Task 1 Report – Literature Review

Project Title: Concrete-Filled Steel Tube to Concrete Pile Cap Connections-Further Evaluation/Improvement of Analysis/Design Methodologies

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1 Introduction

The Montana Department of Transportation has found concrete-filled steel tube (CFT) piles connected at the top by a concrete pile cap to be a very cost-effective support system for short and medium span bridges. This type of system offers low initial cost, short construction time, low maintenance requirements, and a long service life. While the gravity load performance of these systems is well understood, their strength and ductility under extreme lateral loads (e.g., seismic events) is more difficult to reliably predict using conventional design procedures. This project aims to further develop newly established design and analysis methodologies to ultimately ensure bridge performance is fully consistent with design intent.

The specific tasks associated with this research are as follows:

Task 1 – Literature Review

Task 2 – Experimental Design

Task 3 – Testing

Task 4 – Analysis of Results

Task 5 – Reporting

This report documents the work completed as part of Task 1 – Literature Review. This review includes recent research pertaining to CFT pile cap connections that has been completed since the previous phase of research. It should be noted that the document will continue to be updated as research progresses. This report outlines research that is pertinent to the current project and reflects on areas of research that need further development.

2 Background

Despite the efficiencies that CFT elements provide, the behavior and expected performance of the connections between CFTs and reinforced concrete elements is not well understood, especially regarding their performance under lateral loads. These connections contain complicated load transfer mechanisms that are difficult to predict and model. This literature review is focused on finding recent research aimed at better understanding the behavior/performance of CFT to pile cap/beam connections. Specifically, it focused on research that has been conducted since the completion of the previous phase of research [1].

2.1 Structural Behavior of Double-CFT Pile Foundations under Cyclic Loads

Li, Xiao [2] investigated the structural behavior of double CFT-Piles embedded in concrete pile caps subjected to seismic loads. Specifically, they tested vertical and battered piles under cyclic lateral loads, and documented the observed failure modes, ultimate strength, lateral stiffness, displacement ductility, and energy dissipation capacity of the specimens. A total of three double CFT-pile specimens with differing configurations were tested in this research, as shown in Figure 1. A finite element model was also calibrated and used to investigate the effects of varying embedment depth and inclination angle.

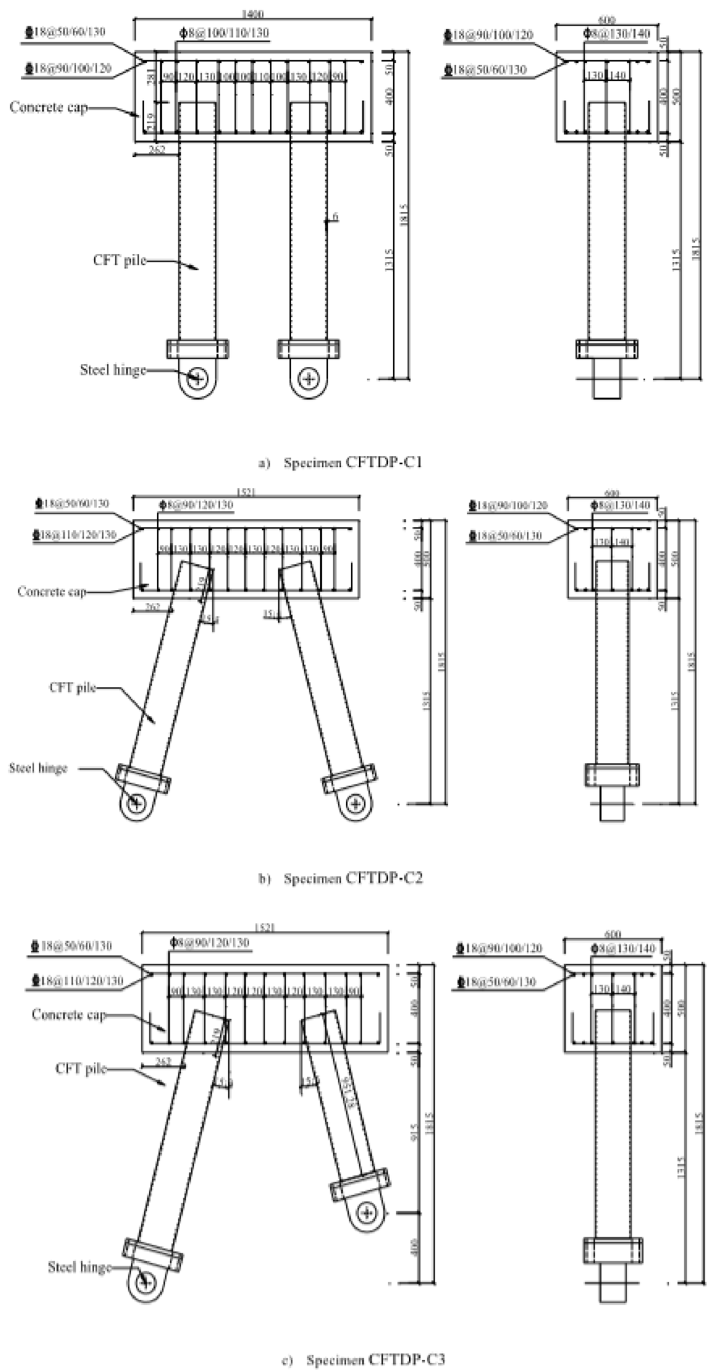

Figure 1: CFT Pile Configurations Tested by Li, Xiao [2]

The vertical pile configuration was designed with embedment depth prescribed by Chinese structural codes, which specify a minimum embedment depth of 1.0 times the diameter of the CFT (D). This specimen ultimately failed due to block shear in the pile cap at the two free ends, after initial yielding of the CFT piles. Due to the block shear failure in the cap and separation between CFT piles, the plastic hinges in the CFT piles were not fully developed, resulting in a pinched hysteresis curve, and subsequently the lowest energy dissipation capacity. As expected, the ultimate capacity of this specimen was the lowest of three specimens, was the most flexible, and had the most ductile response.

The battered pile configurations experienced higher ultimate capacities and were significantly stiffer than the vertical-pile specimen. This is expected since a portion of the lateral load is carried by the axial component of the battered piles. Ultimately these specimens failed due to cracking, concrete pry out, and buckling of the CFT. It was observed that the loading capacity deteriorated rapidly at drift ratios higher than 6% due to concrete pry out of the pile cap, resulting in a lower deformation capacity. Additionally, relative to the vertical pile specimens the battered piles were observed to have an increased energy dissipation capacity, and a reduction in ductility.

It was concluded that an embedment depth of 1.0D is adequate for forming plastic hinges at the ends of both vertical and battered CFT piles. However, it was observed that block shear failure and concrete pry-out at large drift ratios prevent the complete development of the plastic hinges. Modeling in ABAQUS validated this finding. Thus, an embedment depth of 1.5D is recommended for these connections to improve energy dissipation capacity. It was also concluded that the battered piles significantly increase the ultimate capacity, lateral stiffness, and energy dissipation capacity of the connections, but resulting damage reduces the deformation capacity and ductility. In regard to the effects of unequal pile heights, the shorter piles experienced increased shear and axial loads, resulting in the premature failure of the shorter pile. That being said, the ultimate lateral load carrying capacity of the connection was not significantly affected by the unequal heights, but the deformation capacity decreased with an increase in the ratio between heights.

2.2 Punching Shear in CFT Connections

The punching shear capacity of CFT to pile foundation connections was recently investigated [3]. While this behavior is relatively well understood for RC columns, CFT column to pile cap connections have more complicated load transfer mechanisms. As part of this research, five CFT column to pile cap specimens were tested under punching shear loads, and the effects of embedment depth, shear studs, face annular rings, and double-headed shear reinforcement were investigated. Each specimen consisted of a pile cap suspended by four CFT piles, shown in profile view in Figure 2. The contribution of soil below the piles was not considered in this study, and piles were placed on a rigid steel platform. Monotonic vertical loading was applied towards the floor with a hydraulic actuator, while measuring the applied loads, strains in the CFT columns and steel reinforcement, and center deflection of pile caps. An analytical study was also carried out using ABAQUS.

All five specimens failed due to punching shear, and the observed failure mechanisms were greatly affected by the connection details. The specimen with the face annular ring showed the highest load carrying capacity and exhibited the most ductile behavior, due to the fact that the annular rings were able to increase the effective perimeter of the critical section for punching shear. All other tested specimens experienced brittle punching shear failure leading to a substantial drop in load-carrying capacity. The reduction of column embedment depth resulted in an increase in effective depth for the RC pile caps, leading to a significant increase in punching shear capacity of the connection. The headed shear reinforcement included in the pile cap also significantly increased the punching shear capacity of the connection. It was also concluded that current code predictions (AASHTO and ACI 318-14) for the punching shear capacity of CFT to pile cap connections are overly conservative, and thus an empirical model for predicting the punching shear capacity of CFT column to concrete-cap connections was developed and evaluated.

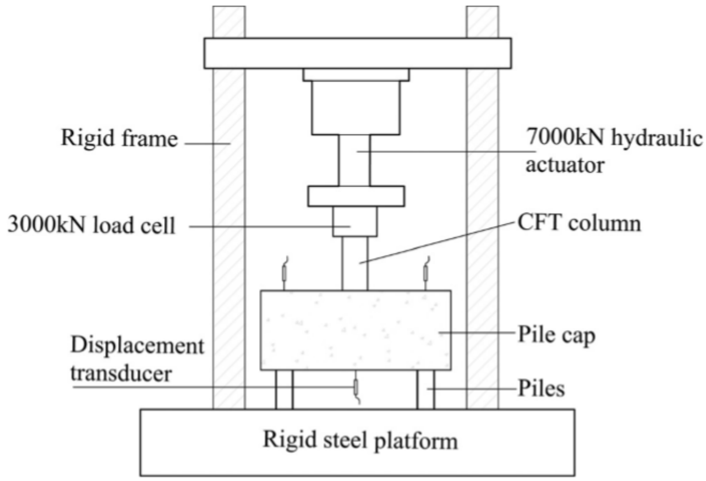

Figure 2: Punching Shear Test Setup [3]

3 University of Washington Studies

The University of Washington has conducted several research programs focused on investigating the structural performance of CFT's and their connections to concrete foundation caps/beams. Their investigation of the topic began in 2005 with the goal of understanding a foundation connection capable of developing the full plastic moment capacity of CFT piles. The early phases of research involved testing 19 half-scale CFT column-to-foundations connections [4-7]. These connections included flanged annular rings welded to the base of the CFTs. These specimens evaluated the effects of various connection parameters (e.g., embedment depth, steel strength and connection type) on the performance of the CFT under seismic loading. Two variations of the embedded connection were developed and tested: a CIP monolithic option and a partial height pocket option. These tests were successful, resulting in full plastic hinging of the embedded CFTs.

The early phases of research also investigated the behavior of the CFTs independently from the connection. These studies included nonlinear finite element analyses of high strength CFTs under flexural loading [8]. This modeling led to better understanding of CFT behavior, especially with respect to local buckling of the steel tube. Another notable research project was aimed at further understanding composite action in CFT components and connections [9]. Understanding and achieving the shear-stress transfer necessary for composite action is a significant obstacle in the optimal use of CFTs. It was found that circular CFTs develop composite action more readily than rectangular shaped piles. Achieving composite action with mechanical transfer using interior studs or rings may be necessary, but these are difficult to install. Additionally, it was concluded that base annular rings provide direct bearing between the embedded CFT and surrounding concrete, providing a mechanism to efficiently develop large bearing stresses.

Another project focused on modeling CFTs under combined loading (including internal reinforcement), and evaluating and improving design provisions for such elements [10]. This research resulted in an improved P-M interaction curve for these elements, and determined that current US design codes accurately predict performance under axial or bending load, but are overly conservative at predicting behavior under combined loading.

The later phases of research have made progress in developing design expressions for CFT to foundation footing/beam connections subjected to lateral loads [11-17]. In this research, three column-to-cap connections subjected to cyclic deformations were studied, all of which had precast caps that included pockets for the embedded CFTs. These pockets were formed by embedding corrugated pipes in the precast caps and were filled with high strength grout after the CFTs were placed in the sockets. The connection types are illustrated in Figure 3. The embedded ring connection (ER) was similar to the connections studied in the previous research, and included an annular ring welded to the tip of the embedded CFT. This connection detail resulted in large ultimate strengths, high stiffnesses, and large deformation capacities. In testing, local buckling was observed in the steel tube at drifts in between 1.5-3%. However, the buckling did not influence the stiffness or moment resistance of the connection [14]. Testing showed full plastic moment capacity was achieved for decreased annular ring widths of D+16t and cap widths as low as 2D. The ER connection was concluded to have superior seismic performance and accelerated bridge construction (ABC) compatibility in comparison to the other connection types.

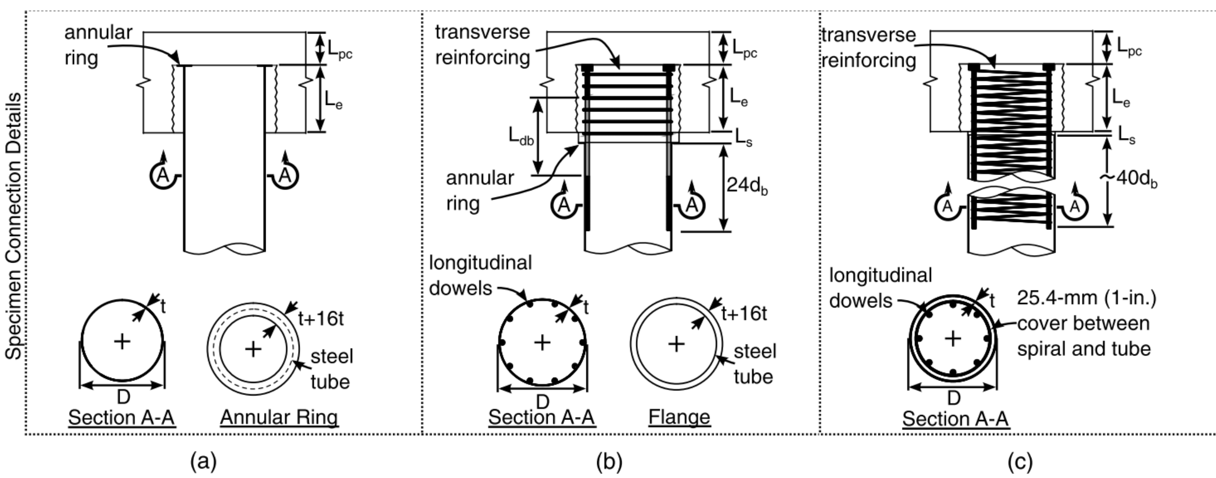

Figure 3: Connection Types Investigated in Later Phases of UW Research: (a) ER connection; (b) WD connection; (c) RC connection [12]

The second connection option studied was the Welded Dowel (WD) connection. This connection implements a ring of headed dowels to resist flexural demand. To maximize moment capacity, the dowel is welded directly to the tube. An outer diameter of D+8t is used and welded to the exterior of the tube. When tested, the connection exhibited large strength, stiffness and deformation capacity. However, comparable ER connections exhibited higher stiffness and strength. The stiffness and strength of the WD connection is controlled by the effective reinforcing ratio of the dowels which extend into the cap beam. Furthermore, the WD connection has several disadvantages in terms of labor efficiency and ABC. Temporary shoring is required, and dowels must be welded to the inside of the tube, which is labor intensive.

The final connection investigated was a RC connection in which the CFT was terminated at the surface of the cap/beam. Experimental results suggest that this connection type exhibits significantly lower strength and stiffness in comparison to a CFT component. This was due to the fact that stiffness and strength are controlled by the effective longitudinal reinforcing ratio in the connection. Yielding and fracture of the longitudinal reinforcing were observed to be the primary failure mechanisms. This method was also labor intensive and required the construction of a reinforcing cage that must be temporarily supported within the steel tube. When comparing all three connections, the ER option was observed to have superior ABC facilitation and seismic performance.

This research included developing and validating a numerical model in ABAQUS [12, 17]. Due to the complexities associated with modeling the nonlinear cyclic behavior of the ER connection, prior numerical efforts have focused primarily on monotonic behavior and failure envelopes rather than cyclic behavior. The model developed in this research aimed to capture the nonlinear cyclic behavior of the ER connection including the composite interaction between the materials. A key component to this modeling strategy was numerically "pre-cracking" the concrete fill. When compared to test data, this modeling strategy was shown to accurately predict damage and overall behavior of the elements.

Finally, a case study was performed to evaluate and quantify the performance of CFT bridges in comparison to RC bridges [12, 16]. Reinforced concrete is commonly used for bridge construction in seismic regions because of its stiffness, strength and inelastic deformation capacity [16]; however, RC bridges require special detailing in regions of plastic hinging as mandated by AASHTO Guide Specifications [16]. Unfortunately, these detailing requirements often result in congested reinforcing that deters ABC and increases cost. On the other hand, CFT connections can achieve the plastic moment capacity of the pile without the use of internal reinforcing in the pile. Further, it has been demonstrated that, for a given strength, the diameter of a CFT column is 20-40 percent smaller than an RC column [16]. This brings weight and materials savings. To compare the performance of CFT and RC bridge structures, several nonlinear modeling approaches were introduced. An RC bridge was redesigned using CFT columns and inelastic modeling was used to conduct the comparison case study. It was found that the CFT structure exceeded the performance of the RC structure for all hazards in the *Multiple Seismic Hazard Analysis* [16]. Furthermore, the drifts seen in the CFT structure remained below the threshold that would require repair, while the RC structure exceeded the threshold warranting repair. Relative to the CFT structure, it was found that the RC structure has a higher probability of *Repair Required, Partial Replacement,* and *Collapse/Replacement* scenarios for lower spectral accelerations. Overall, the CFT was shown to be a more efficient bridge structure in seismic regions.

It should also be noted, that the above research has resulted in a design procedure that has been recently adopted by the Washington Department of Transportation [18].

4 Previous Research at Montana State University

MDT has sponsored previous research at Montana State University (MSU) to investigate the performance of CFST piles under extreme lateral loads and to develop appropriate analysis/design procedures [1, 19-21]. As part of these investigations, MSU conducted physical tests on various half-size models of the CFST to pile cap connections under pseudo-static and cyclic loading (Figure 4). While this research provided useful information regarding the behavior and design of CFST to concrete pile-cap connections, further research is required to more fully characterize this behavior and further develop the analysis/design methodologies. For example, several aspects of these methodologies rely on empirical assumptions that may not be valid for all possible cap configurations. That is, the tests carried out in this previous research did not vary cap dimensions, CFST diameter, or number of embedded piles in the test section, and therefore, some of the empirical observations from these tests that were used in developing the proposed methodologies may not be valid for all conditions. Thus, further testing and/or analytical modeling should be conducted to validate/modify these elements of the proposed methodologies to ultimately ensure the desired system performance.

Figure 4: Typical Test Specimen from Previous MSU Research

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