Factorial	04/28	Splitting
	1-08	110	2.5	2.625	0.75	Factorial	04/28	Splitting
	1-09	75	3.75	2	0.625	Center	04/26	Splitting
	1-10	75	3.75	2	0.625	Center	04/26	Splitting

	Run	**Temperature T (°F)**	**Splice length ℓ_s (in)**	**Side Cover c_b (in)**	**Bar diameter d_b (in)**	**Point Description**	**Date Tested**	**Observed Failure**
Block / Batch 2	2-01	40	2.5	1.375	0.5	Factorial	05/08	Splitting
	2-02	40	5	2.625	0.5	Factorial	05/08	Bar Fracture
	2-03	110	5	1.375	0.5	Factorial	04/28	Splitting
	2-04	110	2.5	2.625	0.5	Factorial	04/28	Pullout
	2-05	40	5	1.375	0.75	Factorial	05/08	Splitting
	2-06	40	2.5	2.625	0.75	Factorial	05/08	Splitting
	2-07	110	2.5	1.375	0.75	Factorial	04/28	Splitting
	2-08	110	5	2.625	0.75	Factorial	04/28	Splitting
	2-09	75	3.75	2	0.625	Center	04/27	Splitting
	2-10	75	3.75	2	0.625	Center	04/27	Splitting
Block / Batch 3	3-01	75	3.75	2	***0.375***	Axial	05/20	Bar Fracture
	3-02	75	3.75	2	***0.875***	Axial	05/20	Splitting
	3-03	***5***	3.75	2	0.625	Axial	05/24	Splitting
	3-04	***145***	3.75	2	0.625	Axial	05/24	Pullout
	3-05	75	3.75	**0.75**	0.625	Axial	05/20	Splitting
	3-06	75	3.75	**3.25**	0.625	Axial	05/20	Bar Fracture
	3-07	75	***1.25***	2	0.625	Axial	05/20	Splitting
	3-08	75	***6.25***	2	0.625	Axial	05/20	Bar Fracture
	3-09	75	3.75	2	0.625	Center	05/20	Splitting
	3-10	75	3.75	2	0.625	Center	05/20	Splitting

Table 2 compares the measured bar stress at failure for six nominally identical specimens (for reference the yield and ultimate strength of the reinforcement were 65.0 ksi and 96.0 ksi, respectively). Because the experimental design was conducted using three separate batches of HCSC, an important consideration was the batch-to-batch variability of the repeated center point. In each batch, two specimens were tested with identical properties, the center point of the design space (T =75 °F, ℓ_s = 3.75 in, c_b = 2.0 in, and d_b = 0.625 in). This comparison also considers the inherent variability between specimens in construction, conditioning, and testing. The strength of the CCD design is the ability to quantify and incorporate this variability in analzing the experimental results. The very low coefficient of variation between the six specimens (<5%) shows that the batch-to-batch variation was small.

Table 2. Bar stress at failure for repeated center point specimens

Run	Bar Stress (ksi)
1-09	85.7
1-10	82.7
2-09	79.0
2-10	81.4
3-09	82.0
3-10	81.1
Mean	82.0
Standard Deviation	2.2
Coeff. Of Variation	2.7 %

Task 4 – Development of Design Recommendations

This task in ongoing. Statistical analysis of the measured data is underway. This analysis will estimate the relationship between bar stress at failure and non-contact splice length, side cover, test temperature, and bar size. Regression of the data will use a regularization technique to estimate the importance of various terms in the linear model, including interactions between the variables. A simplified design expression will be developed based on the regression model considering the influence of sampling variability and model uncertainty.

The results of the non-contact lap-splice tests and the measured mechanical properties will be used to develop design recommendations for precast concrete closure joints using FRPC. These design recommendations will be used to develop example joint configurations for connecting common precast concrete superstructure elements, such as decked girders or precast deck panels.

Task 5 – Interim and Final Reporting

This task in ongoing. The research team will submit timely quarterly reports, present annually at the Research Days meeting, and complete final report summarizing findings reached during the project.

5. Expected Results and Specific Deliverables

The successful completion of the research project will directly impact the design/construction industry, by providing a better understanding of the properties of FRPC and its potential for use in closure joints between precast members, such as decked bulb tees, PCI NEXT beams, or precast deck panels. The main deliverable will be a report that summarizes:

- Recommendations for the selection of FRPC as a closure joint material in ABC applications,
- Design equations for the required development length of epoxy coated reinforcement embedded in FRPC, and
- Example closure joint geometry utilizing FRPC.

In addition, the results of the project will be summarized in a 5-min demonstration video and a journal publication.

6. Schedule

Progress on tasks in this project is shown in the tables below.

Item	% Completed
Percentage of Completion of this project to Date	75%

Research Tasks	2021										2022							
	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A
Task 1 – Literature Review	▨	▨	▨	▨	▨	▨													
Task 2 – FRPC Material Characterization				▨	▨	▨	▨	▨	▨	▨	▨								
Task 3 – Testing of Splice Specimens											▨	▨	▨	▨	▨	▨			
Task 4 – Development of Design Recommendations																	■	■	■
Task 5 – Interim and Final Reporting				▨			▨			▨			▨			▨			■

Work performed ←|→ Work to be performed

7. References

Box, G.E.P., Hunter, W.G., and Hunter, J.S. (2005). Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building. 2nd edition. John Wiley & Sons, New York.

Qiao, P., Zhou, Z., and Allena, S. (2016) "Developing Connections for Longitudinal Joints between Deck Bulb Tees – Development of UHPC Mixes with Local Materials." Report No. WA-RD 869.1, Washington State Department of Transportation, Olympia WA.