FB-MultiPier

Bridge Software Institute

Nonlinear fiber-integrated frame element comparison

FB-MultiPier vs OpenSees®

EXECUTIVE SUMMARY

This report summarizes verification efforts pertaining to computation of nonlinear behaviors of laterally loaded members in FB-MultiPier (v5.9.0). Focus is given to the structural analysis of fiber-integrated frame elements. Presented herein are quantitative comparisons between nonlinear lateral load responses of structure-only models. In particular, a parametric study is carried out using the various default cross-sections available in FB-MultiPier. For each structural configuration considered, a range of lateral loads are applied and the response is computed for each load application. Maximum horizontal displacements are then cataloged across the range of lateral loads considered. The overall process is carried out in FB-MultiPier and correspondingly in OpenSees. To verify the computed results obtained using FB-MultiPier, computed lateral displacements obtained from the FB-MultiPier analyses are compared to those obtained from respective configurations modeled using OpenSees. In addition, for selected cross-sections, comparisons are made between the load-moment interaction diagrams computed using FB-MultiPier relative to manually generated interaction diagram points (with use of an algorithm identified from the literature).

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Chapter 1

Square Piles

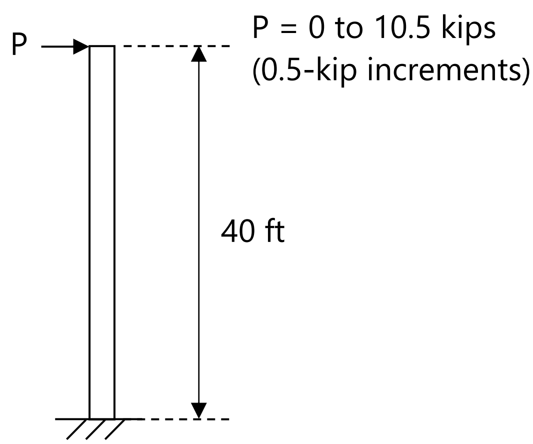
In this chapter, pile head horizontal displacement results are compared as obtained from nonlinear static analyses of laterally loaded square piles in FB-MultiPier and OpenSees. Because the focus of this verification effort is placed on assessing the nonlinear fiber-integrated frame element implementation in FB-MultiPier, relatively simple structural configurations are investigated. Namely, several of the configurations considered are modeled as free-standing piles with fixed bases. Other cases are modeled as a pile that is fitted with a single lateral spring at some distance from the pile head along with a fixed base. In all cases, lateral loads are placed at the pile head. Also, for all cases, structure-only analyses are conducted with no detailed treatment of surrounding soil.

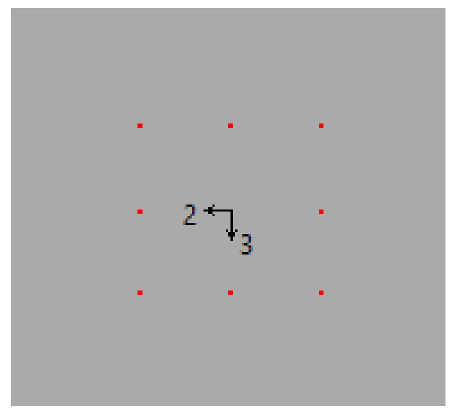
Lateral load response comparisons are made between the pile head horizontal displacements computed by FB-MultiPier and OpenSees over a range of lateral loads. Whenever feasible, the range of lateral loading is chosen such that a nonlinear response is visibly evident among the computed pile head horizontal displacements. Nonlinear behavior of piles and shafts in FB-MultiPier is modeled in a manner that is consistent with available features within OpenSees (i.e., fiber-integrated frame elements), which computes resultant forces using numerical integration of cross-section stresses over numerous integration points (called fibers). Upon request, FB-MultiPier models may be made available to licensed program users.

Stress-strain relationships used in the analyses are presented in Appendix A. For selected cross-sections, the associated load-moment interaction diagrams are presented in Appendix B.

Example 1-1: Single 12″ Square FDOT Standard Prestressed Steel

Problem Description: Analyze a single 12″ square FDOT Standard pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 10.5 kips in load increments of 0.5 kips).





12″ Square FDOT Standard Pile

File: *Example_1-1.in*

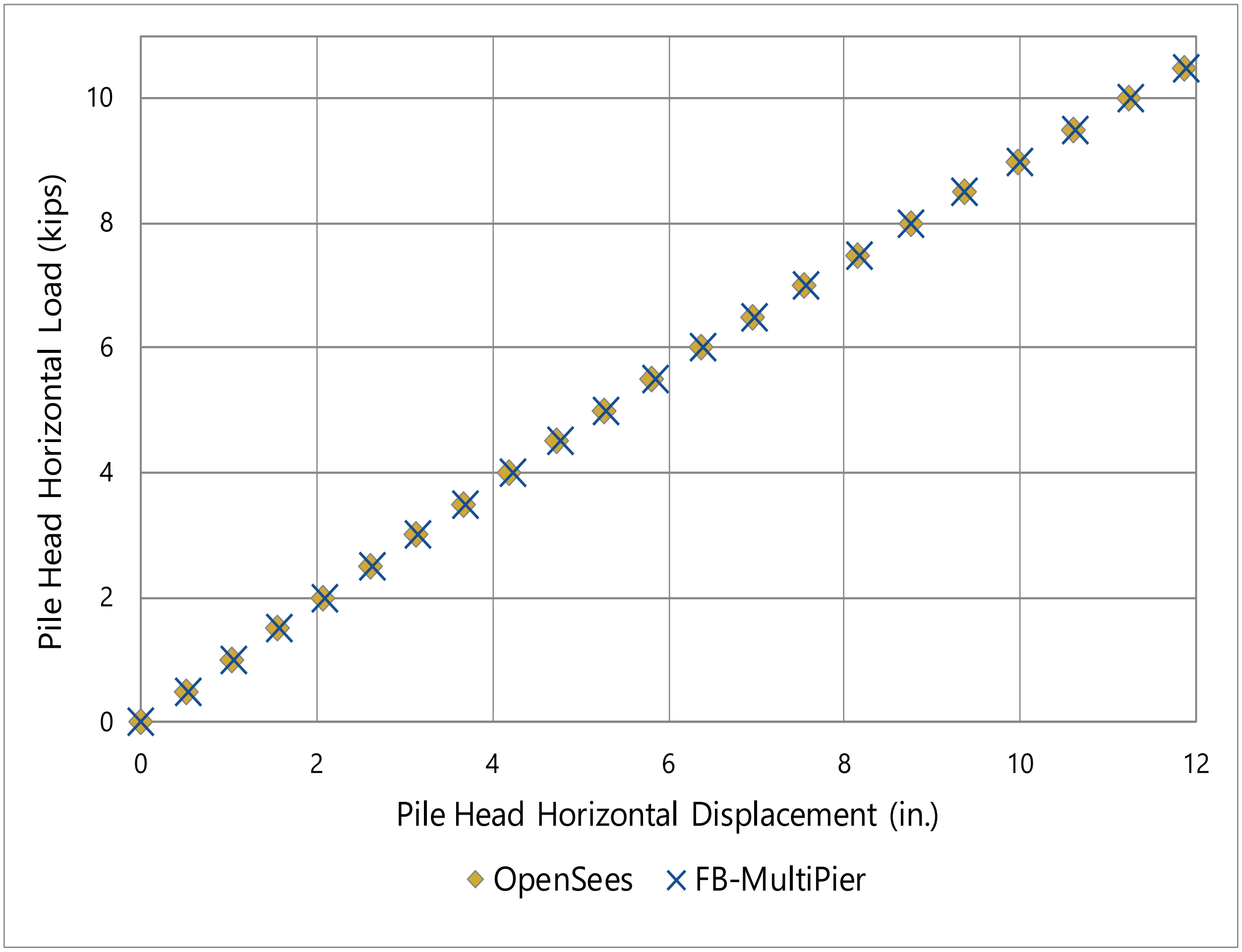
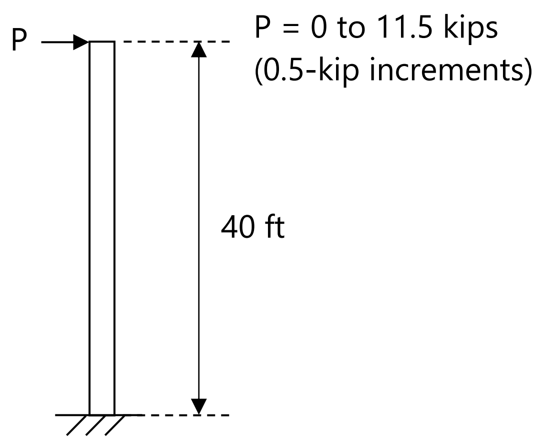
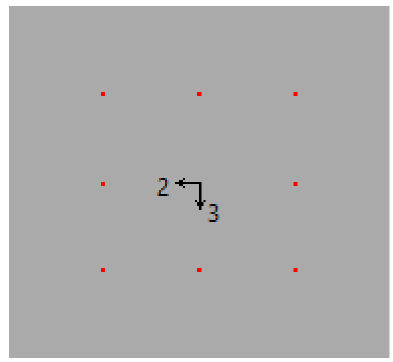


Figure 1.1 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-2: Single 14” Square FDOT Standard Prestressed Steel

Problem Description: Analyze a single 14” square FDOT Standard pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 11.5 kips in load increments of 0.5 kips).





14” square FDOT Standard pile section

File: *Example_1-2.in*

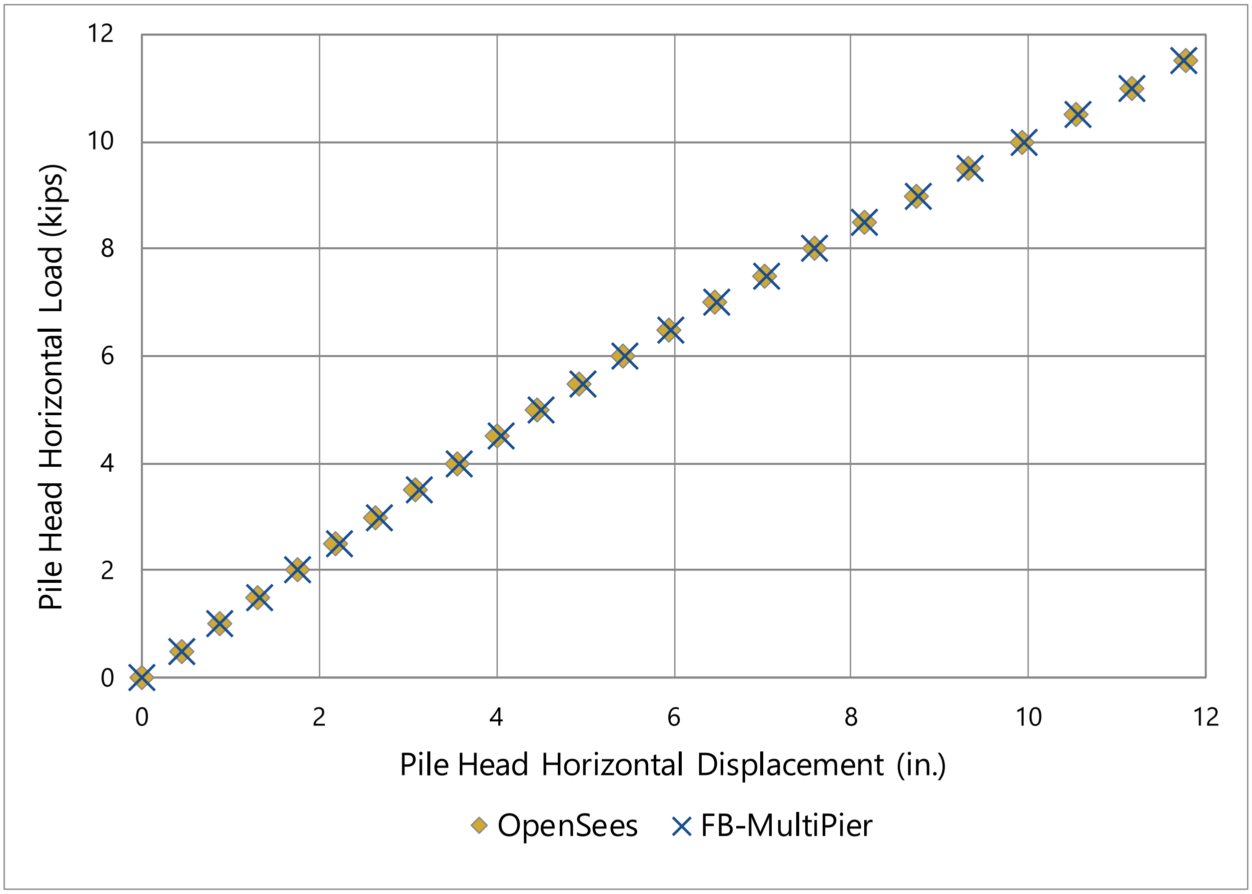
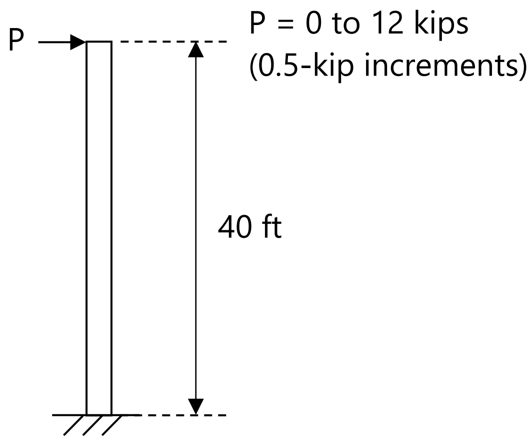
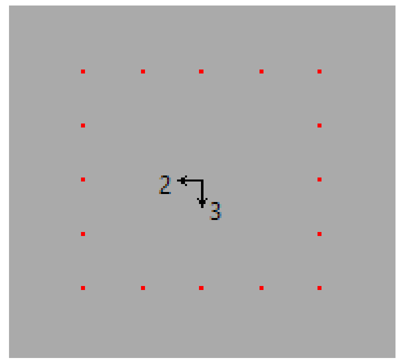


Figure 1.2 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-3: Single 18″ Square FDOT Standard Prestressed Steel

Problem Description: Analyze a single 18″ square FDOT Standard cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 12 kips in load increments of 0.5 kips).





18″ Square FDOT Standard Pile

File: *Example_1-3.in*

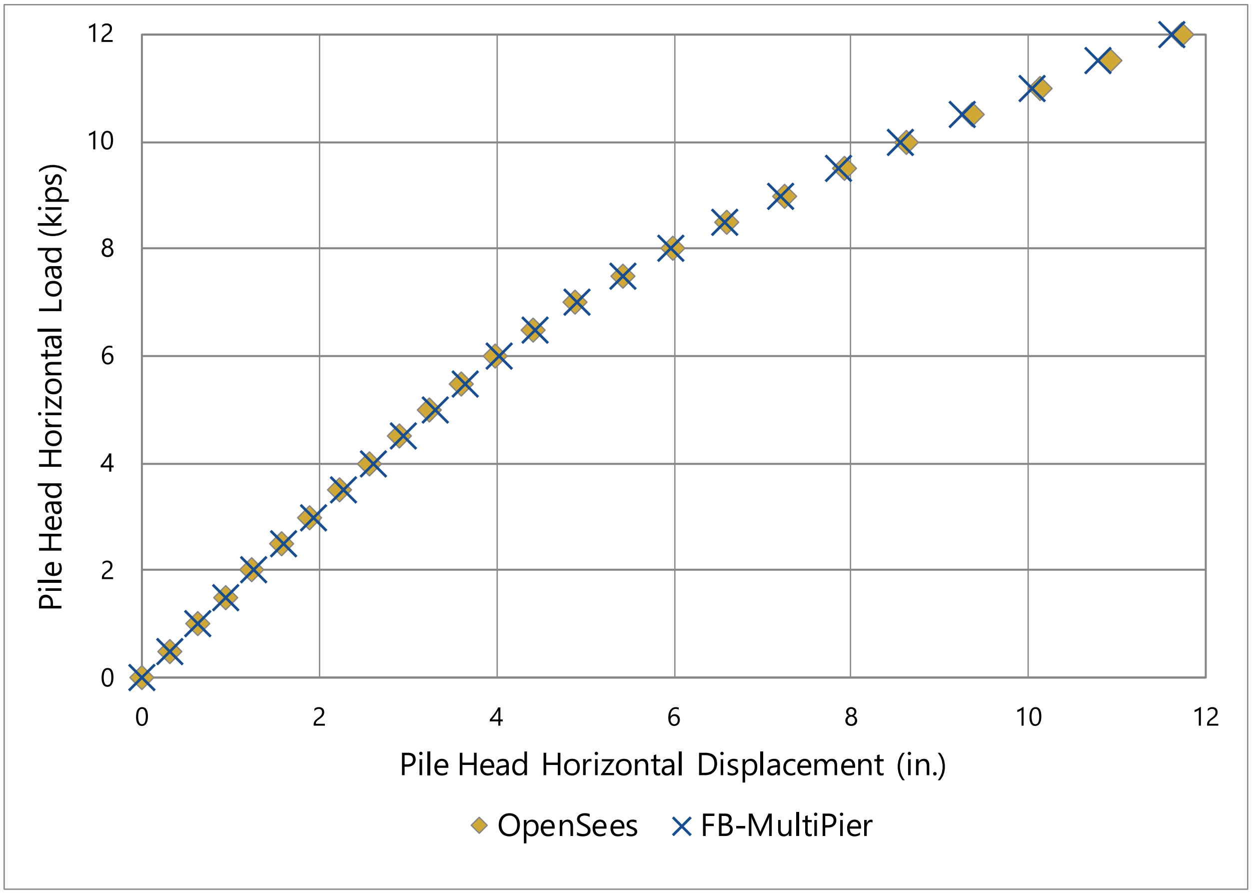
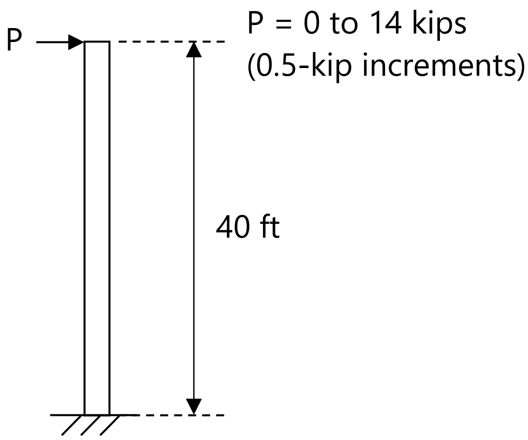
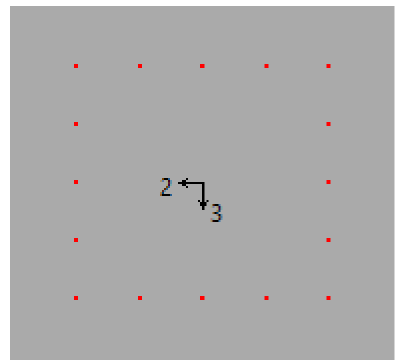


Figure 1.3 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-4: Single 20″ Square FDOT Standard Prestressed Steel

Problem Description: Analyze a single 20″ square FDOT Standard pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 14 kips in load increments of 0.5 kips).





20″ Square FDOT Standard Pile

File: *Example_1-4.in*

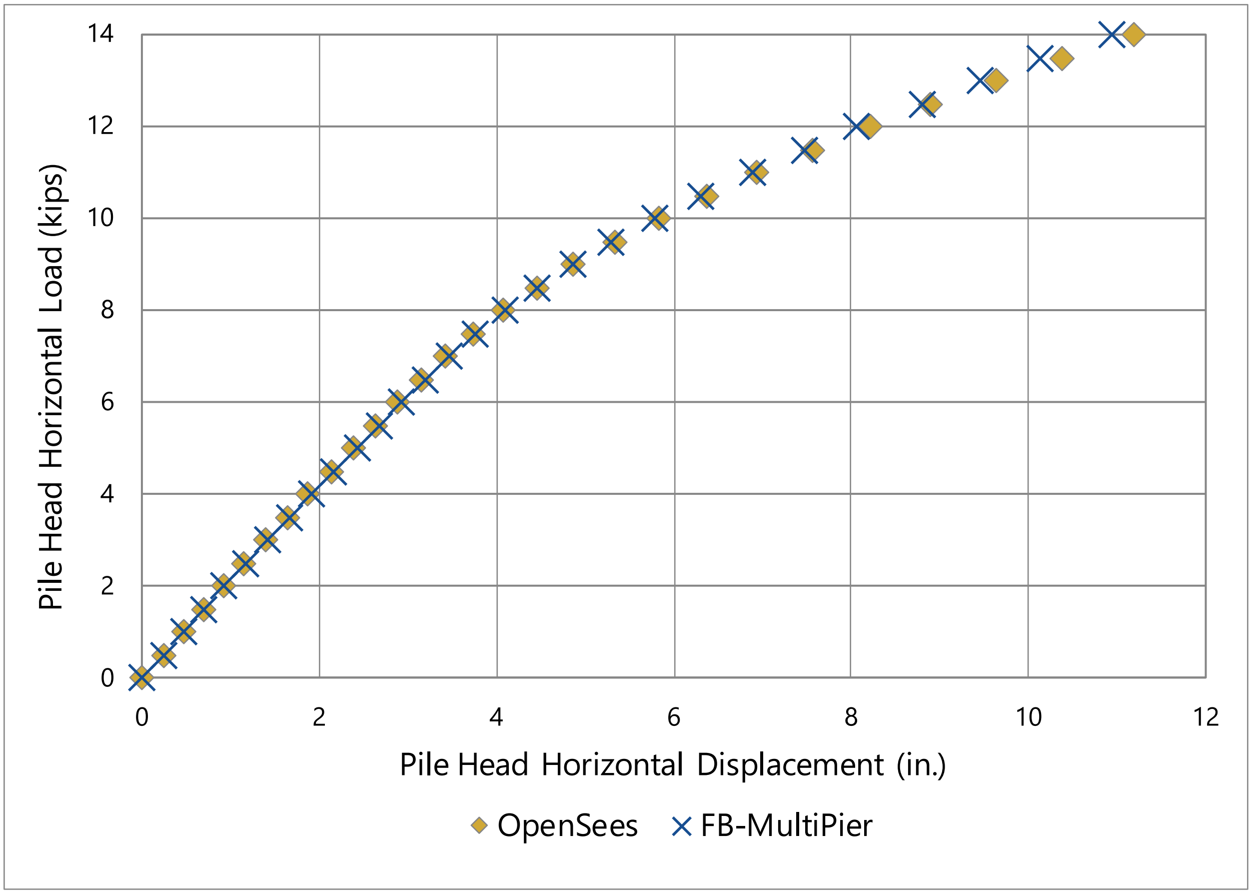
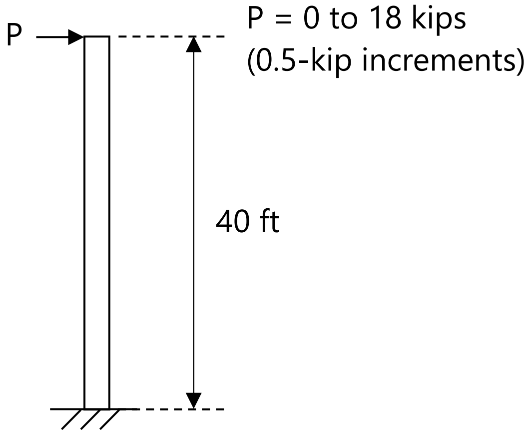
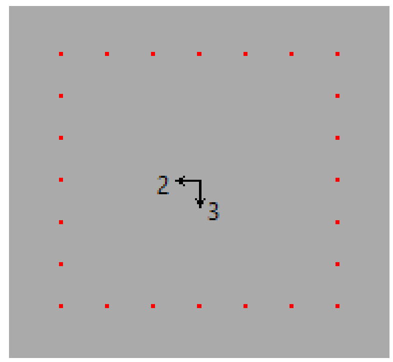


Figure 1.4 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-5: Single 24″ Square FDOT Standard Prestressed Steel

Problem Description: Analyze a single 24″ square FDOT Standard pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 18 kips in load increments of 0.5 kips).





24″ Square FDOT Standard Pile

File: *Example_1-5.in*

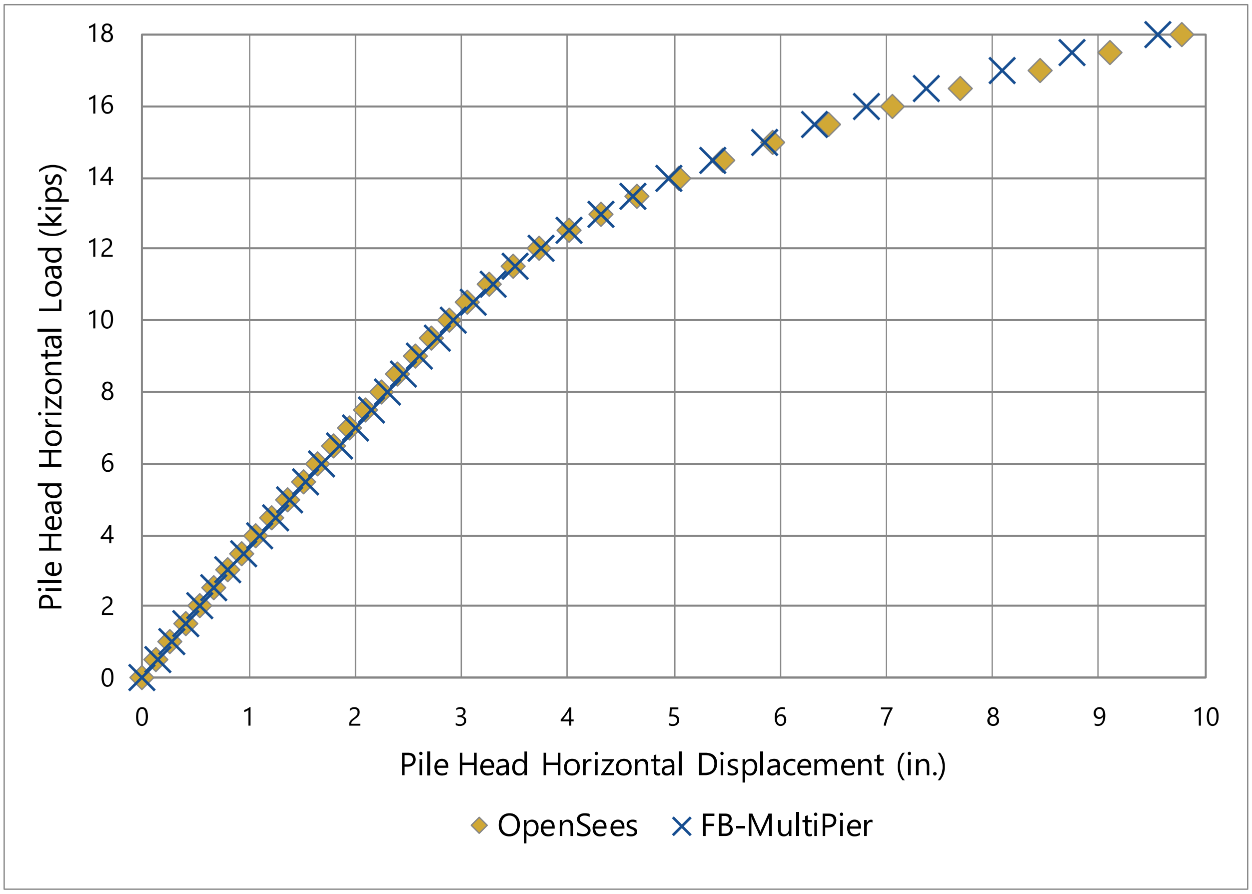
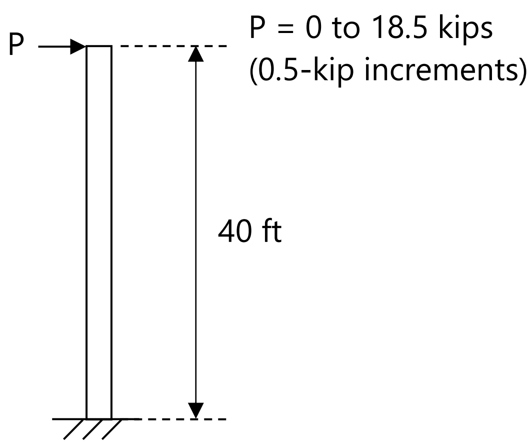
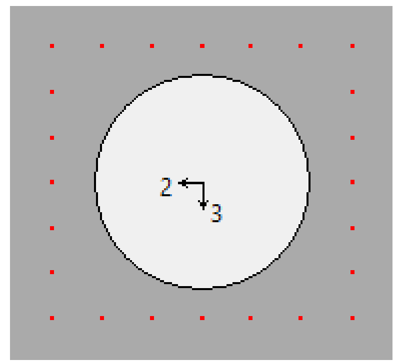


Figure 1.5 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-6: Single 30″ Square FDOT Standard Prestressed Steel

Problem Description: Analyze a single 30″ square FDOT Standard pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 18.5 kips in load increments of 0.5 kips).





30″ Square FDOT Standard Pile

File: *Example_1-6.in*

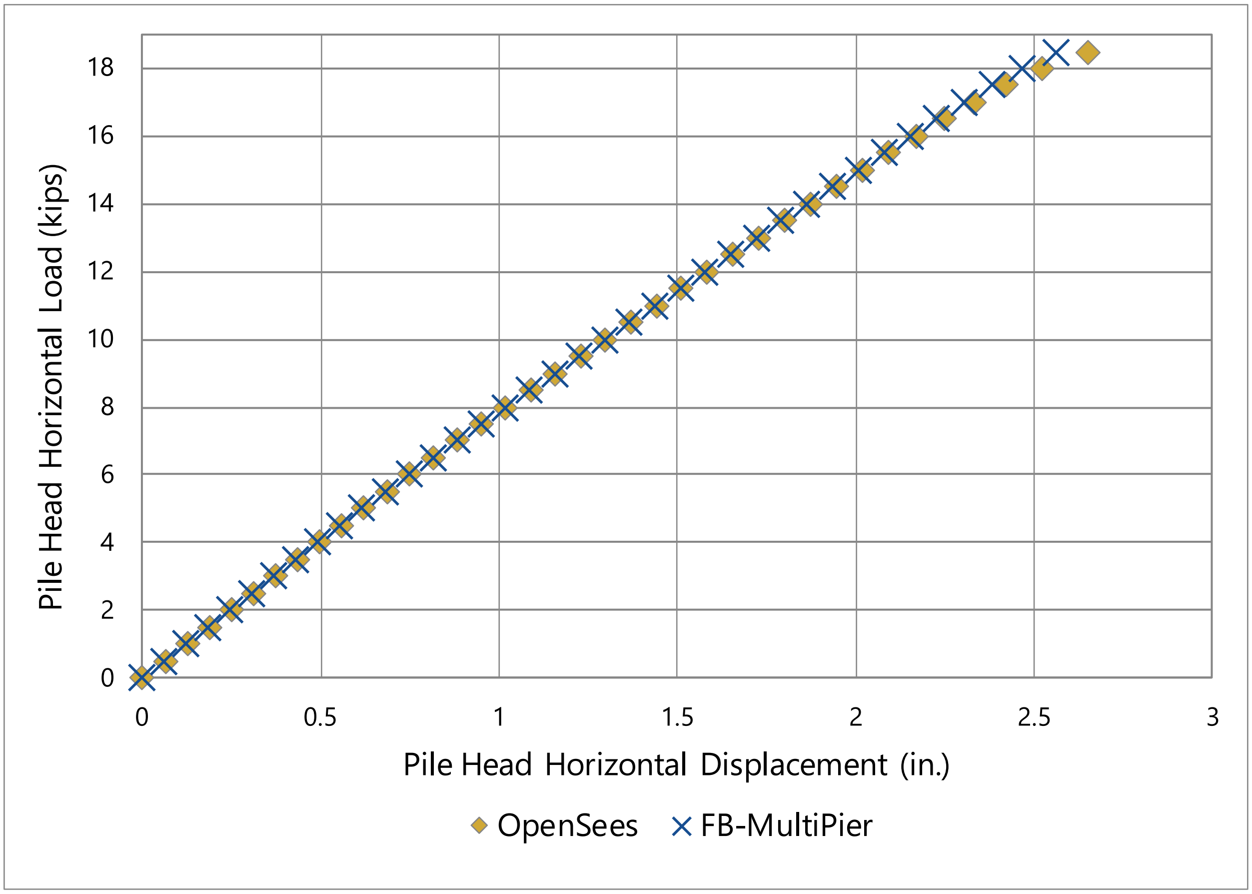
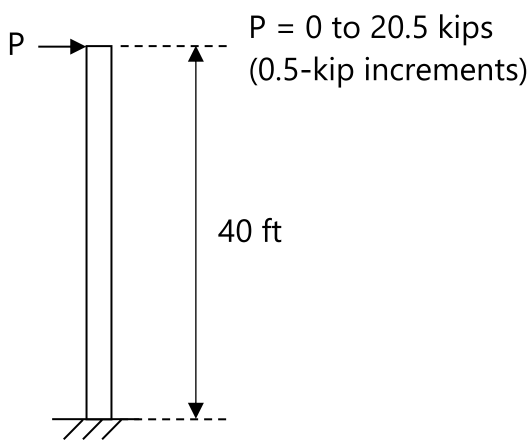
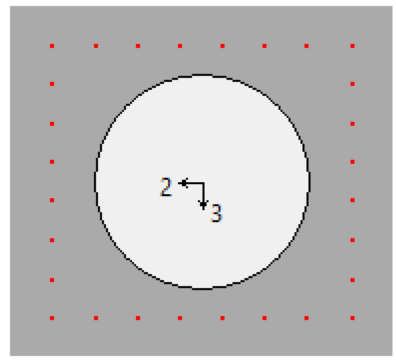


Figure 1.6 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-7: Single 30″ Square FDOT Standard Prestressed HC Steel

Problem Description: Analyze a single 30″ square FDOT Standard high moment capacity pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 20.5 kips in load increments of 0.5 kips).





12″ Square FDOT Standard Pile

File: *Example_1-7.in*

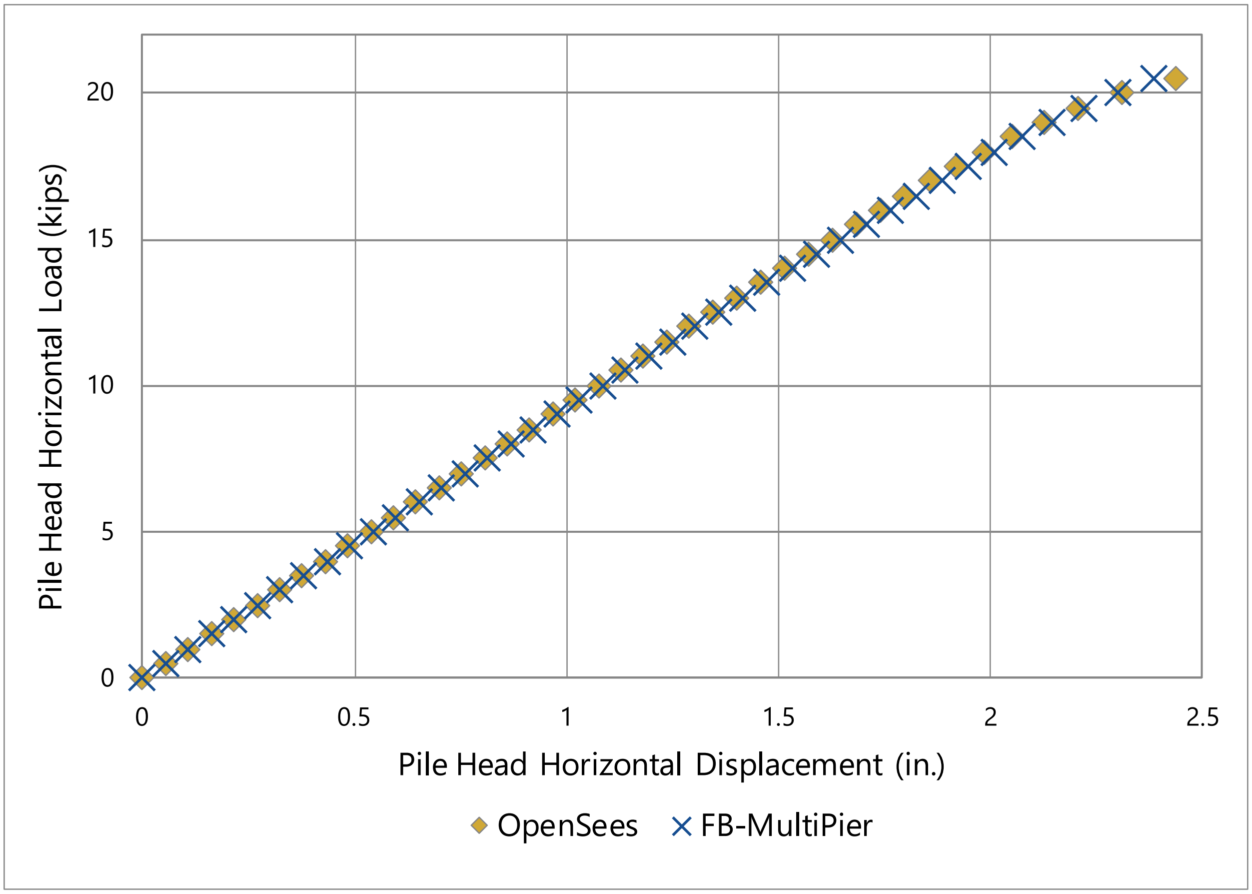
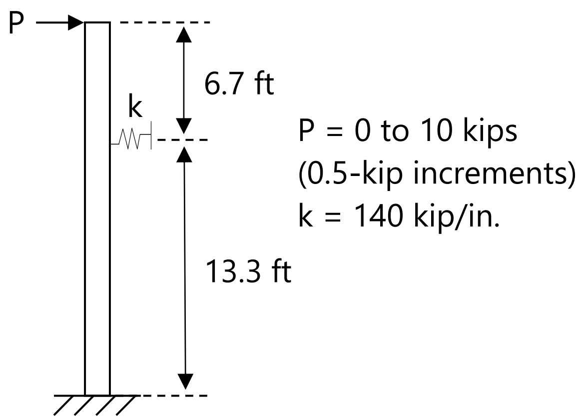
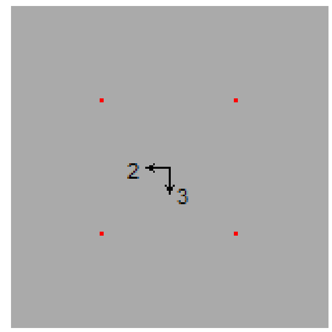


Figure 1.7 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-8: Single 12″ Prestressed CFRP

Problem Description: Analyze a single 12″ CFRP pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 10 kips in load increments of 0.5 kip).





12″ Square CFRP Pile Section

File: *Example_1-8.in*

Note: The load-moment interaction diagram for this cross-section is presented in Appendix B.

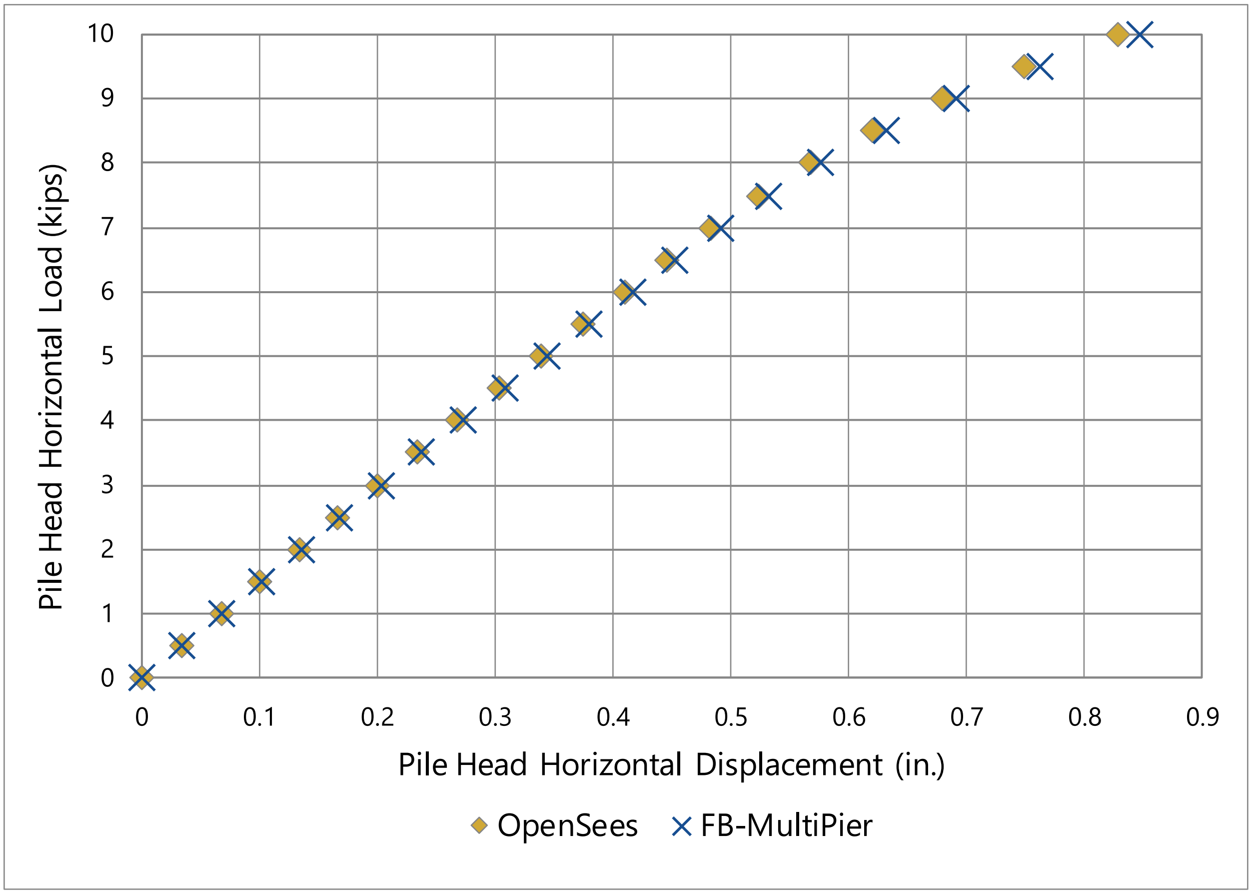
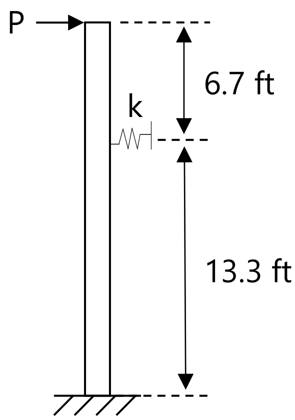


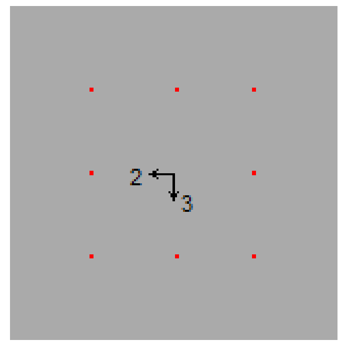
Figure 1.8 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-9: Single 14” Prestressed CFRP

Problem Description: Analyze a single 14” CFRP pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 16 kips in load increments of 1 kip).



P = 0 to 16 kips
(1-kip increments)
k = 140 kip/in.



14” Square CFRP Pile Section

File: *Example_1-9.in*

Note: The load-moment interaction diagram for this cross-section is presented in Appendix B.

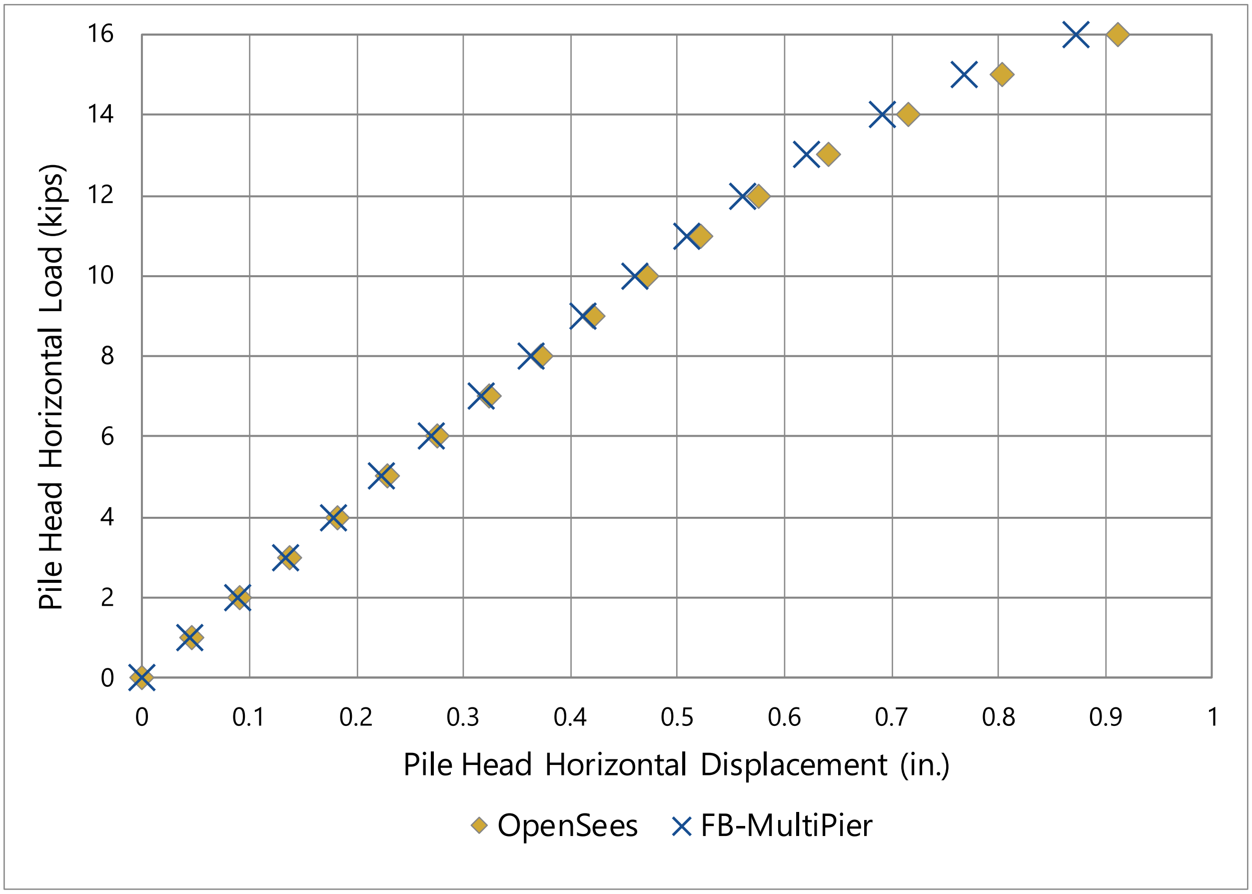
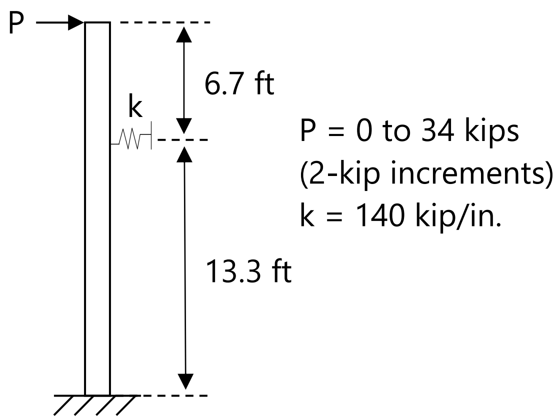
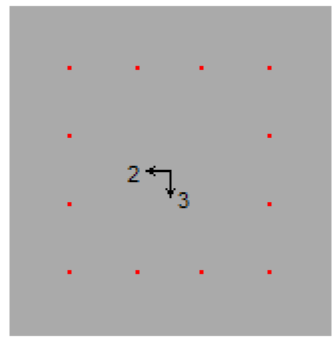


Figure 1.9 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-10: Single 18″ Prestressed CFRP

Problem Description: Analyze a single 18″ CFRP pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 34 kips in load increments of 2 kips).





18″ Square CFRP Pile Section

File: *Example_1-10.in*

Note: The load-moment interaction diagram for this cross-section is presented in Appendix B.

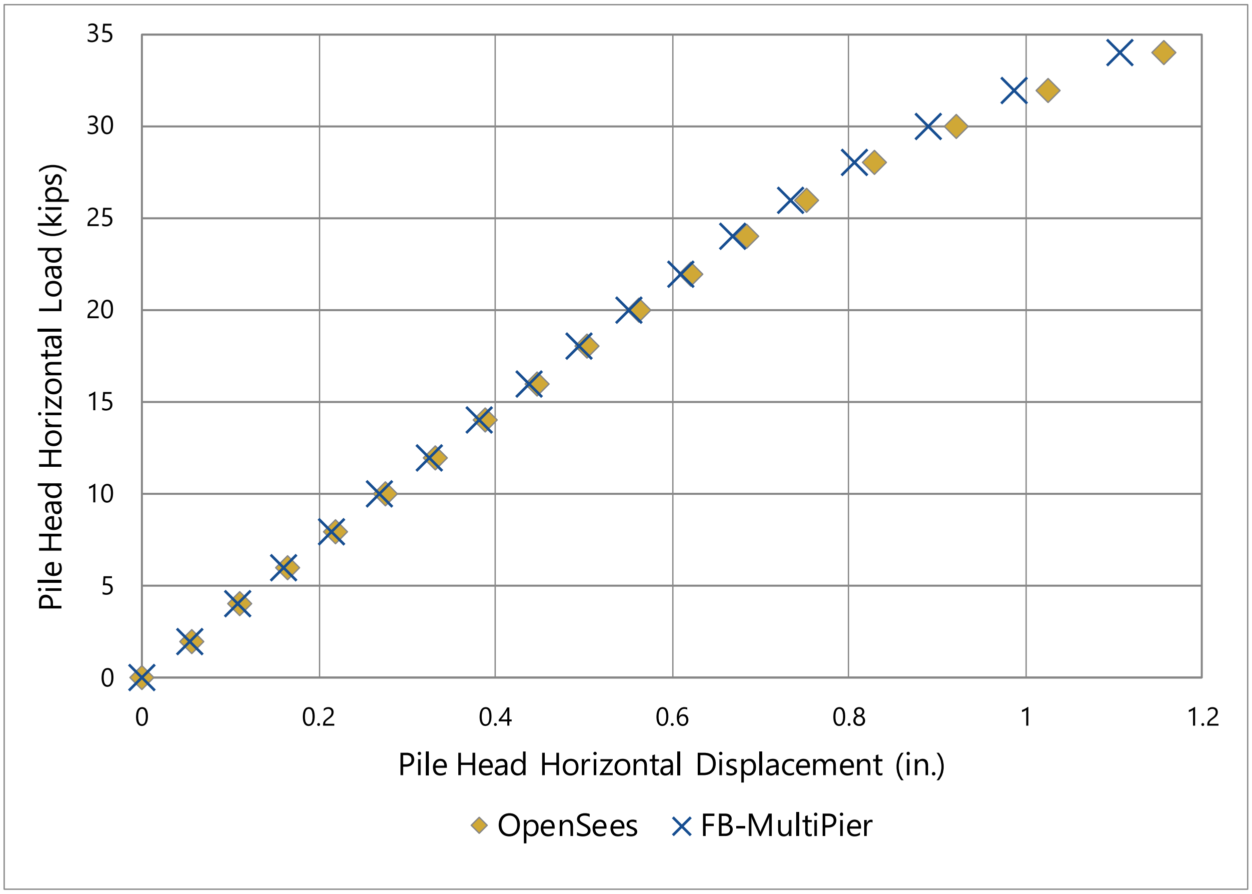
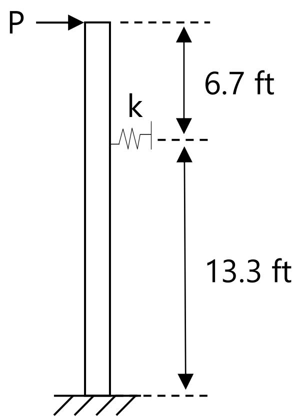


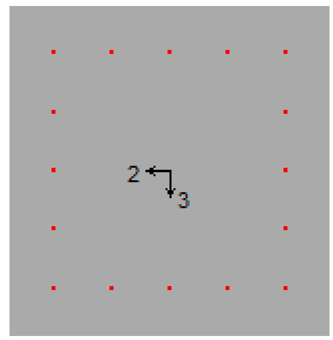
Figure 1.10 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-11: Single 24” Prestressed CFRP

Problem Description: Analyze a single 24” CFRP pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 76 kips in load increments of 4 kips).



P = 0 to 76 kips
(4-kip increments)
k = 140 kip/in.



24” Square CFRP Pile Section

File: *Example_1-11.in*

Note: The load-moment interaction diagram for this cross-section is presented in Appendix B.

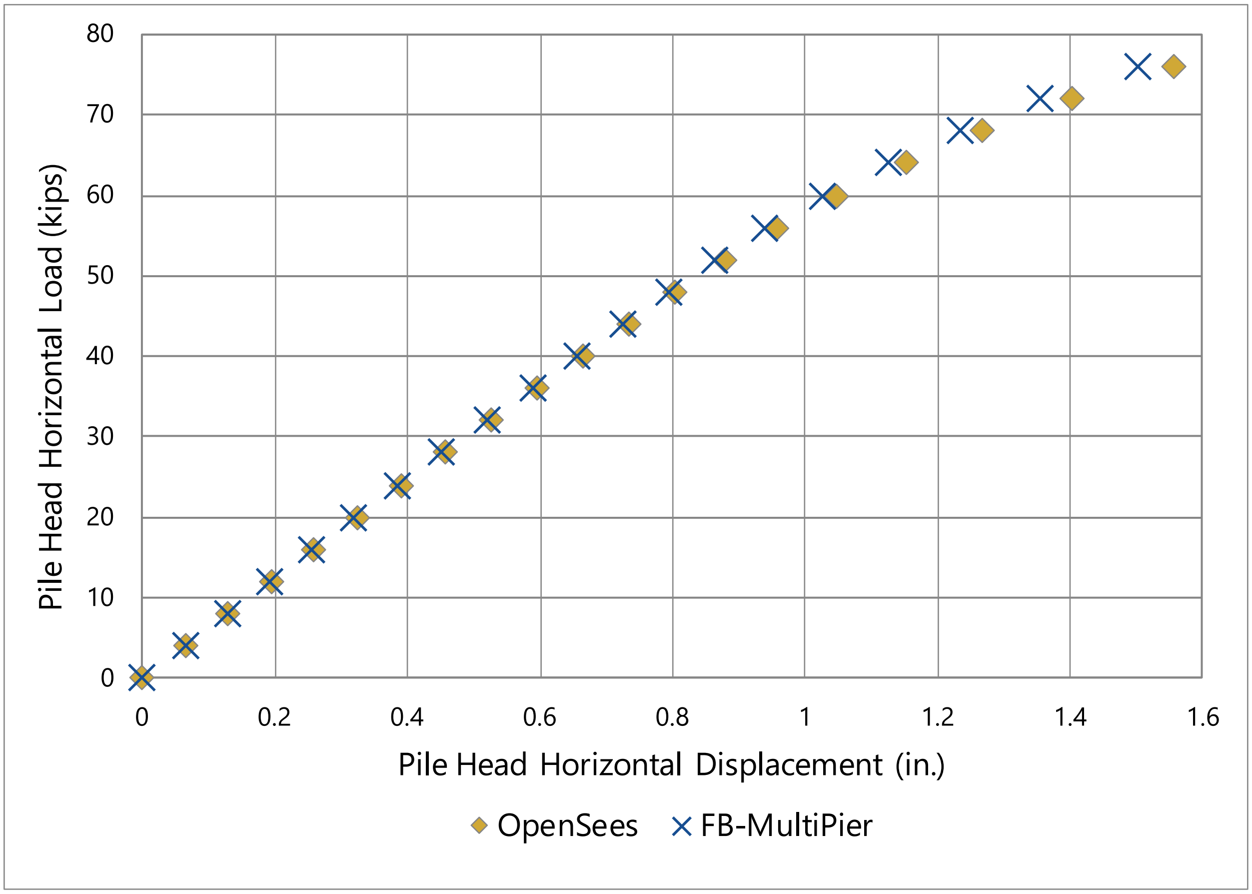
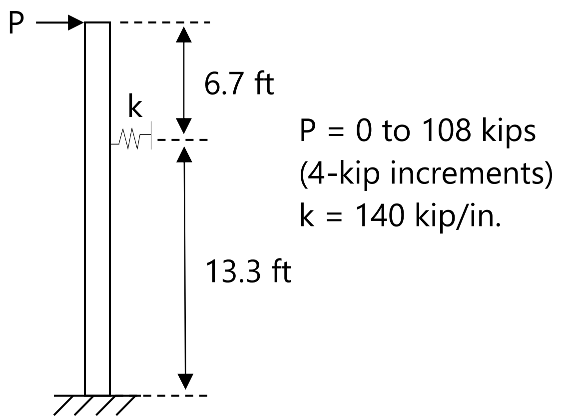
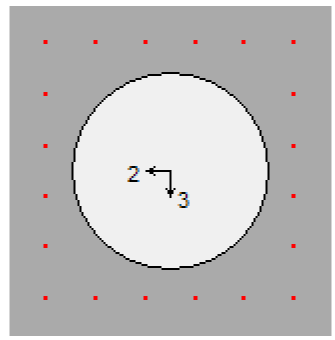


Figure 1.11 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-12: Single 30″ Prestressed CFRP

Problem Description: Analyze a single 30″ CFRP pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 108 kips in load increments of 4 kips).





30″ Square CFRP Pile Section

File: *Example_1-12.in*

Note: The load-moment interaction diagram for this cross-section is presented in Appendix B.

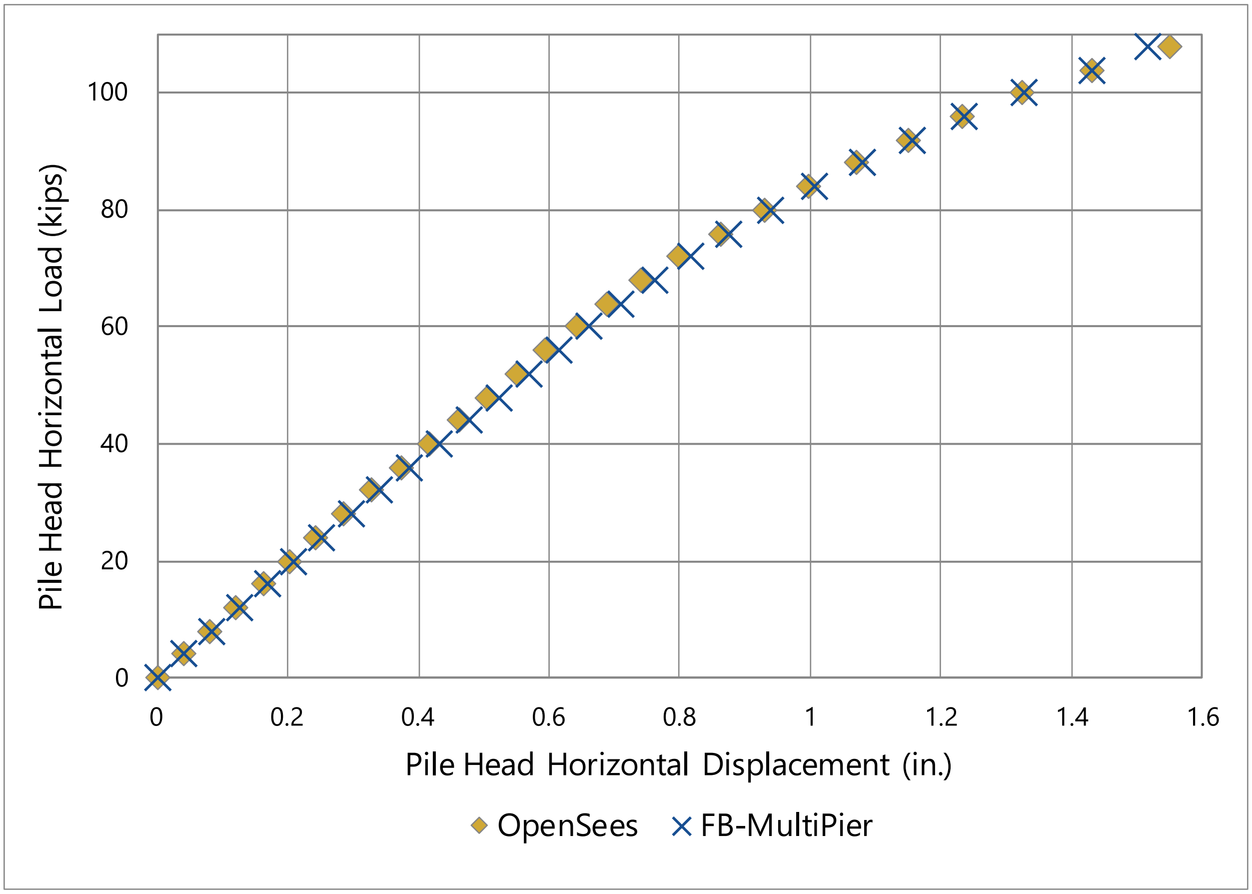
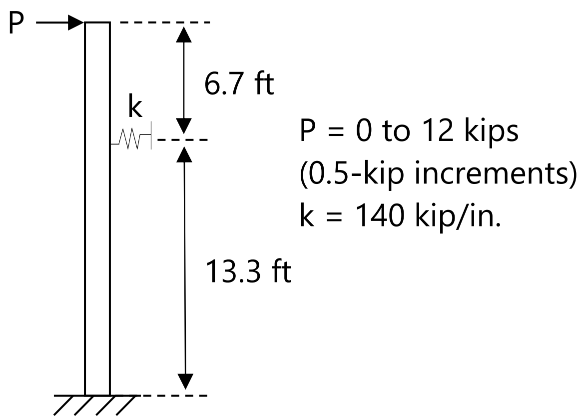
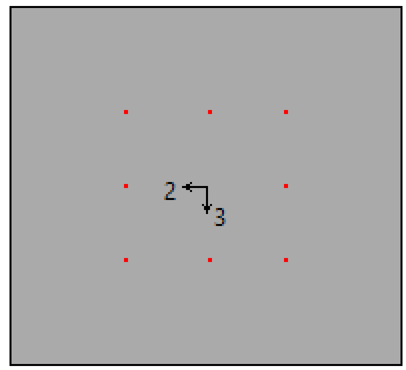


Figure 1.12 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-13: Single 12″ Prestressed HSSS

Problem Description: Analyze a single 12″ HSSS pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 12 kips in load increments of 0.5 kip).





12″ Square HSSS Pile Section

File: *Example_1-13.in*

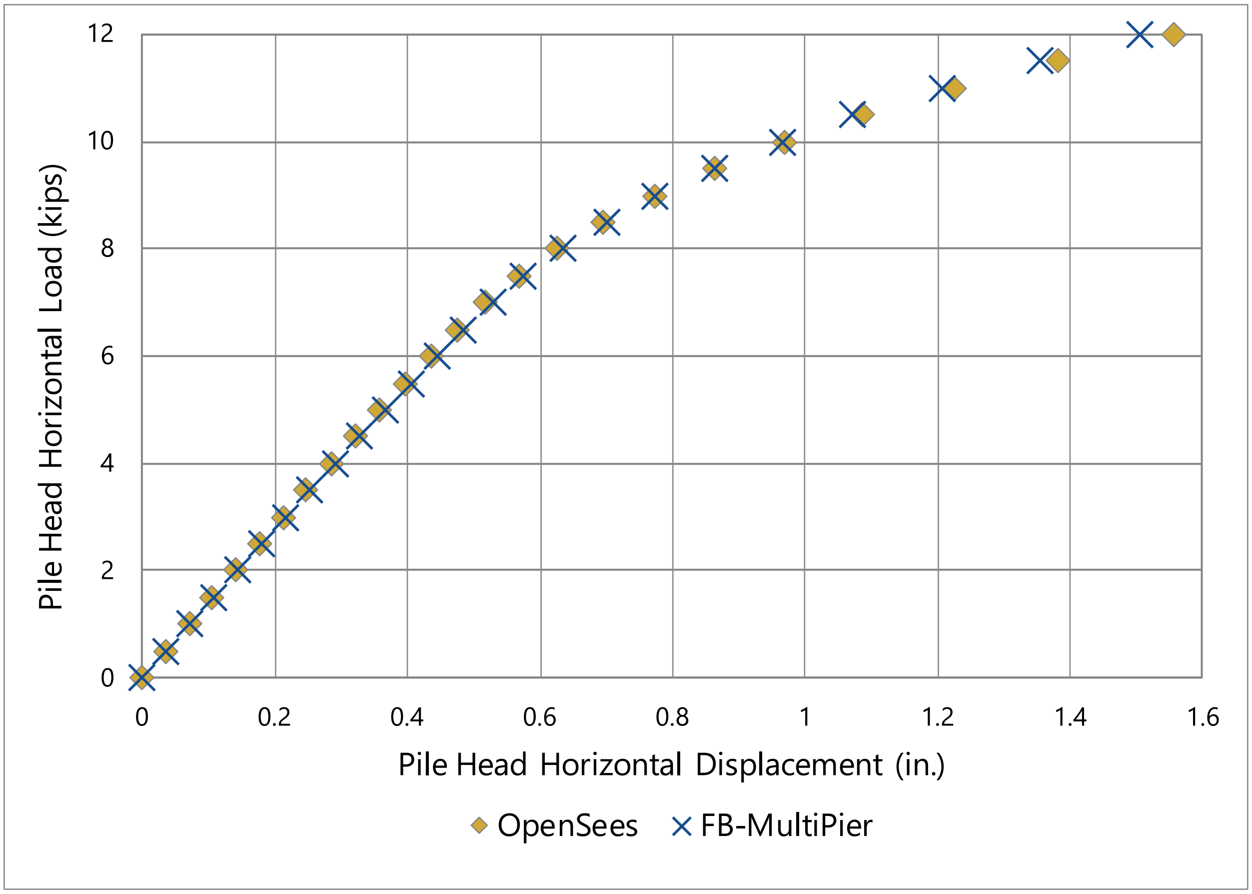
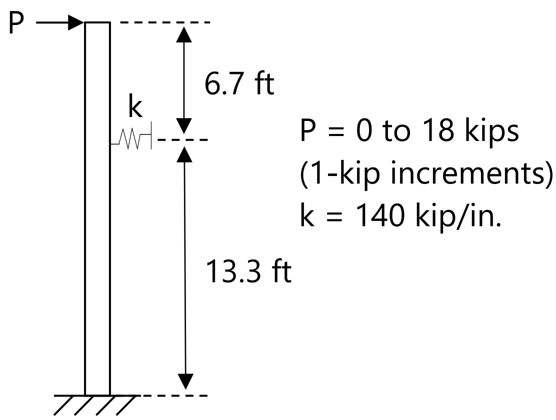
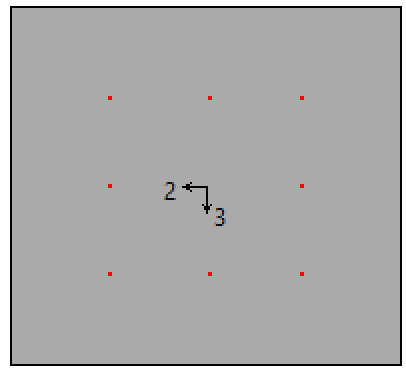


Figure 1.13 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-14: Single 14” Prestressed HSSS

Problem Description: Analyze a single 14” HSSS pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 18 kips in load increments of 1 kip).





14” Square HSSS Pile Section

File: *Example_1-14.in*

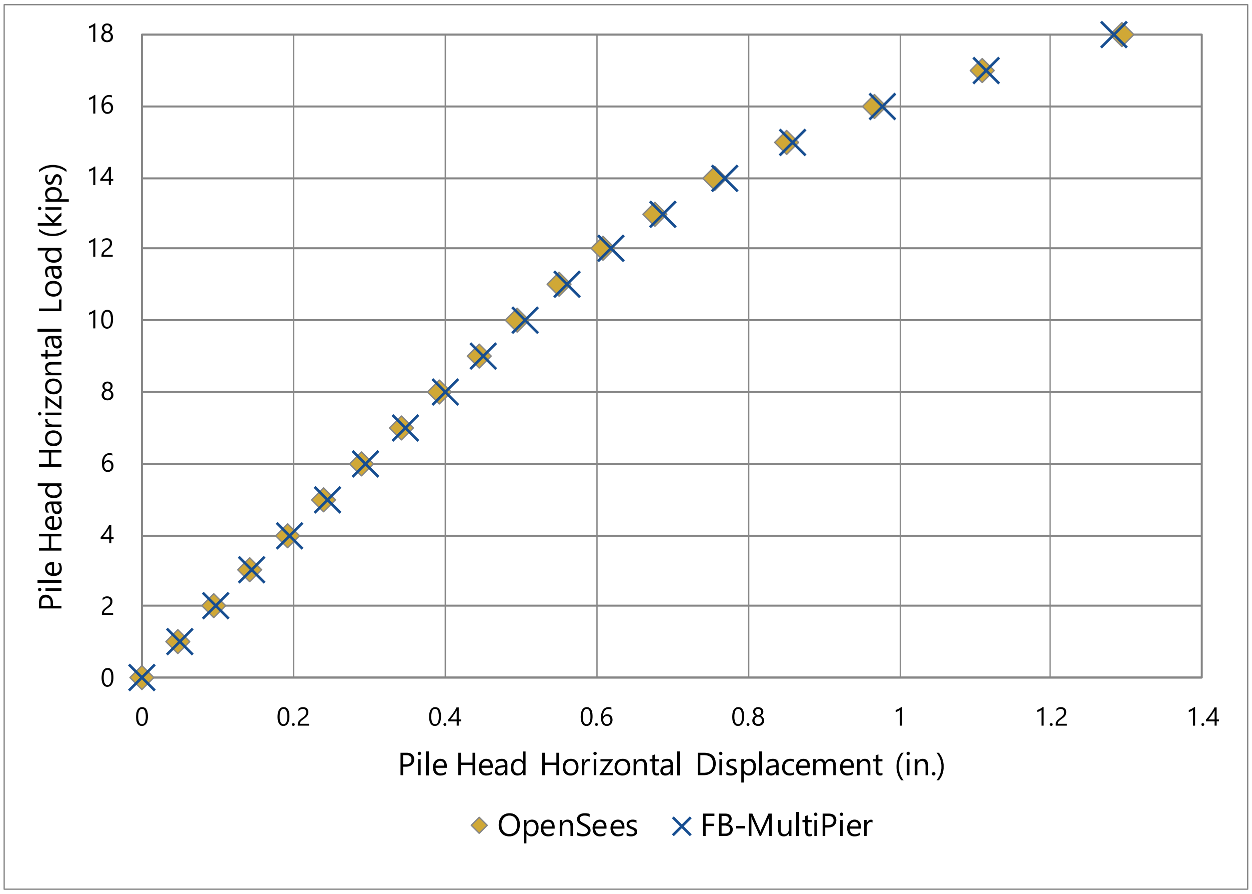
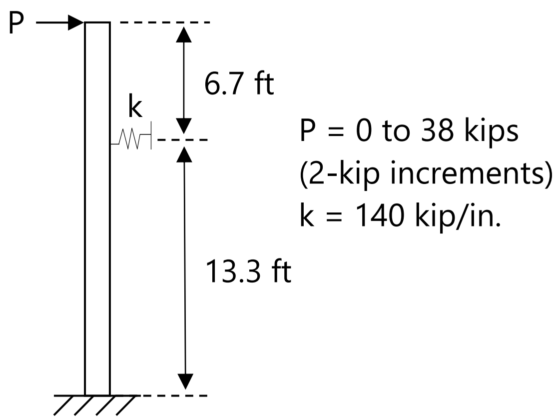
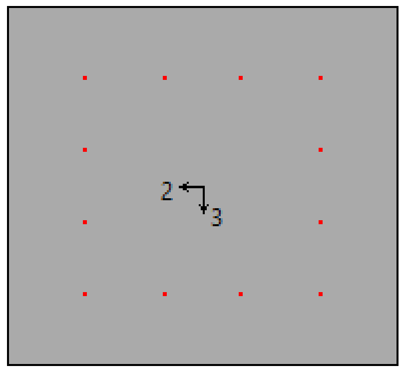


Figure 1.14 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-15: Single 18” Prestressed HSSS

Problem Description: Analyze a single 18” HSSS pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 38 kips in load increments of 2 kips).





18” Square HSSS Pile Section

File: *Example_1-15.in*

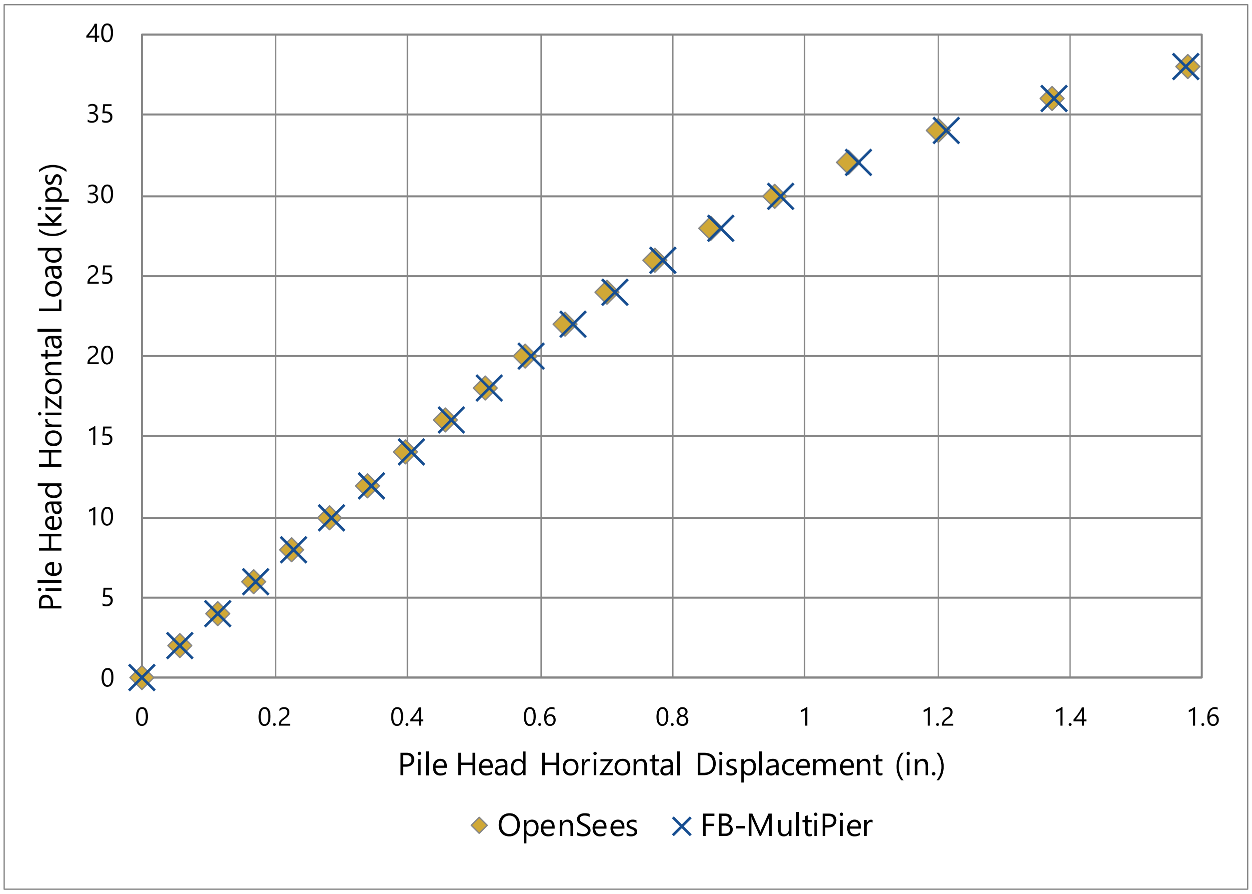
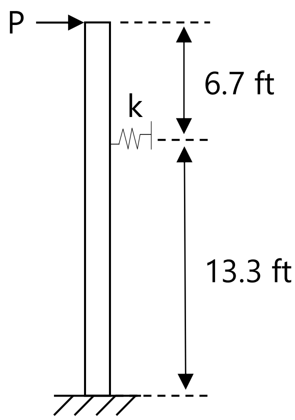


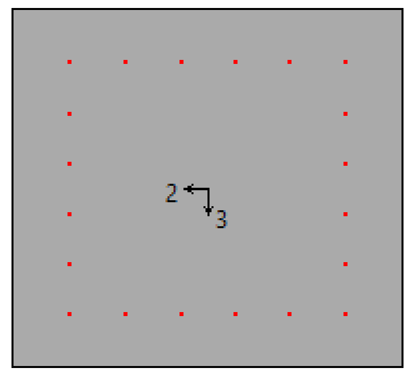
Figure 1.15 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-16: Single 24” Prestressed HSSS

Problem Description: Analyze a single 24” HSSS pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 84 kips in load increments of 4 kips).



P = 0 to 84 kips
(4-kip increments)
k = 140 kip/in.



24” Square HSSS Pile Section

File: *Example_1-16.in*

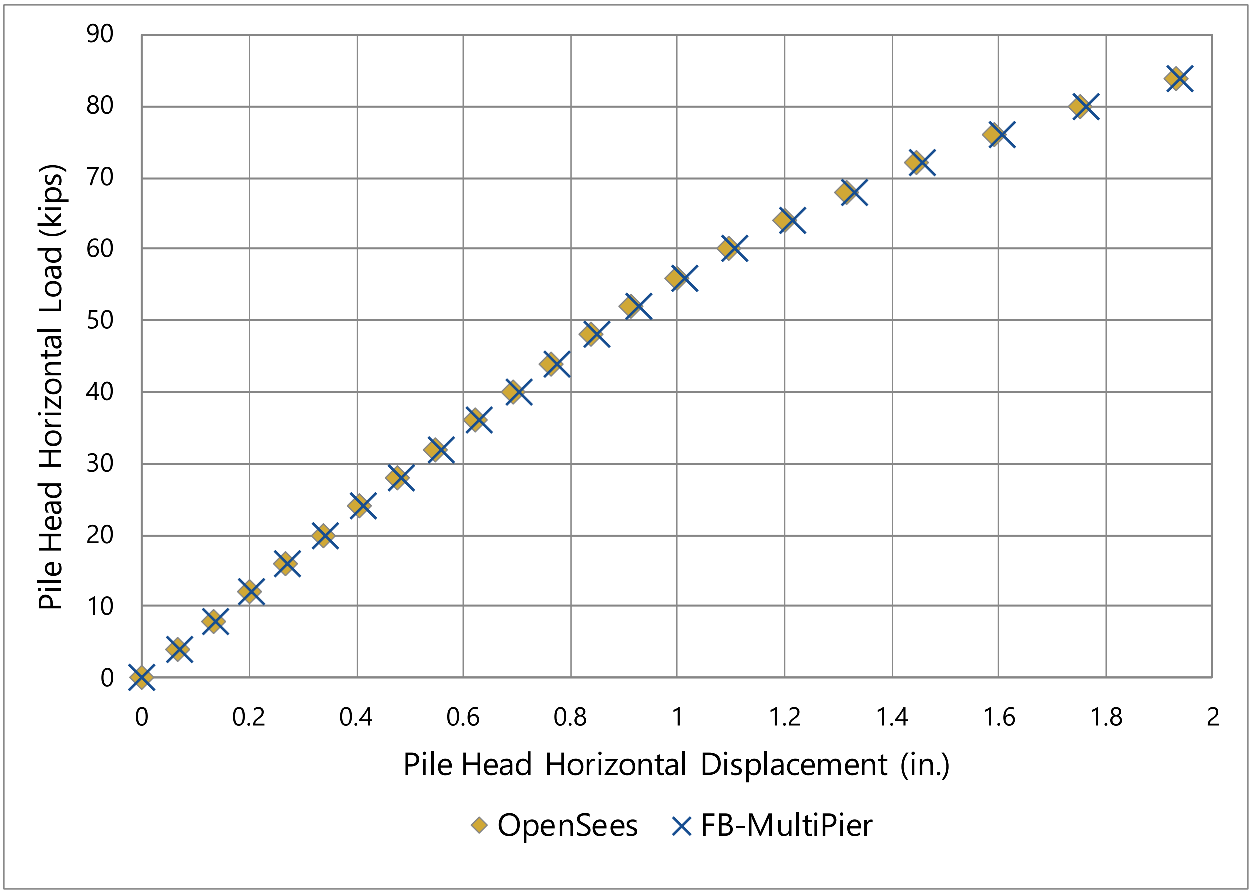
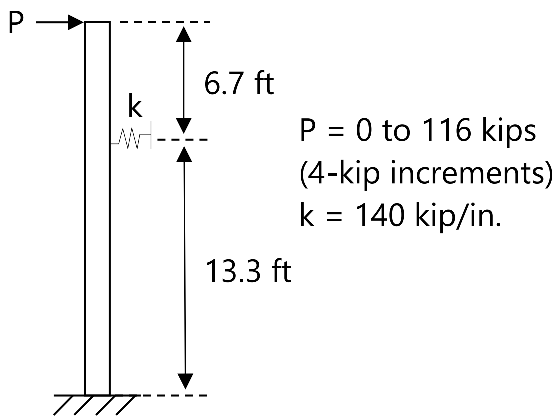
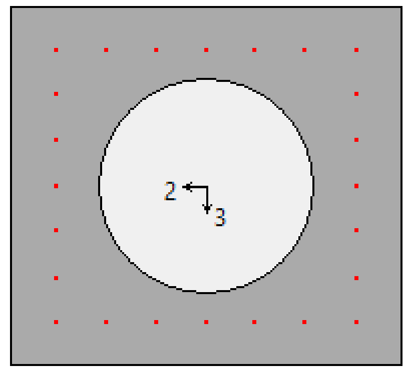


Figure 1.16 – Comparison of Results Between FB-MultiPier and OpenSees

Example 1-17: Single 30″ Prestressed HSSS

Problem Description: Analyze a single 30″ HSSS pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 116 kips in load increments of 4 kips).





30″ Square HSSS Pile Section

File: *Example_1-17.in*

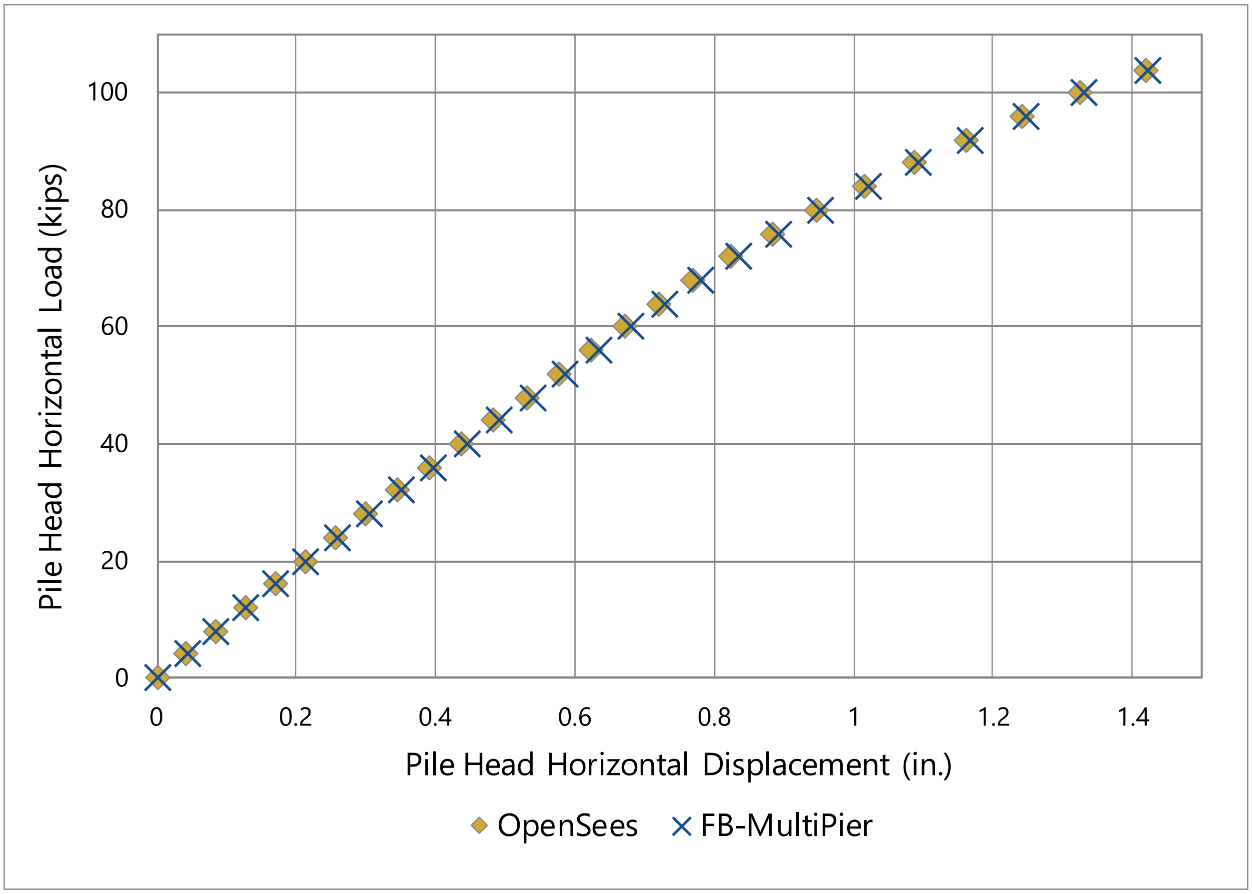


Figure 1.17 – Comparison of Results Between FB-MultiPier and OpenSees

Chapter 2

Circular Piles

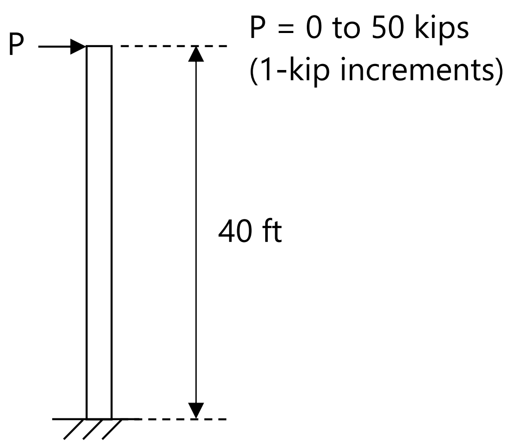
In this chapter, pile head horizontal displacement results are compared as obtained from nonlinear static analyses of laterally loaded circular piles (including cylinder piles, pipe piles, and drilled shafts with casing) in FB-MultiPier and OpenSees. Because the focus of this verification effort is placed on assessing the nonlinear fiber-integrated frame element implementation in FB-MultiPier, relatively simple structural configurations are investigated. Namely, several of the configurations considered are modeled as free-standing piles with fixed bases. Other cases are modeled as a pile that is fitted with a single lateral spring at some distance from the pile head along with a fixed base. In all cases, lateral loads are placed at the pile head. Also, for all cases, structure-only analyses are conducted with no detailed treatment of surrounding soil.

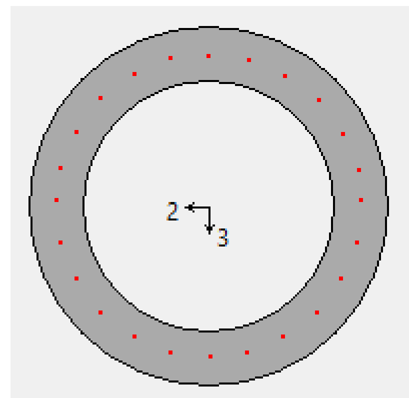
Lateral load response comparisons are made between the pile head horizontal displacements computed by FB-MultiPier and OpenSees over a range of lateral loads. Whenever feasible, the range of lateral loading is chosen such that a nonlinear response is visibly evident among the computed pile head horizontal displacements. Nonlinear behavior of piles and shafts in FB-MultiPier is modeled in a manner that is consistent with available features within OpenSees (i.e., fiber-integrated frame elements), which computes resultant forces using numerical integration of cross-section stresses over numerous integration points (called fibers). Upon request, FB-MultiPier models may be made available to licensed program users.

Stress-strain relationships used in the analyses are presented in Appendix A. For selected cross-sections, the associated load-moment interaction diagrams are presented in Appendix B.

Example 2-1: Single 54″ Cylindrical FDOT Standard Prestressed Steel

Problem Description: Analyze a single 54″ cylindrical FDOT Standard pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 50 kips in load increments of 1 kip).





54″ Square FDOT Standard Pile

File: *Example_2-1.in*

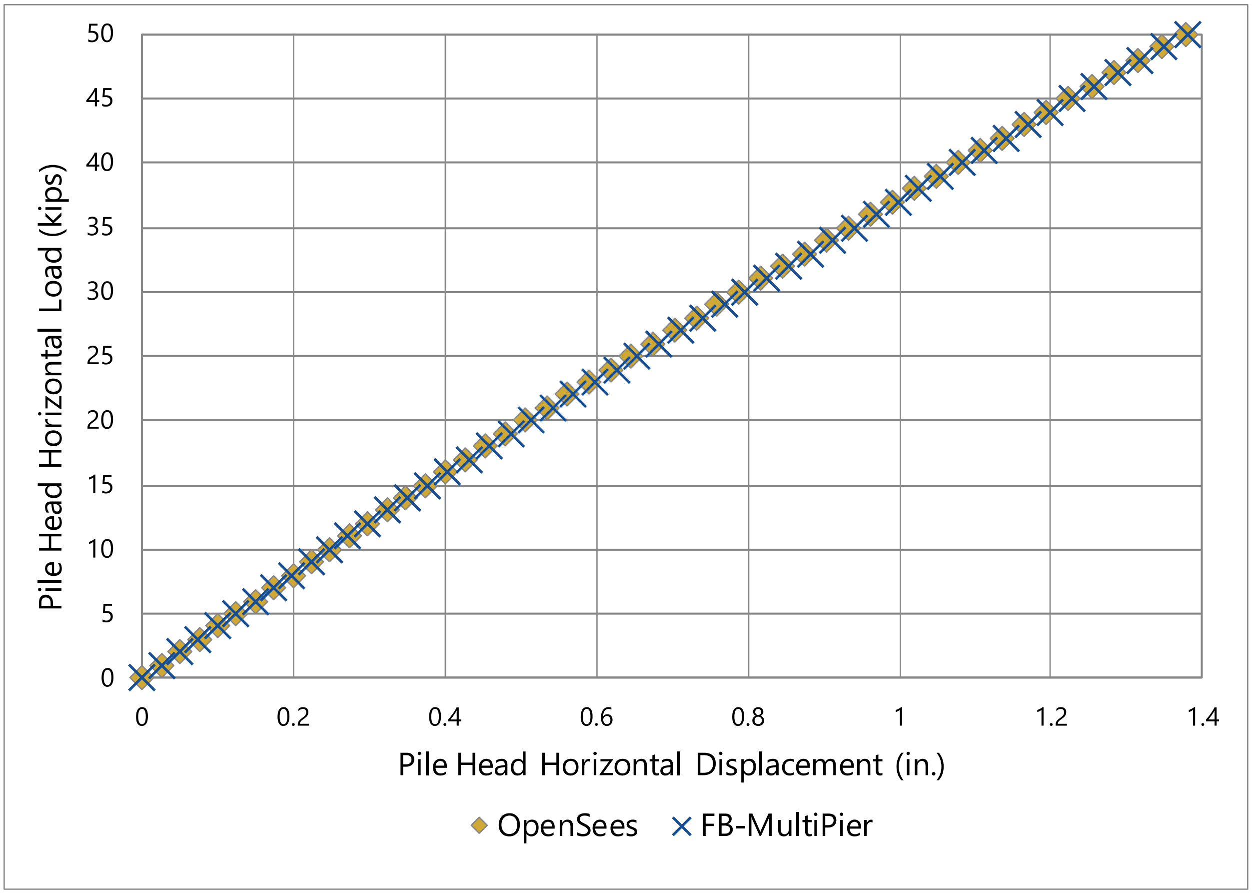
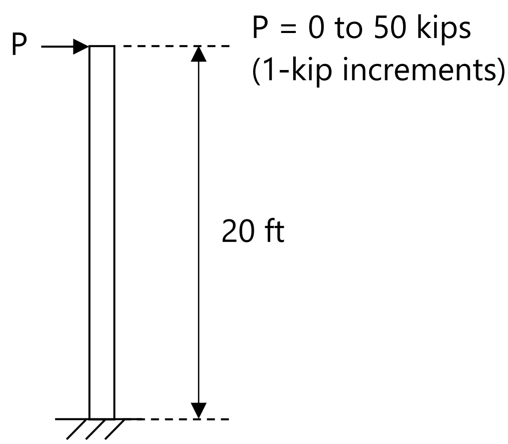
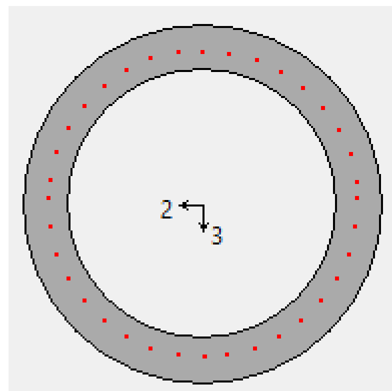


Figure 2.1 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-2: Single 60″ Cylindrical FDOT Standard Prestressed Steel

Problem Description: Analyze a single 60″ cylindrical FDOT Standard pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 50 kips in load increments of 1 kip).





60″ Square FDOT Standard Pile

File: *Example_2-2.in*

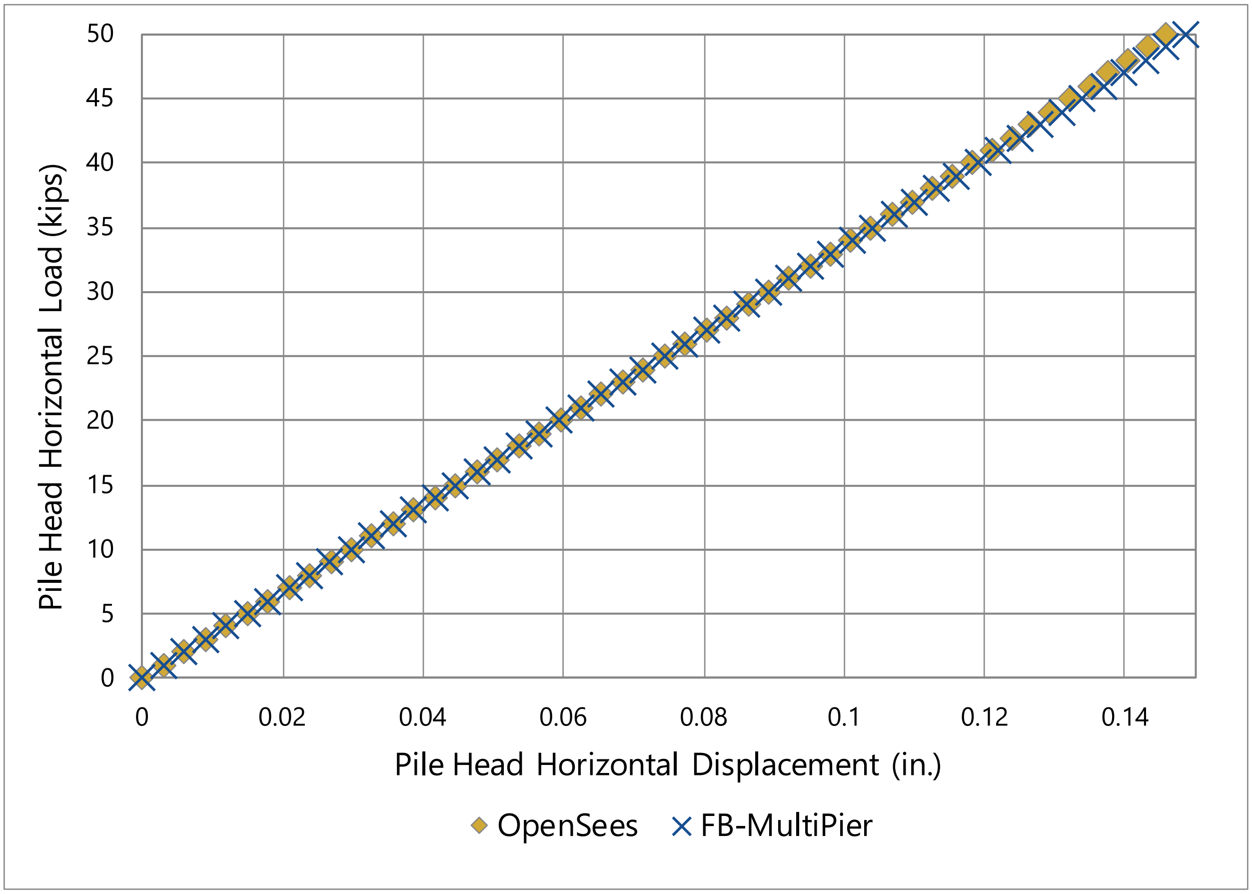
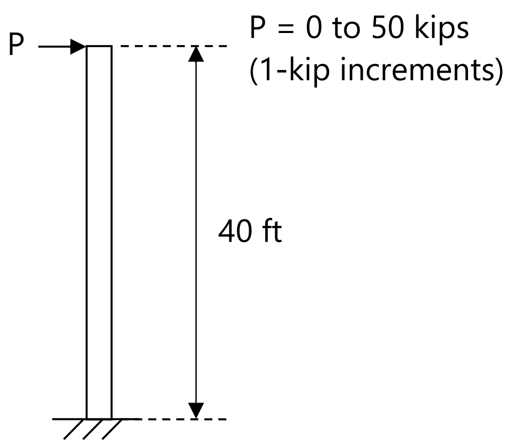
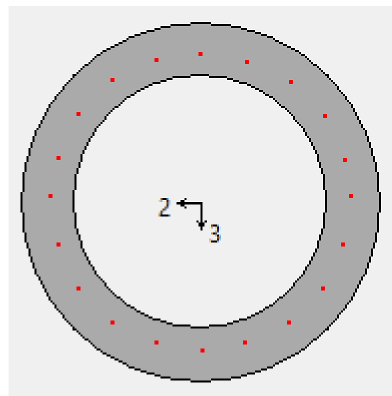


Figure 2.2 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-3: Single 54″ Cylinder Pile

Problem Description: Analyze a single 54″ cylinder pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 50 kips in load increments of 1 kip).





54″ Cylinder Pile Section

File: *Example_2-3.in*

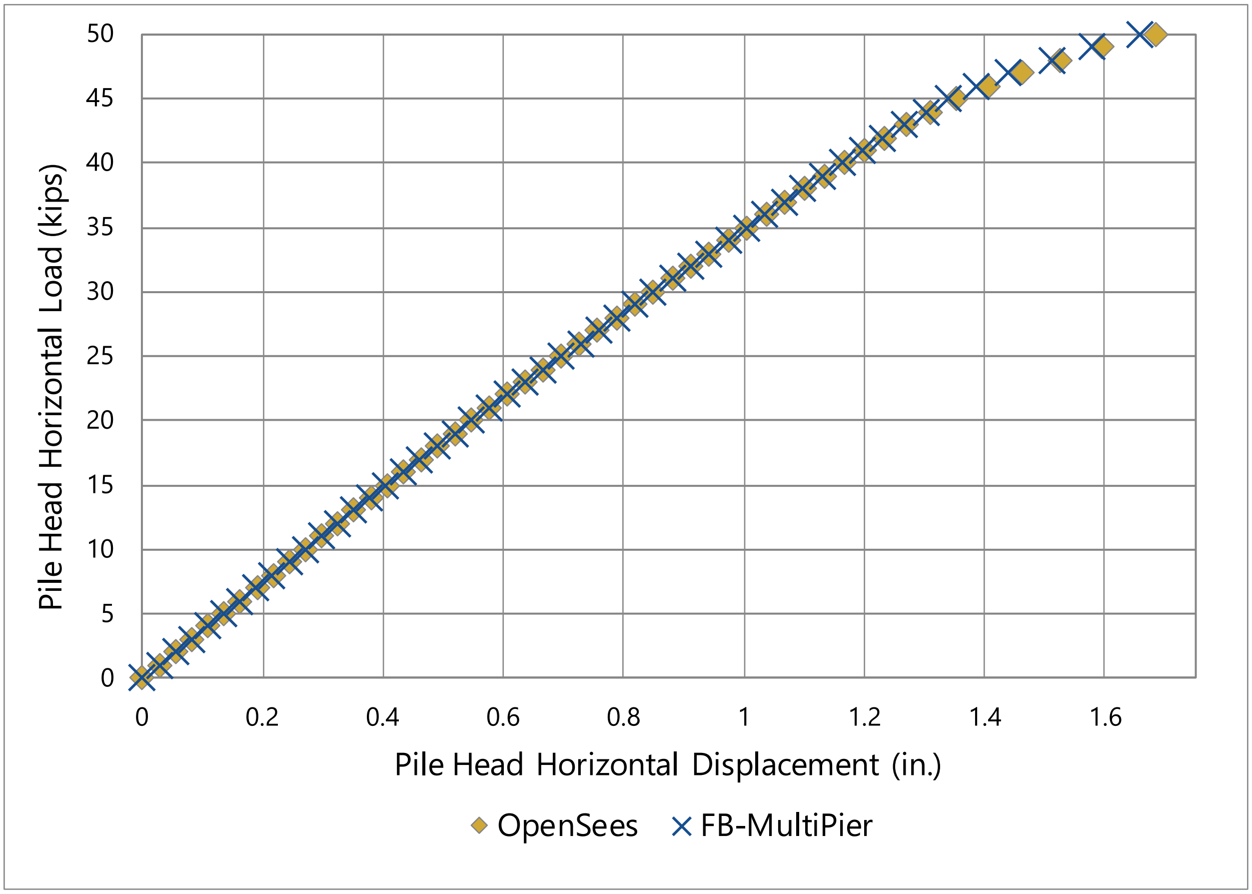
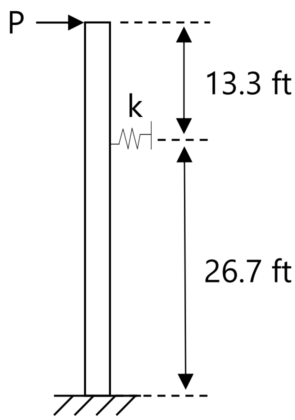


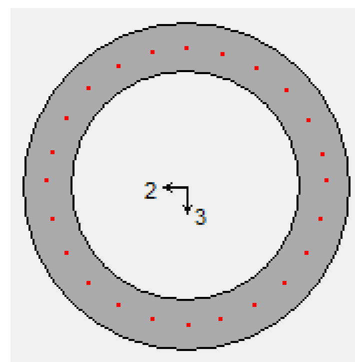
Figure 2.3 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-4: Single 54” Prestressed CFRP

Problem Description: Analyze a single 54” CFRP pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 192 kips in load increments of 8 kips).



P = 0 to 192 kips
(8-kip increments)
k = 140 kip/in.



54” Cylindrical CFRP Pile Section

File: *Example_2-4.in*

Note: The load-moment interaction diagram for this cross-section is presented in Appendix B.

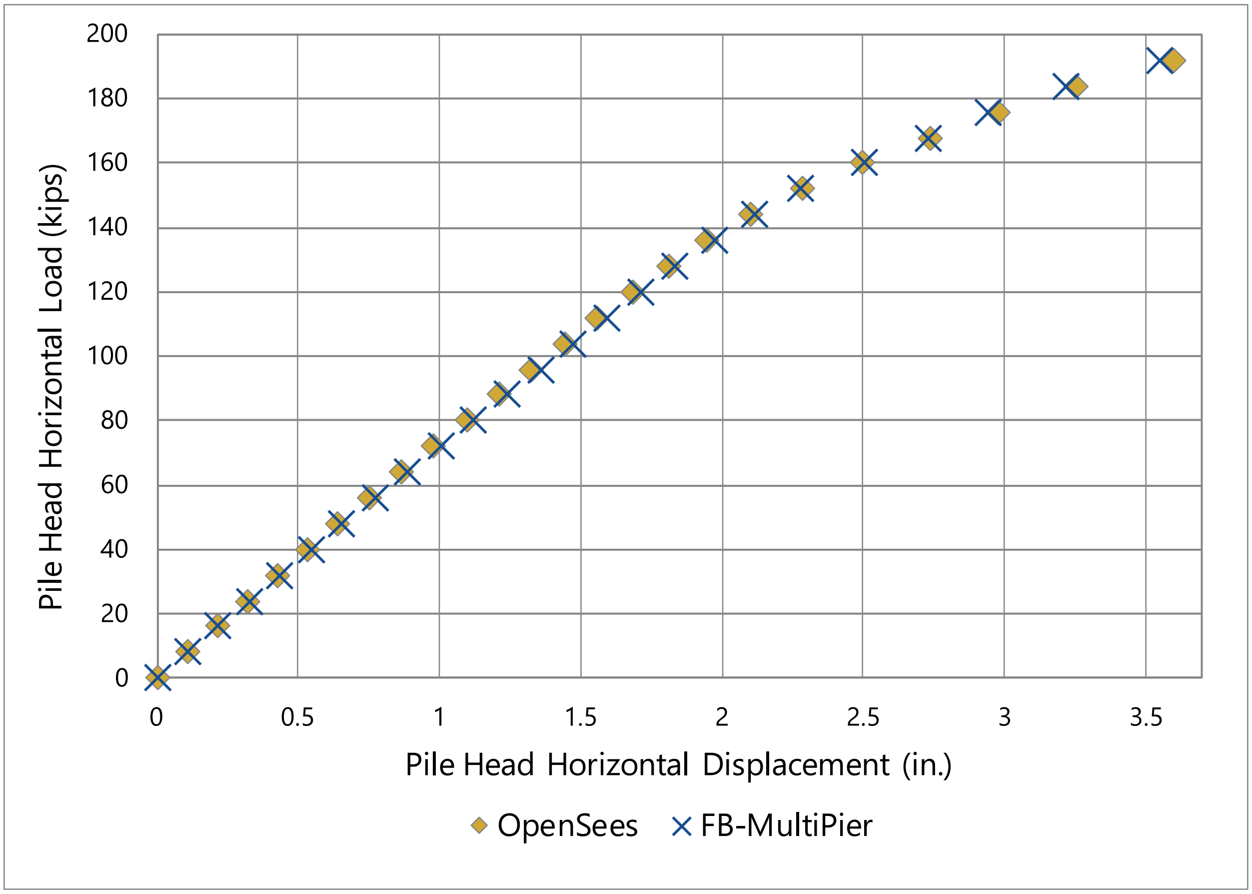
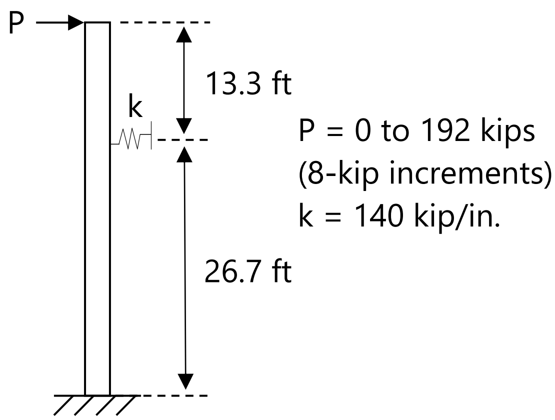
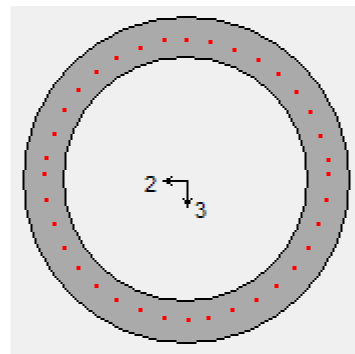


Figure 2.4 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-5: Single 60″ Prestressed CFRP

Problem Description: Analyze a single 60″ CFRP pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 192 kips in load increments of 8 kips).





60″ Cylindrical CFRP Pile Section

File: *Example_2-5.in*

Note: The load-moment interaction diagram for this cross-section is presented in Appendix B.

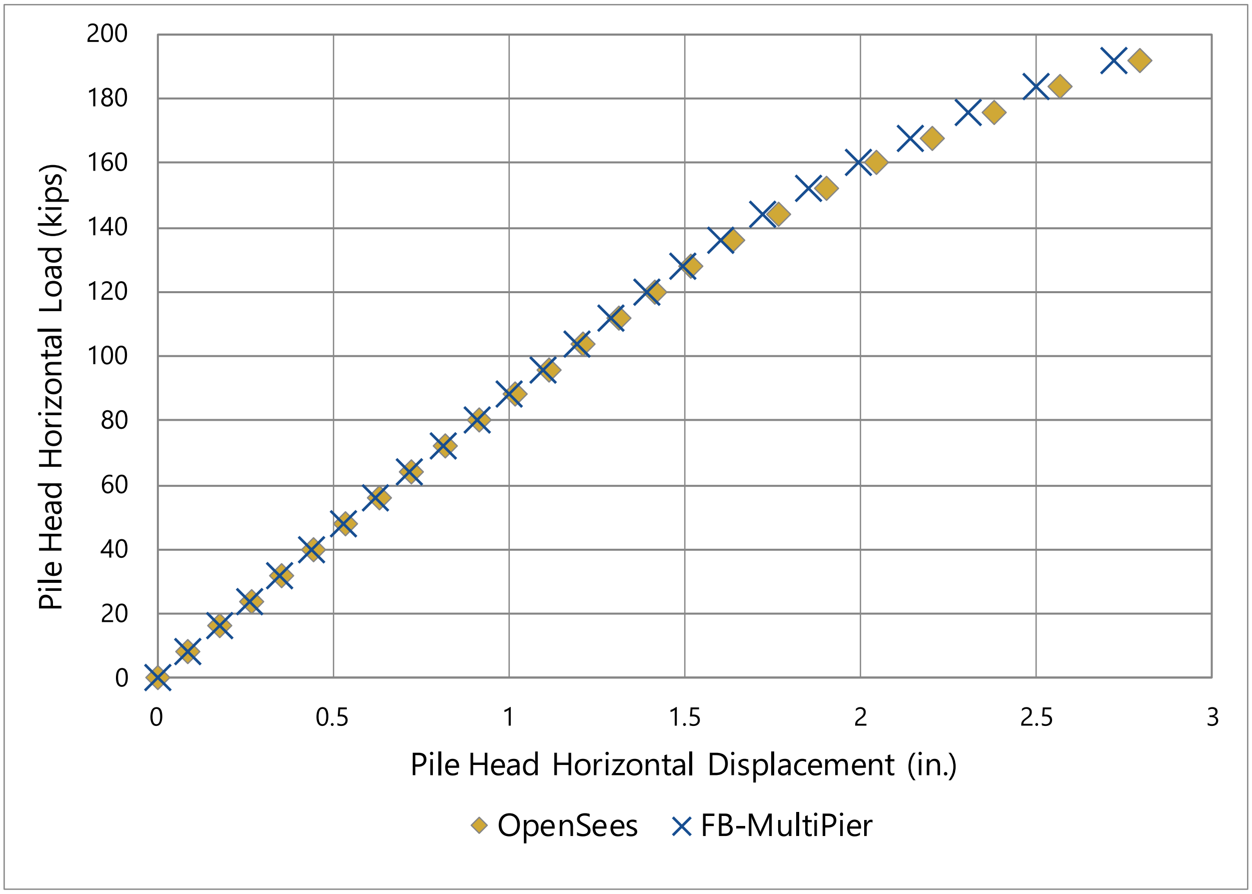
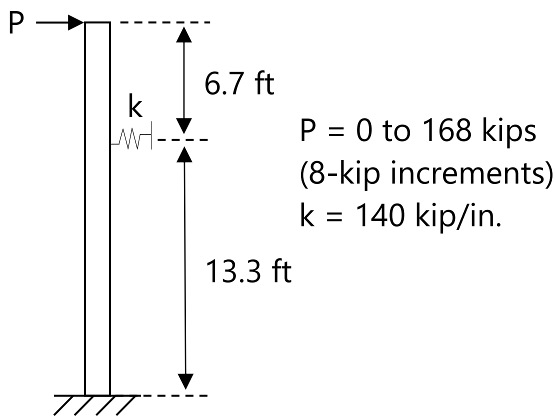
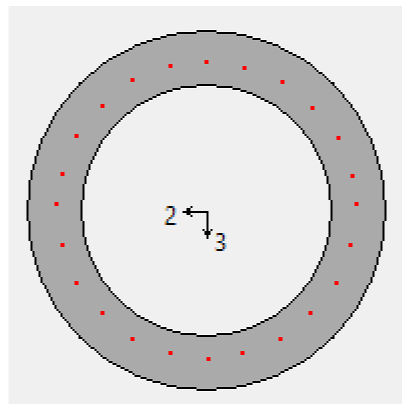


Figure 2.5 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-6: Single 54” Prestressed HSSS

Problem Description: Analyze a single 54” HSSS pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 168 kips in load increments of 8 kips).





54” Cylindrical HSSS Pile Section

File: *Example_2-6.in*

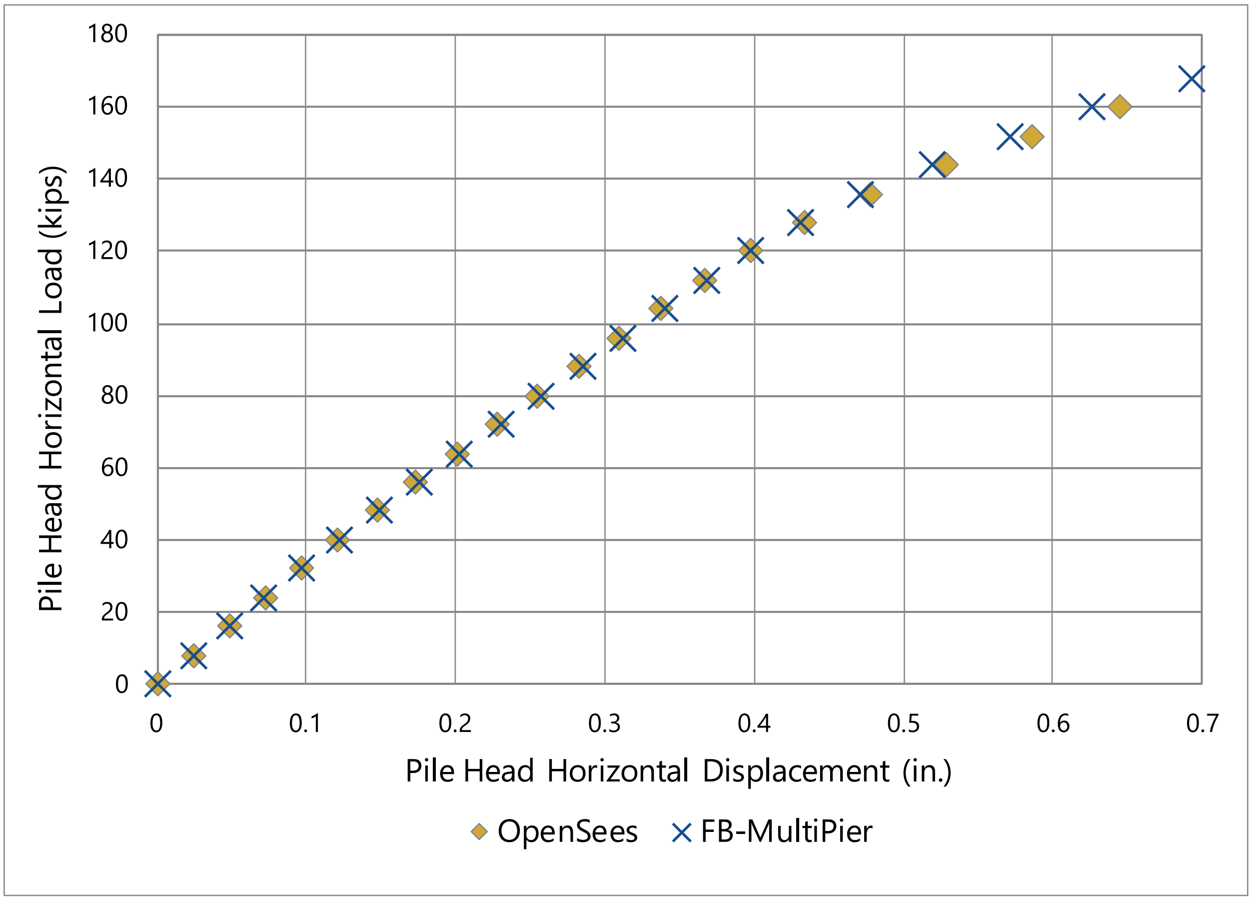
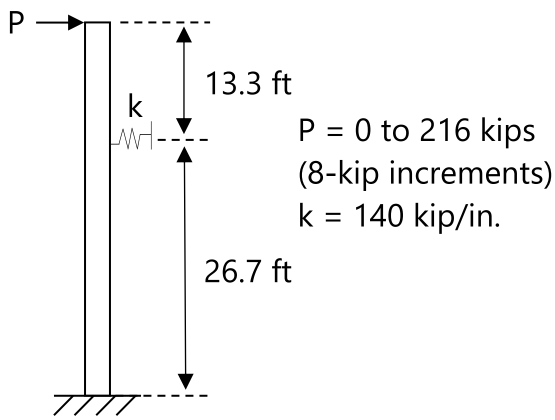
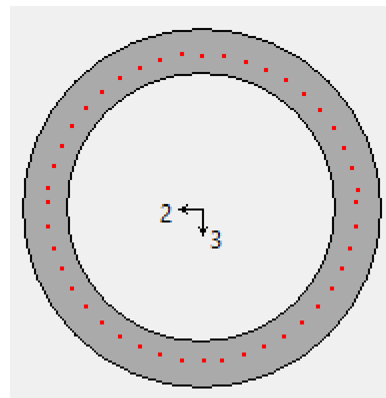


Figure 2.6 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-7: Single 60” Prestressed HSSS

Problem Description: Analyze a single 60” HSSS pile cross-section with a fixed base and lateral bracing subjected to lateral loading of different magnitudes (0 kips to 216 kips in load increments of 8 kips).





60” Cylindrical HSSS Pile Section

File: *Example_2-7.in*

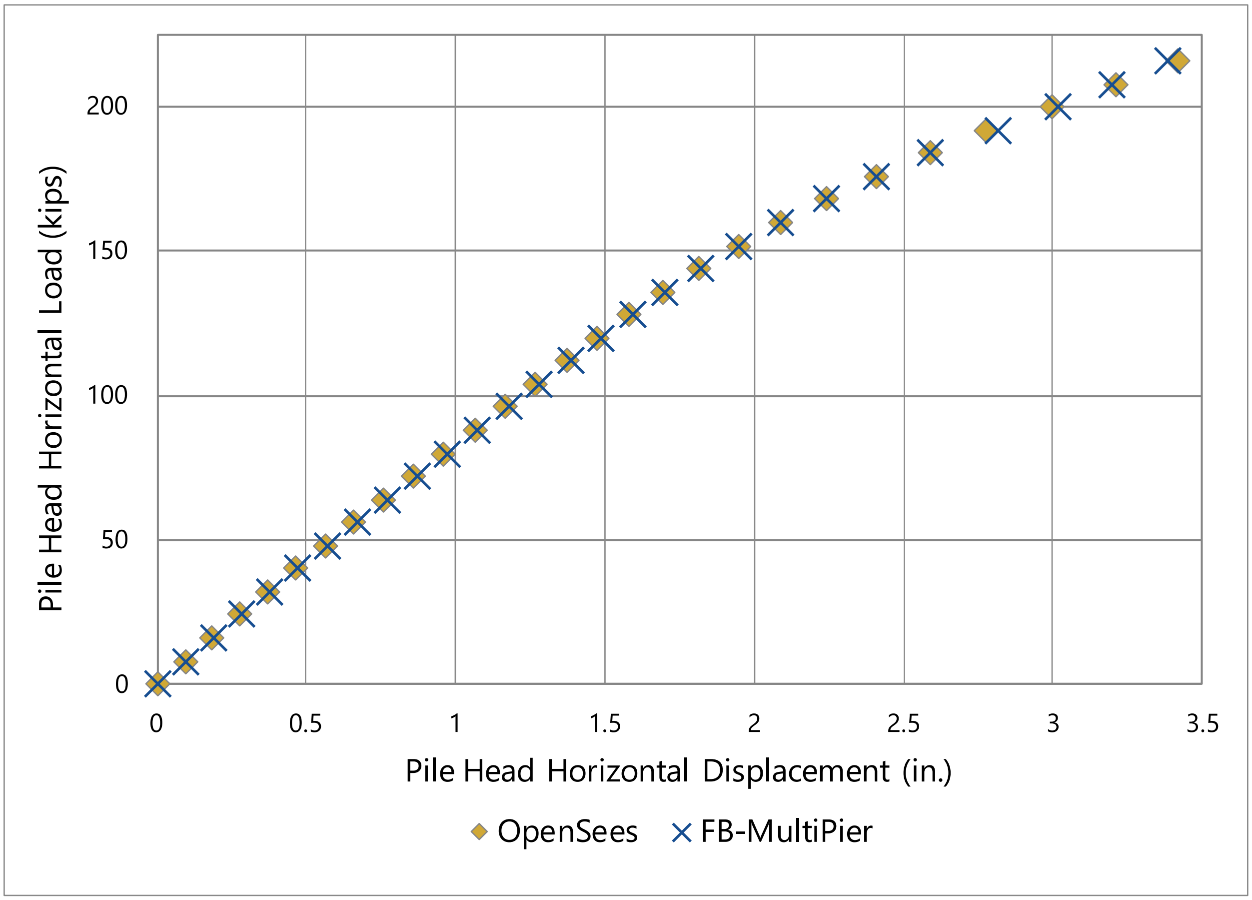
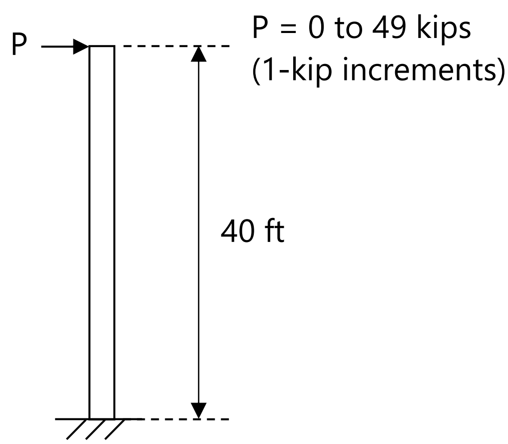
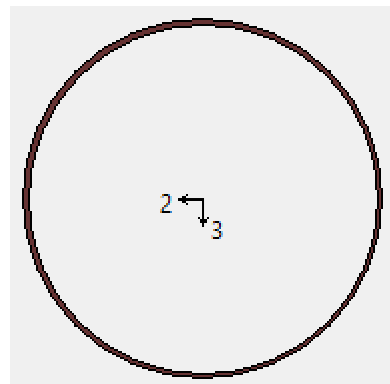


Figure 2.7 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-8: Single 12” Steel Pipe Pile

Problem Description: Analyze a single 12” pipe pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 49 kips in load increments of 1 kip).





12” Pipe Pile Section

File: *Example_2-8.in*

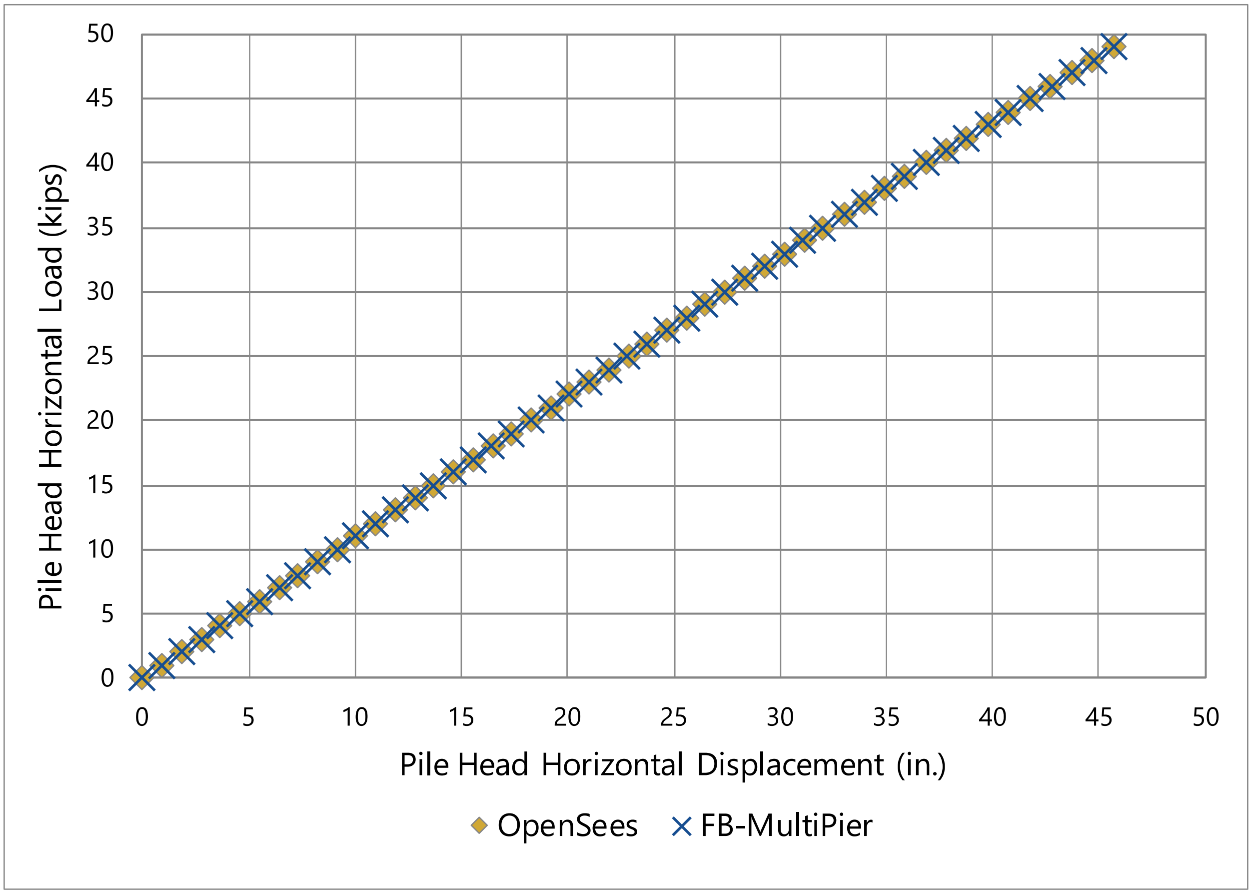
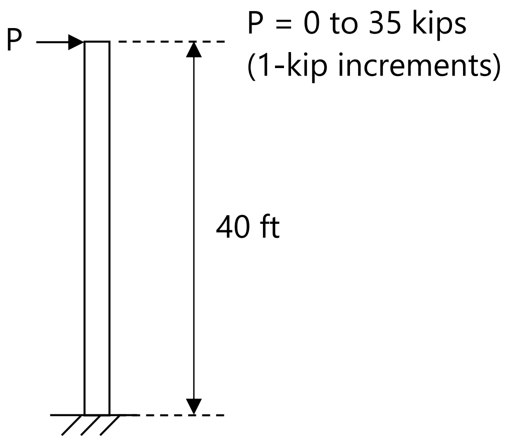
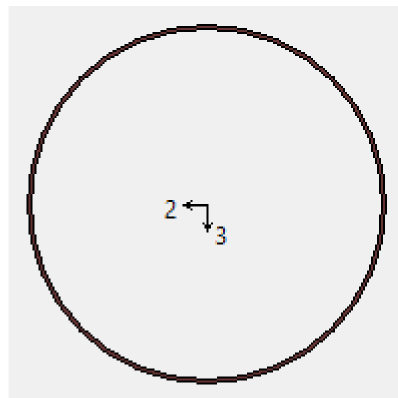


Figure 2.8 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-9: Single 18" Steel Pipe Pile	
Problem Description: Analyze a single 18" pipe pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 35 kips in load increments of 1 kip).	
	 18" Pipe Pile Section
File: *Example_2-9.in*	

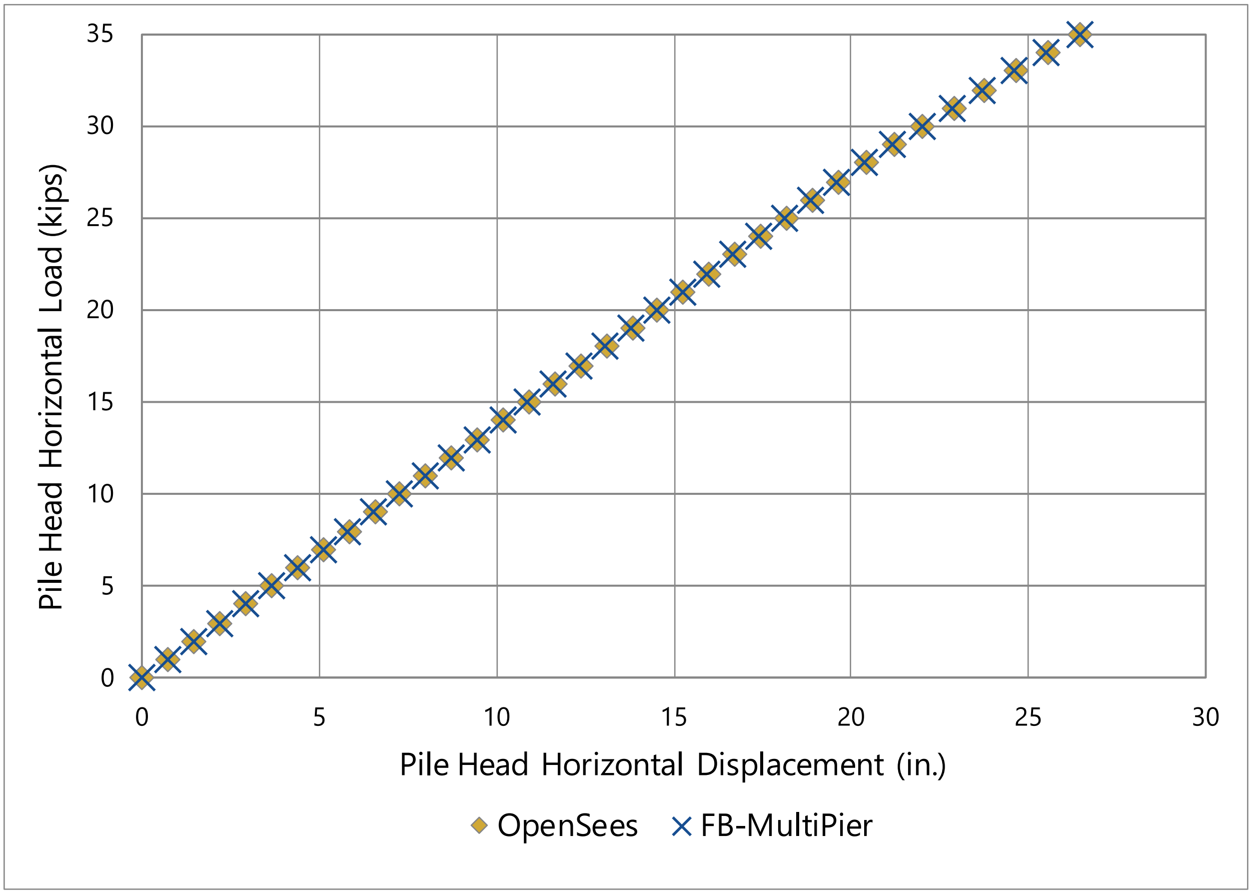
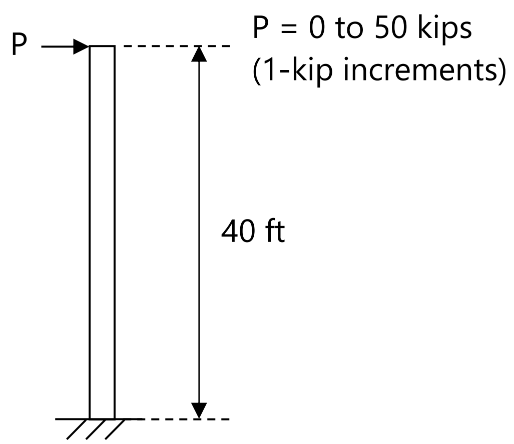
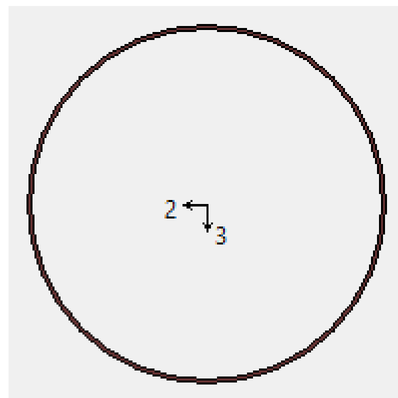


Figure 2.9 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-10: Single 24″ Steel Pipe Pile

Problem Description: Analyze a single 24″ pipe pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 50 kips in load increments of 1 kip).





24″ Pipe Pile Section

File: *Example_2-10.in*

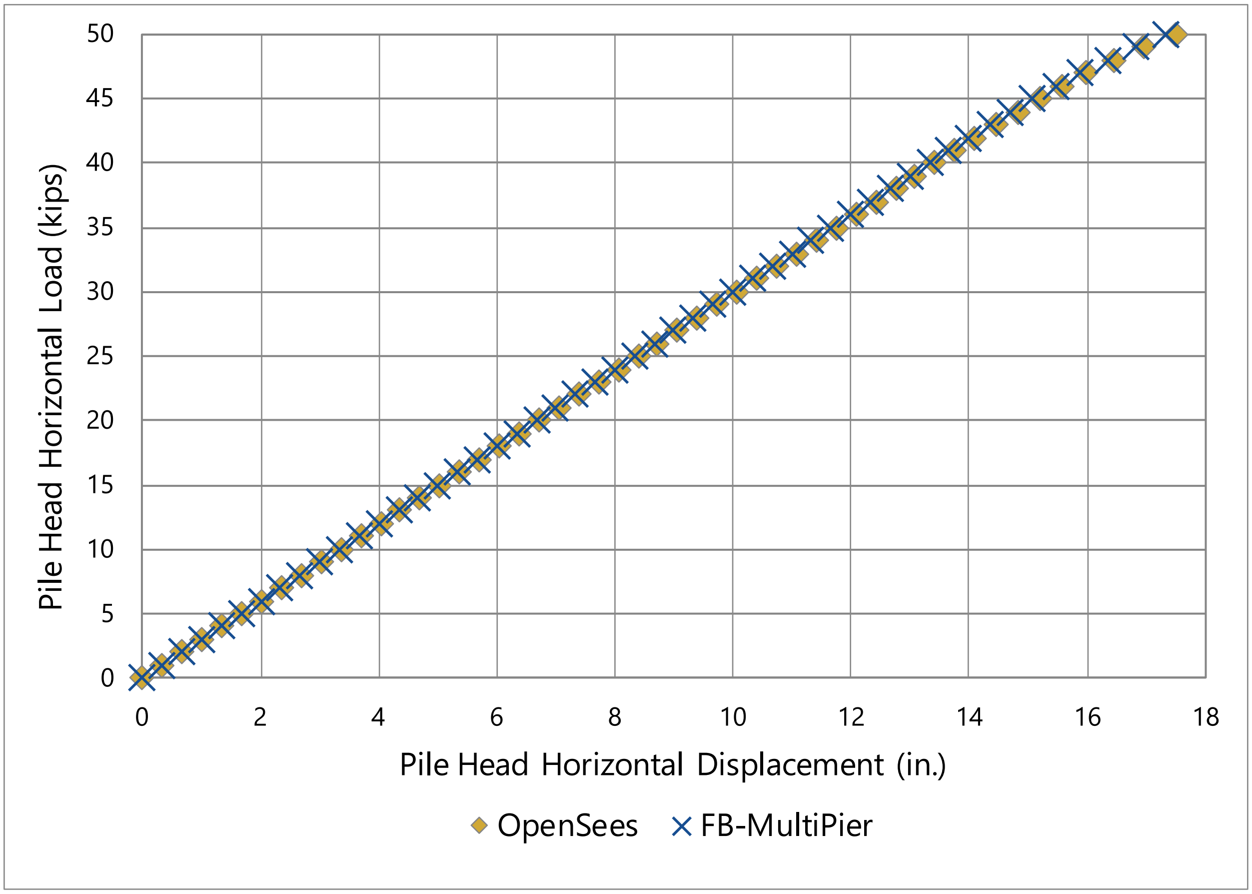
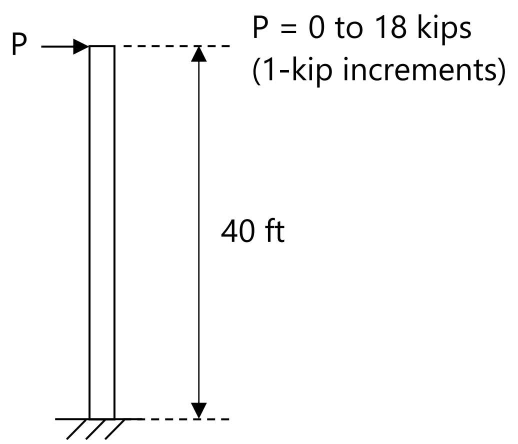
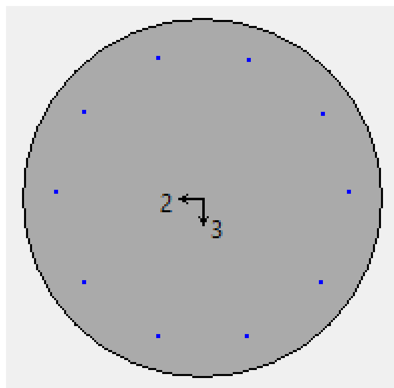


Figure 2.10 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-11: Single 36” Drilled Shaft	
Problem Description: Analyze a single 36” drilled shaft cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 18 kips in load increments of 1 kip).	
	 36” Drilled Shaft Section
File: *Example_2-11.in*	

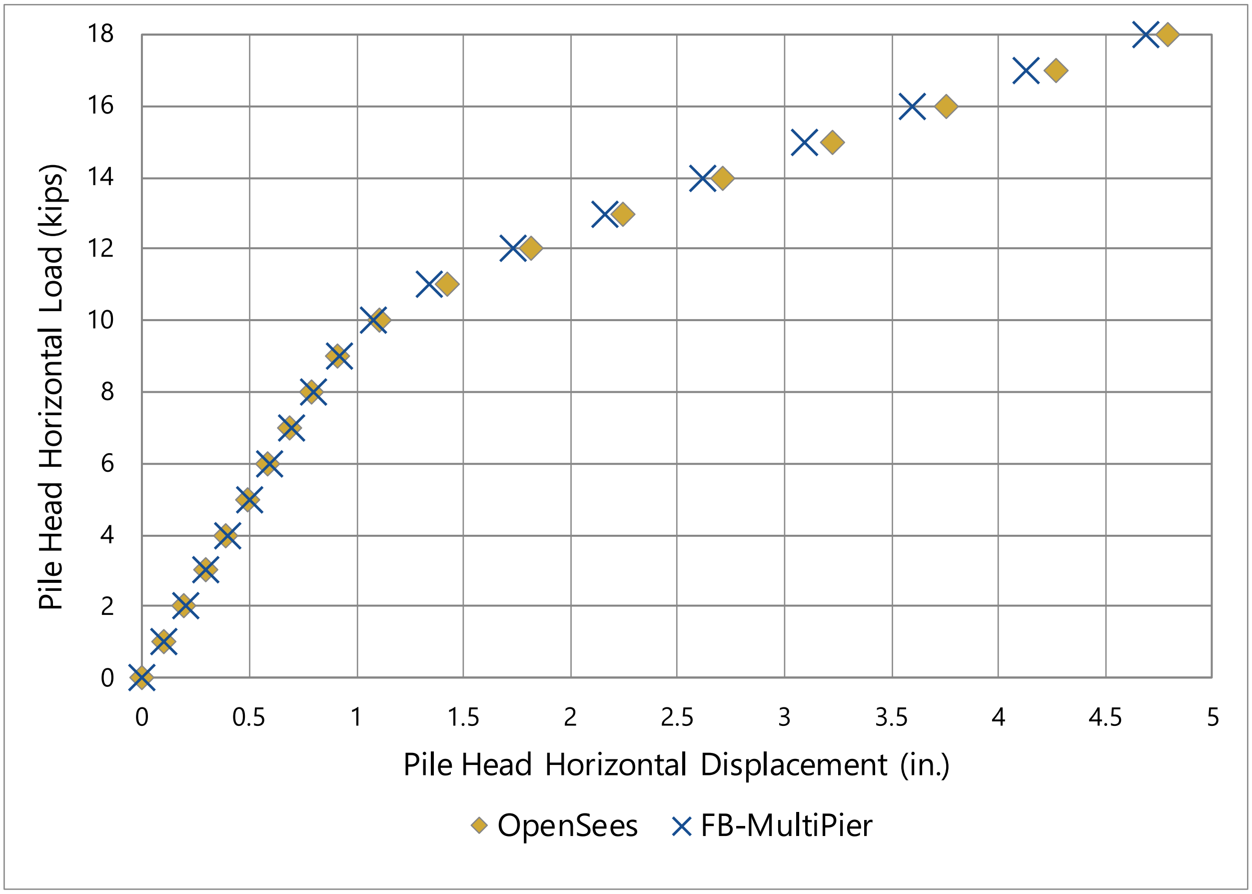
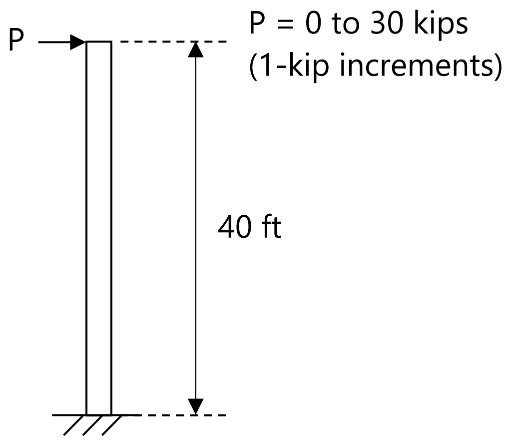
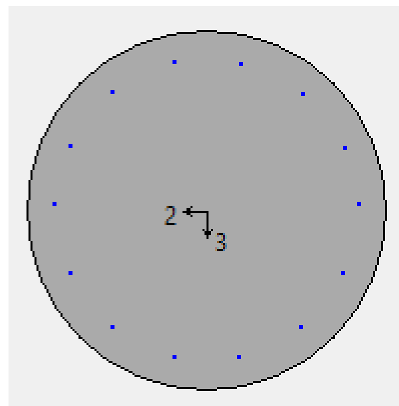


Figure 2.11 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-12: Single 42″ Drilled Shaft

Problem Description: Analyze a single 42″ drilled shaft cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 30 kips in load increments of 1 kip).





42″ Drilled Shaft Section

File: *Example_2-12.in*

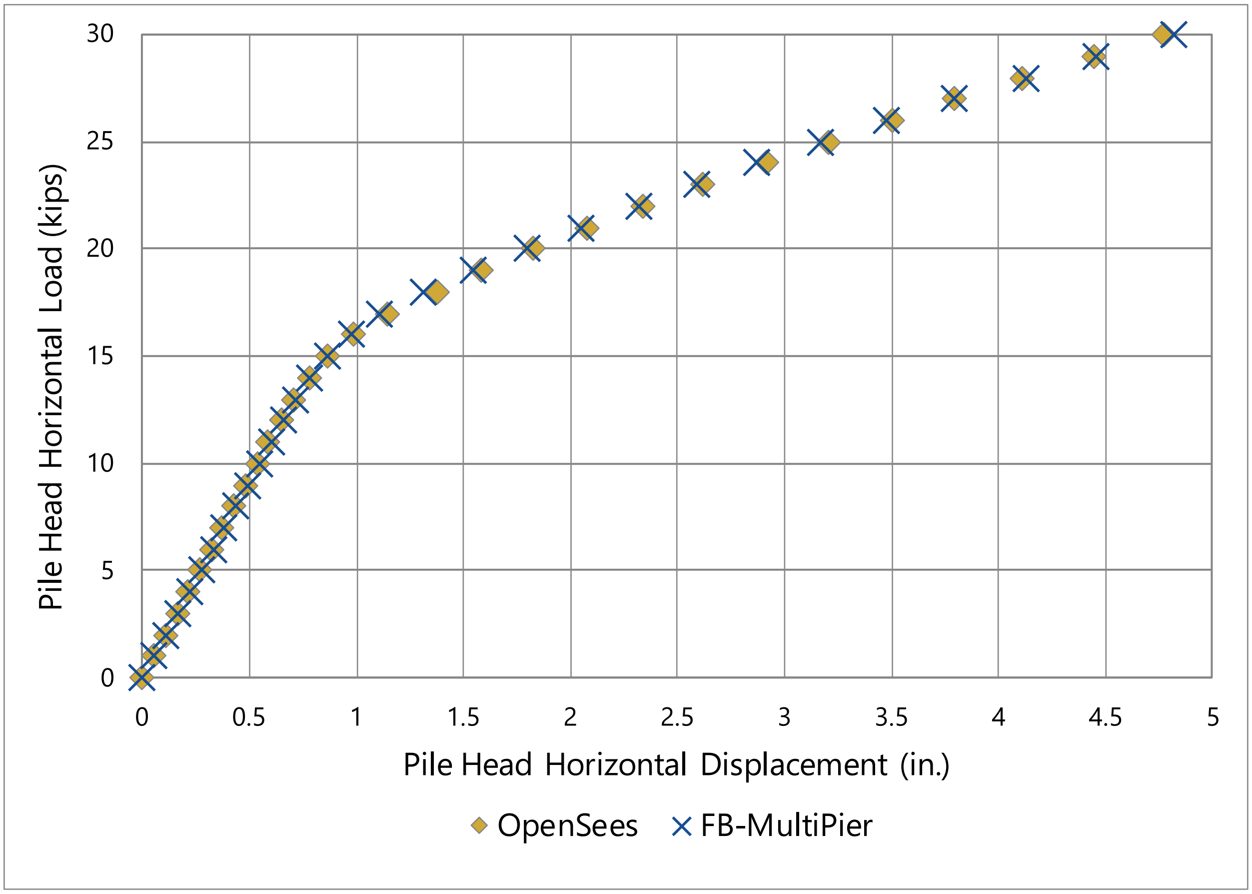
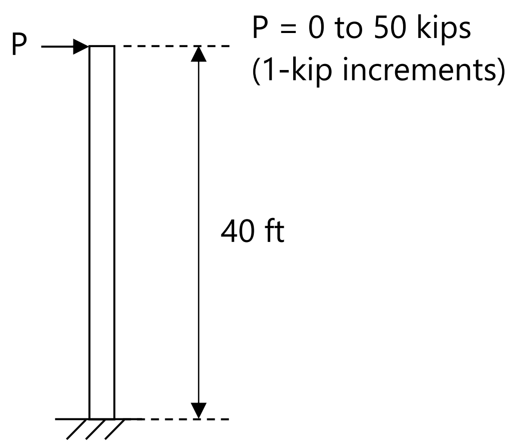
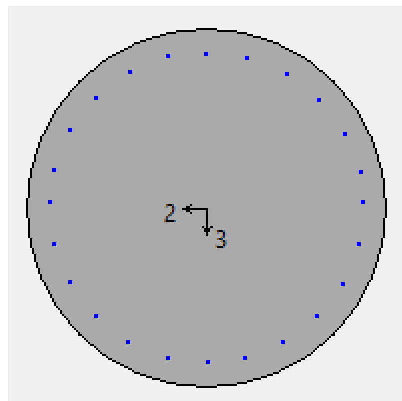


Figure 2.12 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-13: Single 54” Drilled Shaft

Problem Description: Analyze a single 54” drilled shaft cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 50 kips in load increments of 1 kip).





54” Drilled Shaft Section

File: *Example_2-13.in*

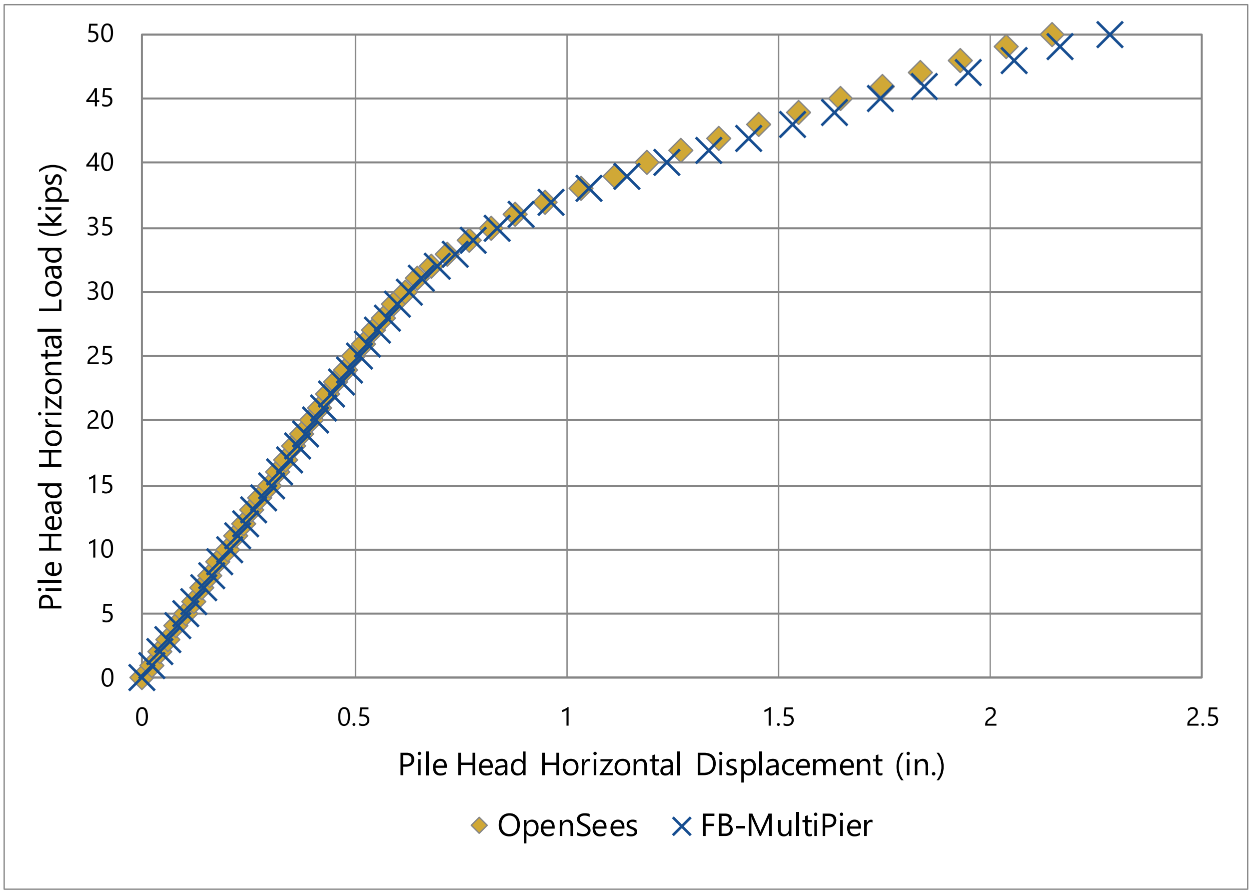
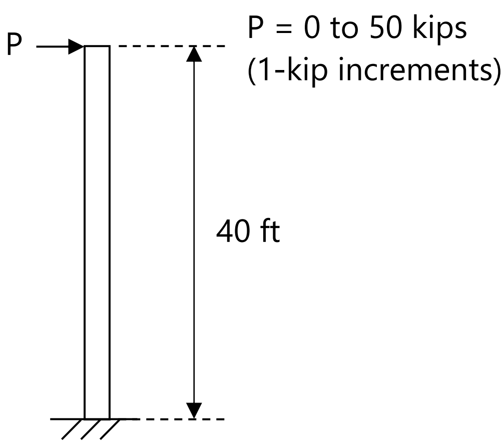
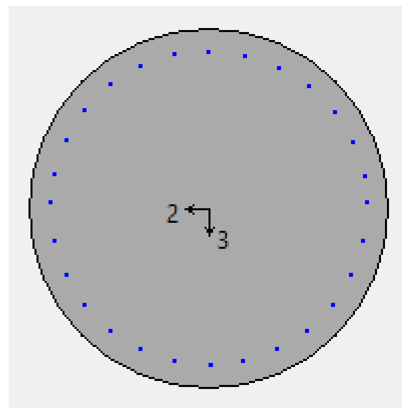


Figure 2.13 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-14: Single 60″ Drilled Shaft

Problem Description: Analyze a single 60″ drilled shaft cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 50 kips in load increments of 1 kip).





60″ Drilled Shaft Section

File: *Example_2-14.in*

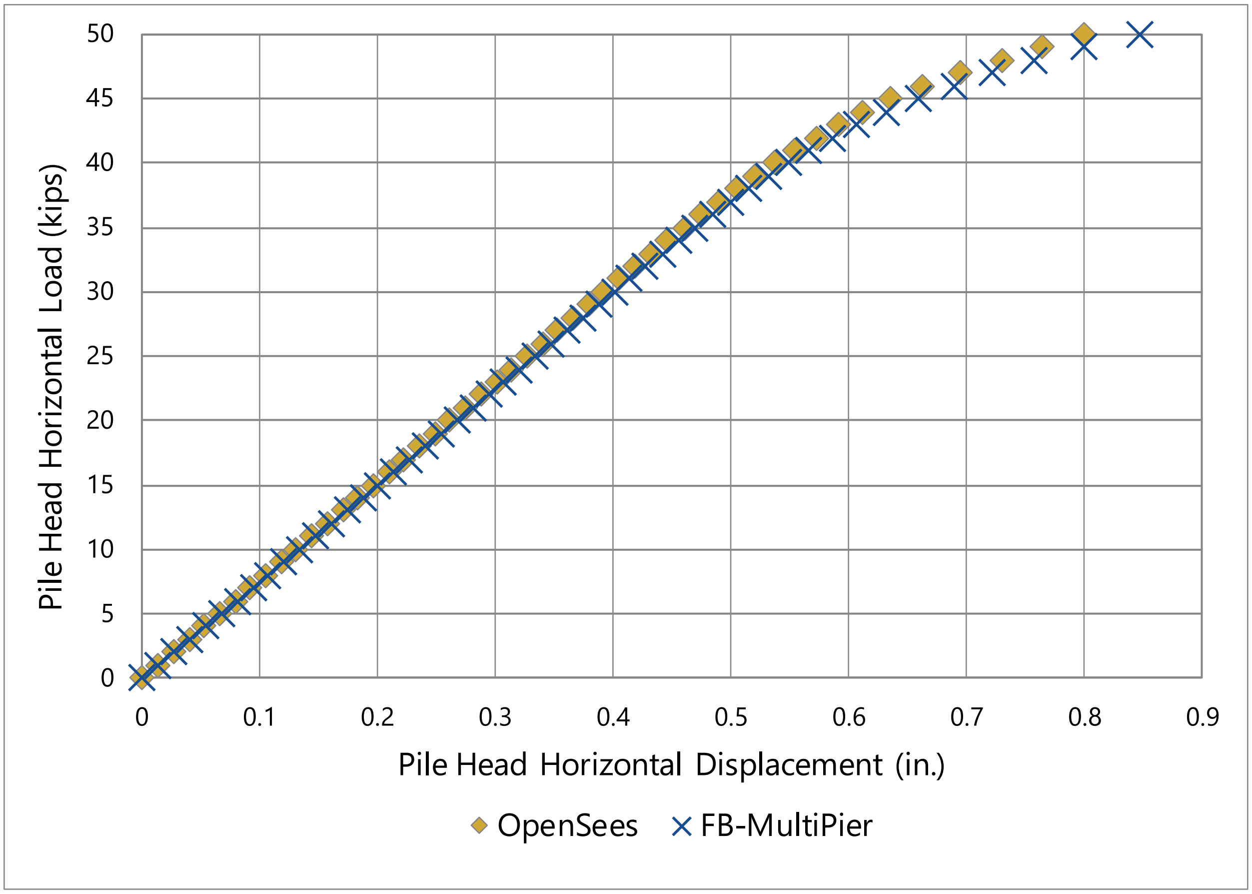
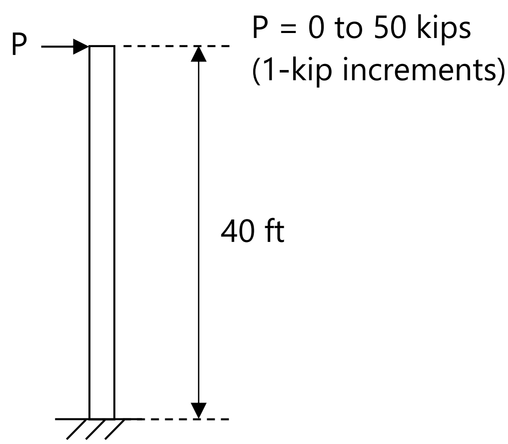
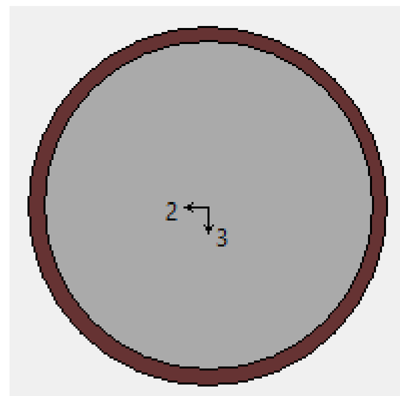


Figure 2.14 – Comparison of Results Between FB-MultiPier and OpenSees

Example 2-15: Single 24" Concrete Filled Steel Pipe Pile

Problem Description: Analyze a single 12" concrete filled pipe pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 50 kips in load increments of 1 kip).





24" Concrete Filled Pipe Pile Section

File: *Example_2-15.in*

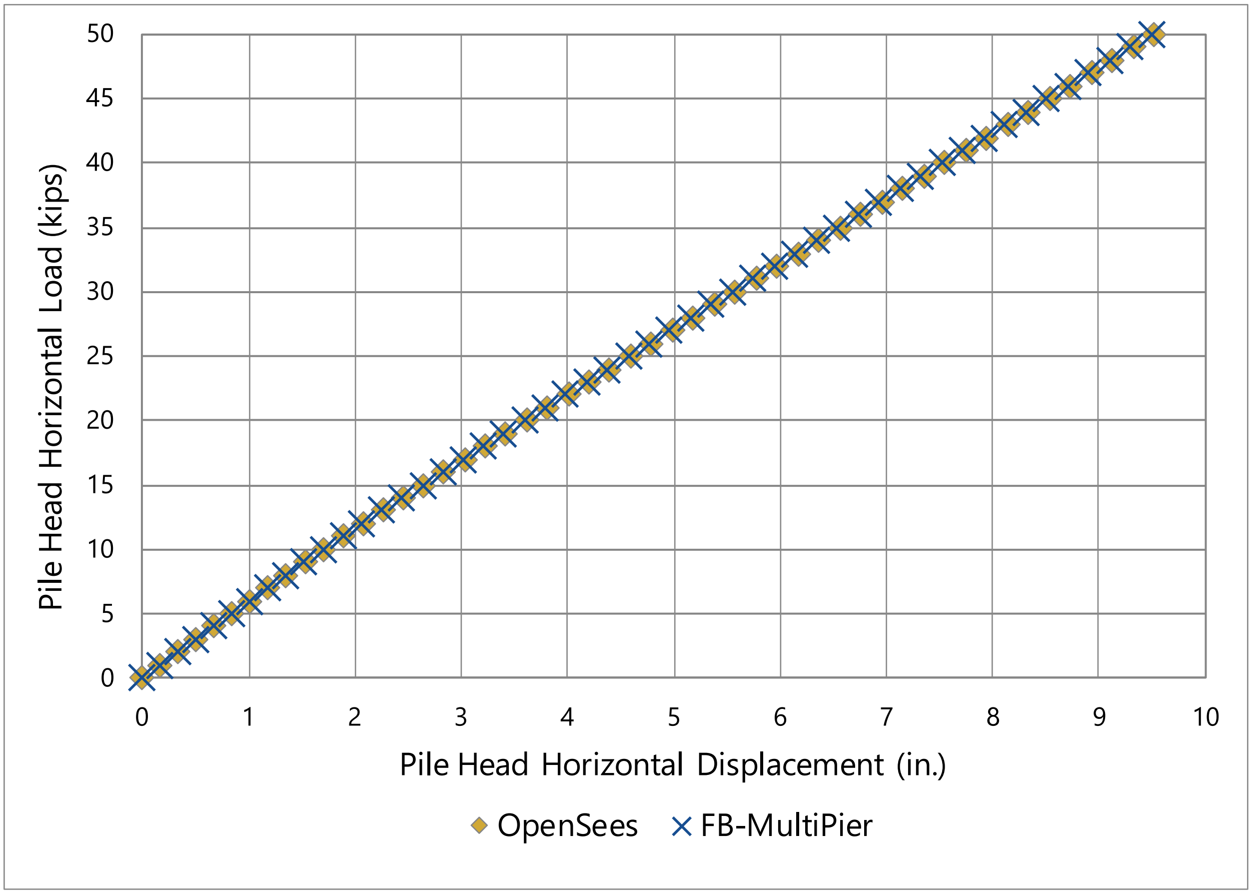


Figure 2.15 – Comparison of Results Between FB-MultiPier and OpenSees

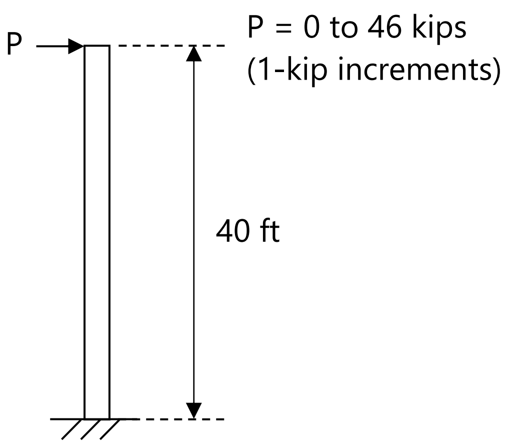
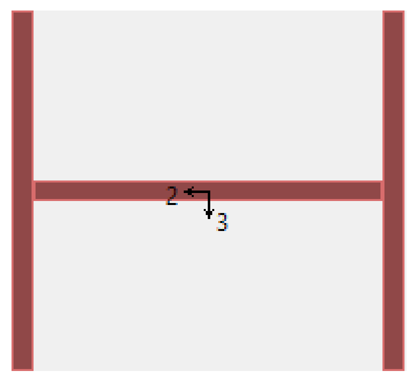
Chapter 3

H-Piles

In this chapter, pile head horizontal displacement results are compared as obtained from nonlinear static analyses of laterally loaded H-piles in FB-MultiPier and OpenSees. Because the focus of this verification effort is placed on assessing the nonlinear fiber-integrated frame element implementation in FB-MultiPier, the piles are modeled as free standing with fixed bases. That is, structure-only analyses are conducted with no surrounding soil.

Lateral load response comparisons are made between the pile head horizontal displacements computed by FB-MultiPier and OpenSees over a range of lateral loads. Whenever feasible, the range of lateral loading is chosen such that a nonlinear response is evident among the computed pile head horizontal displacements. Solely for the purpose of capturing nonlinear response, the magnitudes of lateral displacements for these cases are generated over a relatively large range of values, exceeding 2 ft of lateral displacement in some instances. Nonlinear behavior of piles/shafts in FB-MultiPier is modeled in a manner similar to OpenSees, where both programs compute resultant forces using numerical integration of cross-section stresses over numerous integration points (called fibers). Upon request, FB-MultiPier models may be made available to licensed program users.

Stress-strain relationships used in these analyses are presented in Appendix A.

Example 3-1: 12x84 H-Pile	
Problem Description: Analyze a single 12x84 H-pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 46 kips in load increments of 1 kip).	
	 12x84 H-Pile Section
File: *Example_3-1.in*	

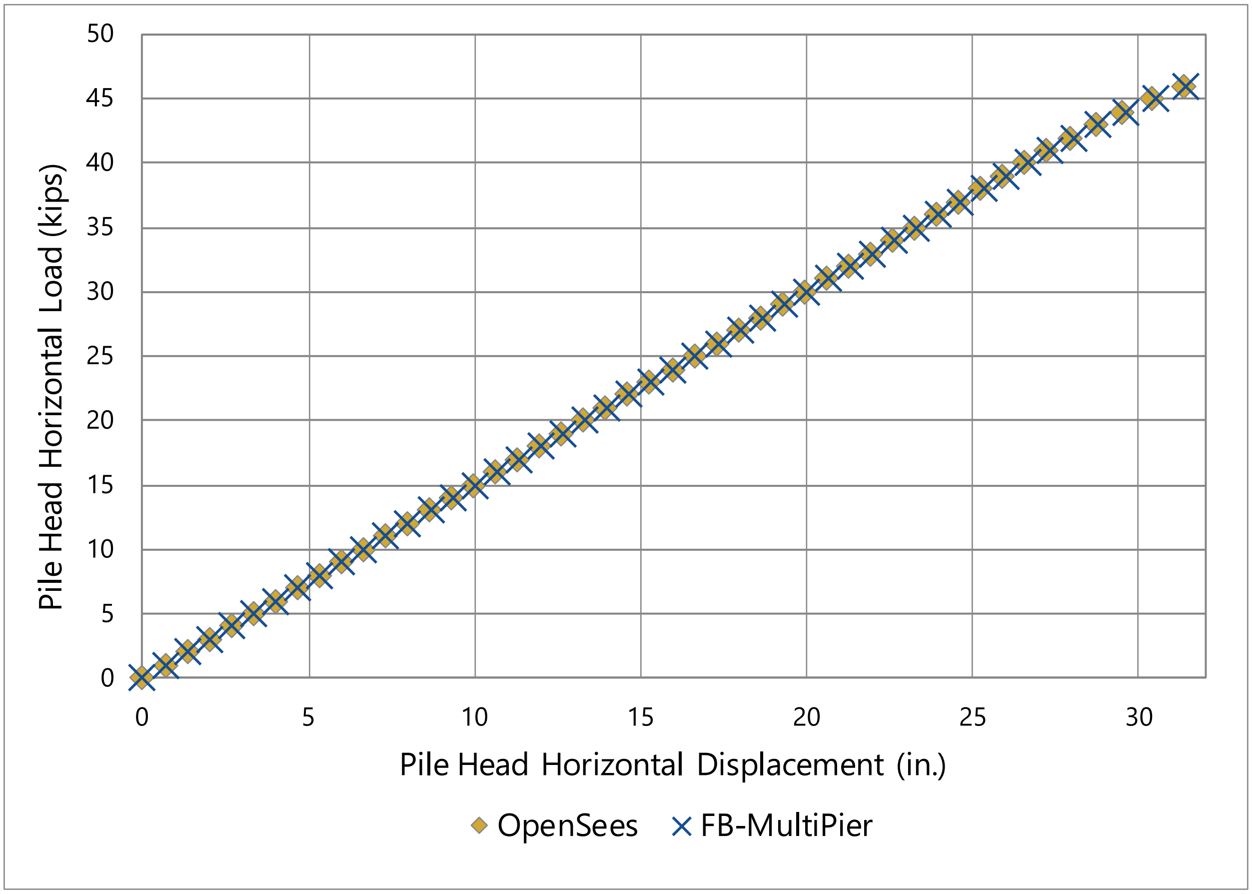
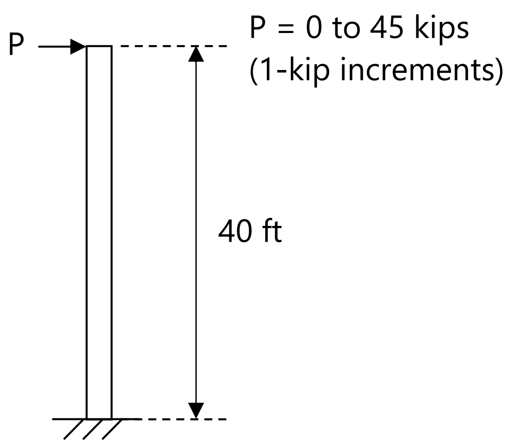
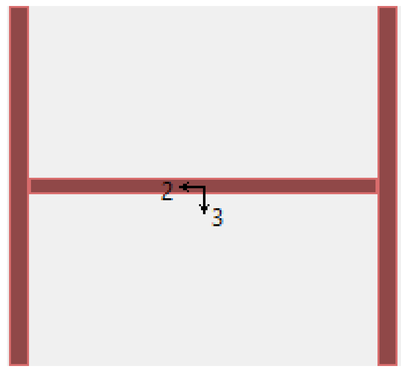


Figure 3.1 – Comparison of Results Between FB-MultiPier and OpenSees

Example 3-2: 13x87 H-Pile

Problem Description: Analyze a single 13x87 H-pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 45 kips in load increments of 1 kip).





13x87 H-Pile Section

File: *Example_3-2.in*

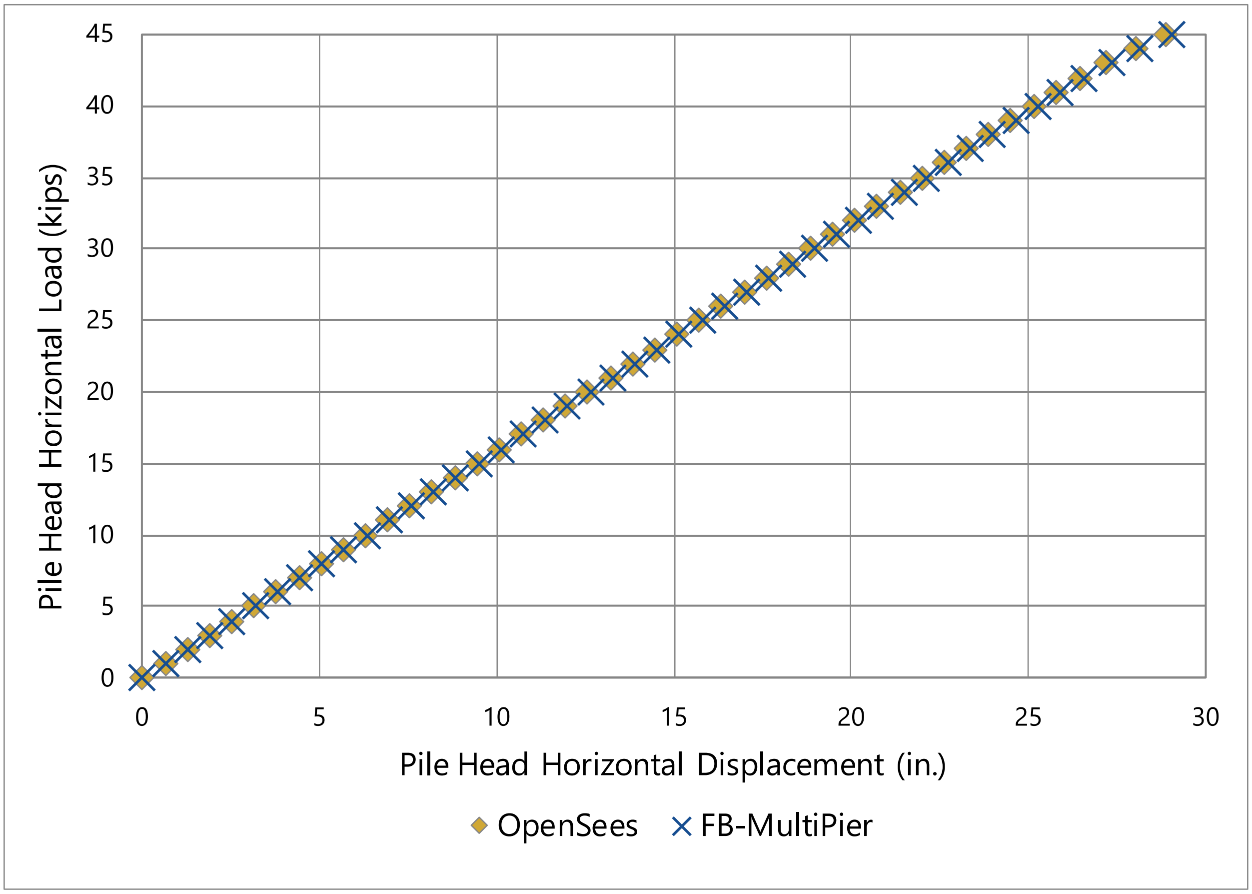
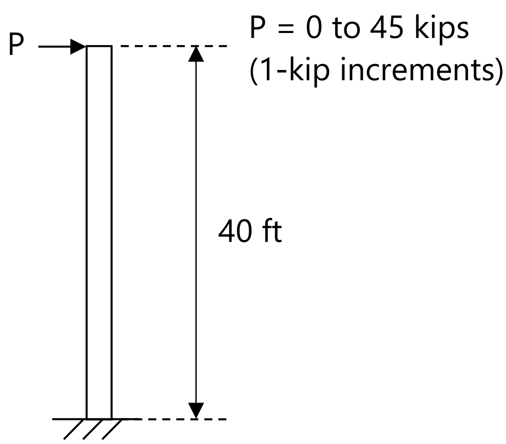
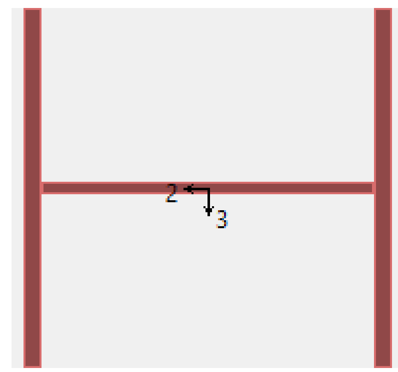


Figure 3.2 – Comparison of Results Between FB-MultiPier and OpenSees

Example 3-3: 14x89 H-Pile

Problem Description: Analyze a single 14x89 H-pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 45 kips in load increments of 1 kip).





14x89 H-Pile Section

File: *Example_3-3.in*

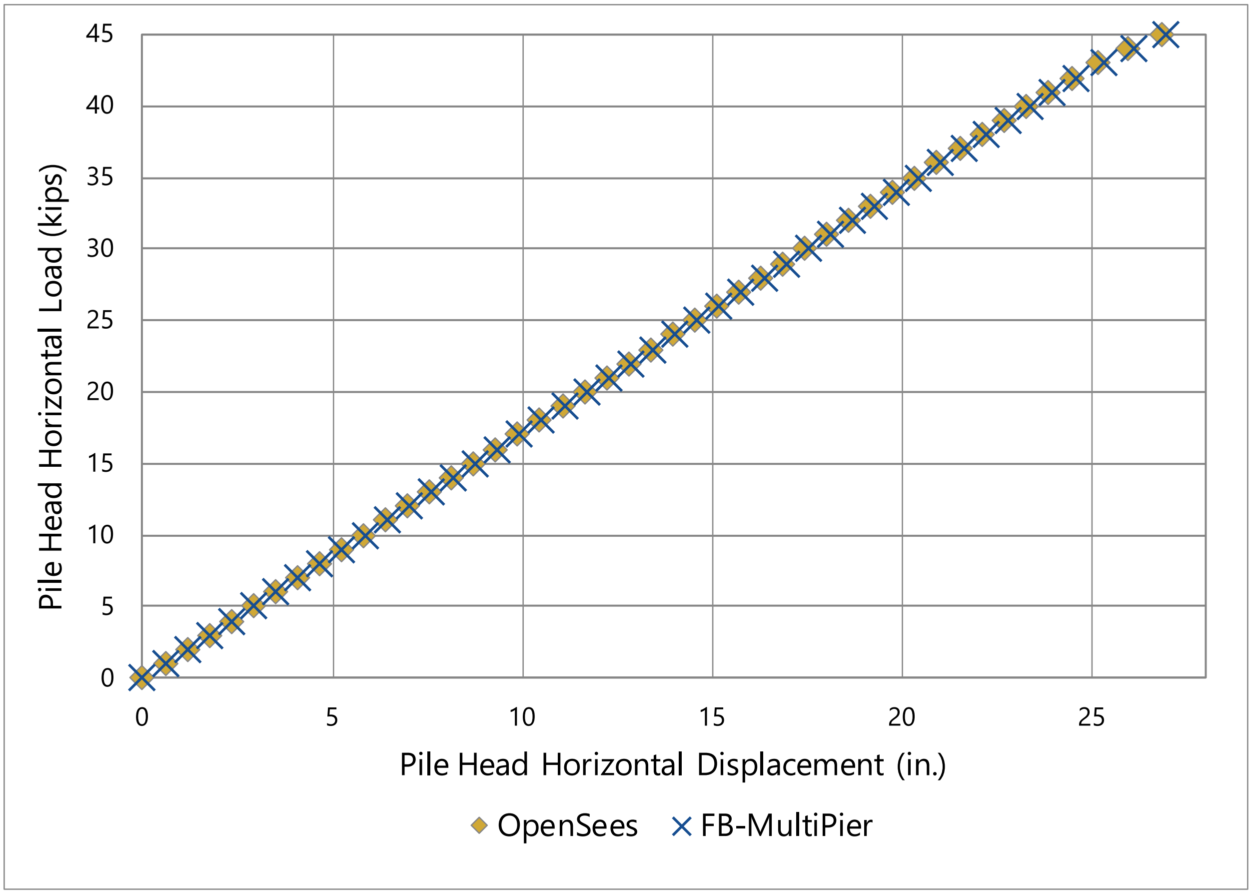
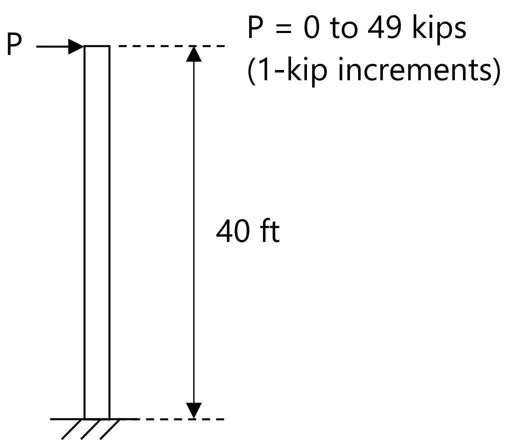
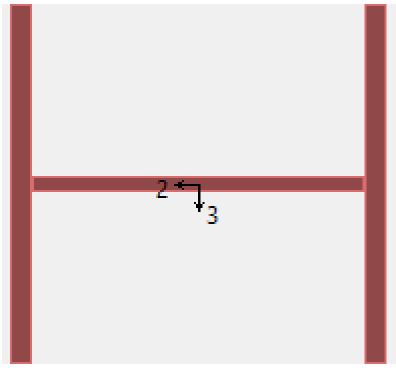


Figure 3.3 – Comparison of Results Between FB-MultiPier and OpenSees

Example 3-4: 14x117 H-Pile	
Problem Description: Analyze a single 14x117 H-pile cross-section with a fixed base and subjected to lateral loading of different magnitudes (0 kips to 49 kips in load increments of 1 kip).	
	 14x117 H-Pile Section
File: *Example_3-4.in*	

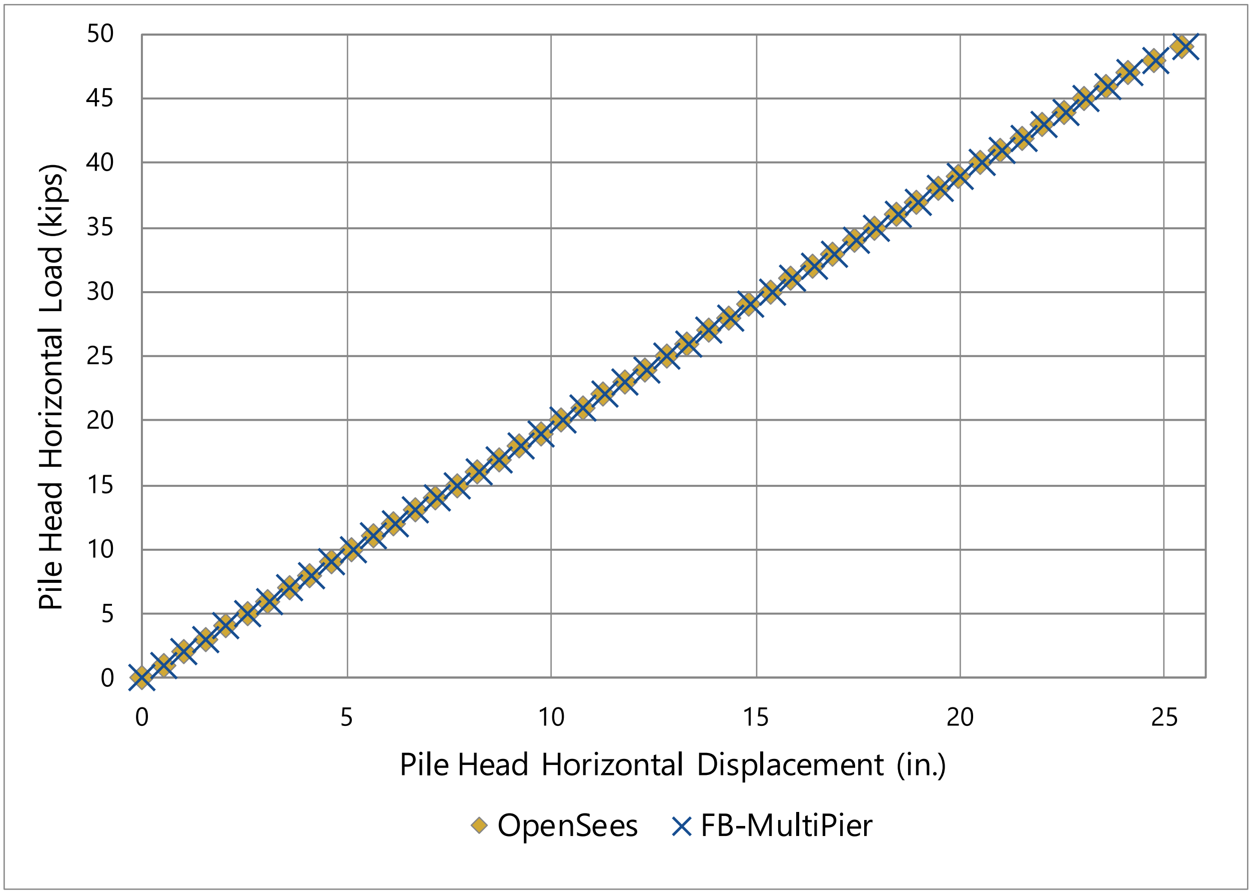


Figure 3.4 – Comparison of Results Between FB-MultiPier and OpenSees

ACKNOWLEDGEMENT

This report was developed by BSI engineers and researchers, including, but not limited to: Michael Davidson, Anand Patil, Alexander Shishlov, and Wilmer Carrion.

Appendix A

Stress-Strain Relationships

Presented in this appendix are the stress-strain relationships utilized for material modeling of concrete, mild steel, prestressed steel, CFRP, and HSSS strands.

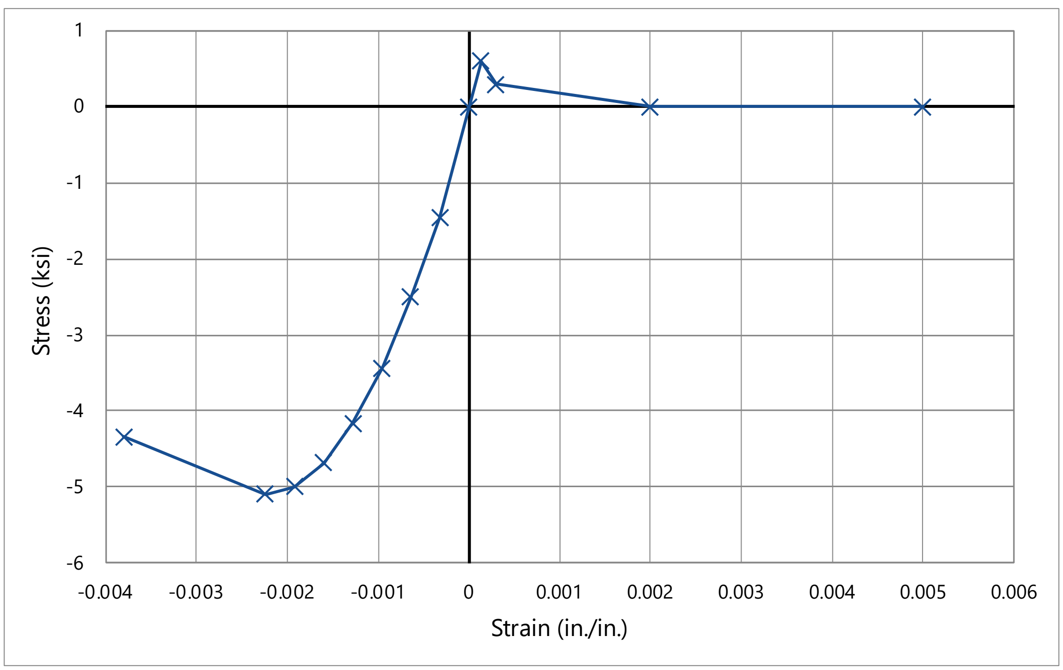


Figure A.1 – Stress-Strain Relationship for Concrete

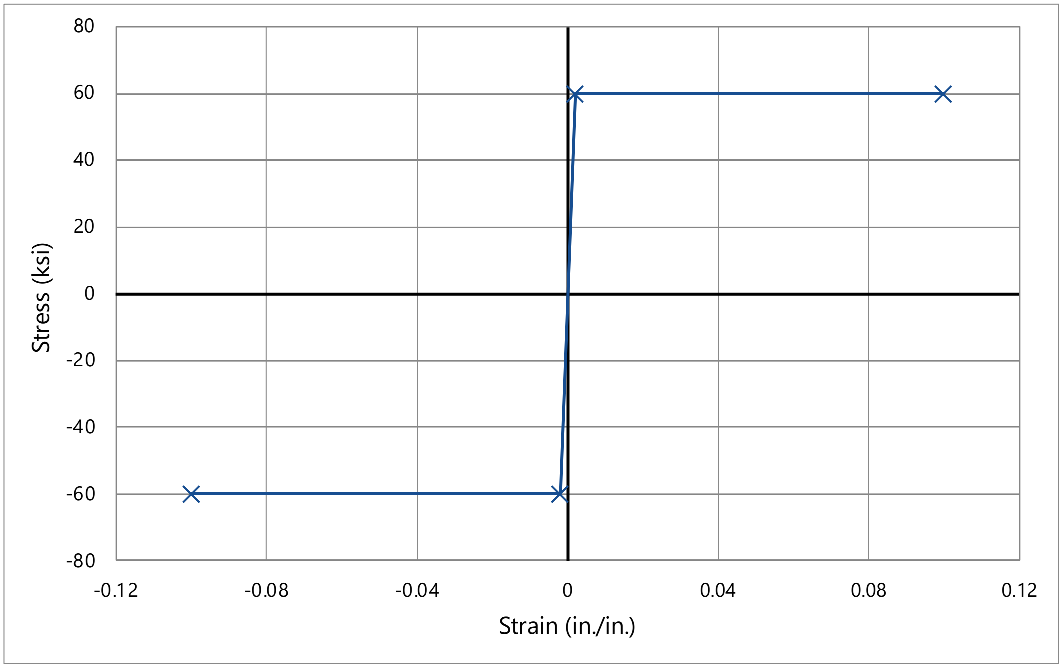


Figure A.2 – Stress-Strain Relationship for Mild Steel Longitudinal Reinforcement

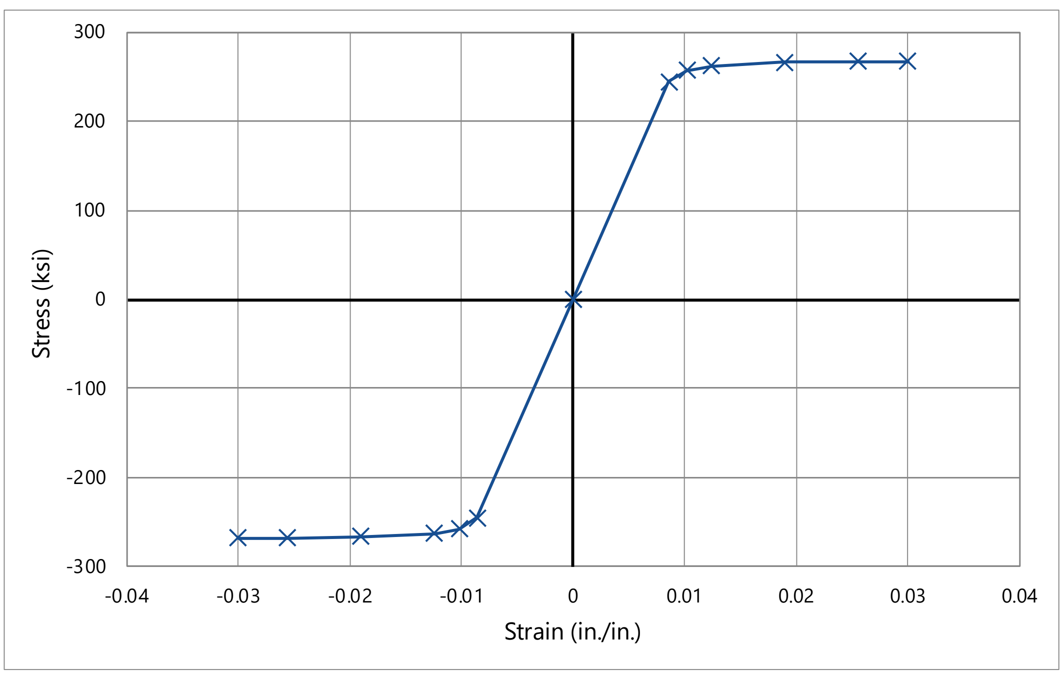


Figure A.3 – Stress-Strain Relationship for (270 ksi) Prestressed Steel

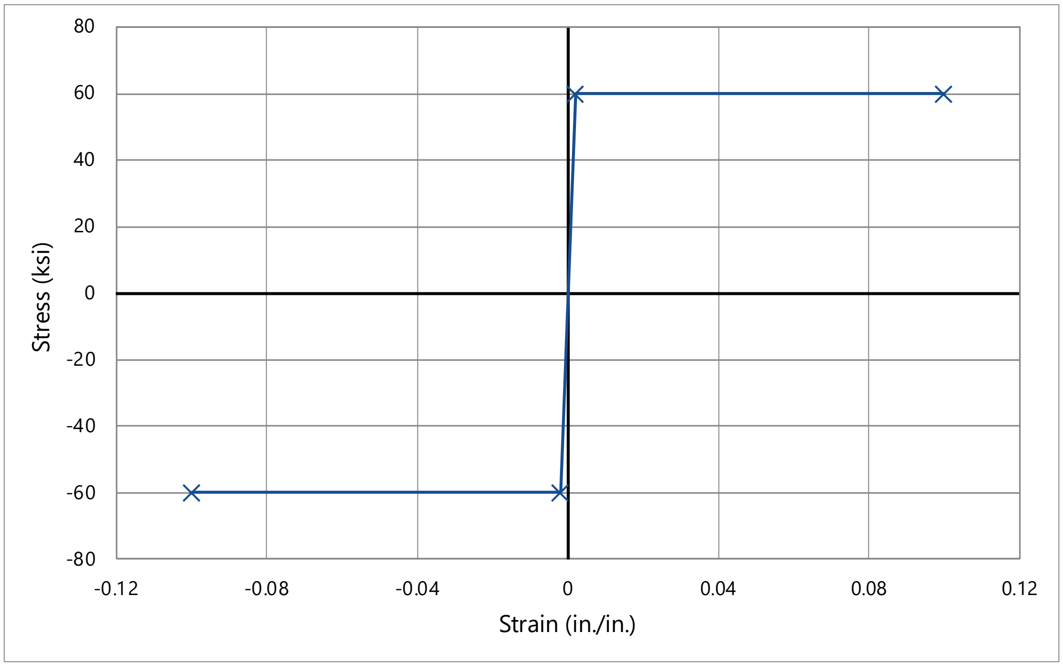


Figure A.4 – Stress-Strain Relationship for Steel in Casing Portions of Cross-Sections and Pipes

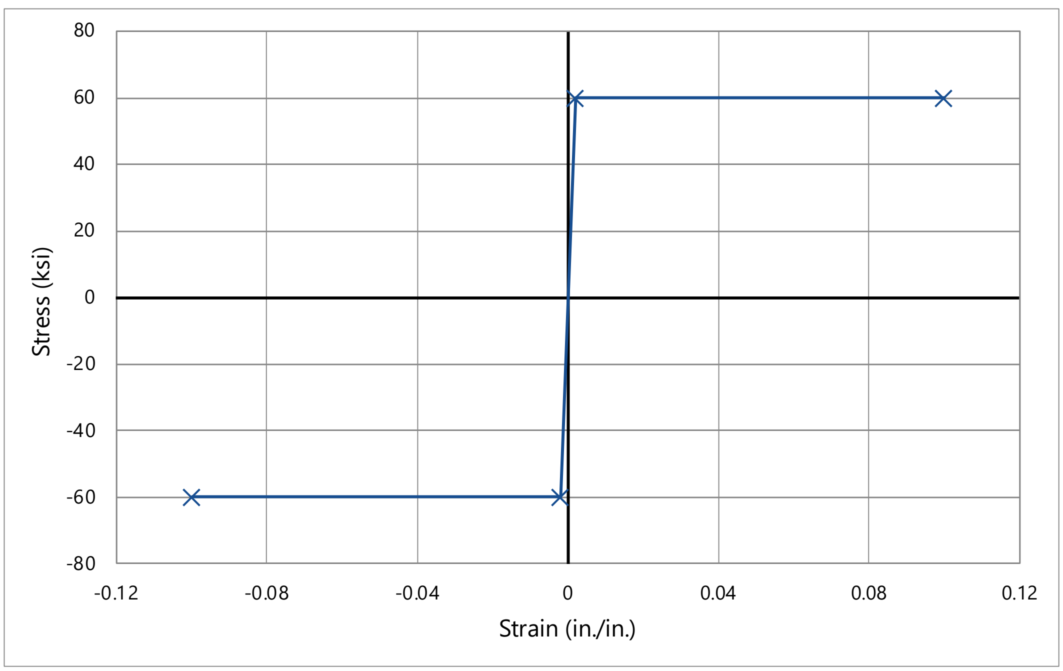


Figure A.5 – Stress-Strain Relationship for Steel in H-Pile Sections

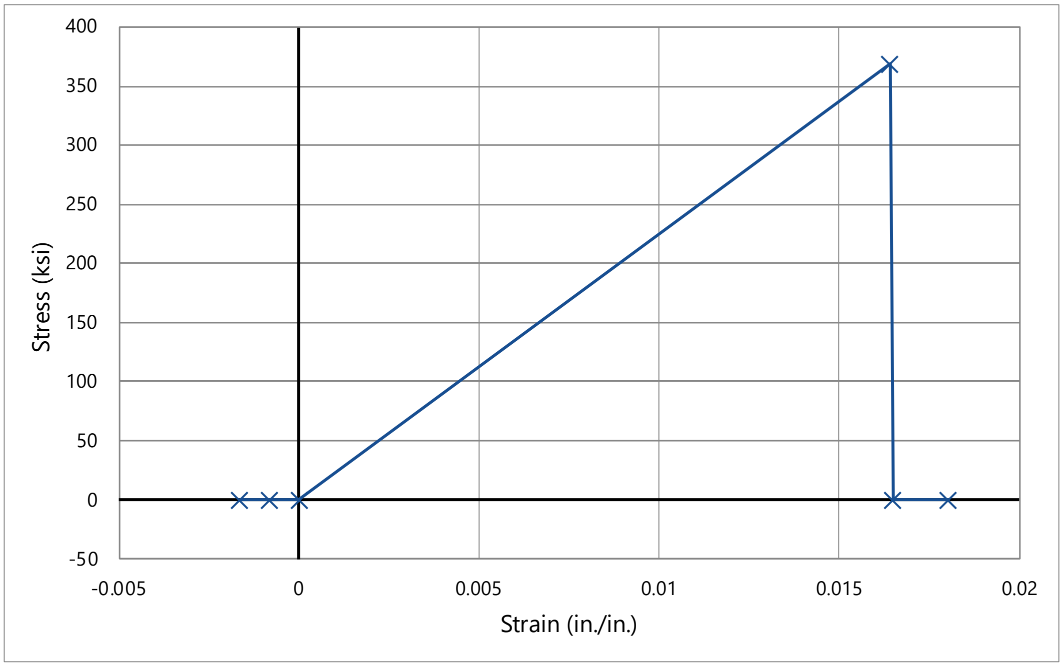


Figure A.6 – Stress-Strain Relationship for CFRP Strands (Compression is Neglected)

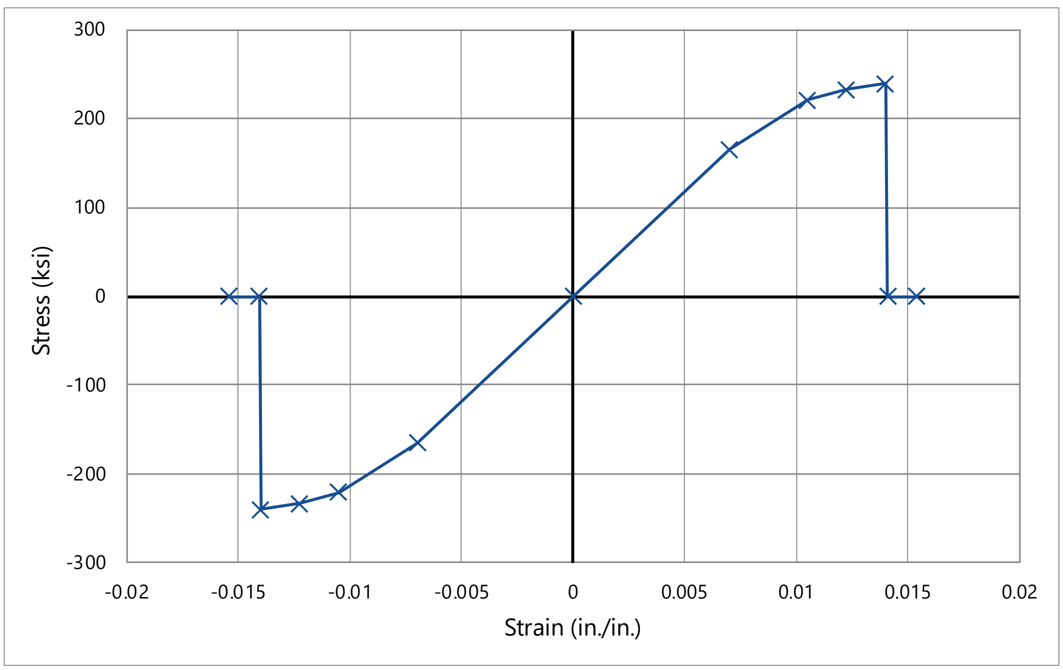


Figure A.7 – Stress-Strain Relationship for HSSS Strands

Appendix B

Interaction Diagrams for Selected Cross-Sections

Presented in this appendix are interaction diagrams for selected cross-sections. The interaction diagrams provided herein pertain to FDOT standard cross-sections of prestressed CFRP and HSSS piles. The algorithm presented in Consolazio et al. (2004) for generating load-moment pairs is utilized herein to establish "benchmark" interaction diagrams for each cross-section. More specifically, the algorithm documented in Consolazio et al. (2004) is implemented in a Mathcad sheet, and utilized to generate load-moment interaction diagrams, which serve as verification for interaction diagrams generated using FB-MultiPier. Note that, as part of implementing the algorithm, it is ensured that stress-strain relationships for both the concrete stress-strain and reinforcing material (i.e., the prestressed CFRP or HSSS strands) are consistent with those relationships utilized within FB-MultiPier (see Appendix A).

As a first step in generating results for verification of the load-moment interaction diagrams, the diagram points pertaining to each cross-section are generated directly from within FB-MultiPier. Specifically, axial forces and corresponding moments are extracted from the interaction diagrams generated by FB-MultiPier for each cross-section. Then for each interaction diagram, points of interest are identified, including: crushing of concrete in compression; maximum moment; pure flexure; balance (simultaneous concreate crushing and strand rupture); and, points near to pure tensile and compressive axial capacities. Axial loads (obtained from FB-MultiPier) are then supplied, one at a time, to the Mathcad tool (along with the respective cross-section description) at or near the points of interest to generate benchmark pairs of load-moment values.

Note that, as exceptions, the "benchmark" values of pure compression and pure tension axial forces are manually generated in accordance with the AASHTO LRFD bridge design provisions (e.g., Sec. 5.6.4.4 of AASHTO 2020). Manually quantifying the pure tensile and compressive axial capacities, along with computing sets of load-moment pairs generated using the algorithm given in Consolazio et al. (2004), enables the manual computation of points throughout all regions of interest associated with interaction diagrams, and further enriches verification of load-moment points generated using FB-MultiPier.

For all cases considered, negative axial force signifies compression while positive axial force signifies tension.

References:

1. Consolazio, G.R., Fung, J., Ansley, M., “M-phi-P Diagrams for Concrete Sections Under Biaxial Flexure and Axial Compression”, *American Concrete Institute (ACI) Structural Journal*, Vol. 101, No. 1, pp. 114-123 (2004).

2. AASHTO (2020). AASHTO LRFD Bridge Design Specifications, 9th Edition, Washington, DC.

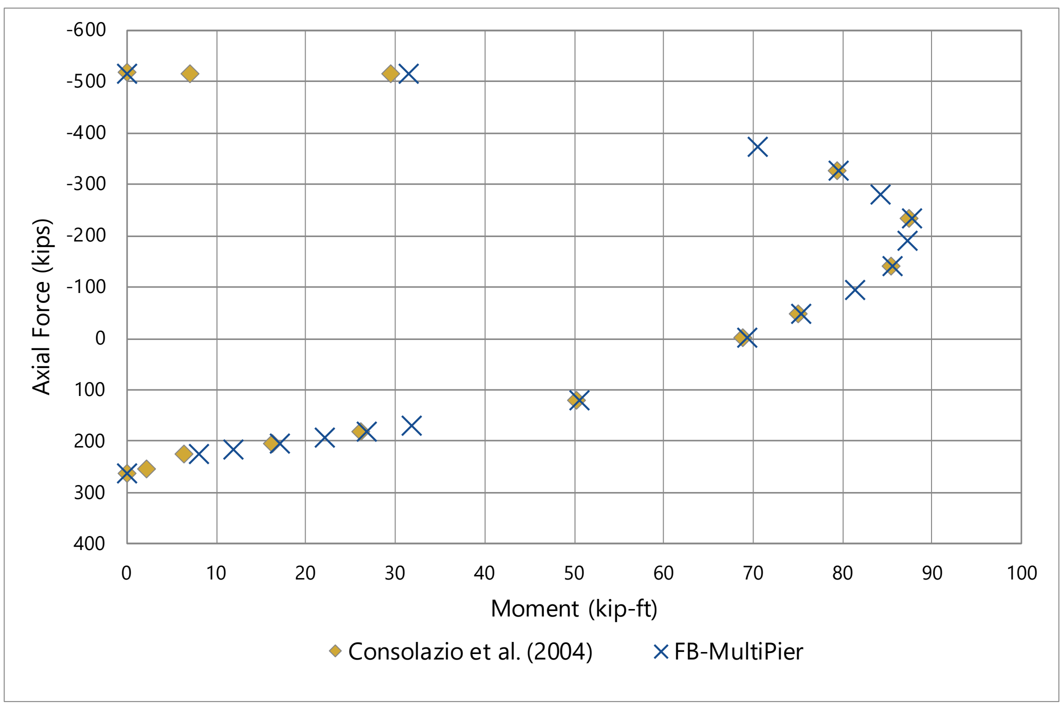


Figure B.1 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for a 12” Standard FDOT Prestressed CFRP Pile

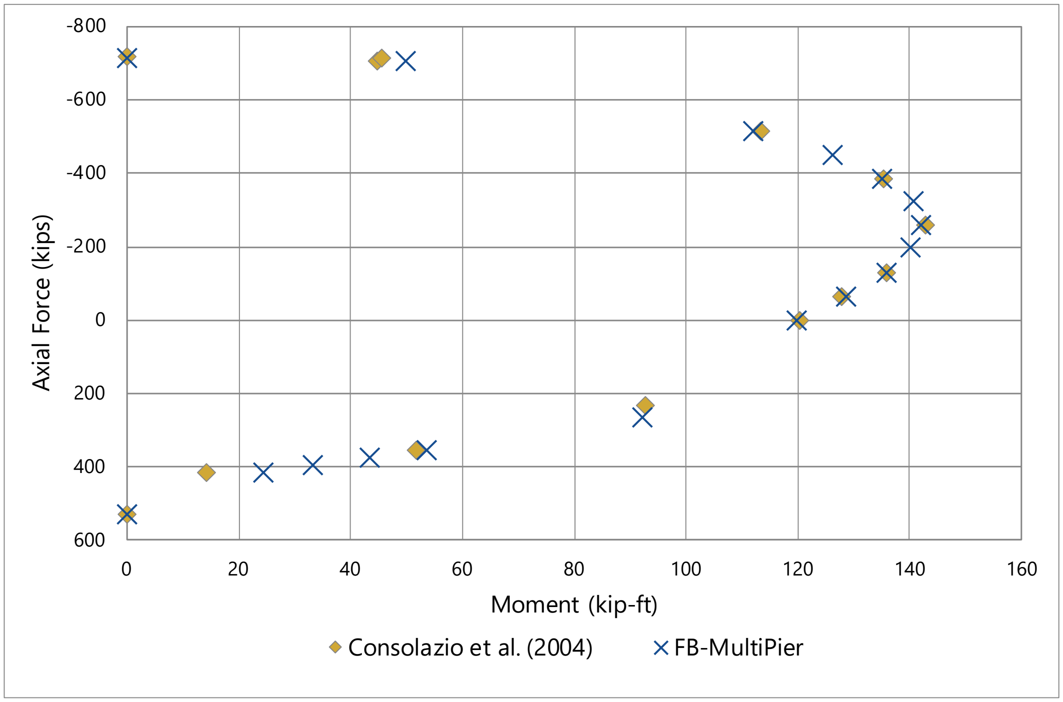


Figure B.2 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for a 14" Standard FDOT Prestressed CFRP Pile

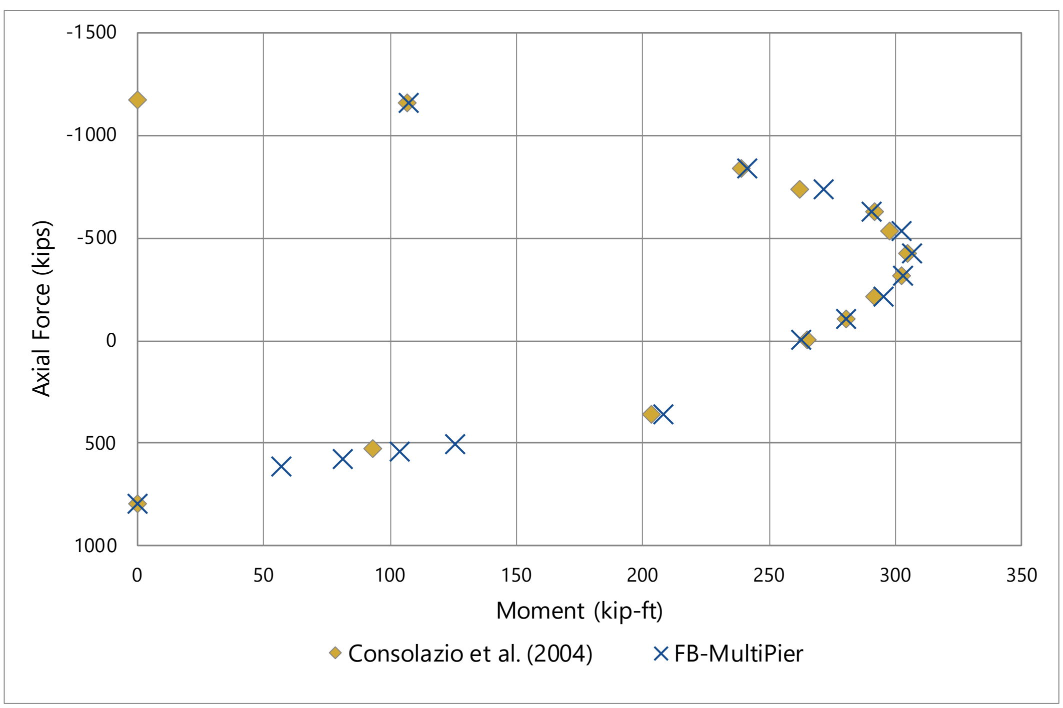


Figure B.3 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for an 18" Standard FDOT Prestressed CFRP Pile

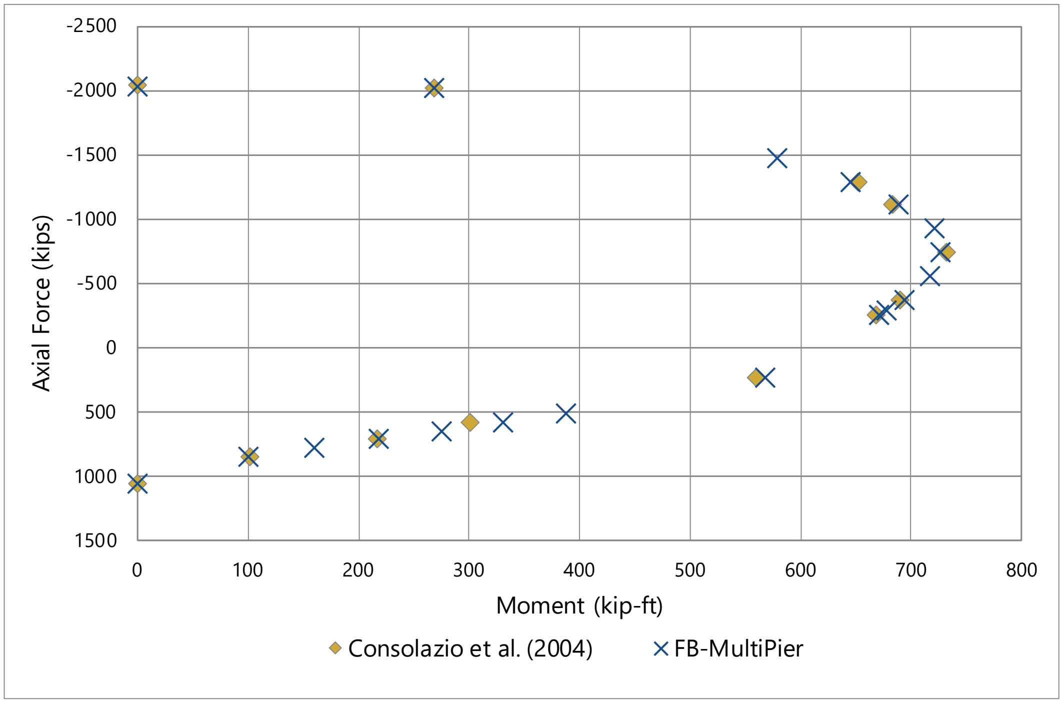


Figure B.4 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for a 24" Standard FDOT Prestressed CFRP Pile

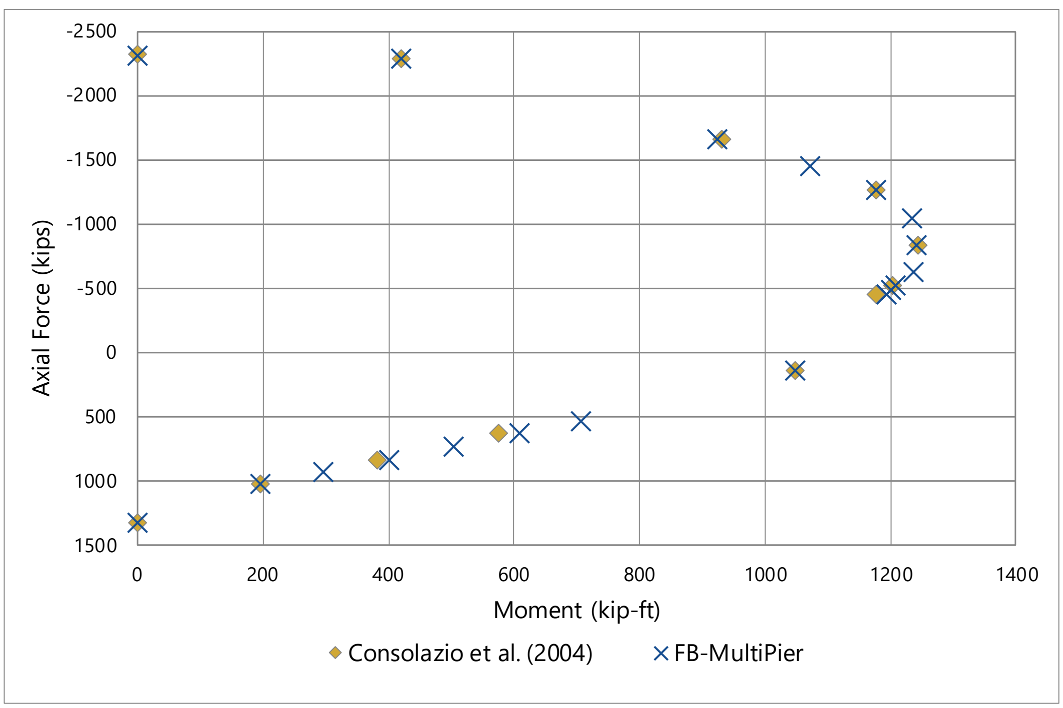


Figure B.5 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for a 30" Standard FDOT Prestressed CFRP Pile

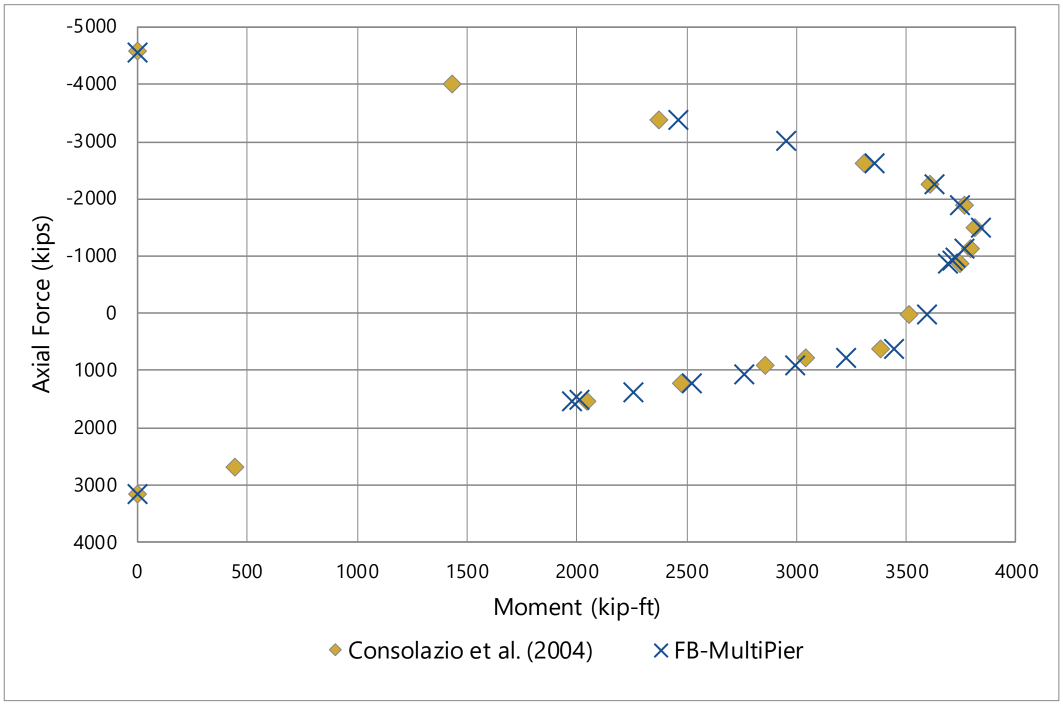


Figure B.6 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for a 54" Standard FDOT Prestressed CFRP Pile

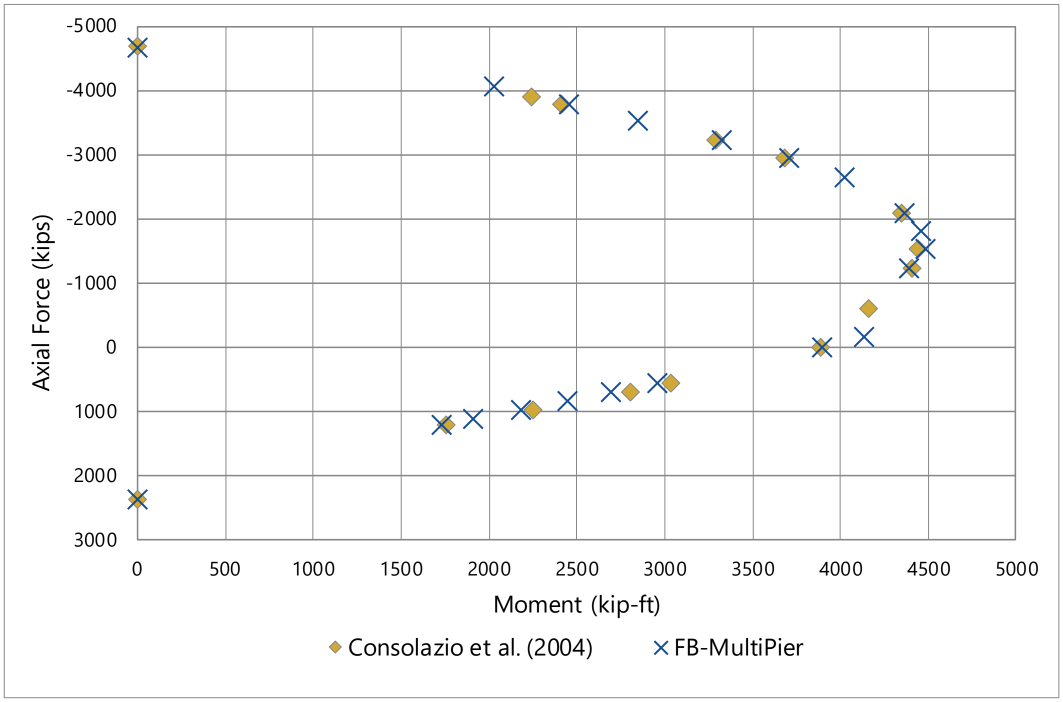


Figure B.7 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for a 60" Standard FDOT Prestressed CFRP Pile

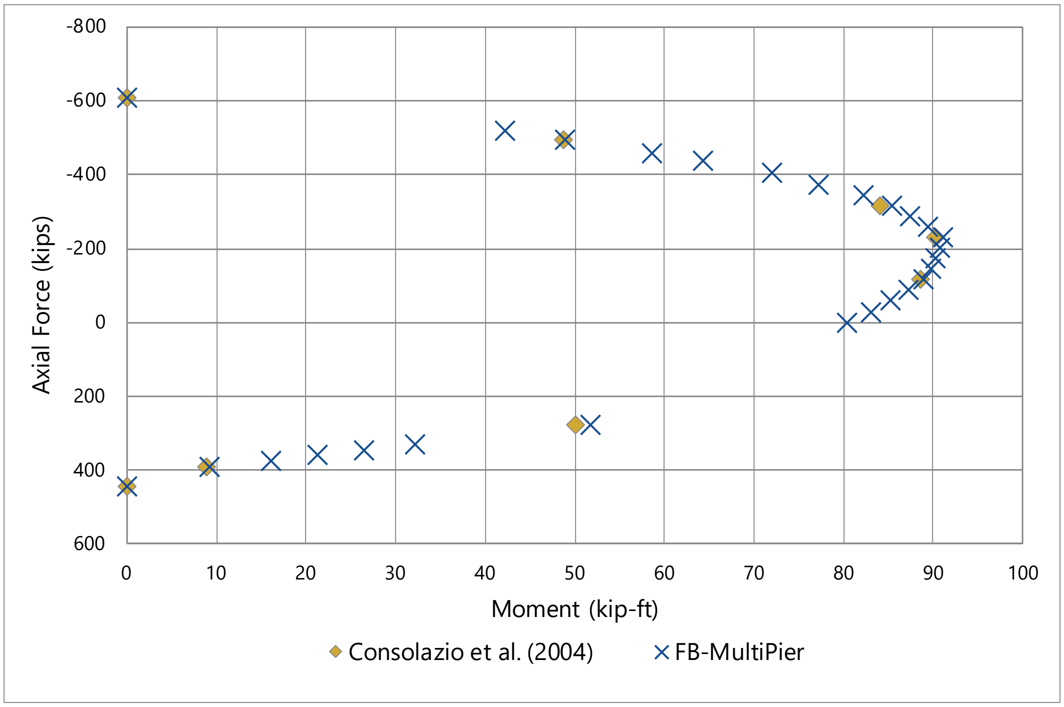


Figure B.8 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for a 12″ Standard FDOT Prestressed HSSS Pile

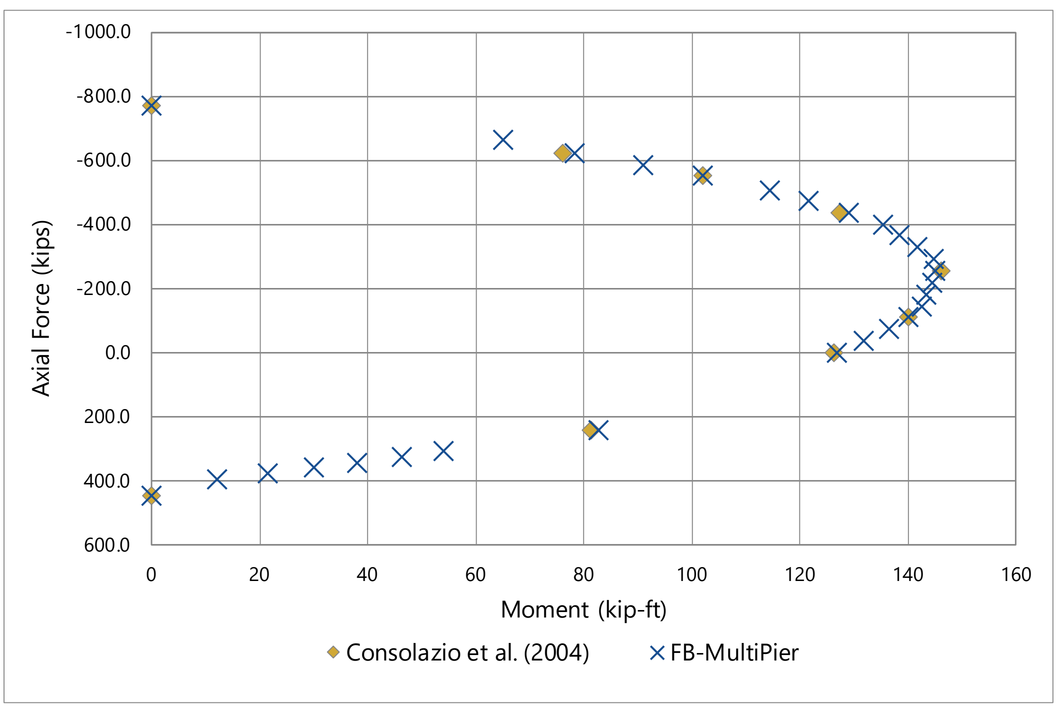


Figure B.9 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for a 14″ Standard FDOT Prestressed HSSS Pile

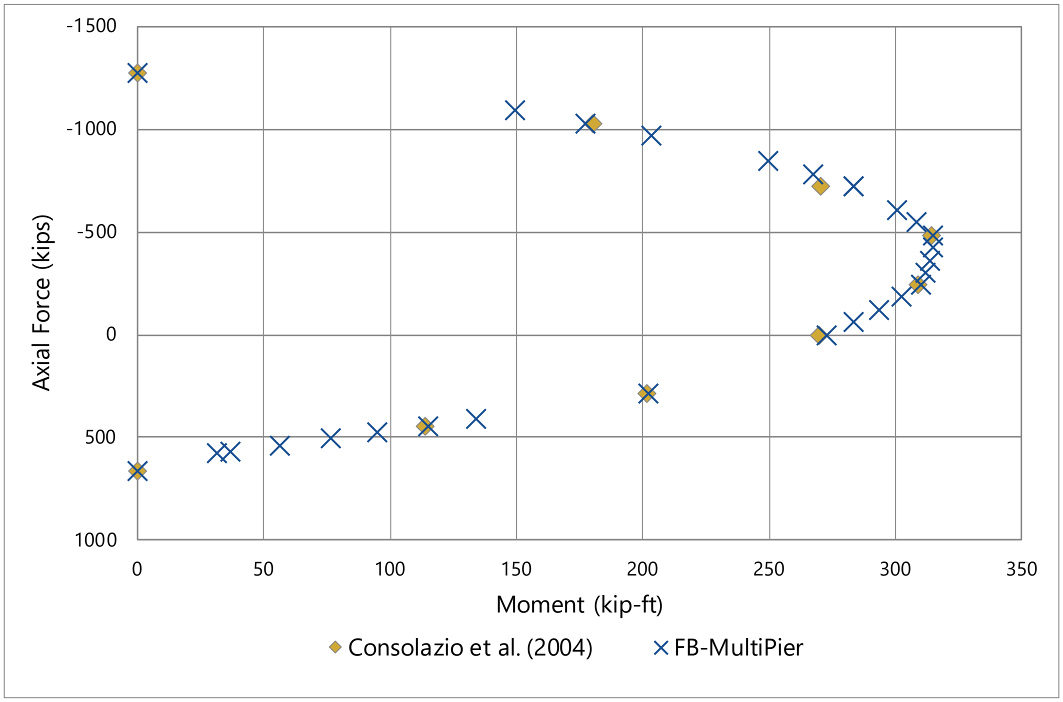


Figure B.10 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for an 18" Standard FDOT Prestressed HSSS Pile

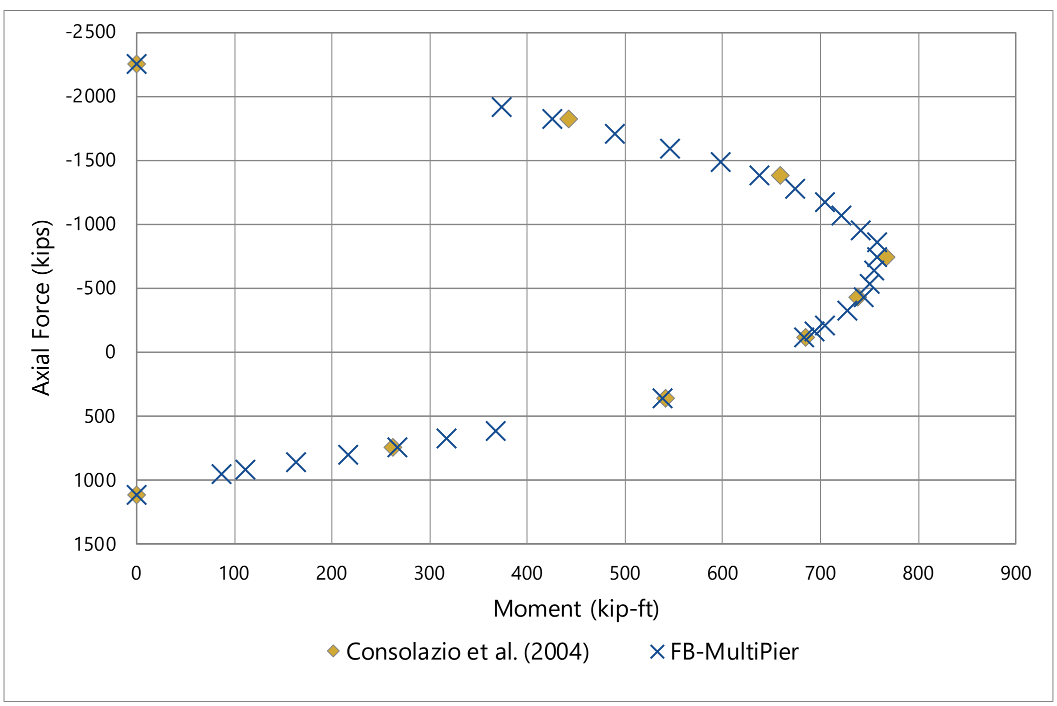


Figure B.11 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for a 24" Standard FDOT Prestressed HSSS Pile

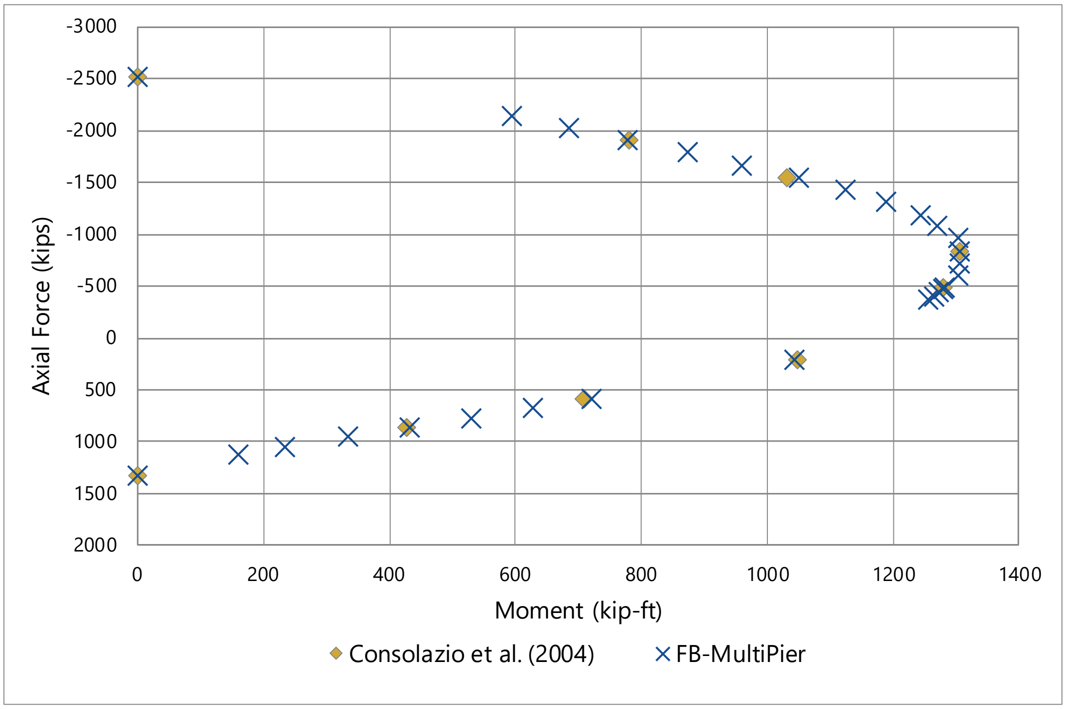


Figure B.12 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for a 30" Standard FDOT Prestressed HSSS Pile

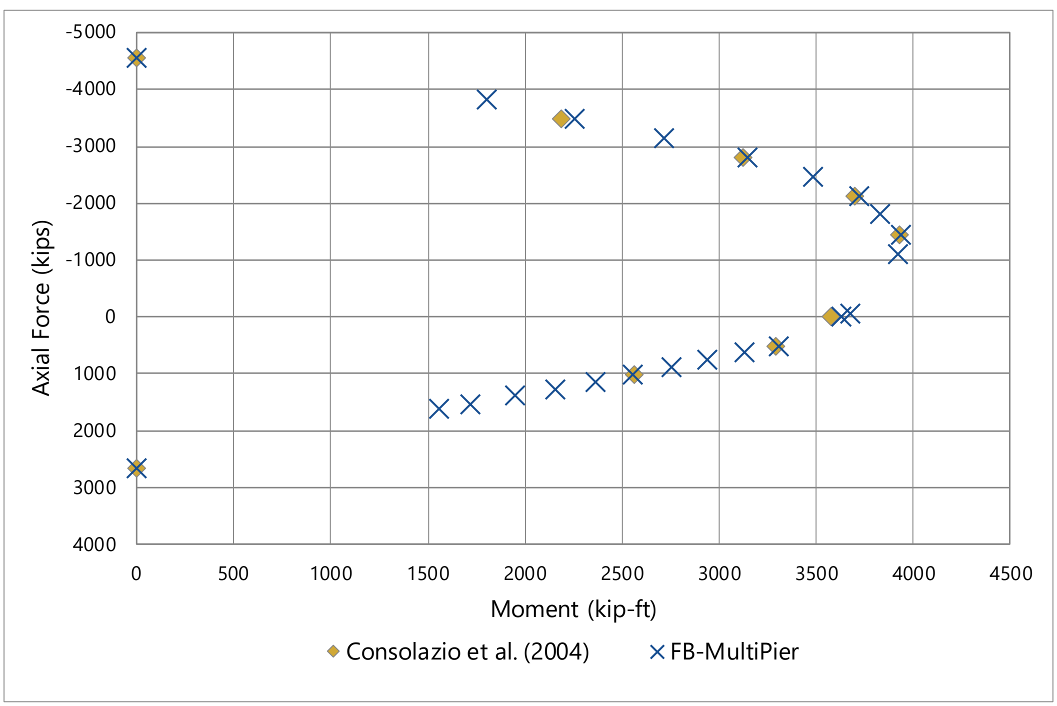


Figure B.13 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for a 54" Standard FDOT Prestressed HSSS Pile

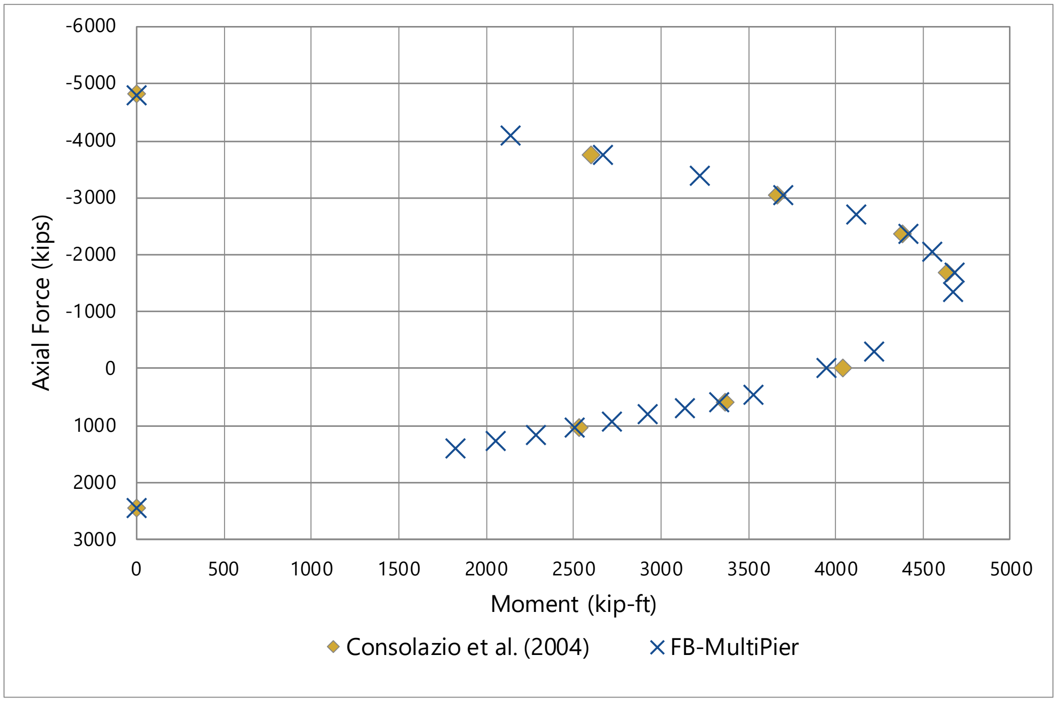


Figure B.14 – Comparison of Interaction Diagrams Between FB-MultiPier and Consolazio et al. (2004) for a 60" Standard FDOT Prestressed HSSS Pile