June 2024

Project Summary Report

FHWA/MT-23-003/9630-628

CONCRETE-FILLED STEEL TUBE TO CONCRETE PILE CAP CONNECTIONS - FURTHER EVALUATION/IMPROVEMENT OF ANALYSIS/DESIGN METHODOLOGIES

https://www.mdt.mt.gov/research/projects/structures/seismic.aspx

Introduction

The Montana Department of Transportation (MDT) has found concrete-filled steel tube (CFST) piles connected at the top by a concrete pile cap to be a very cost-effective support system for short and medium span bridges. A typical pile cap using this system is shown in Figure 1.

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.

Figure 1: Typical MDT concrete-filled steel pile and concrete pile cap bridge substructure support system.

The primary objectives of this research were to (a) further validate/improve MDT's CFST to concrete pile cap connection design/analysis methodologies, (b) ensure the efficacy of these methodologies for a wide variety of potential design configurations, (c) gain further insights on the basic connection behavior under extreme lateral loads, and (d) determine possible improvements in the design methodology.

What We Did

The objectives of this research were realized through the following tasks:

- A comprehensive literature review was conducted to evaluate the state-of-the-practice and recent advances in CFST connection design.
- An experimental program was developed, which included the load setup, instrumentation, and specimen design and details. A total of four specimens were designed in this research. The first specimen was a half-size specimen, which provided continuity between this and the previous test series, where all specimens tested were half-size. This specimen was lightly reinforced and represented a typical MDT connection design for use in situations where the lateral demand is not expected to control the design. The research then progressed to a 2/3rd-size specimen with similar reinforcement to isolate any potential effects associated with specimen scale (Figure 2). The third specimen was the same size and had the same reinforcing scheme as the second specimen but had a higher strength concrete to isolate the effect of concrete strength. The final specimen was also identical to the second specimen but isolated the effect of including U-bars in the reinforcing scheme.
- All four specimens were tested under monotonic loading until failure, while recording observable damage and applied lateral force and displacements. The measured force-deflection curves for several test specimens are provided in Figure 3, while Figure 4 shows one of the specimens near failure.
- Test results were then analyzed to determine the effects of the key parameters tested in this research. These results were then used to evaluate the efficacy of a newly developed moment-rotation methodology for predicting the capacity of the connection between the CFST and concrete cap.

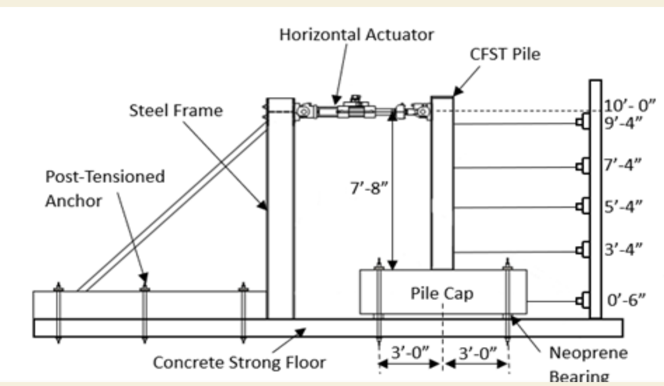

Figure 2: Test setup for 2/3-scale specimen.

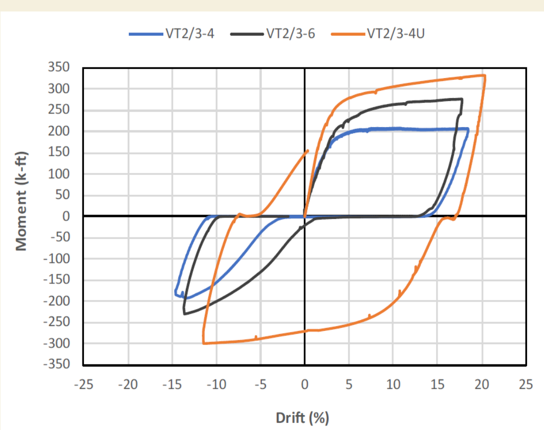

Figure 3: Typical moment-drift curves.

Figure 4: Final specimen being tested.

What We Found

Based on this investigation, the following conclusions were made:

- Apart from the specimen including U-bars, all specimens demonstrated the same overall moment-drift response, progression of damage, and failure mechanisms. In these specimens, damage initiated with the formation of cracks on the side of the cap, which progressed into the expansion of these cracks and the formation of 45-degree angle cracks propagating along compression struts on the bearing side of the pile. Failure in the specimens ultimately occurred due to a combination of (1) concrete crushing on the bearing side of the pile and on the backside of the pile near the tip of the embedded pile, (2) tension cracks on the backside of the pile that extended the full height of the specimen, and (3) 45-degree angle cracks propagating along compression struts originating from the pile to the edge of the cap.
- The inclusion of U-bars increased the capacity of the cap enough to force the failure mechanism of the specimen into the CFST pile, which failed due to the formation of a plastic-hinge. The inclusion of U-bars increased the cap capacity by around 50%.
- Specimen scale was observed to have a significant effect on connection performance (as expected), with the larger specimens having higher stiffness and strength relative to the smaller size specimen. That being said, both scales exhibited similar overall moment-drift responses and patterns of damage progression, indicating that besides the obvious increased strength and stiffness, scale did not affect the performance of the connection.
- An increase in concrete strength from 4 ksi to 5.5 ksi (a 33% increase) led to approximately a 33% increase in the initiation of damage and ultimate load capacity. This indicates that the effect of concrete strength on cap performance may be linear.
- A notable influence of U-bars was observed in the tests. Their inclusion significantly enhanced the stiffness and strength of the specimens, evidenced by the increased cap capacity, and altered failure mechanisms. In addition to providing confinement in the connection zone, the U-bars may also be providing reinforcement to resist global bending moments observed in the cap. The shift in failure point from the cap to the formation of a plastic hinge in the CFST also positively affected the hysteresis behavior.
- Regarding the moment-rotation methodology, the study found it to be highly accurate in predicting the capacities of cap connections, with an average measured-to-predicted ratio of 0.95. However, the methodology tends to overpredict capacities for connections without U-bars and underpredict for those with U-bars, indicating a need for further refinement. The overprediction of capacities may be attributed to the fact that global flexural failures are not accounted for in the current methodology, as implemented, and does not consider the role that the longitudinal reinforcement plays in preventing this mechanism. Additionally, no obvious trend was observed in this methodology's accuracy with varying scale or concrete strength.
- The parametric study investigated the effects of various parameters on the predicted capacities of the connections; specifically, it quantified the effects that embedment depth, concrete strength, and amount of U-bar reinforcement have on predicted performance. This study demonstrated that while all studied parameters influenced the predicted capacity, embedment depth had the most effect on capacity, with an increase in strength of 126% and corresponding increase of embedment depth of 50%.

Overall, this research provides substantial insights into the behavior of CFST to concrete pile cap connections under various conditions and validates the use of the moment-rotation methodology as a reliable tool for capacity prediction.

What The Researchers Recommend

Based on these research findings, we recommend a focused effort on refining and enhancing the moment-rotation prediction methodology, particularly addressing the effects of U-bars and global flexural failures. This refinement should be accompanied by the development of a simplified and user-friendly interface for the software or program that implements this methodology, making it more accessible and efficient for engineering practitioners. Furthermore, there is a need for the creation of a standardized design detail that is applicable under a predefined set of conditions—such as seismic activity of bridge location, geometry, and size. This standard detail would streamline the design process, ensuring consistency and reliability in the construction of bridges that utilize CFST pile cap connections, ultimately enhancing their performance under seismic loading conditions.

More Info:

The research is documented in Report FHWA/MT-23-003/9630-628

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