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RESEARCH PROGRAMS

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Performance of Steel Pipe Pile-to-Concrete Cap Connections Subject to Seismic or High Transverse Loading: *Phase III Confirmation of Connection Performance*

http://www.mdt.mt.gov/research/projects/structures/seismic.shtml

Introduction

The Montana Department of Transportation (MDT) 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 (Figure 1). This type of system offers low initial cost, short construction time, low maintenance requirements, and a long service life. From a structural engineering perspective, these systems must provide acceptable performance under gravity (i.e., self weight and vehicle loads) and lateral loads (i.e., extreme ice, wind, and seismic events). While the gravity load performance of these systems is well understood, their strength and ductility under extreme lateral loads is more difficult to reliably predict using conventional design procedures. Therefore, MDT sponsored three phased research projects at Montana State University (MSU) to investigate the performance of these systems under extreme lateral loads.

As part of this investigation, completed in 2005, MSU conducted five physical tests on half-size models of the CFT to steel pile cap connection. The models were designed to replicate the behavior of full-size connections under reversed seismic loads. Four different connection-reinforcing schemes were evaluated. Based on these tests, in conjunction with established structural engineering principles, MDT developed a new design procedure to determine the reinforcing steel required in the pile cap to produce the desired system performance under lateral loads. While the layout of the reinforcing steel generated by this design procedure is generally similar to the successful layout that was evaluated in the final pile cap test, there are several differences between the reinforcing configuration that was tested and what the design procedure generates. Notably, the design procedure provides for a simpler arrangement of the reinforcement (a set of U-shaped reinforcing bars that encircle the embedded CFT) that offers some advantages relative to the constructability of the pile cap.

What We Did

The objective of this project was to further validate MDT's new CFT to concrete pile cap connection design methodology by physically testing connections designed according

Figure 1 - Typical MDT Concrete-filled Steel Pipe and Concrete Pile Cap Bridge Substructure Support System

to this new procedure. A total of six half-size connection specimens were tested under axial and lateral load until failure. Specifically, four different configurations were tested under monotonic and cyclic loads. Three of these configurations were designed in accordance with the design guide; the fourth configuration incorporated a second set of U-bars encircling the pile in the interior of the cap (close to the tip of the embedded pile).

In the first four tests (VT1, VT2, VT2.5, and VT3), the connection configurations were subjected to monotonic loading, capturing the ultimate strength of each configuration, and providing general information on limit states of concern and post-failure ductility. Two more tests were completed using a cyclic load scheme (CT1 and CT2) to capture performance characteristics of the connections under multiple cycles of fully reversed, increasing load. The second of these two cyclic-load tests was conducted on the cap configuration consisting of two sets of U-bars.

Each specimen consisted of a single CFT pile and an attendant length of pile cap, as shown in Figure 2. The pile cap was held in position on each end (at the theoretical points of inflection in the cap of a full bent when subjected to a lateral load), while a lateral load was applied to the tip of the pile.

In addition to subjecting the connections to a lateral load, a constant axial force was applied during the tests. This was done to generate the gravity load effects that were expected to be present in the real structures during a lateral load event. Measurements were subsequently made during each test of the loads applied to the connection, and of the global displacements and internal strains that were produced. The force-deflection response for a typical specimen and the condition of that specimen at the completion of testing are shown in Figures 3 and 4, respectively.

What We Found

Four key limit states were observed in these tests: (1) formation of a plastic hinge in the CFT, (2) internal and exterior crushing of the cap concrete adjacent to the embedded pile, (3) yielding of the longitudinal reinforcement in the cap, and (4) splitting of the concrete cap. Based on the results of this investigation, the following observations were made regarding the efficacy of the MDT design methodology at addressing these limit states.

1. The MDT design methodology predicts the capacity of the CFT solely based on properties of the steel pipe, and ignores the effects of concrete and axial load. In many design scenarios, this simplification would be conservative; however, this simplification would be unconservative if the design of the connection assumes that plastic hinging limits the maximum moment transferred to the cap by the CFT.
2. The design guide accurately predicts/delays the limit state of exterior crushing of the cap concrete in the connection zone (which signifies/initiates ultimate failure). It is not, however, effective at predicting the onset of crushing the concrete in the interior of the cap, which was shown to reduce connection fixity (resulting in a pinched hysteresis response) and increase degradation under cyclic loads.
3. Yielding of the longitudinal reinforcement was predicted well by the design guide; however, this provision may still merit further review and revision. The design methodology primarily addresses this limit state by including additional steel beyond that which is required from a normal design of the cap for global bending. This process is dependent upon a calibration factor (75 percent reduction in required steel from a mechanics model) based on empirical data from the test series completed for MDT at MSU in 2005. Although this methodology was shown to be effective in this test series, the efficacy of this calibration factor has not been verified across all possible cap configurations.
4. The splitting limit state (marked by yielding of the transverse reinforcement and formation of splitting cracks) was observed in all test specimens, but not until after other limit states had been reached. While this limit state was not directly a focus of this investigation, this positive performance indicates that the MDT design methodology using AASHTO's specifications for minimum reinforcement in plastic-hinge zones

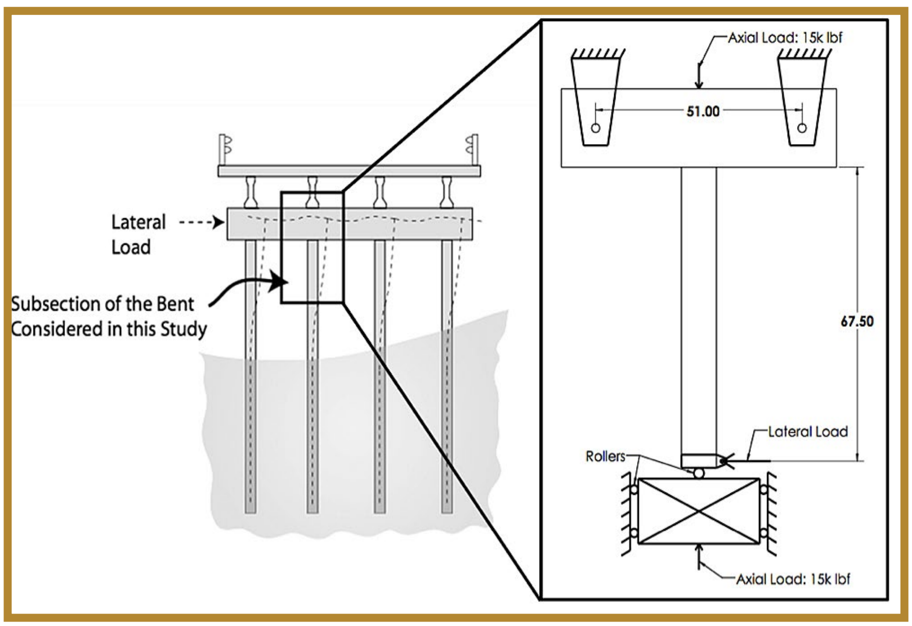

Figure 2 - General Test Setup

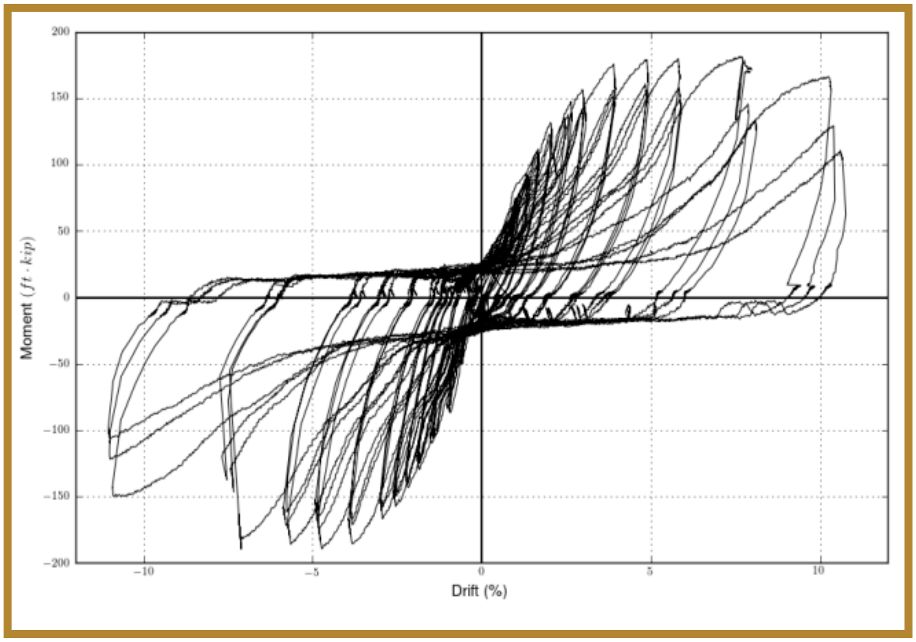

Figure 3 - Pile Cap Force vs. Deflection Response

and including U-bars, is effective at delaying it. That being said, the amount of transverse reinforcement specified following this approach is not directly based on the moment demand the connection must carry.

5. In executing this project, a thorough review of the design guide beyond just those parameters directly exercised in this test series was completed. This review revealed a specific aspect of the design guide that apparently could yield unconservative results, and thus should be addressed. The provision of concern determines whether the connection will be specifically designed to carry the moment demand on it or if the reinforcing provided in a normal flexural design for global bending is sufficient. This branching is based on the moment demand's relation to the plastic-moment capacity of the CFT, and is reliant on an assumption that the dimensions and reinforcing of the cap cross-section proportionally increase with increased pile capacity. However, this assumption may not be valid, as some bent configurations may fall outside of those typically encountered in developing this provision.

What the Researchers Recommend

The researchers recommend the following to address the respective findings listed above.

1. One possible improvement to predicting the plastic-moment capacity of CFTs might be to adopt the American Institute of Steel Construction's methodology for calculating the plastic-moment capacity of CFTs, as this methodology has been shown to be accurate at axial load ratios (i.e., ratio of applied axial load to ultimate axial capacity) common in bridge applications.
2. The concrete crushing limit state could be addressed by reducing allowed concrete compressive strengths and/or including interior U-bars near the tip of the embedded pile, which were shown to delay the onset of this limit state.
3. To more comprehensively address yielding of the longitudinal reinforcement in the cap, it may be desirable to develop a mechanics model to better describe the effect of U-bars on this limit state, and reduce reliance upon empirical factors.
4. Development of a more robust analytical model to predict cap splitting may be merited to reduce reliability on empirical factors and to generally improve design efficiency.
5. To address possible unconservative branching of the design process based simply on level of moment demand on the connection as a fraction of CFT plastic moment capacity, this "branch" could simply be removed. If it were removed, the connection would always be designed based on the moment demand and would include additional reinforcement in the form of U-bars.

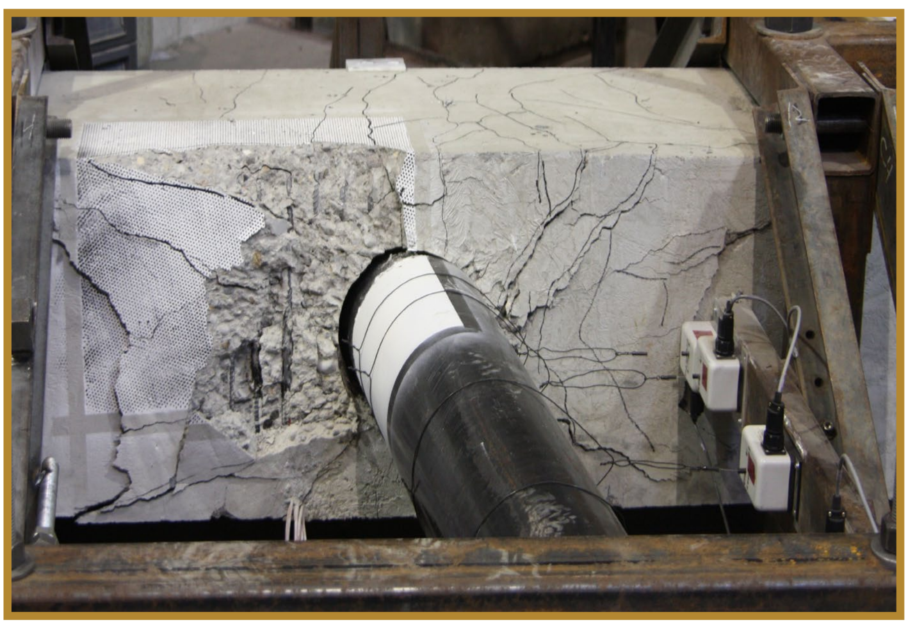

Figure 4 - Typical Pile Cap Near the Completion of Testing

For More Details . . .

The research is documented in Report FHWA/MT-13-001/8203, Performance of Steel Pipe Pile-to-Concrete Cap Connections Subject to Seismic or High Transverse Loading: Phase III Confirmation of Connection Performance.

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MDT Implementation Status
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This research will be implemented immediately. Bridge design crew chiefs will review their projects to determine which bridges would benefit from this new design procedure. Very little training is required for engineering staff to understand and use the new procedure. The additional training can be accomplished informally as needed. Initially, the new technique will be dynamic in nature and will evolve as we gain experience with it. The new Bridge Design Manual will include information on the theory and practice of using the new procedure.

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