Durable UHPC Columns with High-Strength Steel

Quarterly Progress Report
For the period ending December 31, 2017

Submitted by:
PI- Mohamed Moustafa and Ahmad Itani
Graduate Students- Mahmoud Aboukifa/Negar Naeimi

Department of Civil and Environmental Engineering
University of Nevada, Reno

ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

Submitted to:
ABC-UTC
Florida International University
Miami, FL

March 2018

1 Background and Introduction

In the recent decades, Ultra High Performance Concrete (UHPC) has attracted worldwide attention of the industry and academy, due to its significant features, compared to the conventional concrete (RC). UHPC is a cementitious material, reinforced by fiber, which has compressive and tensile strength around 28 ksi and 1.2 ksi, respectively. Strain-hardening behavior of UHPC in tension along with its pre- and post- cracking tensile strength, are of its unique characteristics, associated with the fiber bridging effects. High ductility, energy absorption capacity, considerable shear resistance, self-consolidation, reduced section sizes and low cost of maintenance are other features of UHPC, which make it a desirable candidate in the construction industry, despite its high instant costs. These physical and mechanical outstanding characteristics stems from the particular mix design including: very low water-to-cementitious material ratio (about 0.2) and optimized granular mixture with minimal or no coarse aggregate. The resulting very low porosity of UHPC lead to increased durability, especially for construction in harsh environments. Hence, structures built by UHPC can be much lighter (due to the high strength that lead to smaller cross-sections) and can have longer service life (due to the high durability) than those built by regular concrete. UHPC is currently used in relatively small-scale applications, such as bridge deck joints and connections. However, there is great potential in extending the use of UHPC to larger applications and full structural elements to realize a new generation of resilient and almost maintenance-free structures.

2 Problem Statement

Rapid deterioration of bridge substructures has been one of the major reasons for the increasing number of structurally deficient or functionally obsolete bridges in the past decade. While many of the deteriorating old bridges are originally designed for a 50-year service life, many of the ongoing repairs, retrofits, and new construction aim at extending service life to 75 or 100 years. One approach for protecting and building durable bridge substructures with longer service life is to use very durable materials with very low porosity such as UHPC. If used in substructure elements, UHPC can easily extend the service life of bridge substructures to 100 years where the reinforcement and/or structural steel elements are well protected from corrosion and harsh environments. Due to the exceptional mechanical properties of UHPC, compact substructure elements cross-sections can be achieved if properly designed, which make this solution very suitable for ABC construction where lighter and easier-to-handle and transport bridge components can be pre-fabricated and shipped to the site.

Proper reinforcement detailing can increase columns axial capacity and ductility, but also showed that larger longitudinal reinforcement ratios are desired to fully utilize the UHPC superior strength and reduce cross-sections. Meanwhile, for better constructability, codes and standards limit longitudinal reinforcement ratio in bridge columns, for example, to 4%. Thus, considering high-strength steel with UHPC can help optimize cross-sections while maintaining reasonable reinforcement ratio. However, the use of A706 Grade 100 steel has not been properly investigated, especially when combined with UHPC.

Very limited or no previous research properly investigated UHPC sections design optimization for bridge elements and UHPC confinement effects under combined axial and lateral loading. Similarly, extending the use of high-strength steel to further optimize UHPC cross-sections and reduce structural elements sizes has not been studied. Thus, the objective of this study is to fill this gap and provide the basic knowledge needed to design UHPC sections using high-strength steel for constructing durable and compact pre-fabricated columns for ABC bridges.

3 Research Approach and Methods

The overall objective of this study is to provide the knowledge needed to optimize the design of pre-fabricated bridge substructure elements using UHPC and high-strength steel. In particular, the purpose of this study is to investigate the effect of longitudinal and transverse reinforcement detailing on the design capacity of UHPC pre-fabricated columns. The main core of this proposed study is an experimental program that consists of UHPC cylinders confinement study and several reduced-scale column tests under combined axial and lateral quasi-static (cyclic) loading.

This study will test UHPC bridge columns designed using A706 Grade 100 steel and using two different reinforcement ratios to preliminary investigate the efficiency of high-strength steel in reducing UHPC columns cross-sections while maintaining strength and serviceability design requirements. Another key factor of optimizing columns design under combined axial and lateral loads is understanding the confinement behavior of UHPC along with transverse steel detailing requirements such as minimum hoop spacing. An confinement study will be undertaken in this project on large number of unconfined and confined UHPC cylinders. Moreover, UHPC columns with two different transverse reinforcement ratios and/or hoop spacing will be tested under combined axial and lateral as part of the experimental program to study the effect of UHPC core confinement on the axial/flexural capacity of columns.

4 Description of Research Project Tasks

The following is a description of tasks to be carried out along with progress to date.

Task 1 – Update literature search on structural and seismic performance of UHPC prefabricated bridge components and connections:

An extensive literature search is in progress to comprehensively summarize the different applications of UHPC and high-strength steel in conventional and ABC bridges. The search will focus on the structural and seismic response of UHPC structural members subjected to combined axial and flexural loading (columns) or flexural only (beams). Another topic that will be comprehensively covered in this task is the structural performance and design using high-strength steel (both Grade 80 and 100), with focus on bridge elements. The literature search will also synthesis existing precast and ABC solutions, if any, for durable and sustainable construction where longer service life and no regular maintenance are desired features. This is to identify best future applications for prefabricated UHPC bridge substructure elements.

Task 2 – Carry out preliminary/pre-test analytical study to design the experimental program and specimens:

Three-dimensional (3D) finite element modeling and analysis will be used to preliminary investigate the effect of longitudinal and transverse reinforcement detailing on structural and seismic response of UHPC columns. This is to finalize the test specimens design and parameters for the experimental program. The general purpose finite element package FEA DIANA is currently used along with readily available macro constitutive and damage models (e.g. Total crack strain model) to calibrate and capture the behavior of UHPC under pure tension and compression (Figure 1). The calibrated UHPC material models is being extended to study full columns response with different reinforcement details to help finalize the test specimens design and parameters for the experimental program. The different reinforcement details that will be considered include: longitudinal steel ratio, steel grade, axial load ratio, transverse steel ratio, and hoop or tie spacing.

Preliminary nonlinear pushover analysis has been conducted during this quarter for a 3D model of a UHPC column to investigate the lateral capacity as shown in Figure 2. Three different ratios for reinforcement is considered: 1%, 1.5%, and 2%. As illustrated in the figure, the lateral force capacity of columns of same dimensions but different reinforcement ratios varied from 67.8 kN (15.2 kips) to 83.7 kN (18.8 kips). A refined model for the proposed test specimens will be developed in the next quarter to finalize the test specimens and setup design.

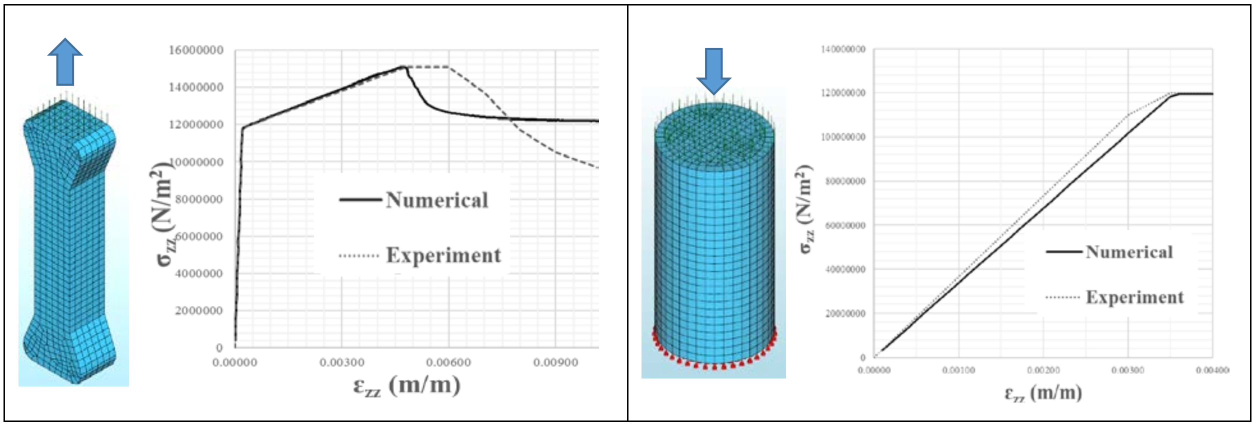


Figure 1. Comparison of tensile (left) and compressive (right) stress-strain relationships of UHPC coupons as obtained from experiments and DIANA numerical modeling.

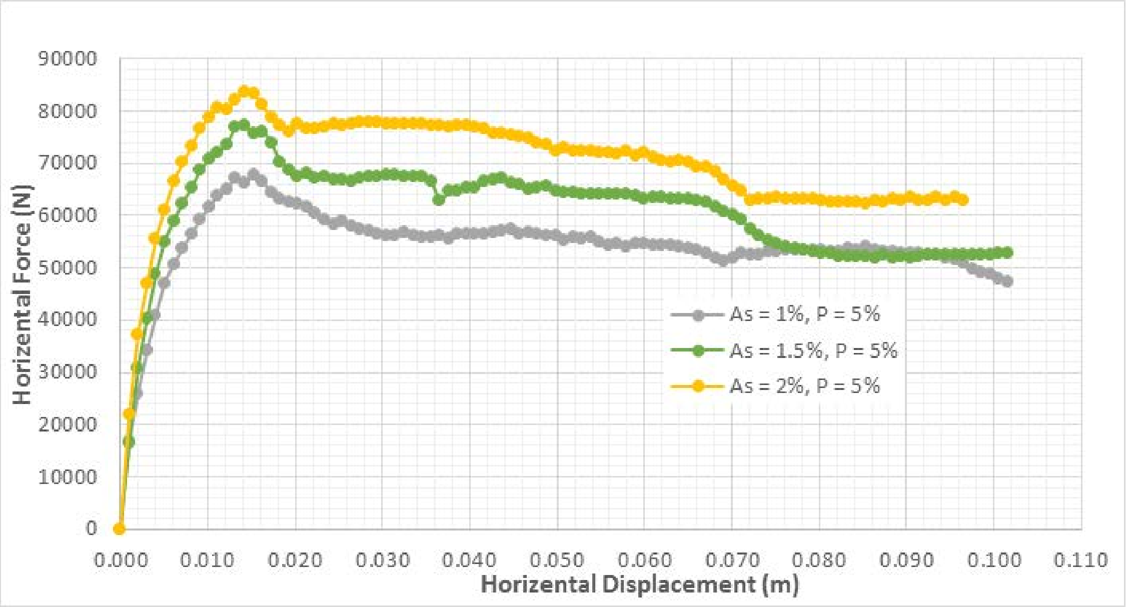


Figure 2. Lateral force-displacement (pushover) curves UHPC columns with different reinforcement ratios.

Task 3 – Conduct UHPC confinement tests:

Most of previous research that studied the compressive behavior of UHPC and developed stress-strain relationships for modeling focused on unconfined UHPC or in other words, tested mainly unconfined UHPC cylinders. For correct estimation of the ultimate strength and displacement design capacity of UHPC columns under combined axial and lateral loading, a better understanding of the effect of confinement on UHPC behavior is crucial. A large number of unconfined and confined UHPC cylinders will be sampled, instrumented, and tested under pure compression to properly define UHPC stress-strain relationships. Wire hoops of different spacing will be used to provide different confinement cases for UHPC cylinder tests. Common confinement models for conventional concrete, e.g. Mander model, will be checked for validity for UHPC. Thus, this task will provide a preliminary idea on the required transverse steel detailing needed for column design, which will be verified through larger scale column tests in Task 4. A comprehensive UHPC material characterization program is ongoing under supervision of the PI and the confinement study will be complemented with additional tensile and bending tests. Compression tests for confined and unconfined cylinders have been recently conducted at UNR and results will be processed for next quarter. However, a brief discussion of the whole material characterization study is summarized below.

Progress of Ongoing Material Characterization Program

A commercial proprietary UHPC mix will be used in this study which is the Ductal® JS1000 mix design. Lafarge commonly delivers UHPC in three different parts: premix (which is a proprietary blend of cement, silica sand, silica flour and silica fume), fibers, and Superplasticizer. The Ductal® mix components is given in Tables 1 and 2. For the material characterization and confinement studies, several UHPC patches have been (and will be) cast at UNR. During UHPC casting, to maintain temperature of UHPC mixture constant, ice is added as a part of water weight. If the daytime temperatures exceed 25°C (77°F), the use of 100% ice substitution, of water, may be required to increase the working time of the mix. Steel fibers with 2% volume are used for mixes and the mechanical properties of steel fibers is given in Table 3. Components and mixing of UHPC is shown in Figure 3. For each batch static and dynamic slump (flow characteristics) are measured to check values are within the allowable ranges. A flow table and brass cone are used for these tests. Note that the allowable slump must be in the range of 180 mm to 250 mm.

Table 1. UHPC mixture by Ductal® (based on number of premix bags).

Number of bags per batch	**3**	**4**	**5**	**6**	**7**
Premix (kg)	68.04	90.72	113.40	136.08	158.76
Superplasticizer (kg)	0.93	1.24	1.55	1.86	2.18
Steel fiber (kg)	4.84	6.45	8.06	9.67	11.29
Water or ice (kg)	4.03	5.37	6.72	8.06	9.40
Volume (m^3)	0.031	0.041	0.051	0.062	0.072

Table 2. UHPC mixture by Ductal®.

	(kg/m^3)	**lb/yd^3**	**Percentage by weight**
Premix	2195	3700	87.6
Superplasticizer (Premia 150)	30	50.6	1.2
Steel Fiber (2.0% volume)	156	263	6.2
Water (or ice)	130	219.1	5

Table 3. Steel fibers properties.

	SI units	**US units**
Tensile Strength	399 MPa	3750 ksi
Length	13 mm	0.5 in
Diameter	0.2 mm	0.008 in

(a) (b)

(c) (d)

Figure 3. UHPC mixture: (a) steel fibers, (b) superplasticizer, (c) ice in superplasticizer, and (d) dry Ductal® premix in mixture

Sampling and Specimens Preparation

Dog-bone shaped, prisms, and 3x6 in. cylinders are the different specimens used for direct tension, bending, and compression characterization tests, respectively. Direct tension and bending tests specimens are readily finished unlike the UHPC cylinders which need surface preparation before testing. Sulpher capping cannot be used and only end grinding can be used for UHPC cylinders. A rough cut is made using a sawing machine and then specimens are grinded at the two ends as illustrated in Figures 5 and 6.


(a) (b)

Figure 5. (a) Demolded UHPC Cylinders (b) Saw cutting of cylinders.

Figure 6. Disc grinder machine used for grinding of UHPC cylinders

Test procedures

An INSTRON UTM machine with capacity of 56 kips (250 kN) is used for direct tension and bending displacement-controlled tests, and a larger capacity UTM with capacity of 500 kips (2225 kN) is used for force-controlled compression test. For direct tension tests, displacements are recorded using laser, conventional DAQ system, and innovative Digital Image Correlation (DIC) system (see Figure 7 for tension test setup and instrumentation). For compression tests, a loading rate in the range of 100-200 lb/min (0.236 psi/sec) is applied. Several cylinders (at least 6) are sampled and tested for each UHPC patch. Test set-up for compression tests is illustrated in Figure 8. Similar to tension tests, various instrumentation types that include: compressometer, DIC and novotechniks are used to measure displacements and strains.

Selected Test results

Selected stress strain curves from the unconfined UHPC cylinders compressive tests are shown in Figures 10 through 11. Given the nature of force-controlled compression tests, a slower loading rate is applied and three different methods are used to measure deformations in an attempt to capture the post-peak behavior. Each of the figures below show a sample result for each of the three measuring methods.

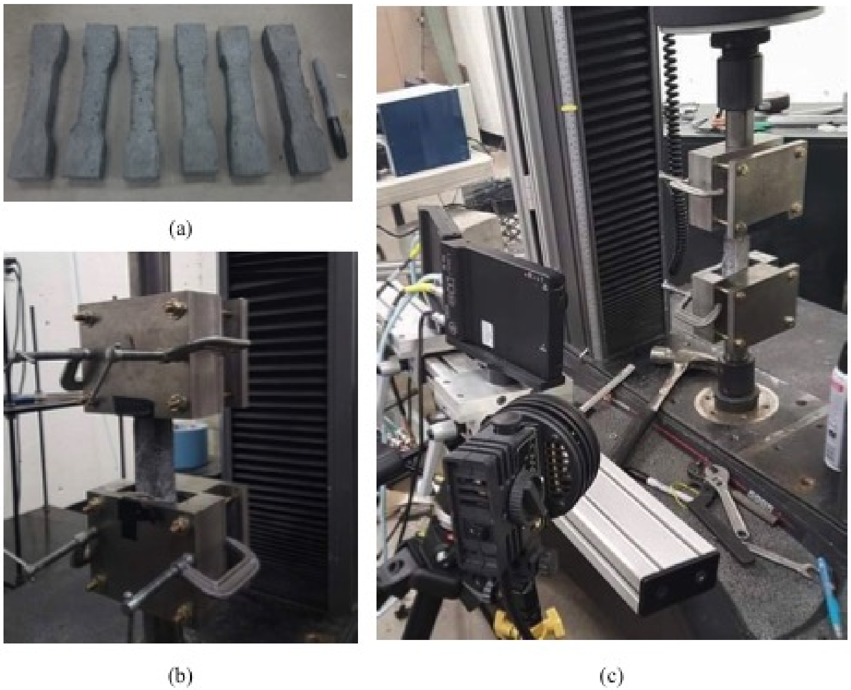


Figure 7. (a) Demolded dog-bone specimens, (b) gripped specimen, and (c) DIC set up to measure deformation for UHPC direct tension test.

Figure 8. UHPC compression test set-up.

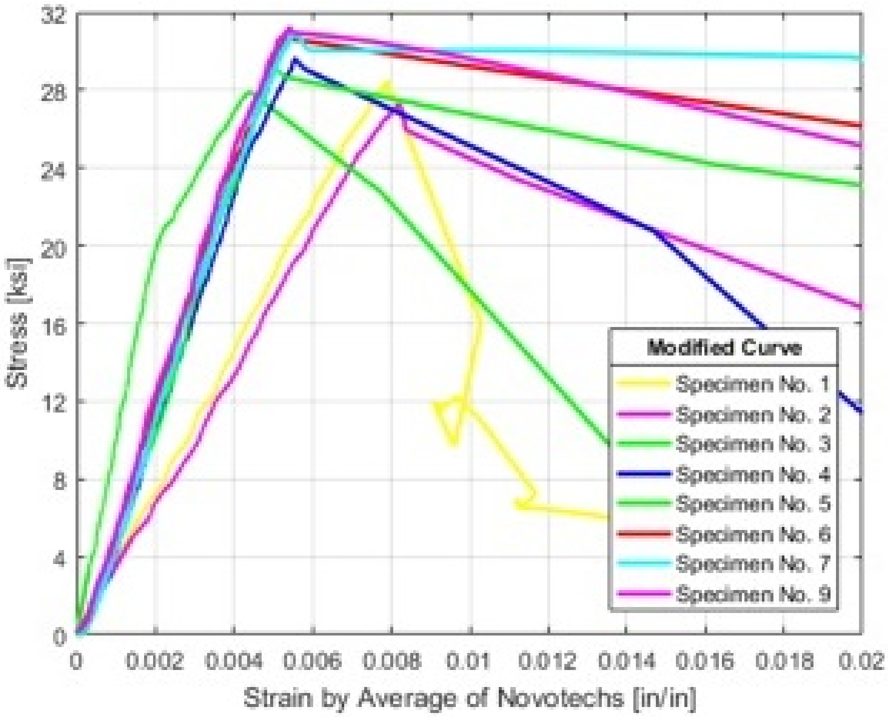


Figure 9. Stress-Strain curves of 9 UHPC cylinders where strain is measured by novotechniks

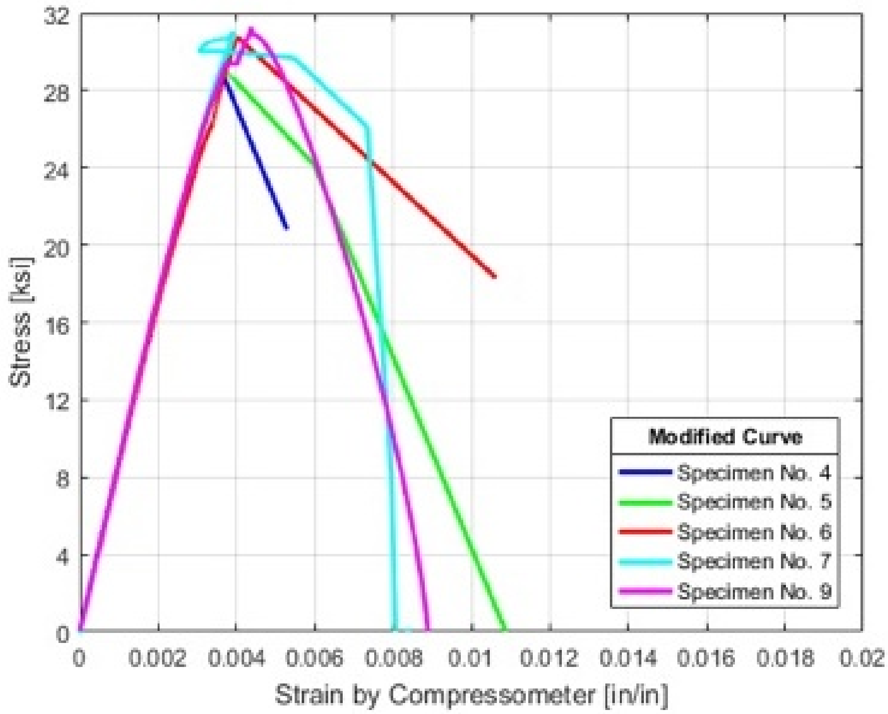


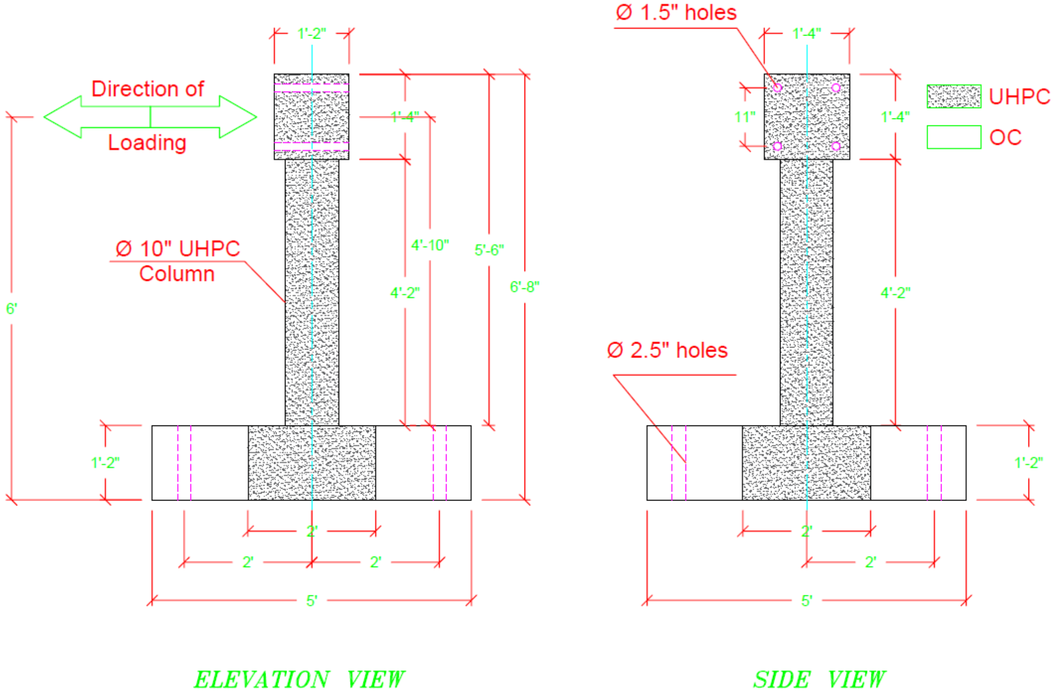
Figure 10. Stress-Strain curves of 6 UHPC cylinders, strain is measured by compressometer

Task 4 – Construct and instrument the UHPC test columns, and conduct quasi-static tests:

This task comprises the main core of the study and aims at testing several reduced-scale UHPC columns with high-strength longitudinal reinforcement under combined axial and unidirectional lateral quasi-static (cyclic) loading. Four specimens with varying longitudinal and transverse reinforcement details will be tested and their details of reinforcement as well as the test parameters are shown in table 4. The different hoop spacing aims at investigating the effect of transverse reinforcement on the confinement behavior of UHPC columns. The use of two different longitudinal reinforcement ratios in the test program will help understand what ratio work better for UHPC to fully utilize its superior behavior for cross-section reduction. Moreover, A706 Grade 100 steel is used in lieu of significantly increasing the reinforcement ratios for UHPC design optimization and its properties will be compared to the properties of the A706 Grade 60 steel rebars used in specimen S4. For actual ABC bridge substructures, pre-fabricated UHPC columns can be plugged into precast or cast-in-place (CIP) footings and bent cap beams through a pocket or socket connection. However, for the sake of this study, pre-fabricated columns with small footing and head for load application all made of UHPC will be used, i.e. a monolithic connection rather than a separate footing and column-to-footing ABC connection will be used. This is because the objective is to test the response of the column itself rather than the connection, and it is more feasible to use a small footing just for specimen fixation to the test strong floor and the 4 specimens' concrete dimensions are shown in Figure 12. All tests will be conducted under combined constant axial load and incremental lateral cyclic loading until failure (see Figure 13 for test setup). The goal is to determine the moment, rotation, and curvature capacities along with displacement ductility of the UHPC columns with high-strength steel and different transverse reinforcement and confinement details. A sample of the reinforcement detailing of the specimens is shown in Figures 14 and 15 for the S1 specimen.

Table 4. Test Matrix for the Proposed Experimental Program.

Specimen	**Long. Rft.**			**Trans. Rft. (Gr. 60)**	**Test Parameter**		**Test Type**
S1	1.5%	6#4	Gr. 100	#3 @ 2 in		Long. Rft. Ratio	Combined gravity and unidirectional lateral cyclic loading
S2	2.4%	6#5	Gr. 100	#3 @ 2 in	Transverse Rft. spacing		
S3	2.4%	6#5	Gr. 100	#3 @ 4 in		Long. Rft. grade	
S4	2.4%	6#5	Gr. 60	#3 @ 4 in			



ELEVATION VIEW

SIDE VIEW

Figure 12. Concrete Dimensions of the Specimens.

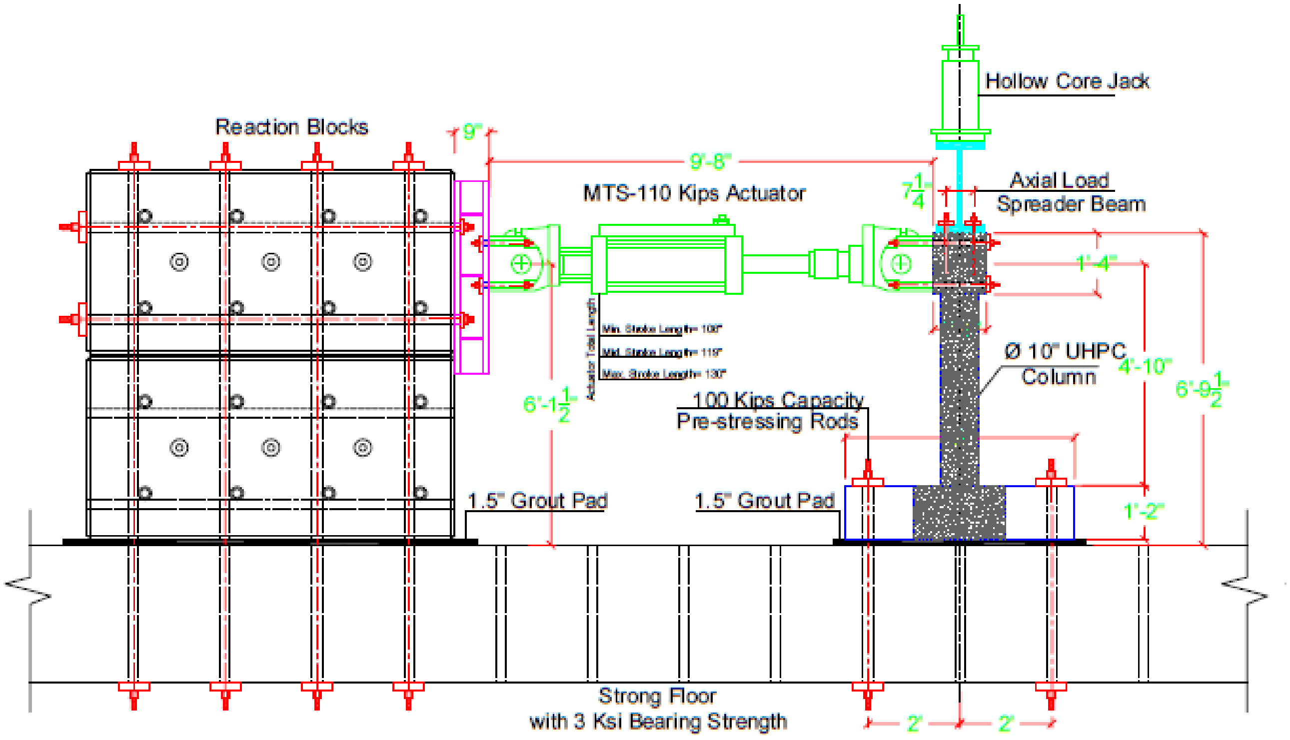


Figure 13. Proposed quasi-static test setup for UHPC columns under cyclic loading.

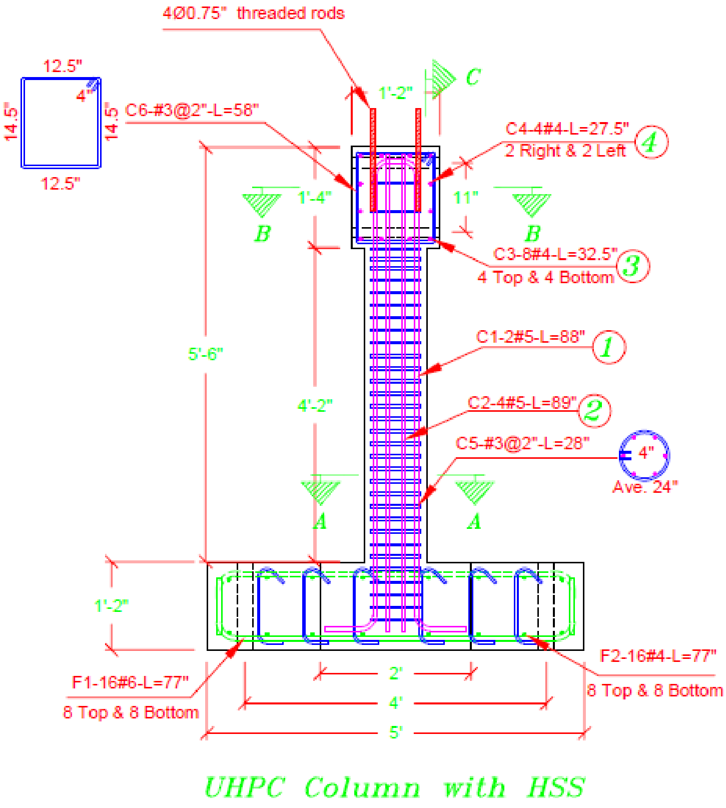


Figure 14. Reinforcement detailing in Elevation view of specimen S1.

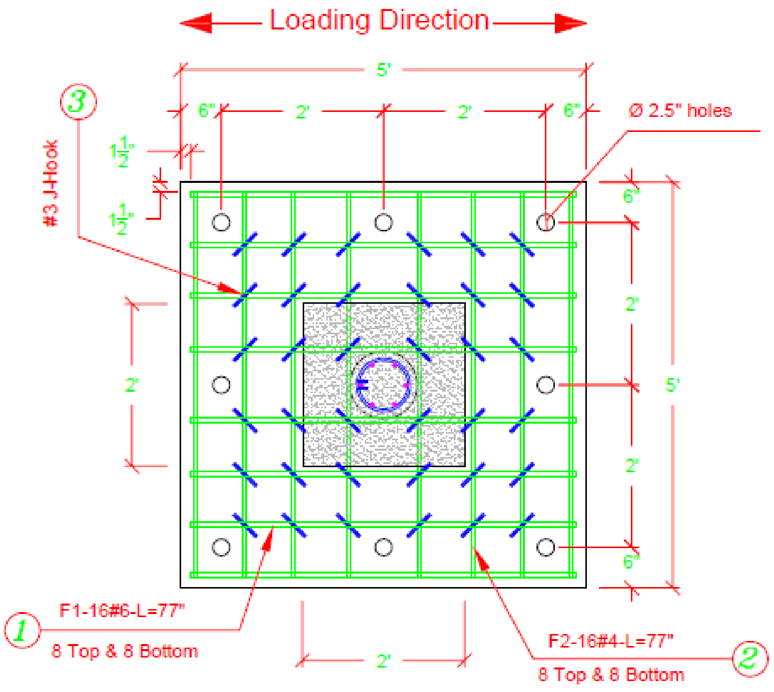


Figure 15. Reinforcement detailing in Plan view of specimen S1.

Task 5 – Process and interpret tests results and assess the structural and seismic performance of UHPC columns:

Upon completion of UHPC column tests, the measured data will be processed, reduced, and evaluated to interpret and explain the structural and seismic response of UHPC columns with high-strength steel along with the effect of transverse reinforcement on confinement behavior and column capacity. The knowledge acquired from the confinement study (Task 3) and the column tests data (Task 4) will be used to develop preliminary optimization and design guidelines for high performance durable UHPC columns with high-strength steel. Available simple design procedures and equations will be verified against the test results as well.

Task 6 - Summarize the investigation and the results in a draft final report:

A final report describing the details of different tasks and preliminary design guidelines for UHPC columns with high-strength steel will be prepared and submitted to the ABC-UTC steering committee for review and comments. Upon addressing the review comments, the report will be finalized and made widely available for dissemination.

5 Expected Results and Specific Deliverables

The deliverables from different tasks are as follows:

Task 1: A synthesis of the literature review providing a summary of the state-of-the-art on large-scale applications of UHPC in structural components, design using high-strength steel, and ABC solutions for durable and sustainable bridges.

Task 2: Final set of parameters and design of UHPC column specimens sought for the experimental study based on preliminary 3D finite element analysis.

Task 3: UHPC compression stress-strain relationships under different confinement conditions and an assessment of validity of existing confinement models for UHPC.

Task 4: Construction drawings and details for different specimens in addition to instrumentation plans and cyclic loading protocol.

Task 5: Key processed data that are indicative of the performance of UHPC columns and photos of damage progression in addition to preliminary design guidelines for UHPC columns with high-strength steel.

Task 6: A report summarizing the key steps and procedures used in the study, the data on structural and seismic performance of UHPC columns, conclusions regarding the confinement behavior of UHPC, and preliminary design guidelines.

6 Schedule

To allow for the completion of all the project tasks, the study will be conducted over a period of 17 months following the schedule in Table 2. The milestones are marked in the schedule, and the following notes explain the deliverables at these milestones.

a- Finalize experimental parameters
b- UHPC stress-strain relationship and constitutive model
c- Experimental test results
d- Final project report.

Table 4. Gant schedule of major project tasks and milestones.

Tasks	Year 1				Year 2	
	Q1	Q2	Q3	Q4	Q1	Q2
1. Literature search	🟦 X					
2. Pre-test analysis	🟦 X	🟥 X[a]				
3. UHPC confinement tests		🟦 X	🟥 X[b]			
4. Construction and column tests			🟦 X	🟥 X	🟥 X[c]	
5. Process/interpret test data					🟥 X	🟥 X
6. Final report						🟥 X[d]

🟦	Completed or work in progress	🟥	Remaining