INNOVATIVE MULTI-HAZARD RESISTANT BRIDGE COLUMNS FOR ACCELERATED BRIDGE CONSTRUCTION

Quarterly Progress Report
For the period ending February 28, 2023

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1. Background and Introduction

The Federal Highway Administration (FHWA) and state departments of transportation (DOTs) are actively promoting accelerated bridge construction (ABC) to minimize construction costs and time and to also enhance work-zone safety. While several techniques are available to accelerate bridge superstructure construction, limited techniques are available to accelerate bridge substructure construction.

Hollow-core FRP-concrete-steel (HC-FCS) columns – a concrete core sandwiched between an outer FRP tube and an inner steel tube – provide a potential solution for accelerating bridge substructure construction and offer the following advantages over traditional construction materials and systems:

- Enhanced ductility and energy absorption
- Improved axial and flexural strength
- Enhanced durability and corrosion resistance
- Simplified construction techniques
- Decreased overall column weight
- Reduced material and labor costs
- Longer life

Because of their significantly enhanced ductility compared to existing bridge columns, HC-FCS columns also provide a column system better able to resist multiple hazards such as earthquakes, vehicular impact, blast, overload, excessive thermal stresses, progressive collapse, and fire.

Previous research combined with the results of this proposed study and a companion Oklahoma Department of Transportation (ODOT) study will provide the necessary performance data and recommendations to move HC-FCS columns into practice. In this regard, the final report will include design procedures and recommendations to determine steel, concrete, and FRP wall thicknesses, concrete type, footing and girder embedment depths, and nominal flexural and shear strengths of HC-FCS columns. An ABC-UTC Guide on HC-FCS columns will also be published, summarizing the research and promoting the use of HC-FCS columns for accelerated bridge construction.

2. Problem Statement

The Federal Highway Administration (FHWA) and state departments of transportation (DOTs) are actively promoting accelerated bridge construction (ABC) to minimize construction costs and time and to also enhance work-zone safety. While several techniques are available to accelerate bridge superstructure construction, limited techniques are available to accelerate bridge substructure construction. Concrete-filled steel tube (CFST) columns have shown some success for accelerating bridge substructure construction but suffer from deterioration and continued maintenance issues once constructed (Perea et al., 2014; He et al., 2019). Concrete-filled fiber-reinforced polymer tubes (CFFTs) have been investigated as an alternative to CFST columns, but research has shown that CFFTs have significantly lower strength and ductility than CFSTs without the addition of supplemental reinforcement within the concrete core (Zhu et at., 2006; Ozbakkaloglu, 2013; Zohrevand and Mirmiran, 2013; Ozbakkaloglu and Vincent, 2014). Precast concrete columns have also shown some success in accelerating bridge substructure construction but have high transportation and erection costs as well as complex splicing details at the foundation, which is also the location of the highest flexural stresses (Zahn et al., 1990; Hoshikuma and Priestley, 2000; Ranzo and Priestley, 2001).

This research focuses on accelerating bridge substructure construction using an innovative multi-hazard-resistant bridge column. The column consists of a concrete core sandwiched between an outer fiber-reinforced polymer (FRP) tube and an inner steel tube. Both tubes will act as stay-in-place forms and confine the concrete core, significantly increasing the strength and ductility of the concrete. The inner steel tube will be embedded into the footing, provide flexural and shear reinforcement, and eliminate the need for a steel reinforcing cage within the concrete core. The concrete core will delay local buckling of the inner and outer tubes, increasing strength and ductility of both the steel and FRP. The outer FRP tube will protect the concrete and steel materials from corrosion and will provide flexural and shear reinforcement. Both high-strength self-consolidating concrete (SCC) and ultra-high performance concrete (UHPC) will be investigated for potential use as the concrete core material.

3. Objectives and Research Approach

The overarching goal of this research study is to implement hollow-core FRP-concrete-steel (HC-FCS) columns for accelerated bridge construction. The objectives necessary to achieve that goal include:

- Determining the benefits of using high-strength SCC and UHPC for the concrete core of HC-FCS columns
- Developing design procedures and recommendations for steel, concrete, and FRP wall thicknesses, concrete type (SCC or UHPC), and nominal flexural and shear strengths of HC-FCS columns

4. Description of Research Project Tasks

The following is a description of the proposed research tasks and the work performed to date.

Task 1 – Design and Construct Half-Scale HC-FCS Columns

Three (3) half-scale HC-FCS columns will be designed and constructed having different steel, concrete, and FRP wall thicknesses, concrete type (SCC or UHPC), and column aspect ratios. These three (3) specimens will augment the eight (8) specimens that are part of the ODOT sponsored HC-FCS research project mentioned previously. The initial column design parameters will be based on procedures derived from recommendations of previous research studies (Teng et al., 2007; Lu et al., 2010; Zhang et al., 2012; Abdelkarim and ElGawady, 2014; Ozbakkaloglu and Idris, 2014; Albitar et al., 2015).

In addition to the three (3) HC-FCS column specimens, the research team will design and construct one (1) conventional, circular, solid, reinforced concrete (RC) column to serve as a control specimen to evaluate the performance of the HC-FCS columns.

The research team completed an initial half-scale column design based on a review of preliminary design methodologies for HC-FCS columns and available standard material sizes for steel and FRP tubes. The result is shown in Figure 1 and consists of an 18-1/2 in. outer diameter FRP shell, a nominal 12 in. outer diameter inner steel shell, and a nominal 3-in.-thick high strength SCC or UHPC core. The test specimen has a free height of 6 ft. 8 in. with a reinforced concrete base at the bottom and a reinforced concrete loading stub at the top. The reinforced concrete base provides the foundation for embedding the steel tube and will be anchored to the test frame during loading. The reinforced concrete loading stub allows for application of the lateral load through a push-pull hydraulic ram.

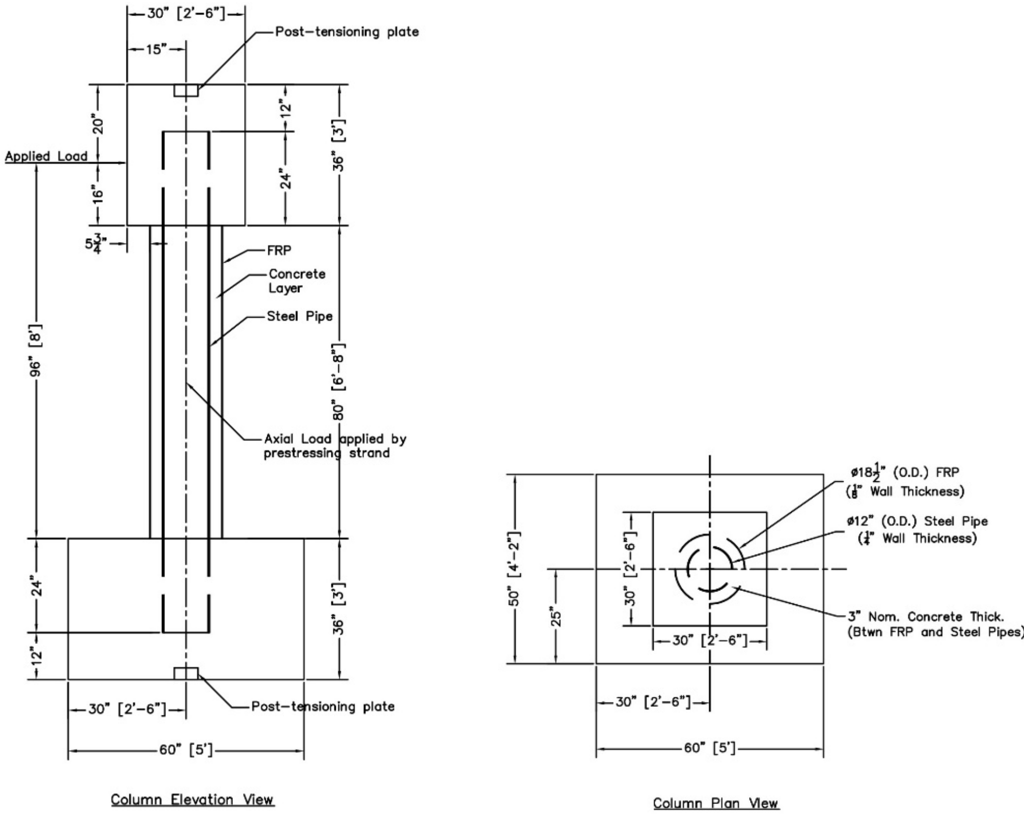

Figure 1. Preliminary HC-FCS Test Specimen Design

The research team then refined the design of the HC-FCS test specimens based on the materials most readily available in the State of Oklahoma. The steel tubes, shown in Figure 2, consist of seamless high yield carbon pipe with a 12-3/4" OD, 1/4" wall thickness, and conforming to API 5L Grade X52 specifications (minimum 52 ksi yield strength, 66 ksi tensile strength), which exceeds ASTM A500 Grade B or C specifications. The FRP tubes, shown in Figure 3, consist of glass fiber reinforced polymer pipe with an 18.93" ID, 1/8" wall thickness, and conforming to Stiffness Class 18 and Pressure Class 150. Based on these dimensions for the fabricated steel and FRP tubes, the concrete core will have a thickness of 3.09". All dimensions satisfy preliminary design guidelines for HC-FCS columns.

The research team fabricated four HC-FCS column bases with the embedded steel tubes, post-tensioning ducts for the applied axial load, and PVC ducts for the eight 1-1/2-in.-diameter high-strength steel rods used to anchor the specimens to the test frame. Concrete placement is shown in Figure 4, and the completed specimens are shown in Figure 5.

Figure 2. Steel Tubes for HC-FCS Column Test Specimens

Figure 3. FRP Tubes for HC-FCS Column Test Specimens

Figure 4. Fabrication of HC-FCS Column Bases with Embedded Steel Tubes

Figure 5. Completed HC-FCS Column Bases with Embedded Steel Tubes

The research team installed strain gages near the intersection of the inner steel tube and concrete base of the four HC-FCS columns. These gages will monitor longitudinal stresses in the tube during testing. The layout included two rows of four strain gages positioned around the perimeter of the steel tubes near the base, as shown in Figure 6. One row of strain gages is located 3 in. above the concrete base, and the second row of strain gages is located 9 in. above the concrete base. After placement of the FRP tube (left photograph of Figure 6) and the concrete core, the research team will install strain gages on the outer surface of the FRP tubes to measure hoop stresses during testing.

Following successful installation of the strain gages, the FRP outer tubes were placed and held in position with spacers installed on the inner steel tubes. Two HC-FCS columns prepped and ready for placement of the inner concrete core are shown in Figure 7. A halo brace was fabricated for the top of the FRP tubes to help secure them using ratchet straps during concrete placement, shown on the left specimen of Figure 7.

Figure 6. Strain Gage Installation for Measuring Longitudinal Stresses in the Steel Tubes

Figure 7. HC-FCS Columns Prepped for Concrete Core Placement

The research team placed the inner concrete cores of the half-scale HC-FCS column specimens, two high-strength SCC cores and two UHPC cores. Initial work involved development and testing of a potential SCC mix design. Figure 8 shows the slump flow characteristics of the SCC mix selected, measuring 28 in. in diameter without any segregation (left photograph of Figure 8) or any halo effect on the outer edge of the flow (right photograph of Figure 8). Figure 9 shows one of the SCC placements and the completed specimen.

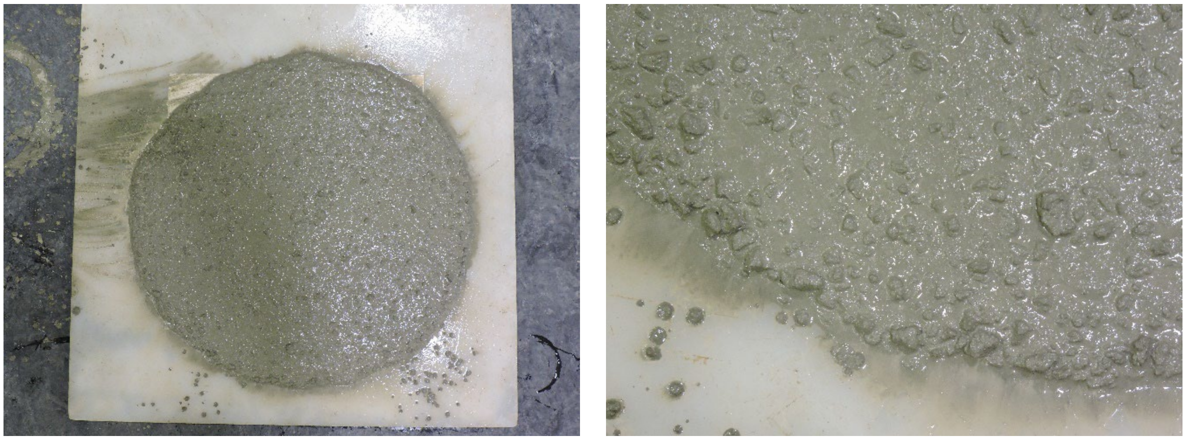

Figure 8. Slump Flow Testing of High-Strength SCC Mix Design, Overall (l) and Close-up of Edge (r)

Figure 9. High-Strength SCC Inner Concrete Core Placement (l) and Completed Specimen (r)

For the UHPC inner concrete core specimens, the decision was made to use the OU-developed J3 mix design instead of a proprietary mix. The choice of a non-proprietary mix allowed greater flexibility instead of tying the results to a specific proprietary UHPC mix. The J3 mix was developed during a previous ODOT-sponsored research project and has been used on a number of other ABC-UTC-sponsored research projects. Figure 10 shows the UHPC placement and completed specimen.

The 28-day compressive strengths for the two high-strength SCC inner cores exceeded the 9,000 psi target strength, with one column reaching 10,220 psi and the other reaching 9,800 psi. The 28-day compressive strengths for the two UHPC inner cores exceeded the 18,000 psi target strength, with one column reaching 19,390 psi and the other reaching 19,820 psi.

Figure 10. UHPC Inner Concrete Core Placement (l) and Completed Specimen (r)

The research team also completed preparations and placed the concrete for the conventional reinforced concrete (RC) column that will serve as the control specimen during testing. Completed strain gage installation of the longitudinal reinforcing steel is shown in Figure 11. The installation pattern was similar to that used on the steel tubes of the HC-FCS column specimens. The left photograph in Figure 12 shows the RC column reinforcing cage just prior to installation of the Sonotube formwork, while the right photograph shows the completed specimen after curing and formwork removal.

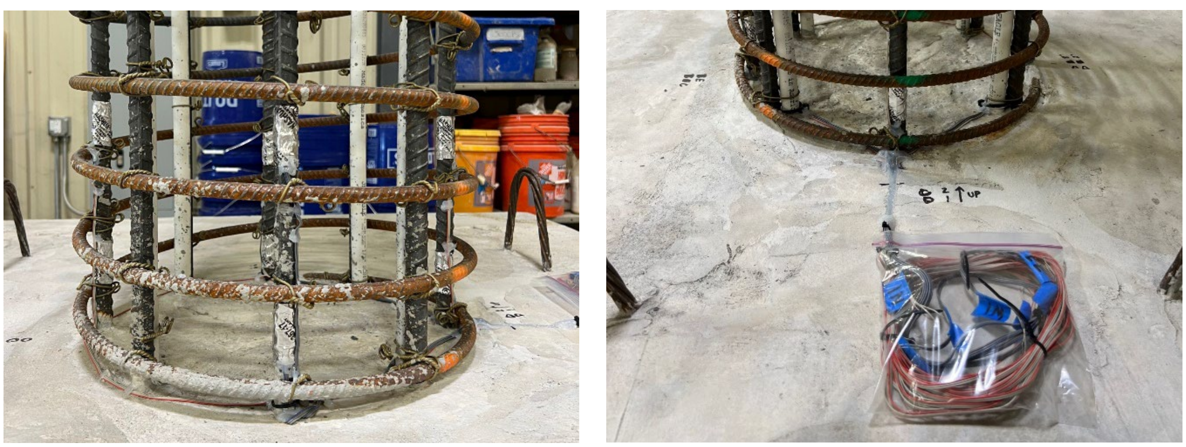

Figure 11. Conventional, Circular, Solid RC Column Longitudinal Steel Strain Gages

The research team completed the design of the reinforced concrete loading stub for the top of each half-scale column specimen. The loading stub allows for application of the lateral load through a push-pull hydraulic ram as well as the application of the nominal column axial compressive load through the longitudinal prestressing strands.

Figure 12. Conventional, Circular, Solid RC Column Reinforcing Cage (l) and Completed Specimen (r)

Task 2 – Test Half-Scale HC-FCS Columns Under Cyclic Lateral Load and Constant Axial Load

The half-scale column specimens will be tested under cyclic lateral loading and a constant axial compressive load. The cyclic loading will be applied in a displacement-controlled manner using a hydraulic actuator connected to the column loading stub. The loading protocol is based on FEMA Publication FEMA P-2082-1 (2020), which recommends increasing each subsequent displacement amplitude by 40%. The protocol includes two cycles for each specified increment of displacement.

Instrumentation for each test will consist of load cells to record the lateral force, wire pots to measure the lateral displacements, and strain gages to measure strain in the FRP and steel tubes for the HC-FCS column specimens and in the internal reinforcing steel for the RC column specimen.

The research team designed a structural steel fixture for testing the half-scale columns under cyclic lateral loading and a constant axial compressive load. The test fixture, shown in Figure 13, was designed to be mounted to the Fears Lab High Bay strong floor. The columns will thus be oriented horizontally when tested. The test fixture will accommodate a maximum column diameter of 24 in. and a maximum column height of 30 ft. A total of four post-tensioning strands will provide the constant axial compressive load during testing.

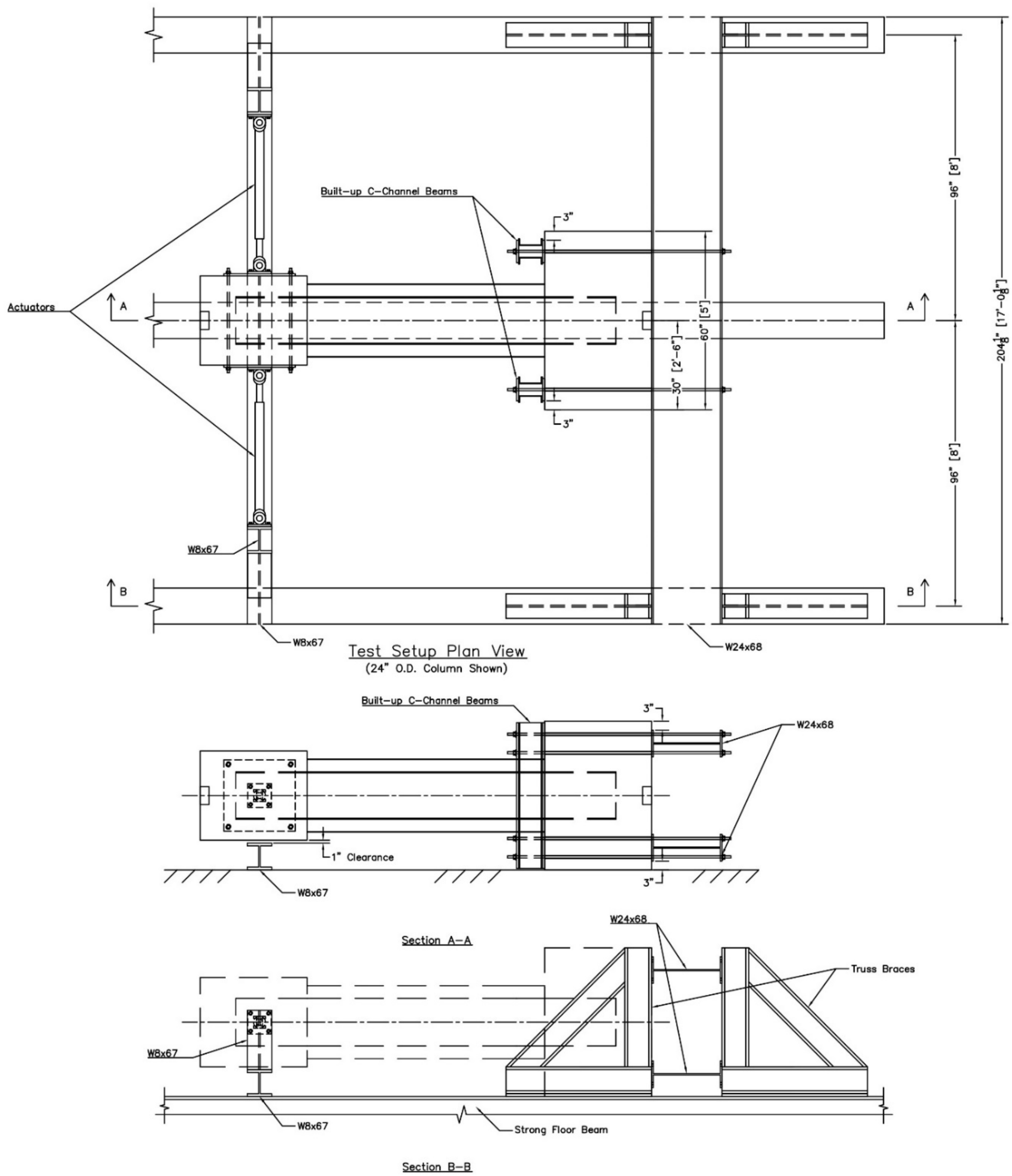

Figure 13. Column Test Fixture Schematic Design

The initial approach was to have the structural steel fabricated by a local detailing shop. However, complications resulting from the pandemic would have required an 18 month lead time, which was unworkable for the project schedule. The decision was made to have the large supporting girders cut to the required lengths but perform all the remaining fabrication and detailing at Fears Lab. This detailing included cutting all other structural steel members and stiffener plates to the required lengths and shapes, performing over 300 ft of welding, and drilling of over 200 holes of various diameters. The completed assembly of the column test fixture base is shown in Figure 14.

Figure 14. Completed Column Test Fixture Base Mounted to Fears Lab High Bay Strong Floor

Figure 15 is a photograph of one of the half-scale HC-FCS specimens with a high-strength SCC core positioned on the strong floor and within the column test fixture. Due to lifting limitations of the overhead crane (2 tons), the specimens must be positioned for testing prior to installation of the loading stub at the top of the column. Once the loading stub is installed and reaches the required strength, the column will be ready for testing.

Task 3 – Perform Parametric Finite Element Study of HC-FCS Columns

The results from Task 2 combined with the results from the ODOT sponsored HC-FCS research project will be used to validate finite element models of the half-scale testing program. Once validated, the finite element models will be used to perform a series of parametric studies to investigate HC-FCS columns having different steel, concrete, and FRP wall thicknesses, concrete type (SCC or UHPC), footing and girder embedment depths, and column aspect ratios. This task will extend the results of the testing program by encompassing a larger range of physical parameters, helping to reinforce the design procedures and recommendations that follow.

No accomplishments during this reporting period.

Task 4 – Develop Design Procedures and Recommendations for HC-FCS Columns

The results of Tasks 1 through 3 combined with the results from the ODOT sponsored HC-FCS research project will form the basis for developing a set of design procedures and recommendations for HC-FCS columns. These guidelines will refine the procedure outlined in

Task 1 and include equations to determine steel, concrete, and FRP wall thicknesses, concrete type (SCC or UHPC), footing and girder embedment depths, and nominal flexural and shear strengths of HC-FCS columns.

No accomplishments during this reporting period.

Task 5 – Document Progress, Results, Recommendations, and Design Guidelines of the Study Through Quarterly Progress Reports, a Final Report, and an ABC-UTC Guide

This task involves documenting, reporting, disseminating, and promoting the results of the research and will include quarterly progress reports, a final report, and an ABC-UTC Guide on HC-FCS columns. The quarterly progress reports will document the progression of the research study. The final report will provide in-depth details and results of the research, as well as guidelines to determine steel, concrete, and FRP wall thicknesses, concrete type (SCC or UHPC), footing and girder embedment depths, and nominal flexural and shear strengths of HC-FCS columns. The ABC-UTC Guide on HC-FCS columns will summarize the research and help promote the use of HC-FCS columns for accelerated bridge construction.

Work completed during this reporting period includes the submission of this quarterly progress report.

Figure 15. Completed HC-FCS Specimen Within Colun Test Fixture Awaiting Installation of Loading Stub

5. Expected Results and Specific Deliverables

The anticipated results from this research study are design procedures and recommendations to determine steel, concrete, and FRP wall thicknesses, concrete type (SCC or UHPC), footing and girder embedment depths, and nominal flexural and shear strengths of HC-FCS columns.

The project deliverables will include quarterly progress reports, a final report, and an ABC-UTC Guide on HC-FCS columns. The quarterly progress reports will document the progression of the research study. The final report will provide in-depth details and results of the research, as well as guidelines to determine steel, concrete, and FRP wall thicknesses, concrete type (SCC or UHPC), footing and girder embedment depths, and nominal flexural and shear strengths of HC-FCS columns. The ABC-UTC Guide on HC-FCS columns will summarize the research and help promote the use of HC-FCS columns for accelerated bridge construction.

6. Schedule

Completion percentage on this project is shown in the table immediately below. Progress of tasks on this project is shown in the next table.

Item	% Completed
Percentage of Completion of this project to Date	55%

Research Tasks	2022							2023			
	J	J	A	S	O	N	D	J	F	M	A	M
1. Fabricate HC-FCS Column Specimens												
2. Test HC-FCS Column Specimens												
3. Perform Parametric Finite Element Study												
4. Develop Design Procedures for HC-FCS Columns												
5. Reporting, Documentation, and Promoting												

Work Performed

Work to be Performed

7. References

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