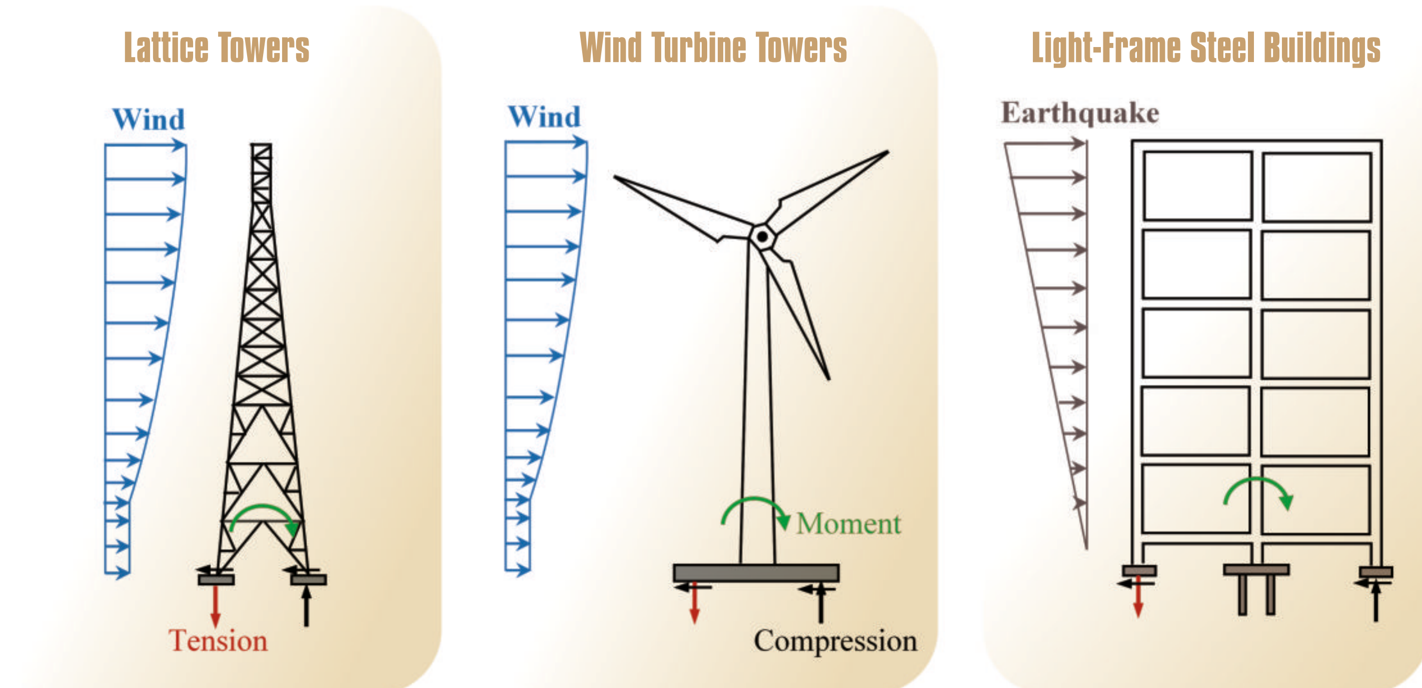
Improving Helical Pile-to-Foundation Connections



Tall, light structures impacted by tension forces

Many structures are subjected to *cyclic loads*, which involve sequential applications of compression and tension loads due to events such as windstorms, earthquakes or heavy vehicular traffic. Tall and light structures — such as telecommunication or transmission towers, wind turbines, and light-frame steel buildings — are particularly vulnerable to the tensile components of cyclic loads. Owing to their high-tension capacities, helical piles present a significant potential to create cost-effective, practical and robust foundation systems for resisting significant tension forces. To realize their full potential, helical pile-to-foundation connections must be properly designed. Even a well-designed pile group and a concrete foundation may fail if their connection cannot resist the applied forces. However, there is a lack of research, knowledge and specific code provisions on creating robust connections for resisting tensile loads.

While geotechnical studies typically focus on the behavior of isolated or grouped piles without considering the influence of the connection zones, structural studies exclusively focus on the concrete foundation response without considering the influence of piles. The connection design is also typically left unaddressed and is commonly dealt with as an afterthought, using general code equations not intended for application to pile-to-foundation connections nor tensile loads.

DFI's Helical Piles and Tiebacks Committee funded a research study from May 2018 to September 2019 to advance knowledge on the influence of the connection zones of helical piles, to understand the effectiveness of current connection designs, and to publish recommendations for improving robust connection design. Conducting large-scale experimental tests was neither practical nor cost-effective due to the large foundation dimensions and numerous design configurations that would have been involved, and due to complex loading protocols that would need to be tested. To overcome these challenges, the research team from The University of Toledo, Ohio, used state-of-the-art high-fidelity computational modeling along with experimental verification studies as a first step in developing design recommendations for helical pile connection zones subjected to tensile loads.

This article describes the use of this approach to create 162 full-scale foundation systems and to digitally examine the influences of connection bracket types and embedment depths, reinforcement percentages, shear span-to-depth ratios and loading conditions. The copious simulation data generated allowed the team to quantify the influences of each variable, identify undesirable design configurations and make design recommendations. While this study addresses helical piles, the research findings are also applicable to micropiles because they use the same termination brackets.

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Foundation System Details

A concrete foundation system, representative of a pile cap, was designed using two helical piles. This configuration creates a one-way stress flow and helps better isolate the connection response. The helical piles are terminated with one of three bracket types, as shown in Figure 1: a single plate, a studded plate or a double plate. The influencing parameters investigated include three bracket embedment depths (h_e); three longitudinal reinforcement percentages (also called reinforcement ratios, or ρ_x); three shear span-to-effective depth ratios (a/d ratios of 1.68, 1.42, and 1.11), which represent how thick a concrete pile cap or footing is; and three loading conditions: monotonic tension, monotonic compression and reversed cyclic.

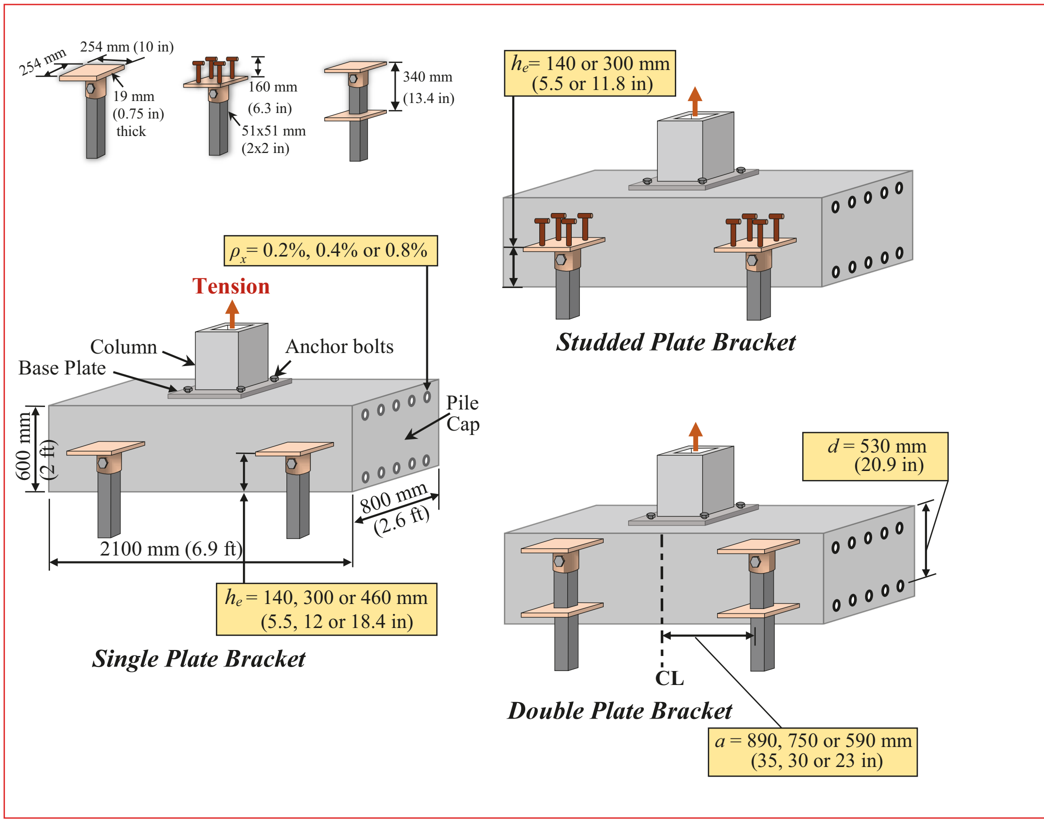

Figure 1. Pile termination bracket types studied

Experimental Approach

Computational Modeling

A two-dimensional (2D), continuum-type, nonlinear plane-stress element was used for the computational models through the computer program VecTor2. The formulation employed is based on the Modified Compression Field Theory (MCFT), which has been adopted by several design standards worldwide. The MCFT employs a smeared, rotating crack approach within a total-load, secant-stiffness solution algorithm, and allows for the consideration of the coupled flexure, axial and shear effects. Although a 2D model is involved, the triaxial concrete confinement is accounted for by in- and out-of-plane reinforcement components. Additionally, VecTor2 incorporates a large number of advanced material behavior models.

Although 2D numerical models are computationally more efficient and faster than 3D counterparts, they commonly assume that stresses and strains are constant through the out-of-plane thickness of the elements. This assumption is not valid when modeling helical pile connections where the stresses propagate in a conical shape from the edges of the termination plate towards the surface of the concrete, as shown in Figure 2a. This stress pattern results in a conical failure termed

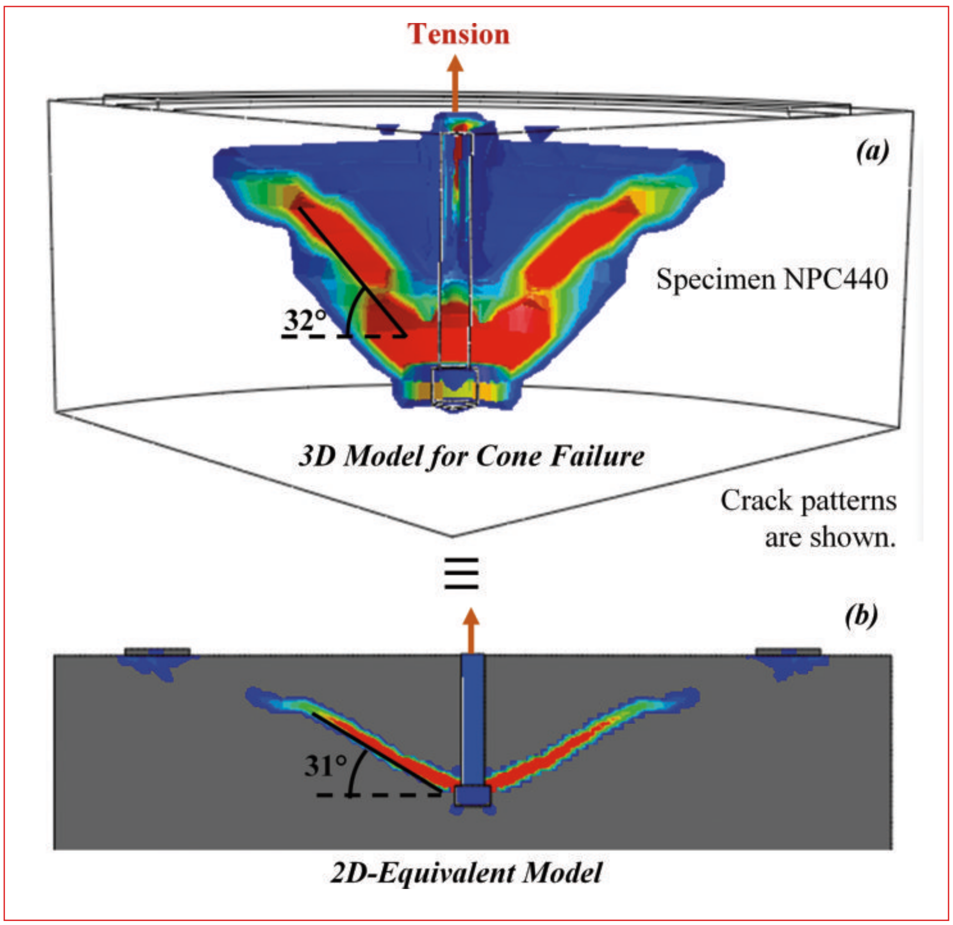

Figure 2. The equivalent cone method

the concrete breakout (or cone) failure. To capture this failure mode using 2D models, the research team developed the Equivalent Cone Method (ECM). This method determines an equivalent concrete thickness for use in 2D models to a yield breakout failure load that is approximately equal to the load which would be predicted by a 3D model (see Figure 2b).

Experimental Verification

The numerical models were verified using the experimental data generated by the research team of Dr. M. Hesham El Naggar from Western University, Canada. Their experimental study tested nine specimens consisting of a single plate bracket embedded into foundation specimens of 500 mm by 500 mm by 1600 mm (20 in by 20 in by 64 in). Note that the test setup was an inverted foundation where the pile shaft at the top applies tension loads. These specimens were modeled using the high-fidelity modeling approach presented above, and the simulated responses have been compared to the experimental ones (see Figure 3). The simulations captured the experimental load capacities with a simulated-to-experimental average of 1.01 with a coefficient of variation of 6% – an excellent accuracy for numerical simulations at the ultimate collapse conditions. The failure modes and crack patterns were also simulated very well. These results demonstrated the successful verification of the numerical modeling approach.

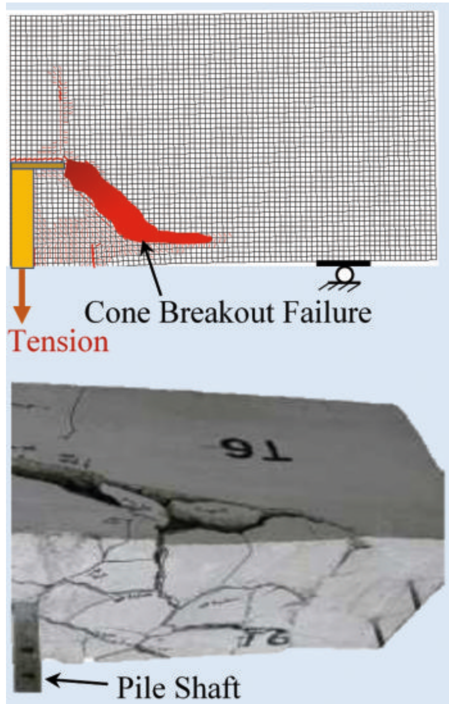

Figure 3. Verification of the failure mode predictions

Simulation Results

System-Level Load Capacities

The effect of the connection zone configurations on the system-level load capacities in the 162 numerical simulations were systematically analyzed and compared according to the load cases to which they were subjected. As with typical cyclic reversals, the reversed-cyclic-load results are divided into two parts as cyclic tension and cyclic compression.

Load-Displacement Response Simulation

The peak load capacities were graphically represented and contain 27, 9 and 18 simulation results, respectively. The results demonstrated that:

- The load capacity increases by an average of 30% when the embedment depth (h_e) is changed from bottom to middle. The further increase in h_e from middle to top does not appear to affect the capacity (see overlapping red and green lines in Figure 4a).
- The studded bracket has two h_e positions considered in this study. The change in h_e did not influence the load capacity (see overlapping lines in Figure 4b), except for the higher reinforcement

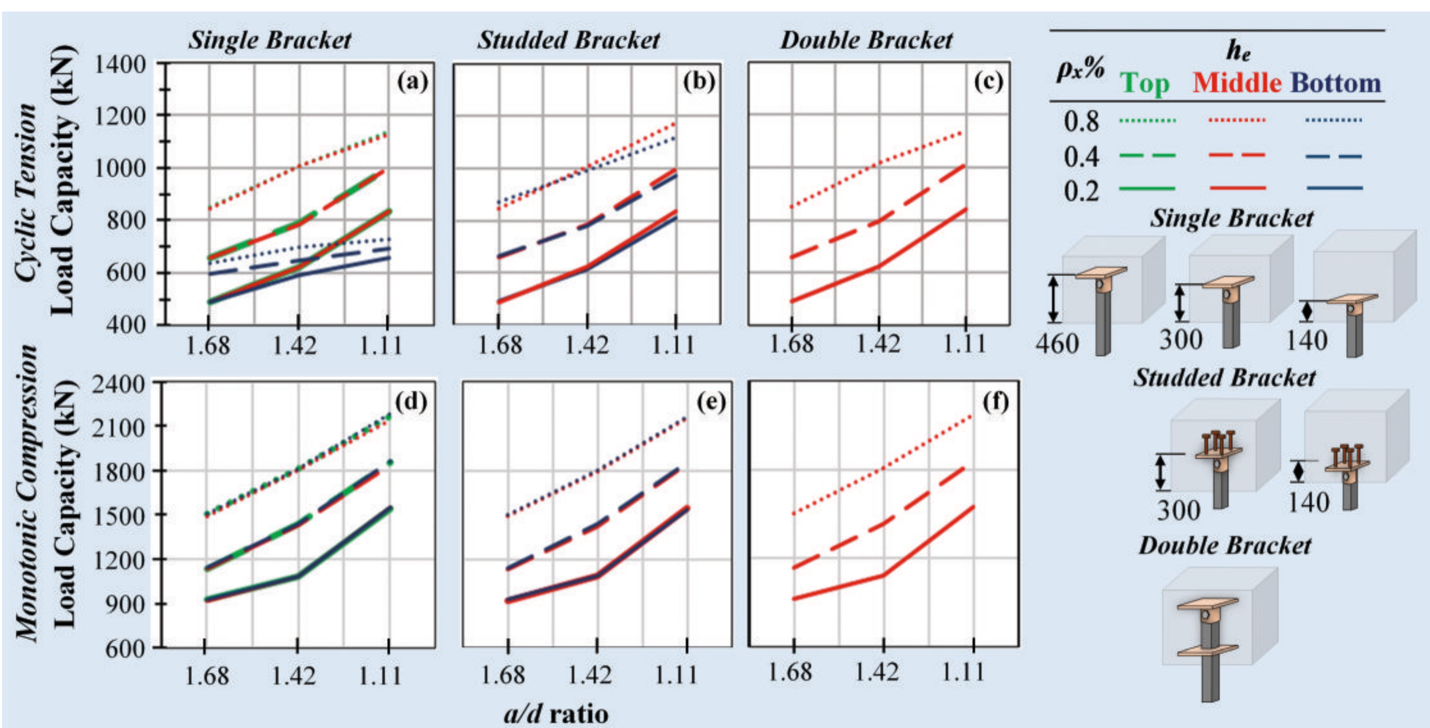

Figure 4. Load capacities at failure subjected to tension and compression load cases

ratio (ρ_x) percentages where the increased system load capacity resulted in connection zone cracking in the bottom h_e position, such that the connection zone starts to influence the response (see the deviation in dashed and dotted lines of Figure 4b).

- The *a/d* ratio, which represents how thick a concrete pile cap or footing is, affects the system capacity significantly, with lower ratios (i.e., thicker members) providing exponentially higher system capacities (see bi-linear nature of lines in Figures 4a to 4c).
- The double plate bracket has only one h_e position, which exhibits a good performance since the connection zone does not influence the system capacity (see Figure 4c).
- The tensile capacity of all bracket types increased significantly with higher ρ_x, except for the bottom h_e, where the connection zone failure prevents any significant capacity increase with higher ρ_x.
- The compression load results are presented in Figures 4d to 4f, where the overlapping, colored lines demonstrate that the compressive load resistance is independent of h_e changes for all bracket types examined.

Crack Patterns and Failure Modes

The simulated deflected shapes, crack patterns and failure modes are presented in Figure 5 for the selected, representative specimens. Major connection zone cracking and failures are predicted for some of the specimens subjected to tensile loads. The bottom h_e of the single plate bracket exhibited the least favorable performance by sustaining connection zone failures, as shown in Figure 5a. While performing better, the bottom h_e of the studded bracket exhibited major connection zone cracking (see Figure 5b), which reduced, but did not govern, the system capacity. This type of cracking may be detrimental to the long-term durability of helical pile foundations. The double plate bracket (Figure 5c), the middle h_e of the single plate bracket (Figure 5d) and the middle h_e of the studded bracket (Figure 5e) performed satisfactorily with no major connection zone cracking. The double plate bracket may provide additional advantages, such as resilience to other types of loads and long-term durability, due to the top and bottom plates confining the entire depth of the pile cap. Subjected to pure compression loads, all specimens with all bracket types exhibited global failure modes of either flexure or shear, without exhibiting any major connection zone cracking, as shown in Figure 5f.

Comparison with Sectional Analysis Methods

Both the numerical simulations and the experimental tests include the influence and failure modes of connection zones. The traditional sectional analysis methods, on the other hand, consider the concrete foundation globally while neglecting the local influences such as how the load is introduced or how the supports and connection zones are detailed. To assess the significance of considering or neglecting the connection zone behavior, the experimental specimens were also analyzed with the sectional methods contained in the ACI 318-19 standard. It is clear from Figure 6 that the experimental capacities are much smaller than those predicted by the sectional analysis method. This result confirms that the connection capacity may govern the entire system response and that the use of the sectional analysis may overestimate the system capacity (by a factor of 2.2 on average in this study).

Conclusions and Recommendations

- The results demonstrate that helical pile-to-foundation connections may govern the entire system capacity for the load conditions incorporating net tension components. The traditional global analysis methods, which are not intended for the connection zones, may significantly overestimate the capacity of the helical pile systems, especially for the design configurations involving single plate terminations at the bottom embedment (h_e) position.
- The tension load capacities of the concrete pile caps (all of which are doubly and symmetrically reinforced) are found to be 54% of their compression load capacities. If analyzed with the traditional sectional analysis methods, which neglect the influence of the connection zones, their load capacities in tension and compression would be incorrectly calculated as equal.

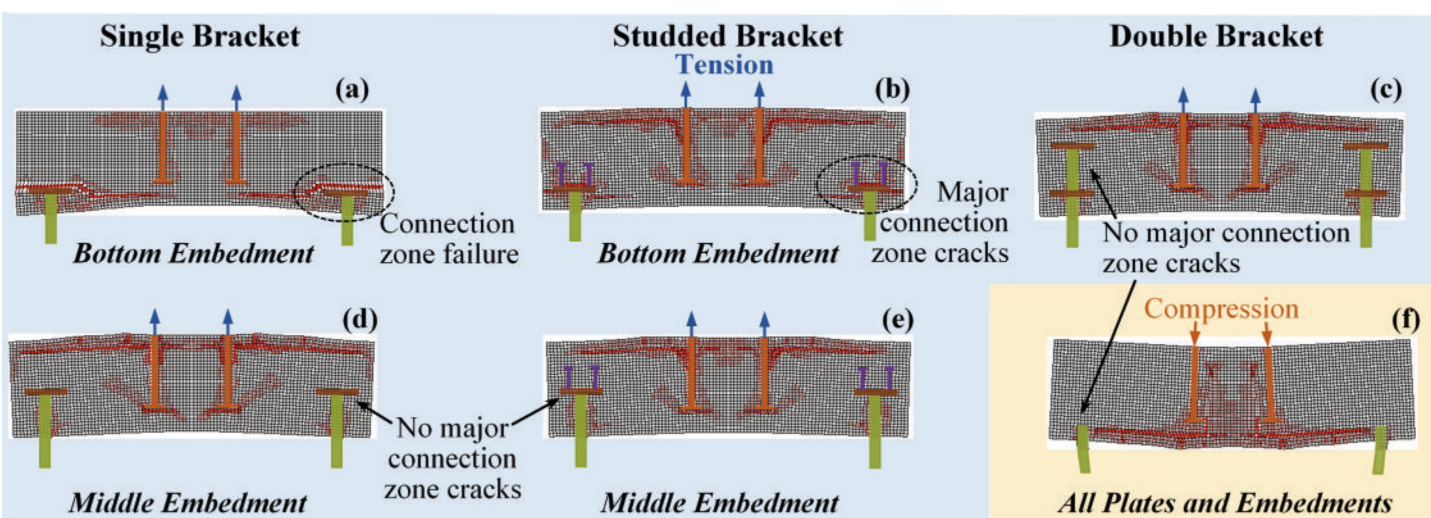

Figure 5. Representative failure modes and crack patterns

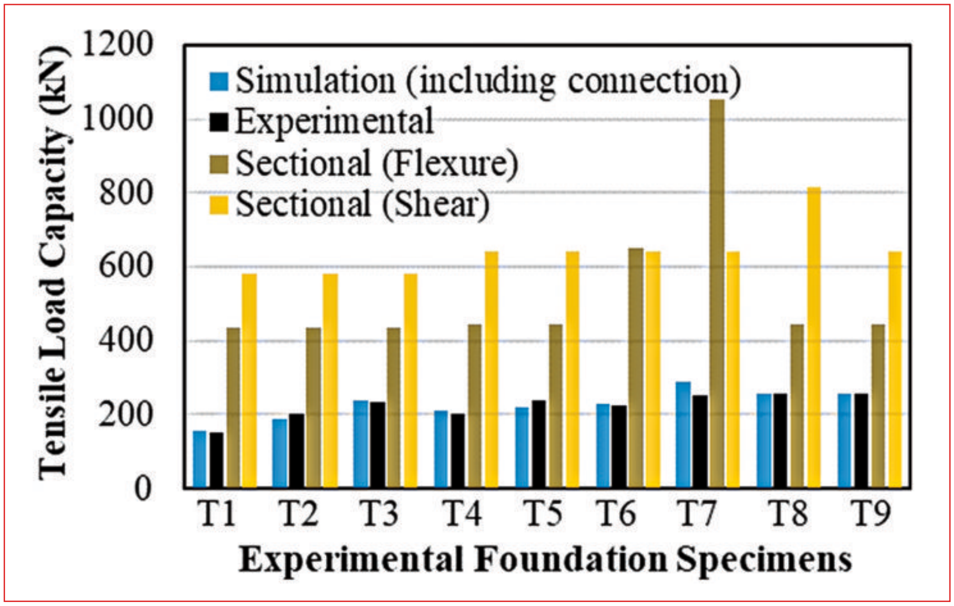

Figure 6. Capacity predictions and experimental results for three methods

- Connection zone failures are predicted for the bottom h_e of the single plate termination, with a decrease in the global load capacity by 25% on average. It is recommended that the middle h_e be used if the single plate termination is used.
- While no connection zone failure is predicted, major connection zone cracking is observed for the bottom h_e of the studded plate termination. For the configurations involving the bottom h_e, the change of the bracket type from single to studded improves the system capacity by an average of 22%; consequently, the studded plate bracket may be preferred over the single plate bracket for the bottom h_e. For the most optimum results, however, the middle h_e is recommended for both the single and studded plate terminations.
- The double plate termination is considered with one embedment depth covering the entire pile cap section, which performed very well with no connection zone failure in all simulations contained in this study.
- Although the bottom h_e of the single plate termination demonstrated the least-favorable behavior, it can still be successfully used for resisting tensile forces if a special connection zone detailing is developed (e.g., sufficient amounts of vertical ties in the connection zone). This recommendation is also applicable to the bottom h_e of the studded plate terminations.

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- The results of this study clearly demonstrate the need for performing an explicit capacity and service-load cracking analysis for the connection zones when resisting tensile forces, in addition to the global structural and geotechnical analyses. The recommended design configurations are not intended to replace the explicit connection zone analyses.
- The helical pile-to-foundation connections are found not to influence the monotonic compression load capacities of the foundation systems in any of the termination bracket types examined; no connection failures are predicted. To maximize the compression load capacities, high ρ_x and low a/d ratios are recommended for all bracket types.
- Future research and large-scale experimental tests are required to further investigate the effects of critical system variables and develop simple design equations for use in practice.
- The full project report, an open-access spreadsheet, YouTube demonstrations of the research and latest journal publications can be downloaded from Dr. Guner's research website at **www.utoledo.edu/engineering/faculty/serhan-guner/Publications.html** and from the Helical Piles and Tiebacks Committee website at **www.dfi.org/commhome.asp?HLPR**

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Sundar Chiluwal is a senior graduate student at The University of Toledo. His research focuses on advancing the understanding of the response and failure modes of helical pile-to-footing connections and creating analysis methods to advance current design practices.