Precast Bridge Substructure System Utilizing Socket Connections

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Use of precast elements for accelerated bridge construction (ABC) is a proven methodology with several advantages over traditional cast-in-place (CIP) construction, which include fast project delivery, improved construction quality, low lift-cyclic cost, minimal environmental impact, and reduced traffic disruption. Precast superstructure elements have been an integral part of bridge construction for many years, and state agencies have utilized precast elements in the construction of bridge substructure.[1] Due to the elimination of shoring and formwork system, precast column and precast bent cap offer significant time saving and improve work-zone safety for constructing bridge frame pier. However, a major issue of promoting precast frame pier is the lack of a reliable connection between precast column and foundation, especially pile foundation as in most cases. In addition, columns are often designed to form plastic hinges and contribute to energy dissipation under seismic forces. This places a significant demand on where the column connects to the foundation, which makes the design of connection for seismic events more challenging. Several connection concepts have been developed. By force transfer mechanism, they can be classified as a bar coupler, grout duct, pocket connection, or socket connection.[2] Among these types of connections, the socket connection that is constructed by embedding a precast element inside another member offers numerous benefits including speedy erection and ample installation tolerances. The current AASHTO LRFD Bridge Design Specifications[3] does not allow the use of mechanical connector in the plastic hinge zone of columns. Hence, the socket connection without mechanical connector in the potential column plastic hinge zone is competitive in high seismic zones. The Washington State Department of Transportation (WSDOT) has developed and successfully implemented the socket connection that was suitable for precast column with CIP spread footing.[4] An experimental study by Mohebbi et al.[5] investigated the feasibility of utilizing precast spread footing with socket connection. To promote precast frame pier in routine bridge construction, this study developed a new precast bridge substructure system. Through the use of sockets that are reserved on the precast pile cap, the frame pier with driven pile foundation can be constructed by insert the piles and precast column into these sockets and establishing the connections with in-situ concrete/grout in the sockets.

The performance of the precast bridge substructure system was explored experimentally. First, a series of socket connection tests was conducted to investigate the behavior of the column socket connection in sustaining axial load resulting from gravity effects. Second, a system test is being performed at an outdoor test site in order to adequately account for the soil-foundation-structure interaction and quantify the overall system performance. A half-scale test unit is under construction, which will be tested under a combination of vertical and lateral loads. This paper summarizes the experimental study on the development of the precast bridge substructure system. Specific areas of interest include: (1) a detailed introduction of precast substructure system; and (2) the findings from the experimental investigations.

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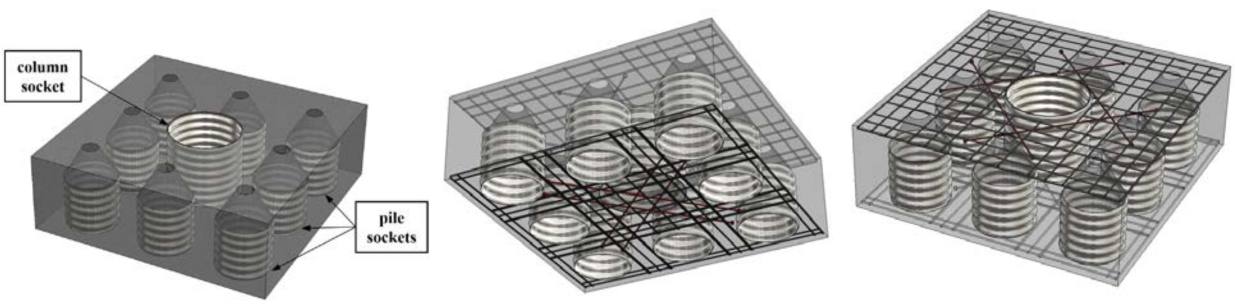
Precast Bridge Substructure System

Frame pier has been widely used as bridge substructure because of its low construction cost. Using precast elements, a typical pier can be constructed in as little as two days once the footings are in place.[1] However, current practice still uses CIP pile cap for bridge with driven pile foundation. To maximize the time savings during construction, this study developed a bridge substructure system employing precast components for the entire substructure. The key innovations of the system are the column socket and the pile sockets that are reserved on the top and bottom of the precast pile cap, as illustrated in **Figure 1**. By embedding bottom end of a precast column and top of steel H-piles into these sockets, followed grout/concrete closure pours, a frame pier can be constructed without CIP members. The sockets are routinely accomplished using commercially available corrugated steel pipes (CSPs) due to their low cost and variability in sizes. In addition to serving as stay-in-place formwork, CSPs offer confinement effect for the connections and their corrugations support a robust load transfer mechanism. The column socket is constructed to partially penetrate the pile cap from the top. Hence, the bottom-layer reinforcing bars of the pile cap is placed underneath the socket. The pile sockets penetrated through the pile cap for conducting closure pours, and the upper portion of these sockets are made in the shape of cone. This configuration allows the top-layer reinforcing bar to be placed through the sockets without notches on the CSPs as this would unnecessarily complicate the construction (Figure 1).



Socket reserved on precast pile cap   Bottom-layer reinforcing bars   Top-layer reinforcing bars

Figure 1. Precast pile cap with reserved sockets

For constructing the system, steel H-piles are first installed, which employs template to maintain the piles in proper position and alignment. Then temporary friction collars are affixed around each pile (**Figure 2**), on which the precast pile cap is shored. At this stage, tops of all H-piles are positioned into the respective pile sockets. The use of friction collars offers the feasibility of conducting construction in poor ground conditions and achieves better erection tolerance control. After erecting the precast column with an intentionally roughed end, as shown in Figure 2, the column, the pile cap, and the piles are connected by filling the column socket and the pile sockets with grout and self-consolidating concrete (SCC), respectively. One commercially available grout with desirable properties such as high-early-strength, fluid consistency, extended working time, and non-shrink is chosen for securing the column socket. The chosen grout can reach a specified compressive strength of 4000 psi (27.6 MPa) in 8 hours, and the friction collars are designed to carry the weight of pile cap, column, and upper structural components before SCC reaches the adequate strength. Therefore, the construction of the superstructure can begin on the day after completing closure pours. When SCC reaches the specified short-term strength, the friction collars can be removed for reusing.

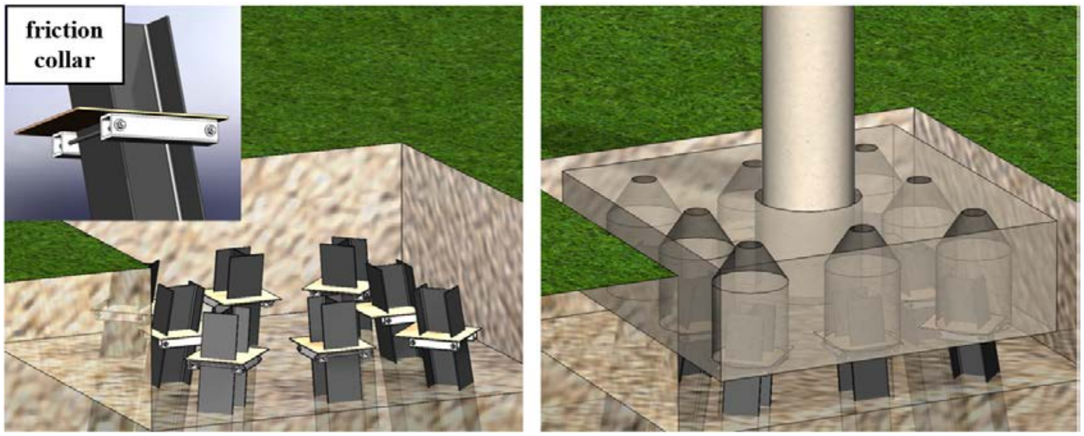


Figure 2. Construction of precast bridge substructure system

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Socket Connection Tests

When connecting to precast pile cap, the precast column should not experience any sliding with respect to the pile cap. In other words, the column socket connection should have adequate axial strength to transfer the gravity loads. The axial strength of the partially penetrated column socket connection results from side shear (P_s) acting along the embedded column and tipping (P_b) at the base of the column, as illustrated in **Figure 3**. Given the potential difference in required displacements to develop significant strength from side shear and tipping, the connection shall be conservatively designed relying on side shear only. However, for the socket connection using CSP and grout closure pour, there is no guideline available as to how the connection parameters (e.g., embedded column surface roughness and the clearance between the column and CSP) would affect the connection performance and how the connection should be detailed for given axial load. Addressing these issues, the socket connection tests were conducted to investigate the side shear behavior in the column socket connection and develop the optimal connection design.

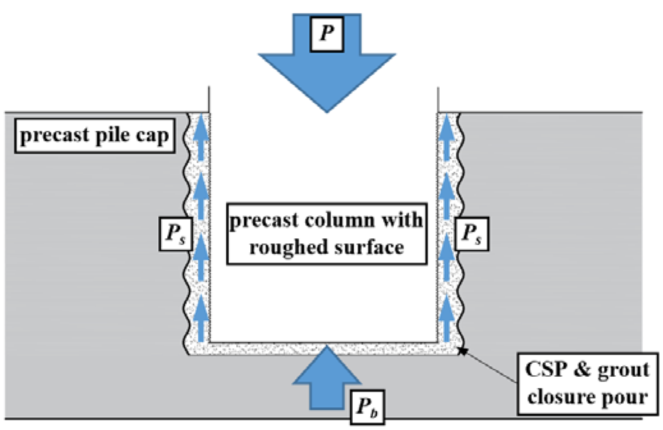

Figure 3. Axial strength of column socket connection

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Testing matrix

For the column socket connection constructed with CSP and grout closure pour, the axial strength resulting from side shear depends on a number of parameters. The parameters that most influence side shear strength include: (1) strength of grout used for closure pour, (2) corrugation pattern in CSP, (3) embedded column surface roughness, and (4) clearance between column and CSP that is filled by grout. The compressive strength of commercial available high-strength grout typically reaches 8000 psi (55.2 MPa) or higher at 28 days.[6] For commercially available CSPs that are applicable to form sockets for typical bridge columns ranging from 1.5 to 4 ft (0.5 to 1.2 m), a corrugation pattern of 2-2/3 in. (67 mm) × 1/2 in. (13 mm) is standard, where corrugations are measured from crest to crest (pitch) and valley to crest (depth). The embedded precast column surface is required to be intentionally roughened for ensuring adequate shear transfer between concrete and grout that are cast separately.[7] Different practical methods such as sandblasting, formwork retarder, and bush-hammering can be used for achieving the desired surface roughness. Form liners can also be used if regularized patterns such as fluted fins or saw-tooth shapes are preferred. Sufficient clearances must be provided in the socket to account for cumulative effects of all allowable tolerances. For inserting precast columns, a minimum clearance of 1 in. (25 mm) is required around the perimeter between the column and the socket.[8] The clearance is also determined by the available size of CSP. For typical bridge columns, the standard CSPs result in a clearance of 1.5 in. (38 mm) for columns smaller than or equal to 2 ft (0.6 m) and a clearance of 3 in. (76 mm) for larger columns. Among the aforementioned connection parameters, the grout strength and CSP corrugation pattern are relatively constant in practice. Hence, the socket connection tests were conducted on eight specimens with standard CSPs, concrete and grout with typical strength, varied column surface roughness, and different column-to-CSP clearance. As summarized in **Table 1**, the column surface roughness included smooth surface with no treatment, exposed aggregate finish using formwork retarder, and 1/2 in. (13 mm) and 3/4 in. (19 mm) trapezoidal shaped fluted fines made using form liners. With the 1/2 in. (13 mm) and 3/4 in. (19 mm) fluted fins, the specified dimensions represented the depth of the fin, while the pitch measured from fin to fin was 1-1/2 in. (38 mm) and 2 in. (51 mm), respectively. Based on the most possible cases, two column-to-CSP clearances of 1.5 in. (38 mm) and 3 in. (76 mm) were tested. In addition, the type of loading was also used as a variable. The first four specimens were tested using monotonic loading, whereas the rests were subjected to cyclic loading. The cyclic loading consisted of two phases: one force cycle per step at 40 kips (178 kN) increment, followed by displacement controlled cycles with three cycles per step.

Table 1. Test matrix used for socket connection tests

Specimen	Measured column concrete strength (psi)	Measured footing concrete strength (psi)	Measured Grout strength (psi)	Column surface roughness	Column-to-CSP clearance (in.)	Loading type
F1G1M	5362	5362	8062	1/2 in. fluted fin	1.5	monotonic
F2G1M	5362	5362	8150	3/4 in. fluted fin	1.5	monotonic
EG1M	5362	5362	8084	exposed aggregate	1.5	monotonic
F2G2M	5362	5362	8203	3/4 in. fluted fin	3	monotonic

EG1C	5715	5362	7904	exposed aggregate	1.5	cyclic
F1G1C	5715	5362	8035	1/2 in. fluted fin	1.5	cyclic
SG1C	5715	5362	8172	smooth	1.5	cyclic
F1G2C	5715	5362	8172	1/2 in. fluted fin	3	cyclic
Note: 1 psi = 6.895 kPa; 1 in. = 25 mm.						

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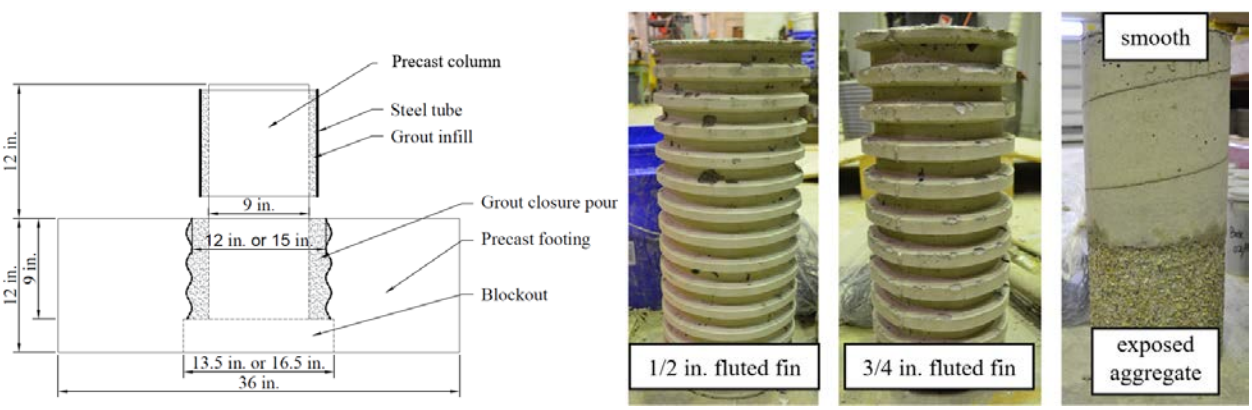
Test specimens and setup

Each test specimen, as shown in **Figure 4**, consisted of a precast footing and a short precast column. In the footings, the 12 in. (305 mm) and 15 in. (381 mm) diameter CSPs with the standard corrugation pattern of 2-2/3 in. (67 mm) × 1/2 in. (13 mm) were used to create 1.5 in. (38 mm) and 3 in. (76 mm) column-to-CSP clearances for grouting. An oversize blockout was formed under the socket in each footing to eliminate the column from bearing on the foundation. The columns were constructed with four different surface roughness as shown in Figure 4. After inserting the column into the reserved socket, the connection for each specimen was established by placing grout. After reviewing specifications of several non-shrink commercially available grouts[6], one particular type was chosen due to its desirable properties such as high-early-strength, fluid consistency, extended working time, and a specified compressive strength of 8500 psi (58.6 MPa) at 28 days. To prevent the columns above the footing from experiencing damage due to compression failure, they were confined by a steel tube with grout infill. A gap was left between the confinement steel tube and the top of footing so that the tube would not establish contact with the footing during testing.



Dimensions of specimens Different column surface roughness

Figure 4. Test specimens. Note: 1in. = 25 mm.

The testing setup used for the investigation is shown in **Figure 5**. The specimen was positioned on two based blocks in order to access the bottom of the column for instrumentation purposes. Using a hydraulic actuator that was attached to a reaction frame, the vertical downward forces were applied on the top of the column until a sliding failure was observed.

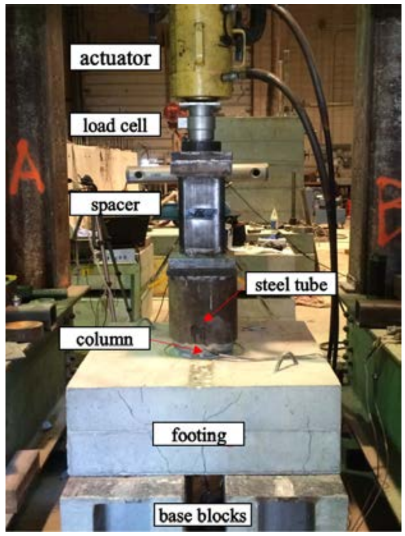


Figure 5. Setup used for socket connection tests

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Test results

Figure 6 depicts the applied vertical force versus the relative displacement between the column and the footing (CF displacement), which represent the overall response of each specimen. During the tests, each specimen began to resist load in an elastic manner, reached its maximum resistance with some nonlinearity associated with the response, and then exhibited considerable ductility beyond the peak strength. Following the peak, some soften in the response was observed. Each connection produced a minimum resistance of 264 kips (1174 kN), except for the smooth column surface which failed at 161 kips (716 kN) and exhibited limited ductility. In bridge columns, it can be conservatively assumed that axial load ratio will not exceed 0.3. For this level axial load, given that 264 kips (1174 kN) corresponded to 0.75 $A_g f_c'$ (where A_g is column gross area and f_c' is measured column concrete 28-day compressive strength), the socket connections with roughened column surface would ensure an elastic response without exhibiting any distress.

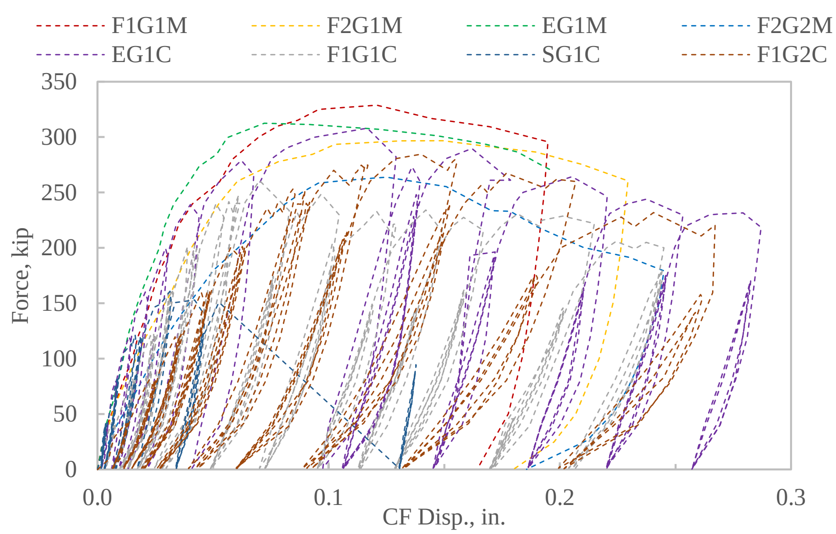


Figure 6. Applied axial force versus CF displacement response. Note: 1 kips= 4.4 kN; 1in. = 25 mm.

As seen in Figure 6, the columns with roughened surface provided adequate side shear strength, but the specimens exhibited different force-CF displacement responses. The CF displacements consisted of the sliding at the column-to-grout interface (CG displacement), the sliding at the grout-to-footing interface (GF displacement), and the deformation within the grout itself (Δ_{grout}) especially when 3 in. (76 mm) thick grout closure pour was included (**Figure 7**). **Figure 8** describes the connection responses in term of each component. To reveal the contribution of each component, the plots were created with the same scale for the axes. All specimens exhibited comparable GF displacement responses before reaching the peak strength. Hence, the differences in overall connection responses were the result of CG displacement and Δ_{grout}. The plot in Figure 8 compares the forces versus CG displacement for the specimens with same column-to-CSP clearance of 1.5 in. (38 mm), but with different column surface roughness. This plot confirms that the adequate roughness was necessary to adequately develop the side shear strength between column and grout. However, the deeper amplitude of 1/2 in. (13 mm) and 3/4 in. (19 mm) could soften the force-CG displacement response. Comparing the force versus CG displacement responses for specimen F1G1C and F1G2C, which had the same column surface roughness but different column-to-CSP clearance, the two specimens exhibited the same responses at the column-to-grout interface, but specimen F1G2C showed a softer overall connection response than specimen F1G1C as seen in Figure 6. Therefore, the thicker grout closure pour in wider column-to-CSP clearance that induced significant Δ_{grout} was proven to soften the connection responses. With reference to the loading type, the plot in Figure 8 presents a comparison of the specimen responses with the same connection parameters but different load types (i.e., monotonic vs. cyclic). For the specimens with exposed aggregate finish, no cumulative damage was caused by the cyclic loading until reaching approximately 50% of the peak strength. However, the cyclic loading caused significant strength degradation for the specimens consisting of the columns with 1/2 in. (13 mm) fluted fins.

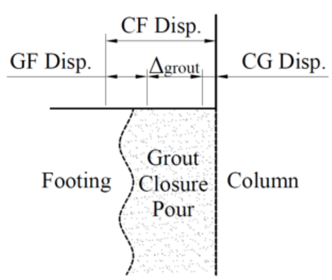
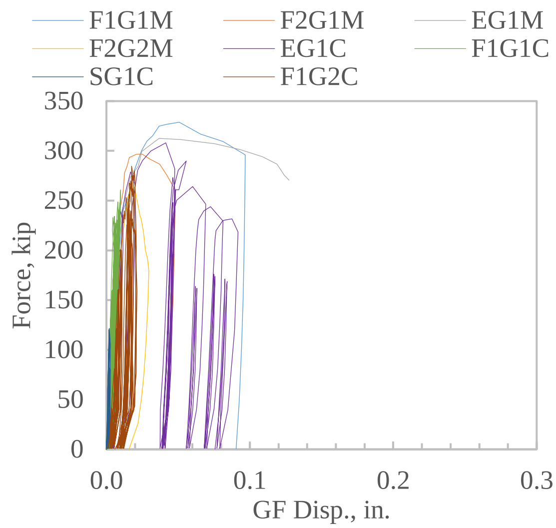
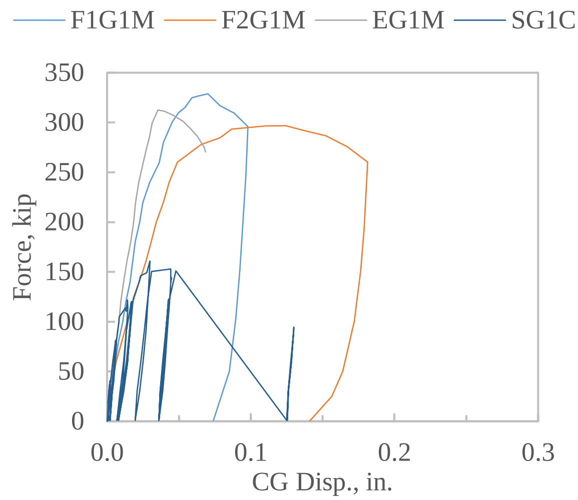


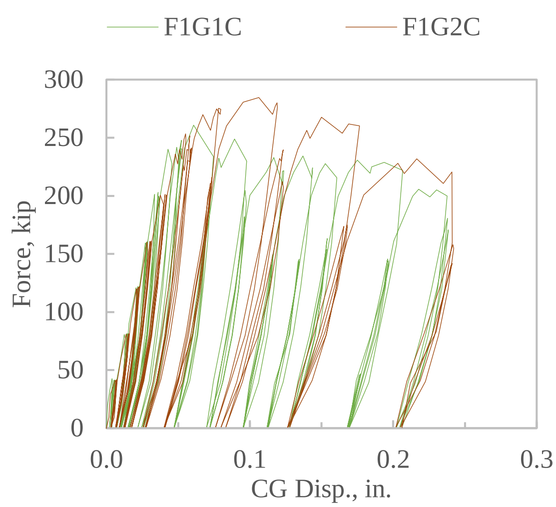
Figure 7. Displacements occurred in the socket connection



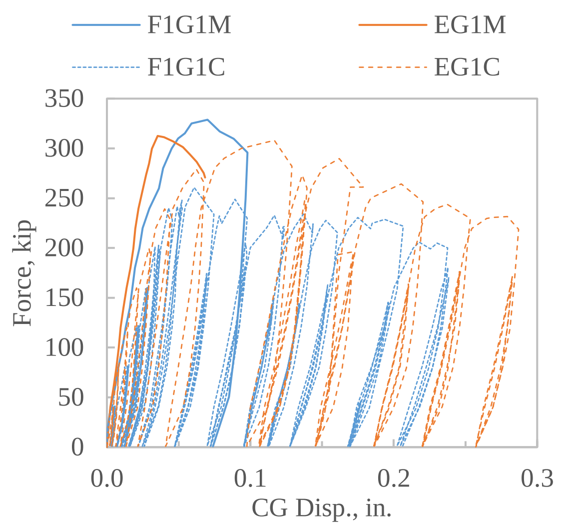
Force-GF displacement responses



Impact of different column surface roughness



CG displacement responses for the specimens with different grout thickness



Impact of cyclic loading

Figure 8. Connection responses in term of components

The performances of the specimens were characterized through the force-displacement relationships. The specimens consisting of the columns with deeper amplitudes for the surface roughness (i.e. fluted fins) exhibited softer force-displacement relationships compared to the one with exposed aggregate finish. The thicker grout closure pour due to wider column-to-CSP clearance also reduced the stiffness of the connection. These softening was attributed to relatively larger deformations occurring at the column-to-grout interface and within the grout itself, which were caused by the properties of grout. When experiencing the applied load, the grout exhibited relatively more flexibility than normal concrete due to the lack of hard coarse aggregates and lower modulus. Because of more participation of grout, the specimen with fluted fins showed softer response at the column-to-grout interface than that with exposed aggregate finish. Similarly, thicker grout closure pour led to relatively larger deformations. The cyclic loading had more effect on the specimens with column surface roughness of deeper amplitude. For the specimen with exposed aggregate column surface, cyclic loading exhibited no effect on the connection response when the applied forces were less than 50% of the peak strength.

Based on the experimental findings of the socket connection tests, the following guidelines have been formulated for the design of socket connection in sustaining axial loads. Considering both the structural performance and constructability, the embedded portion of the column may be adequately prepared with exposed aggregate finish, which can be easily accomplished using formwork retarder. Both 1.5 in. (38 mm) and 3 in. (76 mm) clearance between the column and the CSP ensure that the socket connection sustains vertical loads for routine bridge design, but 3 in. (76 mm) column-to-CSP clearance that caused thicker grout closure pour reduced the stiffness of the socket connection. Therefore, a 1.5 in. (38 mm) clearance or relatively smaller clearance than 3 in. (76 mm) is preferred. Assuming that the shear transfer occurred uniformly along the embedded column, for the column surface of exposed aggregate finish, the stresses for the column-to-grout interface and grout-to-footing interface may be limited to be less than 1.0 ksi (6.9 MPa) and 0.7 ksi (4.8 MPa), respectively. Conservatively, these stress limitations were determined using the lowest axial load of 264 kips (1174 kN). The stress limitations suggested above should be reduced by 50% when the column is expected to sustain cyclic loading of significant amplitudes to minimize any damage accumulation.

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System Test

After success of the socket connection tests, a system test is being conducted to investigate the performance of the entire precast substructure system. Considering the effect of soil-foundation-structure interaction, the test unit with driven pile foundation will be constructed and tested at an outdoor location.

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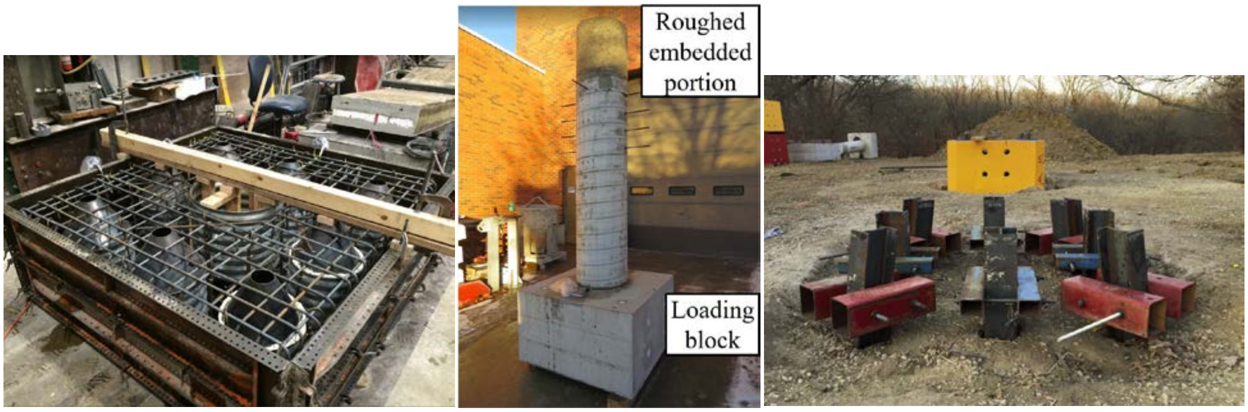
Test unit

A half-scale test unit was constructed to represent the frame pier foundation in a typical pretensioned prestressed concrete beam (PPCB) bridge. The test unit consisted a 6 ft (1.8 m) × 6 ft (1.8 m) × 2 ft (0.6 m) precast pile cap with reserved sockets and a 1.5 ft (0.5 m) diameter precast column, along with eight steel driven piles. The sockets for the column and piles were preformed with a 21 in. (533 mm) diameter CSP and eight 15 in. (381 mm) diameter CSPs, respectively. The column socket was constructed as a partially penetrated socket with the depth of 19 in. (483 mm). In the pile sockets, the custom steel pipe diameter reducers were installed to make a cone shape for the upper portion of these sockets, as shown in **Figure 9**. To verify the construction option of reusing these reducers, three of the eight cones were manufactured with the diameter smaller than the pipes. Thus, after concrete was cured, the reducers can be taken out through the pipes for reuse. The height of the precast column was decided to be 6 ft (1.8 m), which resulted in a flexure-critical column with a height-to-depth ratio of 4. The transverse reinforcement that was arranged following the guidelines for column confinement[3] was extended to the portion of the column that would be inserted into the socket. The column embedded length into the socket was chosen to be 1.5 ft. (0.5 m), which was equivalent to the diameter of the column. The surface of the embedded portion was treated to be exposed aggregate finish using formwork retarder. For applying the combination of vertical and lateral loads, a loading block was added to the top of the column. The column has been constructed upside down, as show in Figure 9. The driven piles were scaled to W6×20 sections in the test unit. Using a template as a pattern, the total of eight 50 ft (15.2 m) piles were driven, in which the four piles at the corners were battered at a 1 horizontal to 6 vertical slope. After the pile installation, the friction collars were affixed around each piles (Figure 9). The piles will be embedded 9 in. (229 mm) into the pile sockets, which represents the embedment length of 18 in. (483 mm) in the prototype substructure as per current practices.



Pile cap before concrete pour | Precast column with loading block | Friction collars affixed on piles

Figure 9. Test unit

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Load protocol

The system test will consist of three phases. Phase I will be conducted to verify the strength of the system at the strength limit states. A combination of vertical and lateral loads will be applied on the top of the column. After the first phase of the test, the test unit will be subjected to a constant vertical load that will correspond to 15% of the column axial load capacity and force-controlled cyclic lateral loads. Once the test unit exhibits nonlinearity associated with the response, displacement-controlled cyclic loading will be used until fully developing a plastic hinge at the column base adjacent to the pile cap. According to the analysis performed on a grillage finite element model, when the column plastic hinge forms, the lateral displacement of pile cap will approximately be 1/4 in. (6 mm), and the pile socket connections will experience relatively small bending moments. To fully test the connections and investigate the soil-foundation-structure interaction, the Phase III will be conducted by applying the lateral loads to the pile cap directly. Eight large diameter headed bars were partially embedded in the pile cap. A CIP loading block will be constructed encasing the column base and the extended headed bars for attaching the actuator as shown in **Figure 10**. Thus, Phase III of the test can be performed until failure occurred in foundation and/or soil.

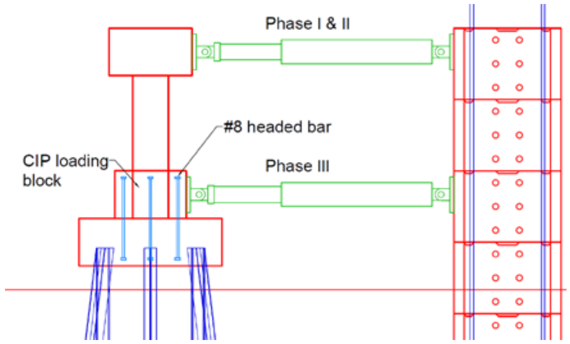

Figure 10. Location of lateral actuator for system test

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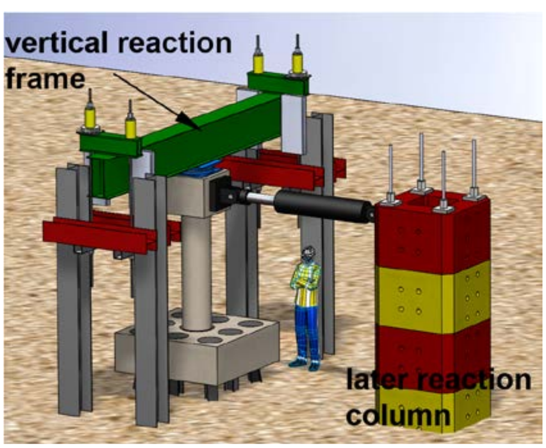
Test setup

To conduct all phases of the system test, a vertical reaction frame and a lateral reaction column were constructed as shown in **Figure 11**. The vertical reaction frame consists of four HP14x73 anchor piles that are driven 50 ft (15.2 m) into the ground. A main reaction beam, which is shown as the green beam in Figure 10, will be attached to the anchor piles through clamping beams and steel rods. Through the main reaction beam, four hydraulic jacks will be used to apply the downward vertical loads to the test unit. A single concave slider will be installed on the top loading block to isolate translation and rotation, while transmitting loads from the main reaction beam to the top of column, and thus the vertical loads can be applied stably when the column drifts under lateral loads. The lateral reaction column is constructed by post-tensioning precast hollow segments on a 45 ft (13.7 m) deep, 6 ft (1.8 m) diameter drilled shaft foundation. As shown in Figure 11, four vertical holes were reserved at the corners of precast segments. Hence, the 1-3/4 in. (44 mm) diameter post-tensioning bars will be placed through the vertical holes, and connected with the bars that were anchored into the drilled shaft for post-tensioning. Each segment has the preformed hole pattern on sides such that the actuator can be attached at various height during different phases of the test.



A schematic testing setup

Precast segments for lateral reaction column

Figure 11. Test setup

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Conclusions

In recent years, there has been interested in using prefabricated elements for entire bridge substructure for accelerating bridge construction. The socket connection that is preformed using standard CSP has been identified as a viable means to construct precast bridge substructure. Thus, to investigate the overall performance of the system as well as the connection behavior, the experimental investigations were conducted on a precast bridge substructure system. The socket connection tests have been conducted to evaluate the side shear behavior in proposed column socket connection and optimize the connection design. A test unit for the system test is being constructed and will be tested at an outdoor location. Based on the completed tasks of the project, the following conclusions can be drawn:

- The precast bridge substructure system with socket connections provides the potentials to significantly reduce the construction time while offering larger construction tolerances than other methods that are developed for precast bridge substructure.
- All specimens of the socket connection tests, except the one with smooth column surface, reached the peak strengths that were equivalent to axial load ratio above 0.75. Hence, the socket connections with roughened column surface would provide satisfactory connection to sustain vertical loads used in routine design practice.
- The connection consisting of the columns with deeper amplitudes for the surface roughness (i.e., fluted fins) exhibited softer connection response compared to the one with exposed aggregate surface. The thicker grout closure pour also reduced the stiffness of the socket connection. Therefore, the column surface with exposed aggregate finish and 1.5 in. (38 mm) clearance or relatively smaller clearance than 3 in. (76 mm) is recommended for the design of the column socket connection.

In addition to the above findings, the presentation will also update the results from the system test.

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Notation

P_s = side shear acting along the embedded column

P_b = tipping at the base of the column

A_g = column gross area

f_c' = measured column concrete 28-day compressive strength

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Abstract

In recent years, there has been interest in using prefabricated elements for entire bridge substructure for accelerating bridge construction. The socket connection that is preformed using standard corrugated steel pipe (CSP) has been identified as a viable means to construct precast bridge substructure. Thus, a new precast bridge substructure with driven pile foundation is established using socket connections. To construct this substructure system, the sockets are preformed on the precast pile cap with CSPs. After inserting the precast column and piles into these sockets, the substructure is completed by filling the sockets with grout and self-consolidating concrete, respectively. This paper presents the experimental investigation on the development of precast bridge substructure system.

Keywords

Bridge, precast, substructure, socket connection, experimental test.

Figure captions

Figure 12. Precast pile cap with reserved sockets

Figure 13. Construction of precast bridge substructure system

Figure 14. Axial strength of column socket connection

Figure 15. Test specimens. Note: 1in. = 25 mm.

Figure 16. Setup used for socket connection tests

Figure 17. Applied axial force versus CF displacement response. Note: 1 kips= 4.4 kN; 1in. = 25 mm.

Figure 18. Displacements occurred in the socket connection

Figure 19. Connection responses in term of components

Figure 20. Test unit

Figure 21. Location of lateral actuator for system test

Figure 22. Test setup