Side Shear Strength of Preformed Socket Connections Suitable for Vertical Precast Members

Zhao Cheng
Iowa State University, zcheng@iastate.edu

Sri Sritharan
Iowa State University, sri@iastate.edu

Follow this and additional works at: https://lib.dr.iastate.edu/ccce_pubs

Part of the Geotechnical Engineering Commons, and the Structural Engineering Commons

The complete bibliographic information for this item can be found at https://lib.dr.iastate.edu/ccce_pubs/216. For information on how to cite this item, please visit http://lib.dr.iastate.edu/howtocite.html.
Side Shear Strength of Preformed Socket Connections Suitable for Vertical Precast Members

Abstract
Use of precast substructure in accelerated bridge construction (ABC) has been gaining popularity due to its advantages over traditional cast-in-place (CIP) construction. When using vertical precast members (e.g., columns and piles) in bridge substructure construction, they must be connected to the adjoining members (e.g., bent cap, pile cap, and abutment) reliably. To accomplish this goal and promote ease of construction, the preformed socket connection has been suggested. This connection is established by inserting the vertical precast member inside a preformed socket in the precast adjoining member and filling the socket with non-shrink, high-strength grout. Using specimens that modeled the full-scaled connection interfaces, this paper experimentally evaluates the side shear strength of preformed socket connections with various connection parameters. Test results show that side shear mechanism in the preformed socket connections can provide significant resistance, facilitating transfer of large vertical loads. This paper also includes recommendations for the socket connections and appropriate stress limits.

Keywords
Connections (structural), Infrastructure construction, Piles, Structural strength, Bridge abutments, Bridge columns, Shear strength, Load tests

Disciplines
Geotechnical Engineering | Structural Engineering

Comments
This is a manuscript of an article published as Cheng, Zhao, and Sri Sritharan. “Side Shear Strength of Preformed Socket Connections Suitable for Vertical Precast Members.” Journal of Bridge Engineering 24, no. 5 (2019): 04019025. This material may be found at DOI: 10.1061/(ASCE)BE.1943-5592.0001391. Posted with permission.

Rights
This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers.
Side Shear Strength of Preformed Socket Connections Suitable for Vertical Precast Members

Zhao Cheng, S.M.ASCE\textsuperscript{1} and Sri Sritharan, Ph.D., M.ASCE\textsuperscript{2}

\textsuperscript{1}Graduate Research Assistant, Dept. of Civil, Construction, and Environmental Engineering, Iowa State Univ., Ames, IA 50011. E-mail: zcheng@iastate.edu

\textsuperscript{2}Wilkinson Chair of Interdisciplinary Engineering, Dept. of Civil, Construction, and Environmental Engineering, Iowa State Univ., Ames, IA 50011 (corresponding author). E-mail: sri@iastate.edu

ABSTRACT

Use of precast substructure in Accelerated Bridge Construction (ABC) has been gaining popularity due to its advantages over traditional cast-in-place (CIP) construction. When using vertical precast members (e.g., columns and piles) in bridge substructure construction, they must be connected to the adjoining members (e.g., bent cap, pile cap, and abutment) reliably. To accomplish this goal and promote ease of construction, the preformed socket connection has been suggested. This connection is established by inserting the vertical precast member inside a preformed socket in the precast adjoining member and filling the socket with non-shrink, high-strength grout. Using specimens that modeled the full-scaled connection interfaces, this paper experimentally evaluates the side shear strength of preformed socket connections with various connection parameters. Test results show that side shear mechanism in the preformed socket connections can provide significant resistance, facilitating transfer of large vertical loads. This paper also includes recommendations for the socket connections and appropriate stress limits.
Keywords: Accelerated bridge construction; Socket connection; Precast; Vertical member; Pile; Column; Design; Testing.

INTRODUCTION

Accelerated bridge construction (ABC) uses innovative techniques to complete bridge projects in a timely and cost-effective manner. Besides reducing mobility impacts, a number of successful projects have demonstrated that ABC can improve quality of construction, reduce onsite construction, and minimize environmental impacts. Use of Prefabricated Bridge Elements and Systems (PBES) in construction is a common strategy adopted in ABC. Although PBSE has been used in bridge superstructure construction for decades, their use in substructures have been very limited. In recent projects, the Department of Transportations in various states have utilized precast components in the construction of bridge substructures (e.g., bent cap, abutment, pile cap, column, and pile). Use of precast components in substructure is attractive because they can eliminate on-site forming and casting while overcoming challenges associated with the site constraints. When using vertical precast members, they need to be designed with reliable connections to the adjoining members (e.g., column-to-bent cap, column-to-pile cap, pile-to-pile cap, and pile-to-abutment connections). These connections should not only be easy to construct, but also produce dependable structural performance when subjected to the expected serviceability and ultimate loads.

Commercially available grouted splice couplers have been used to establish the connection between precast columns and adjoining elements. Other techniques, involving mechanical bar couplers, grouted ducts, a pocket for embedding reinforcing bars extended from precast member, and a socket for embedding the end of a precast member, and unbonded prestressing tendon, have also shown to be practical either through laboratory evaluation or field applications (Marsh et al. 2011; Culmo 2009). The focus of this study is on socket connections due to the ease of construction
and the ability to provide relatively large installation tolerances, with emphasis on transferring high vertical loads through the connection.

Socket connections for vertical precast members can be constructed using two options: (1) cast adjoining member around the end of the vertical member, or (2) insert the end of vertical member into the preformed socket in the adjoining member and secure the socket using grout closure pour. For the second approach, the preformed socket in the adjoining member can be accomplished using commercially available corrugated steel pipe (CSP) due to its low cost and ready availability in different sizes. In addition to serving as stay-in-place formwork, CSP offers confinement effect to the connection material while its corrugations provide a robust load transfer mechanism (UDOT 2017). The preformed socket, which promotes the use of prefabricated elements for the adjoining members, can be constructed with full or partial penetration (Fig. 1).

With any construction option, when the vertical precast member is subjected to the design loads, the socket connection should facilitate the transfer of the loads without sustaining any significant sliding. As illustrated in Fig. 1a, the axial strength of fully penetrated connection depends only on the side shear resistance acting along the embedded portion of the vertical member. For a partially penetrated connection (Fig. 1b), the axial load resistance can be provided by side shear and tipping at the end of vertical member. While relying on both side shear and tipping can be attractive to reduce the required embedment length of the vertical member, this option is not favored herein. This is because the design of such a connection is more challenging due to: (a) the side shear and tipping mechanisms being unlikely to be active simultaneously; and (b) sustaining a tipping mechanism would require design to prevent punching failure caused by the precast vertical member. Given that sufficient axial resistance can be developed over a short embedment length, it
is suggested that both fully and partially penetrated connections be designed relying only on side shear.

The side shear strength in a socket connection depends on how the connection is established. The connections with cast-in-place adjoining members exhibited high side shear strength in an experimental study. Haraldsson et al. (2013), who tested the connections constructed by casting spread footings around precast columns. The specimen with an intentionally roughened column surface and a column embedment length of 1.1 times the column diameter of 508-mm (20-in.) subjected to the high axial load. The corresponding axial load ratio was 58% based on the specified properties, but the connection was not failed using a high axial load ratio.

Several experimental studies have also utilized preformed sockets connections for seismic bridge columns, which were designed to form plastic hinges at the member ends, thereby contributing to energy dissipation under seismic load. To ensure sufficient column ductility, seismic columns are typically designed with a low axial load ratio (e.g., 5 to 10%). Motaref et al. (2011) and Kavianipour et al. (2013), who tested bridge piers with socket connections between a precast column and the precast footing with an embedment length of 1.5 times the column diameter of 370-mm (14.57-in.). The tests showed successful development of plastic hinges with an axial load ratio of 6.3% and 8.8%, respectively. Mehrsorough and Saiidi (2016) tested a scaled bridge pier having preformed socket connections in a bent cap. The corrugated steel pipes (CSPs) were used to create the sockets and the column embedment length was 1.2 times column diameter of 508-mm (20-in.). This test, which induced a maximum axial load ratio of 5.6%, also showed that the column embedment length into the socket was adequate to fully develop the column plastic hinge. Mohebbi et al. (2017) performed an experimental test on a preformed socket connection with a square column. In this test, with an axial load ratio of 14.4%, the column embedment length
of only 1.0 times the column side dimension of 356-mm (14-in.) was used and a full column plastic hinge was successfully formed.

In all of the aforementioned studies with a relatively low axial load ratio, the preformed socket connection remained essentially undamaged while the plastic hinge formed in the column just outside the connection. However, these results cannot be applicable to vertical members subjected to high axial load ratios. Precast piles in seismic and non-seismic regions can be designed to sustain as much as 40% of the axial load capacity while bridge columns in non-seismic regions can be subjected to 25 to 30% of the axial load capacity. In addition, for preformed socket connections that are established using CSP and grout closure pour, no guideline is available to help determining the key connection parameters and side shear strength for design due to lack of investigation that examined the failure modes of socket connections. To address this knowledge gap, an experimental study was conducted to investigate the failure modes of side shear mechanism in preformed socket connections so that the suitable vertical precast members can be designed to transfer large axial load through socket connections. This paper presents the description of the experimental program, test results, and recommendations established from this study.

PARAMETERS AFFECTING SIDE SHEAR STRENGTH

When a preformed socket is established using CSP and the connection is established using grout, the side shear strength will depend on a number of interface parameters. The parameters that most influence the strength include: (1) corrugation pattern of CSP, (2) surface texture along the embedded length of the precast member, (3) clearance between CSP and the embedded member, and (4) the strength and type of grout used for closure pour. More details about each parameter are presented below.
1. A key feature of CSP is its corrugation, which provides additional load transfer capacity. The corrugation types of standard CSPs include annular corrugation and helical corrugation. To make structural connections with CSP, UDOT (2017) recommends annular corrugation over helical corrugation, because helical corrugation is made to intentionally reduce the roughness to improve flow of substance through the pipe. The corrugation pattern in commercially available CSP varies with the pipe size. A pattern with 68-mm (2.67-in.) pitch and 13-mm (0.50-in.) depth is standard for CSPs with inside diameters ranging from 0.30-m (1-ft) to 2.13-m (7-ft), which are suitable for ABC applications.

2. Bond strength between the grout closure pour and the embedded member is another important property as shear sliding failure can trigger at the interface between them. The primary variable that controls the bond strength is surface texture of the embedded member. Smooth surface with no treatment will have lower bond strength, increasing the likelihood of shear sliding at this interface. To ensure adequate shear transfer, AASHTO (2017) suggests intentionally roughening the surface of embedded member to an amplitude of approximately 6-mm (0.25-in.). Exposed aggregate finish is a popular texture for achieving the desired degree of roughness; regularized patterns with deeper amplitude (e.g., fluted fins and saw-tooth pattern) have also been commonly used. Different practical methods such as chemical formwork retarder, sandblasting, and bush hammering can be used to expose coarse aggregate. Note that the mechanical methods (i.e., sandblasting and bush hammering) may soften the exposed aggregate (PCI 2007), which will degrade the bond strength at the interface. The regularized patterns can be
achieved by casting concrete against formliners that are attached to the inside surface of the formwork.

3. The preformed socket connection is secured by filling the clearance between the CSP and embedded member with grout. The thickness of grout closure pour that corresponds to CSP-to-embedded member clearance may affect the transfer of side shear. Sufficient clearance must be provided to conduct grout closure pour and to account for the cumulative effects of all allowed tolerances. For inserting a vertical precast member, a minimum clearance of 25-mm (1-in.) is required around the perimeter between the embedded member and the socket (PCI 2000). This clearance is also controlled by the available sizes of CSP. Considering the available formwork and the weight limits for transportation, the diameter or side dimension of most bridge vertical precast members are fabricated at 0.15-m (0.5-ft) intervals of up to 1.22-m (4-ft). Table 1 presents the inside diameters of the appropriate commercially available CSPs and the resultant CSP-to-embedded member clearances expected for the bridge precast columns and piles. Note that the clearance herein represents the minimum distance between the crest of inside corrugation of the CSP and the most outer surface of the embedded member. As can be seen in the table, the clearances of 38-mm (1.5-in.) and 76-mm (3-in.) are two likely construction clearances in the preformed socket connections for bridge vertical members.

4. For the purpose of establishing a strong socket connection, high-strength grout with the minimum compressive strength of 55.2-MPa (8000-psi) is preferred because the concrete strength of the precast member may be in the range of 34.5 to 48.3-MPa (5000 to 7000-psi). Other desirable properties, such as high-early-strength, fluid consistency, extended working time, and non-shrink, are also required to properly secure the socket connection.
High-early-strength (i.e., a compressive strength not less than 27.6-MPa [4000-psi] at 1 day) would facilitate the connection to gain strength quickly, such that curing of grout will not cause any construction delays. The extended working time and fluid consistency provide the possibility to complete large grout pour into tight clearance between the CSP and the embedded member. Non-shrink feature of the grout will minimize formation of cracks at the interfaces or within the grout itself, which are important for durability of the connection. A scanning of commercial available cementitious grouts has been conducted, and the findings indicated that only limited type of grouts meet all the preceding requirements (Sritharan and Cheng 2016).

Based on the above descriptions, it is apparent that once a specific grout meeting the desirable characteristics and commercially available standard CSPs are chosen, the side shear strength of a preformed socket connection will be determined by the surface texture of the embedded member and CSP-to-embedded member clearance. Therefore, the experimental investigation was conducted with these two variables.

**EXPERIMENTAL PROGRAM**

**Testing Matrix**

A total of eight specimens were constructed to evaluate the side shear strength in preformed socket connection with different surface texture for the embedded portion of the vertical member and CSP-to-embedded member clearance, as detailed in Table 2. Three types of surface textures, including exposed aggregate finish, 13-mm (0.5-in.) deep fluted fins, 19-mm (0.75-in.) deep fluted fins, were tested as they are likely to be used for vertical precast members. For the fluted fin patterns, the fins are routinely made in trapezoid shape, and the fin-to-fin pitches of 38-mm (1.5-in.) and 51-mm (2-in.) are standard for the 13-mm (0.5-in.) and 19-mm (0.75-in.) fin depths,
respectively. As a reference unit, a smooth surface specimen was also tested. Two CSP-to-embedded member clearance of 38-mm (1.5-in.) and 76-mm (3-in.) were chosen to be tested. To investigate the influence of loading type, the first four specimens were tested using monotonic loading, whereas the remaining four were subjected to cyclic loading.

**Details of Test Specimens**

The test specimens were designed to reproduce the interface as expected in full-sized preformed socket connections, but the area of the interface region was reduced by utilizing the small-sized embedded members to keep the applied vertical load to be less than 1779-kN (400-kips). Each test specimen consisted of a short precast column segment that was embedded in a preformed socket on a precast foundation representing the adjoining member, as shown in Fig. 2a. When a compressive force is applied to the top of the column segment, the side shear acting on the connection interface produced the resistance. Hence, the side shear strength could be evaluated by loading the column segment until it experiences a sliding failure with respect to the foundation. An oversized cavity, as illustrated in Fig. 2b, was formed under the socket in each foundation to allow the column segment to be pushed out freely when the side shear mechanism fails. The reinforcement of the specimens is shown in Fig. 2c. The concrete strength of the column segments and the foundations were kept to that expected for precast products. The measured 28-day compressive strength of these members was 36.97-MPa (5362 psi), following the ASTM C39 (2017).

During construction of the precast column segments, the surface textures were formed as they are on full-sized precast members. The exposed aggregate finish was achieved by applying chemical retarder to the formwork prior to casting the concrete, followed by power-washing the laitance after hardening of the concrete mass. The fluted fines were created by casting concrete
against the polystyrene formliners that were installed inside the formwork. For obtaining the smooth surface, the formwork was used without any treatment. The completed surface textures are shown in Fig. 2d.

The socket connection length was chosen to be 229-mm (9-in.), which was equal to the outer diameter of the column segment. After temporarily supporting the column segments in the sockets that was preformed using CSPs, the connections were established by placing grout in the gaps between CSP and the column segments. The 0.30-m (12-in.) and 0.38-m (15-in.) diameter CSPs with standard corrugation pattern of 68-mm by 13-mm (2.67-in. by 0.50-in.) were used. These CSPs reserved 38-mm (1.5-in.) and 76-mm (3-in.) clearances, respectively, which are two clearances in expected between substructure vertical members and preformed socket connections at full scale. Referring to the specifications for the culvert pipe (AASHTO 2017), the CSPs used for creating preformed sockets met the requirements of AASHTO M 218 (2016). The thickness of CSPs was selected to be 1.63-mm (16 gage), which corresponds to the thickest standard CSP and thus is most likely to be used in practice. Having considered different grouts, one was chosen for securing connections in this study. The selected grout has a specified compressive strength of 27.58-MPa (4000-psi) in 8 hours and a specified compressive strength of 58.61-MPa (8500-psi) at 28 days. It also met the other requirements for closure pour such as fluid consistency, extended working time, and non-shrink characteristic. To prevent the column segments above the foundation from experiencing damage due to high axial compression, they were confined by steel tubes. A 51-mm (2-in.) gap was left between the steel tube and the top of foundation so that the tube will not establish any contact with the top of the foundation block during testing. This approach allowed the axial loads on the column segments to be increased, forcing failure in the connection.
Test Setup and Load Protocol

Fig. 3a shows the test setup that was used for the experimental investigation. The specimen was supported on two base blocks in order to access the bottom of the column segment for instrumentation purpose. Using a hydraulic jack that was powered by an electric hydraulic pump, vertical downward forces were applied on the top of the column segment.

A load cell was placed between the jack and the column segment for measuring the applied force. As shown in Fig. 3b, three sets of the displacement transducers were mounted around the column segment. In each set, the transducers were positioned between the column segment and the foundation to monitor the movement of the column segment and grout with respect to the foundation. In this regard, the relative displacement between the column segment and the foundation (CF displacement), the relative displacement between the column segment and the grout closure pour (CG displacement), and the relative displacement between the grout closure pour and the foundation (GF displacement) were quantified. Note that, for the specimens with 76-mm (3-in.) CSP-to-column segment clearance, two transducers were mounted to measure the vertical deformation of grout ($\Delta_{\text{grout}}$). In addition to external instrumentations, the strain gauges were mounted along one longitudinal reinforcing bar in each embedded column segment for capturing force transfer in the connection region.

The specimens were tested by applying uniaxial compression force to the top of the column segment. For the specimen F1G1M, F2G1M, EG1M, and F2G2M, the loads were applied in a monotonically increasing manner. After the column segment began to slide with respect to the foundation, the displacement was used to control the test until the measured relative vertical displacement between the column segment and the foundation reached a value of at least 5.0-mm (0.195-in.). The remaining four specimens were subjected to a cyclic loading sequence consisted
of a force-controlled phase and a displacement-controlled phase. The force-controlled phase was used until it reached 1068-kN (240-kips) at a load step of 178-kN (40-kips). In the displacement-controlled phase, the measured relative displacement between the column segment and the foundation was used as the controlling parameter. The target displacements for this phase were multiples of the relative displacement obtained for the last force-controlled load step. Due to a defect in the load control device, the applied displacements did not exactly reach the targeted values. In cyclic loading sequence, each load step was followed by unloading from a compression to zero force, and reapplying the same displacement two more times.

**EXPERIMENTAL RESULTS**

During the tests, each specimen began to resist loads in an elastic manner, reached its maximum resistance with some nonlinearity associated with its response, and then exhibited considerable ductility beyond the peak strength. Following the peak strength, some softening in the response was observed.

**Failure Modes**

Regardless of whether monotonic or cyclic was used, the specimens exhibited two failure modes as shown in Fig. 4. For the specimens with smooth surface and those with texture of 19-mm (0.75-in.) fluted fins, the sliding failure occurred at the column segment-to-grout interface, whereas the sliding eventually occurred at the CSP-to-foundation interface for the specimens with exposed aggregate finish and 13-mm (0.5-in.) fluted fins. In case of the specimens with 19-mm (0.75-in.) fluted fins, the failure was due to shearing off the concrete fins. When the failure was at the CSP-to-foundation interface, the sliding of CSP occurred with respect to the surrounding concrete in the foundation, implying shearing in concrete of the foundation.
Measured Responses

Fig. 5 depicts the applied vertical forces as a function of CF displacements, which represents the overall response of each specimen. The CF displacements herein were taken as the average values of the measured displacements from three transducers around the perimeter of the column segment. The monotonically loaded specimens exhibited higher stiffness than their counterparts subjected to cyclic loading. The monotonically loaded specimens reached the peak strength in the range of 1174-kN to 1463-kN (264-kips to 329-kips), while the cyclically loaded specimens resisted as much as 1161-kN to 1370-kN (261-kips to 308-kips). The one with smooth column segment surface, which was loaded cyclically, failed at 716-kN (161-kips) and exhibited limited ductility. In bridge vertical members, it can be conservatively assumed that the applied loads will not exceed 50% of the axial load capacity. Given that 1161-kN (261-kips) corresponds to 76% of member axial capacity, the side shear in the preformed socket connection with intentionally roughened surface would provide satisfactory axial strength for connecting vertical precast members to adjoining members. As discussed subsequently, when the horizontal dimension of the vertical member increases, the appropriate embedment length should be designed in order for the vertical members to sustain large axial load ratios.

Overall, the intentionally roughened surface provided adequate bond strength between the grout and the embedded column segment, but the textures with deeper amplitude (i.e., 13-mm [0.5-in.] and 19-mm [0.75- in.] fluted fins) led to softer force-displacement responses. This is because fins that were constructed as integral part of column segment increased the flexibility of the connection in the vertical direction. Longer the fins, more flexible the connection became. In addition, a thicker grout closure pour resulting from wider CSP-to-column segment clearance
tended to reduce the shear stiffness of the connections as deformation within the grout closure pour increased.

As illustrated in Fig. 6, the CF displacements consisted of CG displacements and GF displacements. When a thicker grout closure pour was included, the vertical deformation of grout \( \Delta_{\text{grout}} \) was also quantified. Fig. 7 describes the connection responses in terms of each component. To reveal the contribution of each component, plots were created with the same scale for the axes. As shown in Fig. 7a, all specimens exhibited comparable GF displacement responses before reaching the peak strength. Hence, the differences in overall connection responses seen in Fig. 5 were the result of sliding at the column segment-to-grout interface (CG displacements) and the deformation within the grout closure pour itself (i.e., \( \Delta_{\text{grout}} \)). Fig. 7b plots the vertical forces versus CG displacements for the specimens with 38-mm (1.5-in.) CSP-to-column segment clearance, but with different column segment surface textures. This plot confirms that the adequate roughness was necessary to successfully develop the bond strength between the grout and the embedded member. However, the textures with deeper amplitude of fins would soften the response at the embedded member-to-grout interface. Fig. 7c compares the force versus CG displacement responses for the specimens F1G1C and F1G2C, which have the same column segment surface texture but different CSP-to-column segment clearance. Specimen F1G2C with thicker grout closure pour resulting from wider CSP-to-column segment clearance showed a softer overall connection response than Specimen F1G1C, but the two specimens exhibited similar responses at the column segment-to-grout interface. Therefore, given the comparable GF displacement responses, it can be stated that a thicker grout closure pour that induced significant \( \Delta_{\text{grout}} \) would soften the connection response. With reference to the loading type, Fig. 8 presents a comparison of the specimen responses with the same connection parameters but subjected different loading
types (i.e., monotonic vs. cyclic). For the specimens with the exposed aggregate finish (i.e., EG1M
and EG1C), no significant cumulative damage was caused by cyclic loading until the applied load
was increased to 667-kN (150-kips), which was approximately 50% of the peak strength. However,
the cyclic loading caused increased strength degradation for the specimens with deeper amplitude
for the column segment surface texture (i.e., F1G1M and F1G1C).

**Force Transfer Behavior**

The strain values measured along the longitudinal bar in the embedded column segment reflect
the transfer of force from the column segment to the foundation through the side shear mechanism.
Fig. 9 presents the normalized embedded column segment longitudinal bar strains as a function of
depth ratio under different load levels, in which the strains at the top of the foundation under the
applied load of 222-kN (50-kips), 445-kN (100-kips), 667-kN (150-kips), 890-kN (200-kips), and
1112-kN (250-kips) were normalized to 0.2, 0.4, 0.6, 0.8, and 1.0, respectively, for comparison
purposes. The depth ratio herein is defined as the depth where the strain was measured to the
embedment length of the column segment. A linear response is assumed between two adjacent
gauge locations, which implies a constant shear stress along the column embedment length. Based
on the observations from these plots, the specimens with same CSP-to-column segment clearance
but with different surface textures (F1G1, F2G1, EG1, and SG1) exhibited similar force transfer
behavior when subjected to the loads up to 445-kN (100-kips) (Fig.9a). When loads were further
increased, the force transfer took place mostly in the top half of the connections for the specimens
with column segments having deeper amplitude textures (F1G1 and F2G2) (Fig.9b). In other
words, when subjected to high loads, the surface textures with deeper amplitude (i.e., fluted fins)
were more efficient in transferring the applied force through the side shear mechanism although
the corresponding stiffness was earlier found to be softer. As a result, the deep amplitude surface
texture may be used to reduce the force transfer length.

DISCUSSIONS

Structural Performances

The structural performances of the specimens presented above facilitated characterization of
side shear mechanism and better understanding of force transfer behavior. The socket connections
that consisted of embedded members with deeper amplitude surface textures exhibited softer force-
displacement relationships compared to the one with exposed aggregate surface, while the surface
textures in these connections would transfer the force in a more efficient manner (i.e., over a
shorter depth). The thicker grout closure pour resulting from wider CSP-to-embedded member
clearance also reduced the stiffness of the socket connection. The softening was attributed to
relatively larger deformations occurring at the column-to-grout interfaces and within the grout
closure pour itself, which were caused by the properties of grout. Under the applied loads, the
grout exhibited relatively more flexibility than normal concrete due to the lack of hard coarse
aggregate and lower modulus. Because of more participation of grout, the connections with deeper
amplitude surface texture and wider CSP-to-embedded member clearance showed softer
connection responses. However, the deeper amplitude increased the shear resistance, enabling the
force to be transferred over a reduced embedment depth. Even though the participation of grout
led to relatively larger deformation, the failure did not occur at the grout closure pour but at the
stems of concrete fines or foundation concrete surrounding the CSP because the strength of the
gROUT was significantly higher than concrete. The cyclic loading reduced the stiffness on the
connections with deeper amplitude surface texture. However, for the connection with exposed
aggregate surface, limited effect of cyclic loading was exhibited on the connection response when the applied forces were less than 50% of the peak strength.

**Constructability**

Based on the experimental investigation presented herein, the preformed socket connection provides great potentials for use in practice due to its ease of construction. The socket can be easily established by CSP that serves as stay-in-place formwork. Through the construction of the specimens, use of chemical formwork retarder was found to be an efficient method to roughen the embedded member surface. The retarder was applied on the formwork up to 3-hours ahead of the concrete pour. After removing the formwork when the concrete was 3-days old, the laitance was easily removed with high-pressure water to expose the aggregate. The construction process with formliner was also completed with ease. However, the damage on precast fins could possible occur during fabrication and transportation. The experimental study also examined potential time saving measures for the assembly of the socket connection. The process will go smoothly if the right grout is identified for the closure pour. The desirable features for grout include high-early-strength, extended working time, and appropriate fluid consistency.

**Design Recommendations**

Based on the experimental findings and analyses of data, the following recommendations have been formulated for designing and constructing preformed socket connections that are appropriate for vertical precast members:

- Considering both the structural performance and constructability, the exposed aggregate finish is suggested for preparing the surface of the vertical precast member to be embedded in the preformed socket. This finish can be easily accomplished using chemical formwork retarder or an appropriate formliner that can ensure a similar surface texture.
• The CSP-to-embedded member clearance essentially determines the thickness of grout closure pour. The commercially available CSP sizes result in the clearances of 38-mm (1.5-in.) and 76-mm (3-in.) for most bridge vertical members. These two likely clearances are appropriate for grout closure pours to sustain axial loads in the preformed socket connection. The 76-mm (3-in.) clearance between CSP and embedded member would reduce the stiffness of the connection compared to the 38-mm (1.5-in.) clearance. This could be overcome by stiffening the grout using pea gravel with appropriate permission from the grout supplier.

• The CSPs with standard corrugation pattern is sufficient to preforming a socket in the adjoining member. The minimum 28-days compressive strength of grout established according to ASTM C109 (2016) should be 58.61-MPa (8500-psi) to ensure sufficient strength and stiffness for the connection. In addition, to properly securing the connection, the grout should have the following properties: high early strength, fluid consistency, extended working time, and non-shrink characteristic.

• Failure of a preformed socket connections subjected to an axial load can develop at the embedded member-to-grout interface of at the CSP-to-surrounding concrete interface. Therefore, the shear stress acting on these two interfaces shall be limited when designing the socket connection. For the connections following the above construction recommendations and with concrete attaining a compressive strength no less than 37.92-MPa (5500-psi), the limiting stresses at the embedded member-to-grout interface and the CSP-to-concrete interface may be taken as 6.89-MPa (1000-psi) and 4.83-MPa (700-psi), respectively. Conservatively, these stress limits were determined with the lowest axial load of 1174-kN (264-kips) that was reached by the tested specimens and the assumption
that the shear transfer occurs uniformly along the entire length of connection. Therefore, 
the minimum embedment length in a preformed socket connection required for a precast 
vertical member subjected primarily to axial loads can be determined as follows:

\[ l_{\text{min}} = \frac{P}{p_e f_{\text{grout}}} \leq \frac{P}{\pi d_{\text{CSP}} f_{\text{CSP}}} \]

where \( l_{\text{min}} \) = the minimum embedment length of the precast vertical member; \( P \) = the 
design axial load in the vertical member; \( p_e \) = the outer perimeter of embedded vertical 
member cross-section; \( d_{\text{CSP}} \) = inside diameter (nominal diameter) of CSP; \( f_{\text{grout}} \) = 
permissible stress for the embedded member-to-grout interface, recommended as 6.89-
MPa (1000-psi); \( f_{\text{CSP}} \) = permissible stress for the CSP-to-surrounding concrete interface, 
recommended as 4.83-MPa (700-psi).

CONCLUSIONS

The use of ABC has been implemented to speed up bridge construction. In recent years, there 
has been growing interest in using vertical precast members for the substructure, such as columns 
and piles. Precast vertical members can be embedded in a socket that is preformed in the adjoining 
member using CSP and high-strength grout. This type of connection has been identified as a viable 
means to promote the use of precast vertical members. However, there is lack of knowledge 
regarding the side shear mechanisms that provide resistance against axial load and the 
corresponding stress limits so that the preformed socket connection can be designed to sustain high 
axial loads. As a result, an experimental investigation was conducted to evaluate the side shear 
strength in the preformed socket connection. Eight specimens were constructed with the embedded 
potion of the member in the socket connection having the following outer surfaces: a smooth finish, 
exposed aggregate finish, 13-mm (0.5-in.) deep fluted fins, and 19-mm (0.75-in.) deep fluted fins. 
The connection regions replicated typical socket connections at full scale. The specimens with
different connection parameters were tested by subjecting them to monotonic and cyclic axial loading. Based on the findings from the tests and analyses of data, the following conclusions can be drawn:

- All specimens, except the one with smooth column surface, provided significant side shear strength against the axial load applied to the column segments. Hence, the intentionally roughened embedded member surface, as required by AASHTO, is necessary to develop satisfactory side shear strength to sustain axial loads used in routine design practice. However, surface roughness smaller than an amplitude of 6-mm is adequate, which can be easily achieved by exposing the aggregates.

- The specimens consisted of the column segments with deep amplitude surface textures (i.e., fluted fins) exhibited softer connection responses compared to the one with exposed aggregate surface finish. Thicker grout closure pour resulting from wider CSP-to-column segment clearance also reduced the stiffness of the socket connection.

- For the specimens with deeper amplitude column segment surface texture, the force transfer was more efficient when subjecting to high loads due to the increased surface roughness, enabling the load to be resisted over a shorter length.

- Exposed aggregate for embedded member surface preparation, standard CSP, and high-strength grout are recommended for establishing socket connections effectively. For connections established as described in this study, the side stress limitations of 6.89-MPa (1000-psi) and 4.83-MPa (700-psi) suggested, respectively, for the embedded member-to-grout interface and CSP-to-surrounding concrete interface to determine the minimum embedment length of the precast vertical member.
ACKNOWLEDGEMENTS

This study was supported by Iowa Highway Research Board (IHRB) and Federal Highway Administration State Transportation Innovation Council (STIC). The authors would like to thank the members of the Technical Advisory Committee for their advices and suggestions. The experimental investigation used Rapid Set® UltraFlow® 4000/8 and Flex-Liner™ formliner in the construction of the test specimens. We appreciate the material contributions from CTS Cement Manufacturing Corp. and Scott System.
REFERENCES


Kavianipour, F. and Saiidi, M.S. (2013). “Experimental and analytical seismic studies of a four-span bridge system with composite piers”, CCEER-13-17, Center for Civil Engineering Earthquake research, Department of Civil and Environmental Engineering, University of Nevada, Reno, Reno, NV.


Precast/Prestressed Concrete Institute (PCI). (2007). “Architectural Precast Concrete Manual, Section 3.5”, *Precast/Prestressed Concrete Institute*, Chicago, IL.


Utah Department of Transportation (UDOT) (2017). *Structural Design and Detail Manual*, *UDOT SDDM*, Taylorsville, UT.
TABLES AND FIGURES

List of Tables
1. CSP-to-Embedded Member Clearances for Vertical Precast Members ..................... 25
2. Testing Matrix ............................................................................................................. 25

List of Figures
1. Axial strength of (a) a fully penetrated socket connection and (b) a partially penetrated socket connection ........................................................................................................... 25
2. Details of specimens: (a) key dimensions; (b) oversized cavity; (c) reinforcement detail; (d) surface textures of precast column segments ........................................................................... 26
3. Test setup: (a) loading device; (b) instrumentations ................................................... 26
4. Failure modes: (a) column segment-to-grout interface failure; (b) CSP-to-foundation interface failure ...................................................................................................................... 27
5. Overall responses of specimens ................................................................................... 28
6. Components of CF Displacement ................................................................................ 28
7. Comparisons of connection responses: (a) GF disp. responses for all specimens; (b) CG disp. responses for specimens with different column segment surface textures; (c) CG disp. responses for specimens with different CSP-to-column segment clearances .......... 30
8. Impact of cyclic loading ............................................................................................... 30
9. Normalized embedded stub longitudinal bar strains under loads of (a) 222-kN, 445-kN; and (b) 667-kN, 890-kN, 1112-kN ........................................................................................................... 30
Table 1. CSP-to-Embedded Member Clearances for Vertical Precast Members

<table>
<thead>
<tr>
<th>Diameter of vertical member (m)</th>
<th>Inside diameter of CSP (m)</th>
<th>Resultant clearance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30</td>
<td>0.38</td>
<td>38</td>
</tr>
<tr>
<td>0.46</td>
<td>0.53</td>
<td>38</td>
</tr>
<tr>
<td>0.61</td>
<td>0.69</td>
<td>38</td>
</tr>
<tr>
<td>0.76</td>
<td>0.91</td>
<td>76</td>
</tr>
<tr>
<td>0.91</td>
<td>1.07</td>
<td>76</td>
</tr>
<tr>
<td>1.07</td>
<td>1.22</td>
<td>76</td>
</tr>
<tr>
<td>1.22</td>
<td>1.37</td>
<td>76</td>
</tr>
</tbody>
</table>

Table 2. Testing Matrix

<table>
<thead>
<tr>
<th>Test specimen</th>
<th>Surface texture</th>
<th>CSP-to-embedded member clearance (mm)</th>
<th>Loading type</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1G1M</td>
<td>13-mm fluted fin</td>
<td>38</td>
<td>monotonic</td>
</tr>
<tr>
<td>F2G1M</td>
<td>19-mm fluted fin</td>
<td>38</td>
<td>monotonic</td>
</tr>
<tr>
<td>EG1M</td>
<td>exposed aggregate</td>
<td>38</td>
<td>monotonic</td>
</tr>
<tr>
<td>F2G2M</td>
<td>19-mm fluted fin</td>
<td>76</td>
<td>monotonic</td>
</tr>
<tr>
<td>EG1C</td>
<td>exposed aggregate</td>
<td>38</td>
<td>cyclic</td>
</tr>
<tr>
<td>F1G1C</td>
<td>13-mm fluted fin</td>
<td>38</td>
<td>cyclic</td>
</tr>
<tr>
<td>SG1C</td>
<td>Smooth</td>
<td>38</td>
<td>cyclic</td>
</tr>
<tr>
<td>F1G2C</td>
<td>13-mm fluted fin</td>
<td>76</td>
<td>cyclic</td>
</tr>
</tbody>
</table>

Fig. 1. Axial strength of (a) a fully penetrated socket connection and (b) a partially penetrated socket connection
Fig. 2. Details of specimens: (a) key dimensions; (b) oversized cavity; (c) reinforcement detail; (d) surface textures of precast column segments.

Fig. 3. Test setup: (a) loading device; (b) instrumentations.
Fig. 4. Failure modes: (a) column segment-to-grout interface failure; (b) CSP-to-foundation interface failure
**Fig. 5.** Overall responses of specimens

**Fig. 6.** Components of CF Displacement
**Fig. 7.** Comparisons of connection responses: (a) GF disp. responses for all specimens; (b) CG disp. responses for specimens with different column segment surface textures; (c) CG disp. responses for specimens with different CSP-to-column segment clearances.

**Fig. 8.** Impact of cyclic loading

**Fig. 9.** Normalized embedded stub longitudinal bar strains under loads of (a) 222-kN, 445-kN; and (b) 667-kN, 890-kN, 1112-kN.