Structural Design of the Upper-Cased Length of Micropiles

Allen Cadden, P.E., D.GE, F.ASCE / June 2, 2023

Majid Khabbazian, PHD, PE

B. Philip Shull, Jr., PE

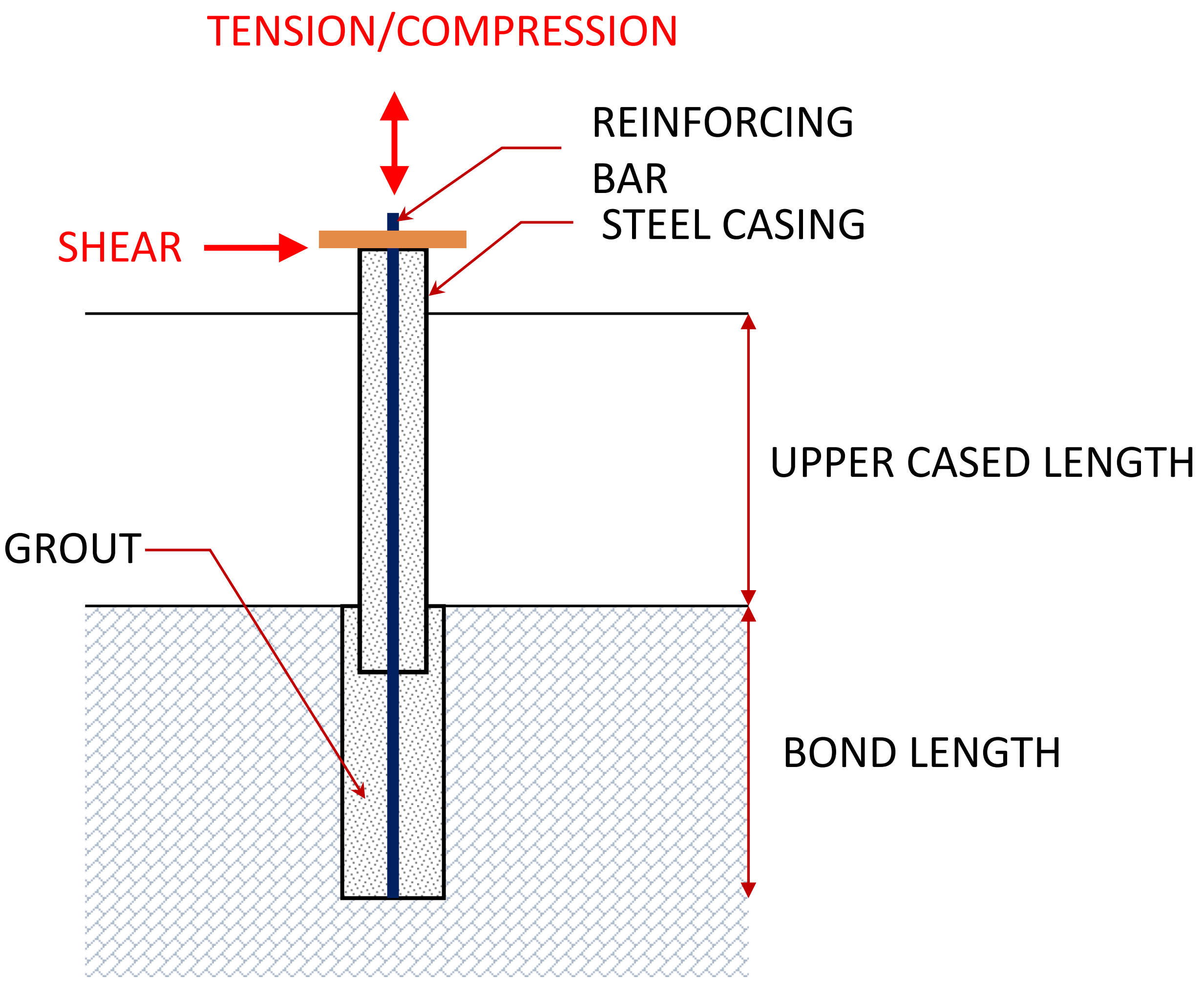
Schnabel ENGINEERING

Build Better. Together.

Outline

- A little background
- Micropiles under combined axial compression and flexure
  - Review of composite action
  - Design methods for upper cased length of micropiles under combined axial compression and flexure
- AASHTO composite design method
- AASHTO CFSTs method
- AASHTO non-composite method
- Examples/Comparison
- Conclusions

Overview of Micropiles

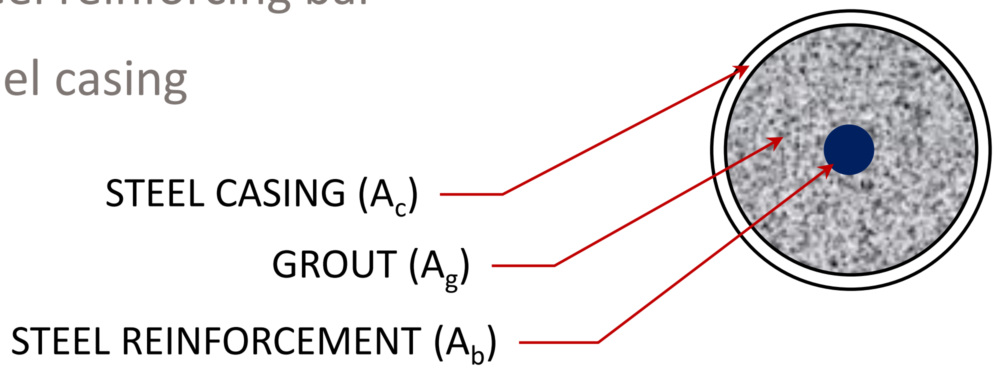


AASHTO Micropile Design

Nominal Axial Compression Resistance of Cased Length (AASHTO Micropiles, 10.9.3.10.2a)

$$R_n = 0.85 [0.85 f'_c A_g + F_y (A_b + A_c)]$$

- f'_c : Comp. strength of grout at 28 days
- A_g : cross-sectional area of grout within micropile casing
- F_y: Yield strength of reinforcement bar or steel casing, or stress in steel reinforcement bar or casing at a strain of 0.003, whichever is less.
- A_b: Cross-sectional area of steel reinforcing bar
- A_c: Cross-sectional area of steel casing

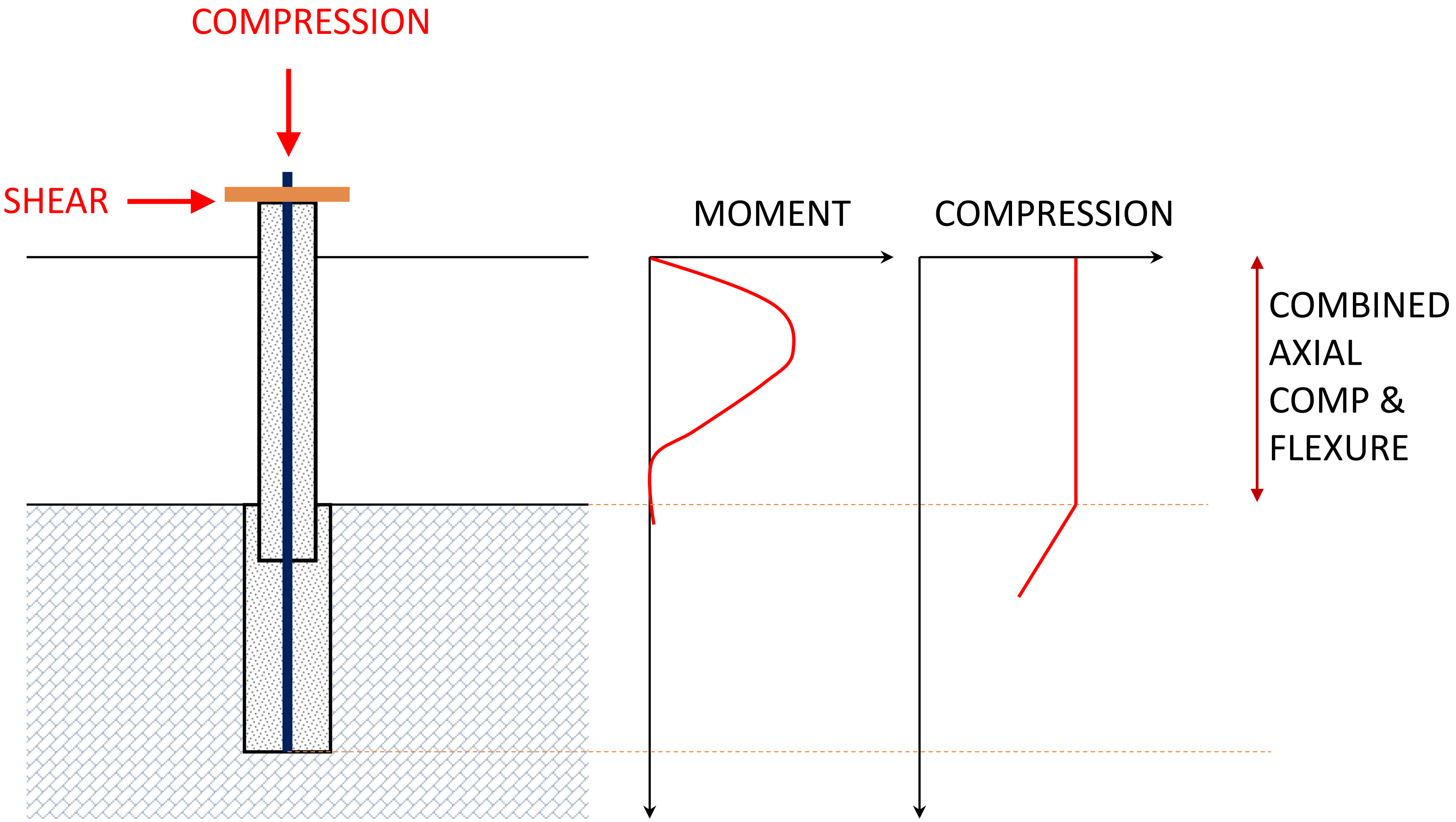


Nominal Axial Compression Resistance of Cased Length (AASHTO Micropiles 10.9.3.10.2a, Cont'd)

Limitations:

- Can only be used for micropiles under axial compression load
  - Cannot be used for micropiles under combined compression and flexure
- F_y: Yield strength of reinforcement bar or steel casing, or stress in steel reinforcement bar or casing at a strain of 0.003, whichever is less.
  - Elastic modulus of steel = 29,000 ksi
  - 0.003*29,000 = 87 ksi
  - A maximum F_y = 87 ksi can be used for steel casing/steel reinforcement
- f'c: No limit is specified on the compressive strength of grout

Micropiles Under Combined Axial Compression and Flexure



Review of Composite Action

- When compression load is applied, both steel and concrete will deform longitudinally.
- At initial strains (strain less than 0.001), Poisson's ratio of the steel exceeds Poisson's ratio of the concrete (~0.28 vs. 0.15 to 0.25).
  - This results in a greater lateral expansion of the steel and little interaction between the two materials.
  - During this stage of loading, steel and concrete sustain load independently.
- At a strain of ~0.001, micro-cracking in the concrete begins and the lateral expansion of the concrete increases and begins to approach the constant lateral expansion of the steel.
  - The concrete expansion reinitiates interactive contact between the two materials, which induces bond stresses to develop.
  - This causes the longitudinal stresses in the steel casing to change as a function of the transfer of force between the steel and concrete.

Review of Composite Action

- When confinement occurs, the casing experiences circumferential stresses from the lateral pressure of the expanding grout in addition to the longitudinal stresses.
  - This biaxial state of stress effectively decreases the amount of additional axial load the steel casing can take before yielding occurs.
  - The load carrying capacity of the grout (axial strength) is enhanced due to the confinement of the steel.
- For circular sections in particular (micropiles), the increase in axial strength of the concrete outweighs the decrease in the steel strength, resulting in an overall increase in the capacity of the circular section.

Reference: Jerome F. Hajjar (2001). A synopsis of studies of the monotonic and cyclic behavior of concrete-filled steel tube beam-columns

Review of Composite Action

General Behavior of Short Concrete Filled Steel Tubes (CFST) under Axial Load

(Fully Laterally Supported Micropiles or Unbraced Length/OD of less than 15)

If strength of steel exceeds approximately 60 ksi (the stress corresponding to a longitudinal strain of approximately 0.002), the concrete will likely reach its compressive strength limit and may crush before the steel yields.

Review of Composite Action

General Behavior of CFSTs under Pure Bending

- CFSTs subjected to pure bending behave much like hollow tubes.
- The steel casing contributes a large portion of the stiffness and strength since it lies at the periphery of the section where the material has the most influence.
- The only contribution of the concrete to moment resistance occurs due to the movement of the neutral axis of the cross section toward the compression face of the beam with addition of the grout.
- In literature, 3 to 37% enhancement of moment capacity of the CFSTs under pure bending has been reported.

Review of Composite Action

General Behavior of CFSTs under Combined Axial and Bending

- Behavior of CFSTs under combined loading is function of several factors like OD/t, axial load ratio, and slenderness of the section.
- As axial compression is added to a CFST, the contribution of the concrete begins to increase utilizing the composite action of the section to a greater extent (similar to a CFST under axial loading).

Design Methods for Micropiles Under Combined Axial comp. and Flexure

Design of Upper Cased Length of Micropiles under Combined Axial Compression and Flexure (AASHTO)

- There are three methods in AASHTO that can be used
  - Composite Members – AASHTO 6.9.5
  - Composite Concrete-Filled Steel Tubes (CFSTs) – AASHTO 6.9.6
  - Non-composite Sections – AASHTO 6.9.4 and 6.12.2

AASHTO Composite Method

Composite Members – AASHTO 6.9.5

- The specified minimum yield strength of steel, modulus of elasticity, and the radius of gyration of steel section are modified to account for the effect of grout and of longitudinal reinforcement.
- Nominal compressive resistance (P_n) and nominal flexural resistance (M_n) are calculated independently.
- The combined axial compression and flexure are checked with interaction equation.

$$\text{If } \frac{P_u}{P_r} < 0.2, \text{ then}$$

$$\frac{P_u}{2P_r} + \left(\frac{M_{ux}}{M_{rx}} + \frac{M_{uy}}{M_{ry}} \right) \leq 1.0$$

$$\text{If } \frac{P_u}{P_r} \geq 0.2, \text{ then}$$

$$\frac{P_u}{P_r} + \frac{8}{9}\left(\frac{M_{ux}}{M_{rx}} + \frac{M_{uy}}{M_{ry}} \right) \leq 1.0$$

  - P_r, M_{rx}, M_{ry}: Factored resistances
  - P_u, M_{ux}, M_{uy}: Factored loads

AASHTO Composite Method

Composite Members – AASHTO 6.9.5 (Cont'd)

Limitations

- Cross-sectional area of steel section (casing) should be at least four percent of the total cross-sectional area of the member.
- The specified minimum yield strength of the casing and the longitudinal reinforcement shall not exceed 60 ksi.
- The compressive strength of the grout shall be between 3.0 ksi and 8.0 ksi.
- Casing wall thickness requirement for compression
  - $OD/t < 0.11*E/F_y$

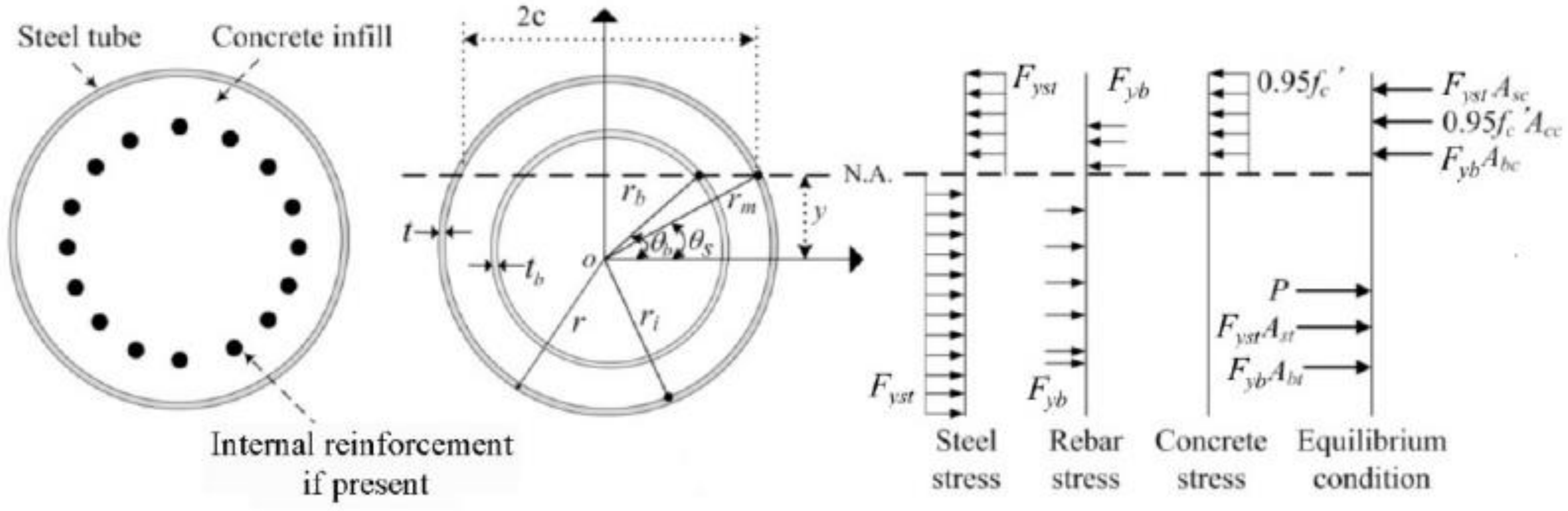
These limitations are specified to help to insure that some ductile yielding of the steel generally occurs prior to its local buckling or to crushing of the grout.

This method does not assure full composite action.

AASHTO CFSTs Method (Composite Method)

Composite Concrete-Filled Steel Tubes (CFSTs) – AASHTO 6.9.6

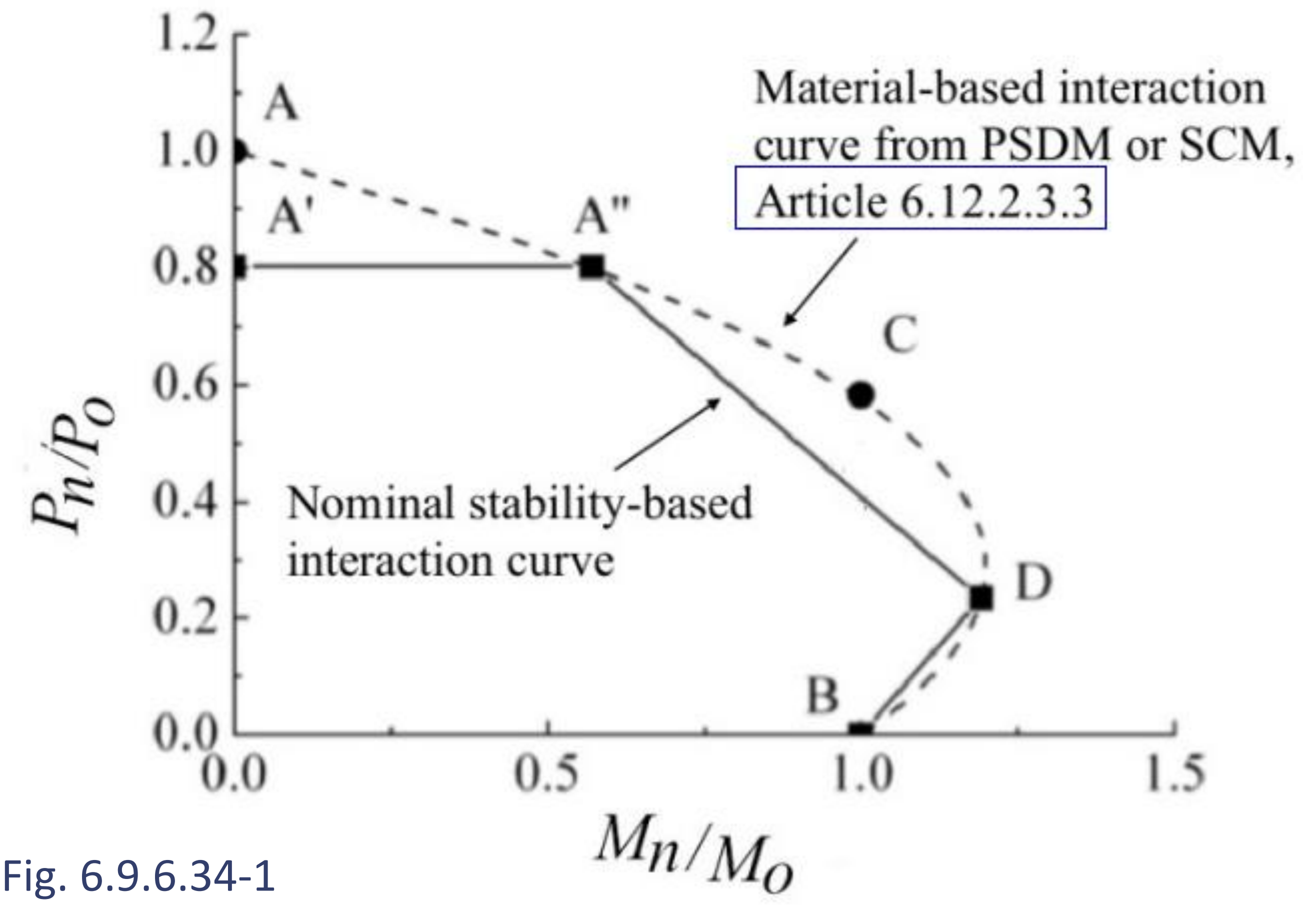
- The nominal flexural composite resistance in the presence of axial compression load is determined from a cross-sectional analysis based on equilibrium at full plastification of the section.



AASHTO Fig. C6.12.2.3.3-1

AASHTO CFSTs Method (Composite Method)

Composite Concrete-Filled Steel Tubes (CFSTs) – AASHTO 6.9.6 (Cont'd)



AASHTO Fig. 6.9.6.34-1

AASHTO CFSTs Method (Composite Method)

Composite Concrete-Filled Steel Tubes (CFSTs) – AASHTO 6.9.6 (Cont'd)

Limitations

- Can be used for micropiles subject to significant compression only or significant compression and flexure. CFSTs should not be used as pure flexural members.
  - Significant compression is not defined at AASHTO!
- Casing wall thickness requirement

  $$(OD/t) < 0.15\ (E/F_y)$$

- The specified minimum 28-day compressive strength of the grout shall be the greater of 3.0 ksi and $0.075F_y$
- There is no requirement for the specified minimum yield strength of the casing!

AASHTO Non-Composite Section Design

Non-Composite Section (AASHTO 6.9.4 and 6.12.2)

- Ignores the contribution of grout and the center bar
- It is basically steel design of the casing
- There is no limitation on the yield strength of the steel

Examples

Micropiles Under Axial Compression Loading

Micropile Casing			Center Bar		Grout	Composite (CFST)	Composite	Non-Composite	AASHTO Micropile
OD	t	Fy	Bar #	Fy	f'c	Pr	Pr	Pr	Pr
(in)	(in)	(ksi)		(ksi)	(ksi)	(kip)	(kip)	(kip)	(kip)
12.75	0.5	80	-	-	5	1501	1533	1461	1214
			-	-	8	1779	1796	1461	1390
			20	75	5	1745	1793	1461	1435

Note:
Even though AASHTO doesn't specify a limit on the yield strength of steel, a maximum yield strength of 60ksi is used for the CFST method per recommendations in literature.

Examples

Micropiles Under Axial Compression Loading

Micropile Casing			Center Bar		Grout	Composite (CFST)	Composite	Non-Composite	AASHTO Micropile
OD	t	Fy	Bar #	Fy	f'c	Pr	Pr	Pr	Pr
(in)	(in)	(ksi)		(ksi)	(ksi)	(kip)	(kip)	(kip)	(kip)
7.0	0.5	80	-	-	5	670	694	774	565
			-	-	8	743	762	774	611
			10	75	5	731	759	774	620

Note:
Even though AASHTO doesn't specify a limit on the yield strength of steel, a maximum yield strength of 60ksi is used for the CFST method per recommendations in literature.

Examples

Micropiles Under Combined Axial Compression and Flexure

Bending resistance of upper cased length of micropile at a given axial compression load

Micropile Casing			Center Bar		Grout	Axial Load	Composite (CFST)	Composite	Non-Composite	AASHTO Micropile
OD	t	Fy	Bar	Fy	f'c	Pu	Mu	Mu	Mu	N/A
(in)	(in)	(ksi)	#	(ksi)	(ksi)	(kip)	(kip-ft)	(kip-ft)	(kip-ft)	
12.75	0.5	80	-	-	5	1050	140	135	155	-
			-	-	8	1150	185	152	117	-
			20	75	5	1175	195	145	108	-

Notes:

1- Even though AASHTO doesn't specify a limit on the yield strength of steel, a maximum yield strength of 60ksi is used for the CFST method per recommendations in literature.

2- Since AASHTO doesn't define the "significant axial load", an axial load at strain of 0.001 is used per literature recommendations.

Examples

Micropiles Under Combined Axial Compression and Flexure

Bending resistance of upper cased length of micropile at a given axial compression load

Micropile Casing			Center Bar		Grout	Axial Load	Composite (CFST)	Composite	Non-Composite	AASHTO Micropile
OD	t	Fy	Bar	Fy	f'c	Pu	Mu	Mu	Mu	N/A
(in)	(in)	(ksi)	#	(ksi)	(ksi)	(kip)	(kip-ft)	(kip-ft)	(kip-ft)	
7.0	0.5	80	-	-	5	425	43	46	72	-
			-	-	8	450	50	48	66	-
			10	75	5	450	52	48	66	-

Notes:

1- Even though AASHTO doesn't specify a limit on the yield strength of steel, a maximum yield strength of 60ksi is used for the CFST method per recommendations in literature.

2- Since AASHTO doesn't define the "significant axial load", an axial load at strain of 0.001 is used per literature recommendations.

Conclusions

- Micropiles under axial compression load
  - AASHTO micropile design methodology can significantly underestimate the axial compression resistance of the upper-cased length of micropiles when compared to both composite section designs and non-composite section design methodologies (2 to 27% underestimation for the examples presented herein).

- Micropiles under combined axial compression and flexure
  - AASHTO recommendations on the CFST composite design is not clear.
    - AASHTO doesn't define a limit on the yield strength of the steel casing (while literature suggests a maximum yield strength of 60ksi).
    - AASHTO doesn't define "significant compression load" on the micropiles.

Conclusions

- Micropiles under combined axial compression and flexure
  - For larger micropile casings with either high strength grout or a center bar, the effects of composite action can have significant impact on the flexural resistance of the pile. In this case, use of composite section designs would be more beneficial than non-composite section design.
  - For steel casing with yield strength of greater than 60ksi, the use of composite section design (specially for small diameter casing) may not be beneficial. However, for yield strength of casing less than 60ksi, the contribution of composite action will be more significant.
  - For micropiles under combined axial compression and flexure, look at both AASHTO composite section (6.9.5) and non-composite section and select the method that gives greater bending resistance.

QUESTIONS?

References:

1. AASHTO LRFD Bridge Design Specifications. 9th edition, 2020.
2. FHWA. Micropile Design and Construction, FHWA-NHI-05-039, 2005.
3. Jerome F. Hajjar. A synopsis of studies of the monotonic and cyclic behavior of concrete-filled steel tube beam-columns. 2001.