Evaluation of Strut-and-Tie Method for Drilled Shaft Footings subjected to Uniform Compression Loading

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Research in Progress Session

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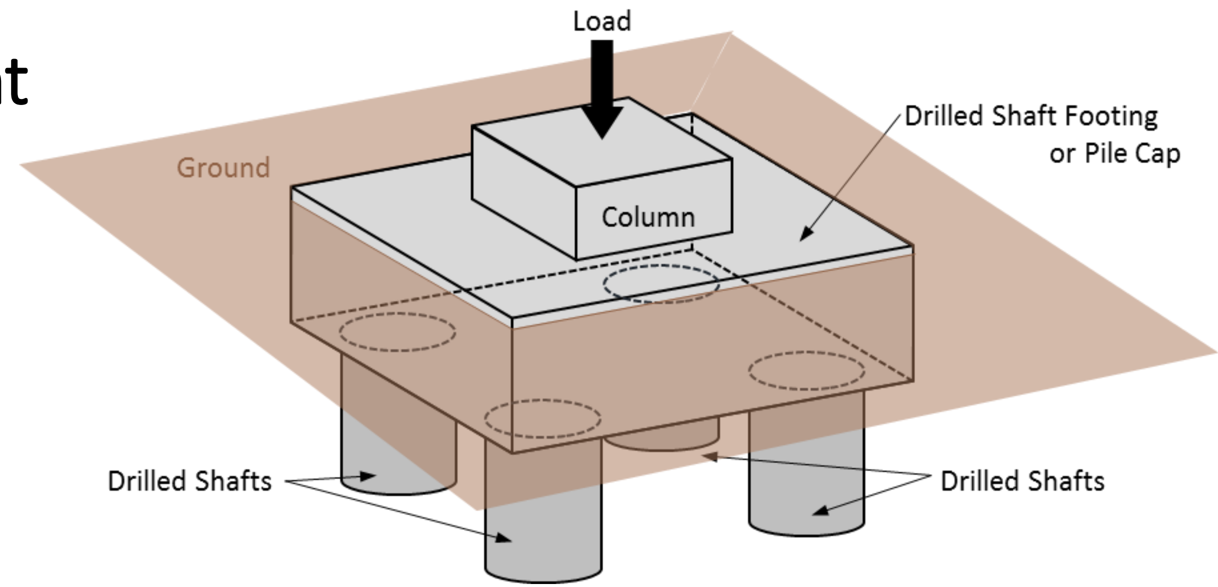
- Experimental Program
- 3D Strut-and-Tie Method (STM)
- Summary and Conclusion

Research Project Overview

- **Primary Objectives**
  - Study behavior of footings having four drilled shafts
    - Large scale loading tests
    - Reinforcement and geometric design parameters
  - Design recommendation to implement three dimensional (3D) STM for drilled shaft footings



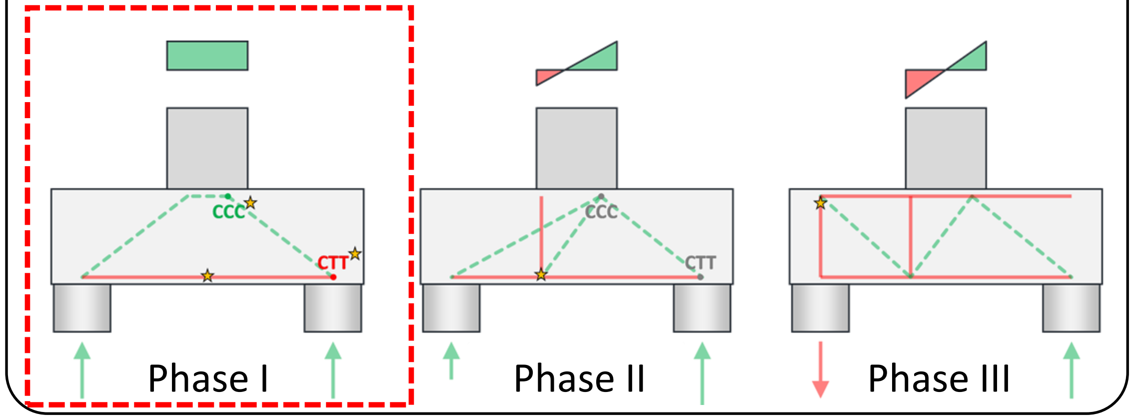
Research Project Overview

- **Research Scope**

Literature Review →

Design Parameter Review →

Experimental Program



↔ **Finite Element Analysis**

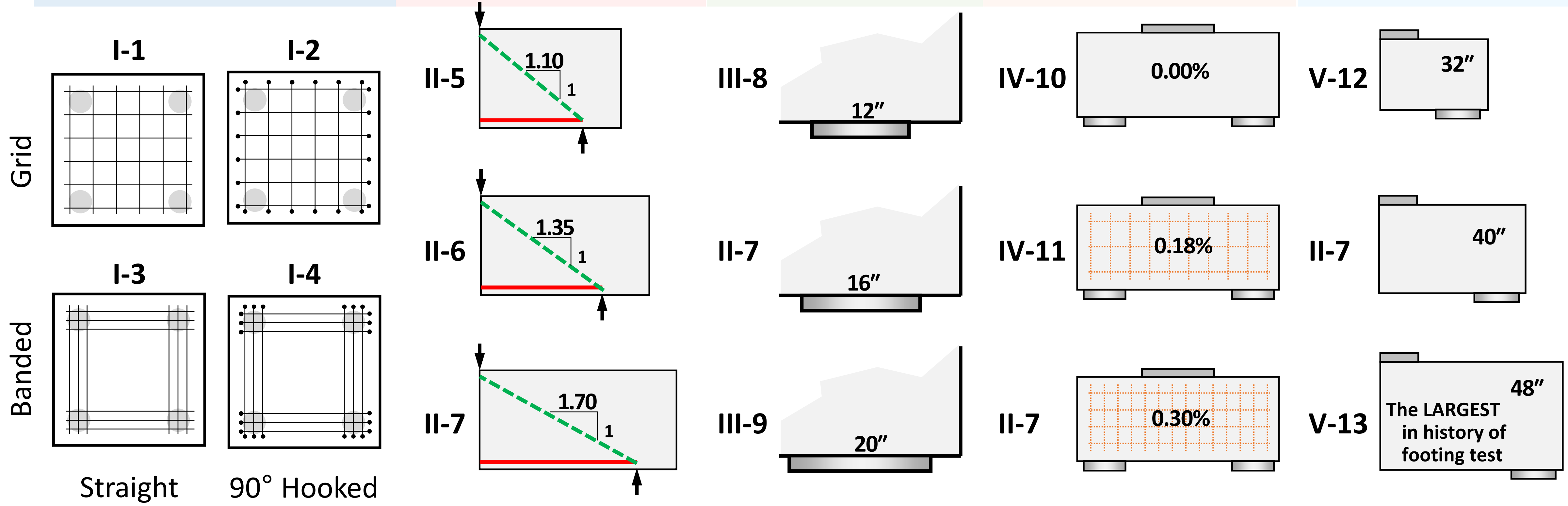
↓

Development of Strut-and-Tie Modeling Guidelines

Experimental Program

- **Test Variables**

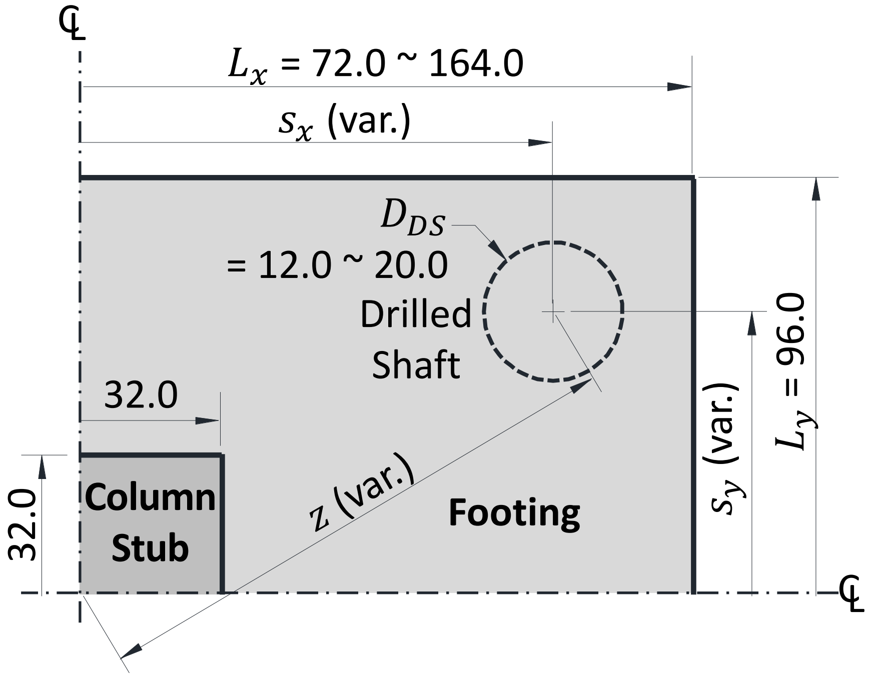
Series I	Series II	Series III	Series IV	Series V
Bottom Mat Reinf. Details	Strut Inclination	Shaft Diameter	Side Face Reinf. Ratio	Footing Height



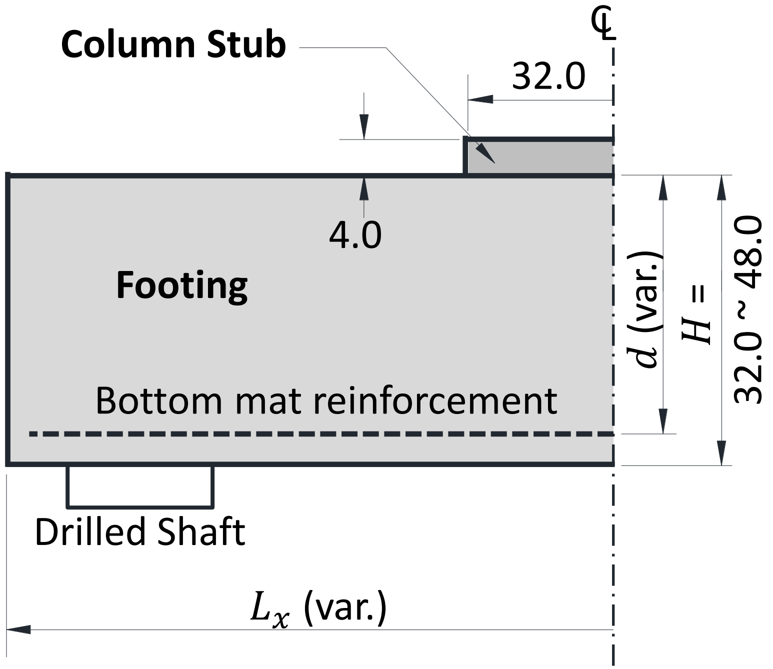
Experimental Program

- **Specimen Design**

Unit: in.



(a) Plan view



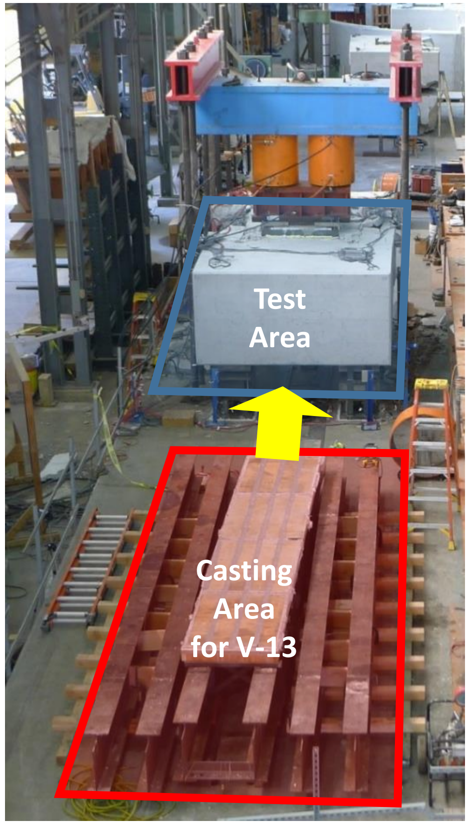
(b) Side view

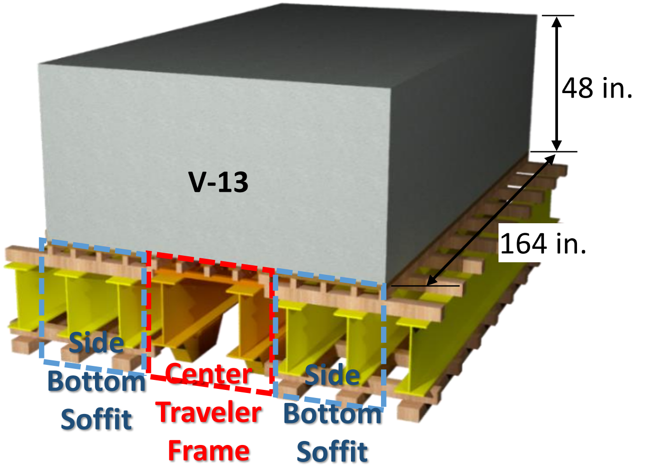
Bottom mat reinforcement

Experimental Program

- Specimen Fabrication

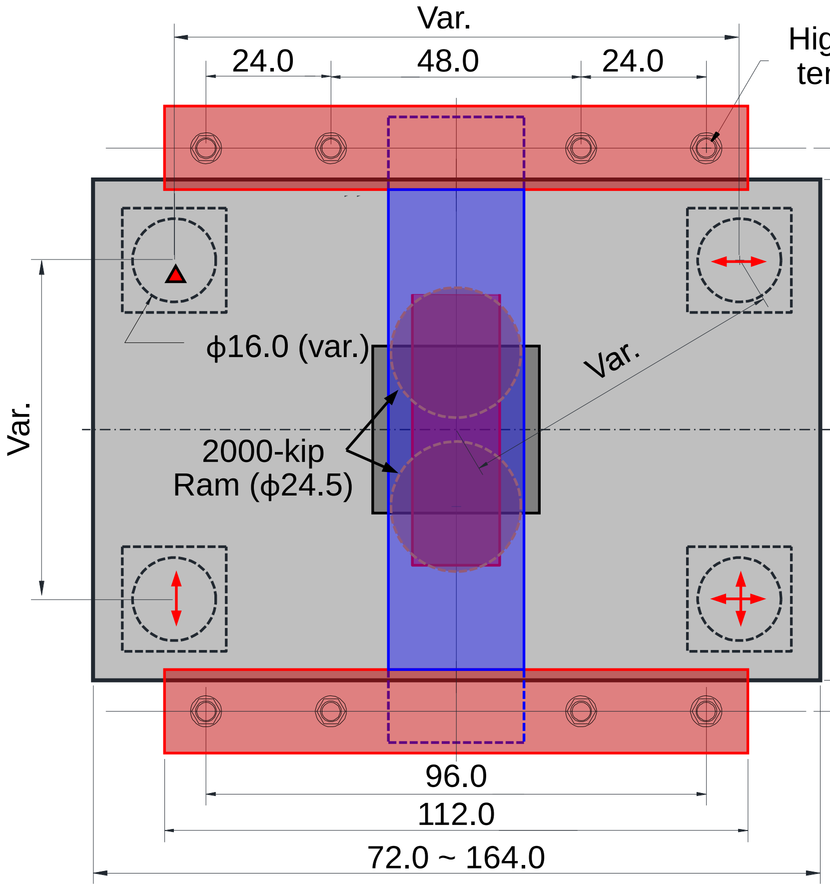
- LARGEST Specimen



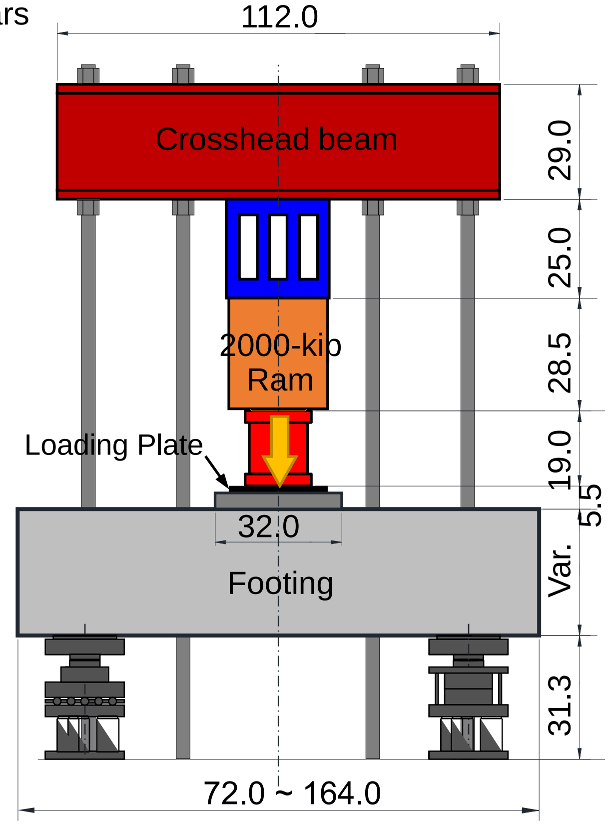


Experimental Program

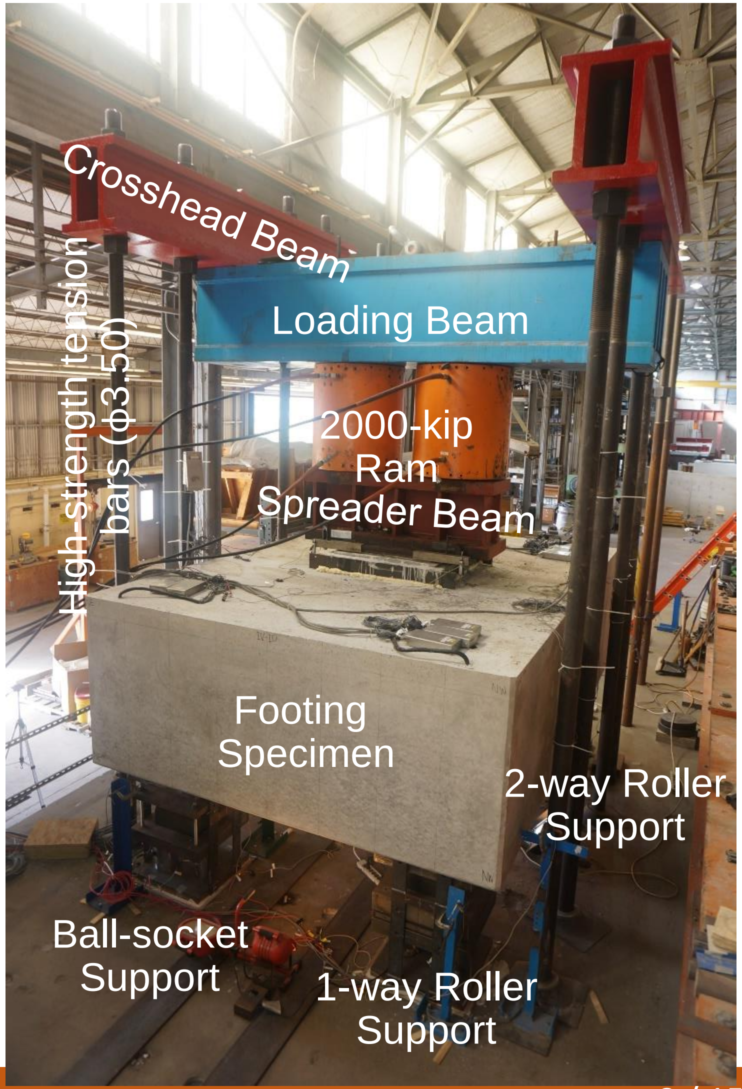
- **Structural Loading Test**



Top View



Side View

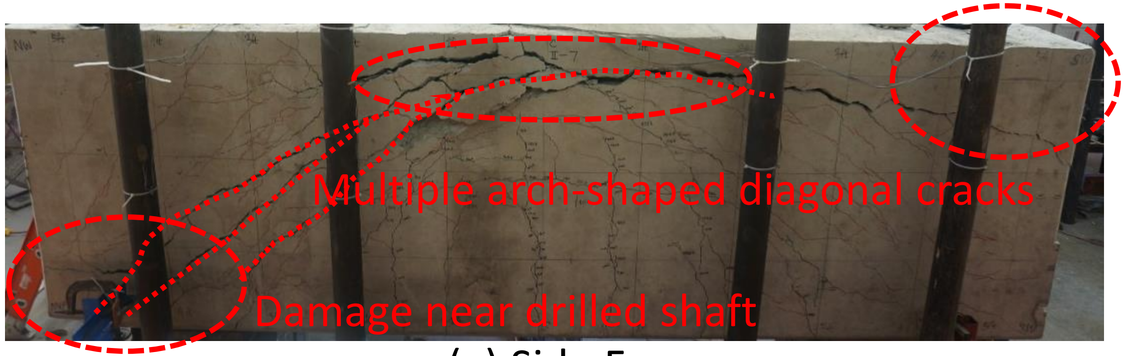


Experimental Program

- **Experimental Results**

Failure (V-13)

Typical Post-failure Crack Pattern of Footings having Grid Layout and Side Face Reinforcement



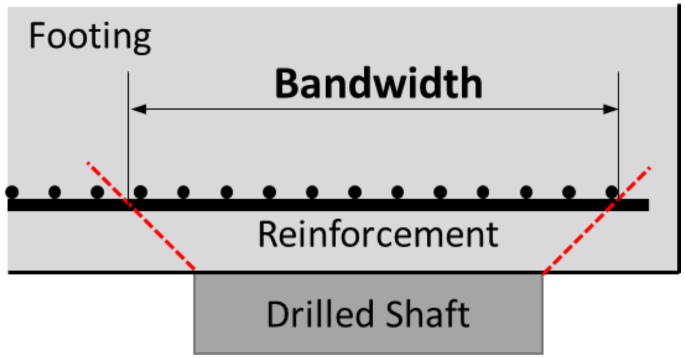
(a) Side Face

(b) Bottom Face

Experimental Program

- **Major Findings from Results**
  - Brittle failures of all specimens except V-12
  - Regardless of the layout, contribution of all fully-developed reinforcement not only inside but also outside the bandwidth to tie forces
  - Clear relationship between ultimate strengths and strut inclinations
  - Smaller shaft diameter adversely affected the strain development outside bandwidth
  - Absence of side face reinforcement: Undesirable structural behavior

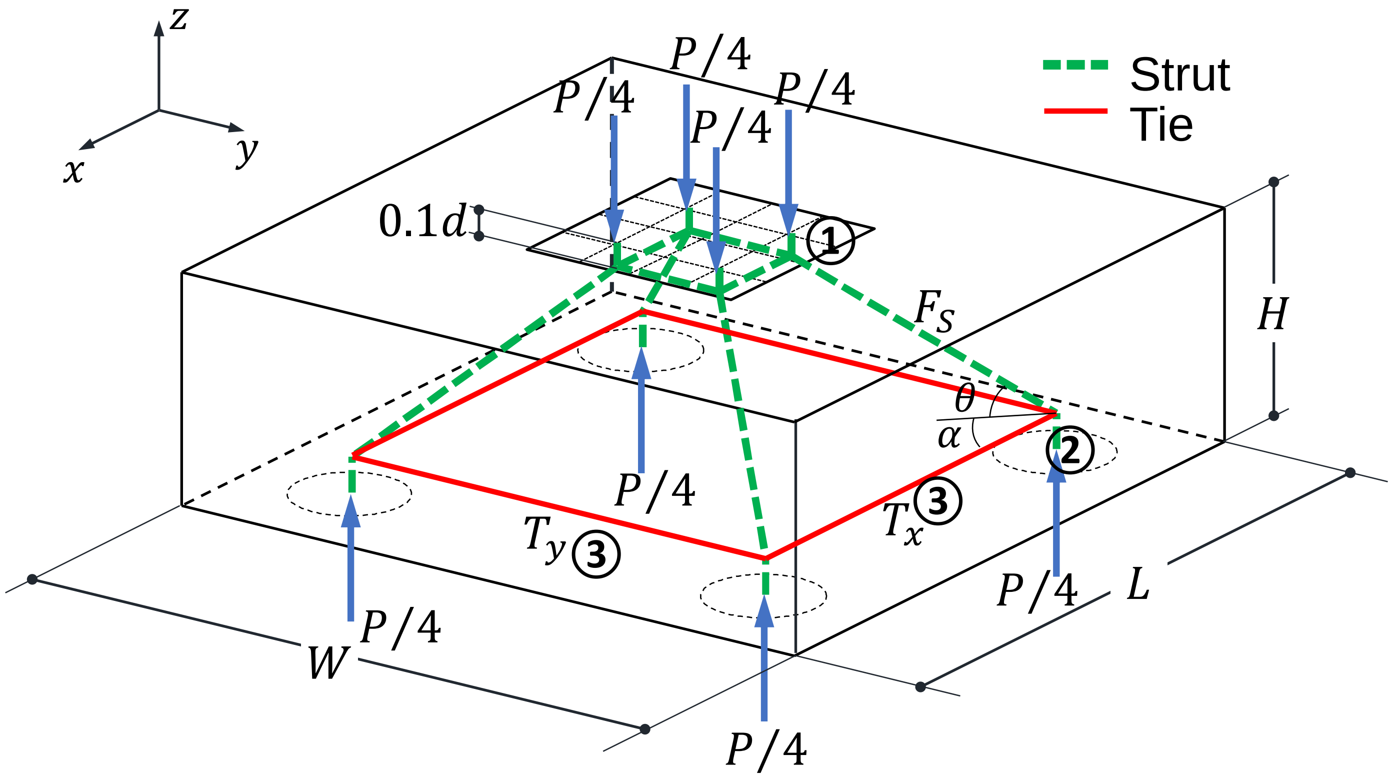
    Most brittle, catastrophic failure, the smallest ultimate load, the least deformation capacity in post-peak state



TxDOT Bridge Design Guide (2020

3D Strut-and-Tie Method

- **Williams et al. (2012)**



$A_{st,x\ or\ y}$: Total steel area of longitudinal reinforcement in the bandwidth in x- or y- direction
$f_{y,x\ or\ y}$: Yield strength of longitudinal reinforcement in x- or y- direction
$*\ l_{ad}/l_d \leq 1.0$

$$F_{n,b} = P/4$$

$$T_x = \frac{P/4}{\sin\theta}\cos\theta\cos\alpha$$

$$F_S = \frac{P/4}{\sin\theta}$$

$$T_y = \frac{P/4}{\sin\theta}\cos\theta\sin\alpha$$

Design Checks

1. Bearing at CCC node below the column
2. Bearing at CTT node above the shaft
3. Ties

3D Strut-and-Tie Method

- **Williams et al. (2012)**

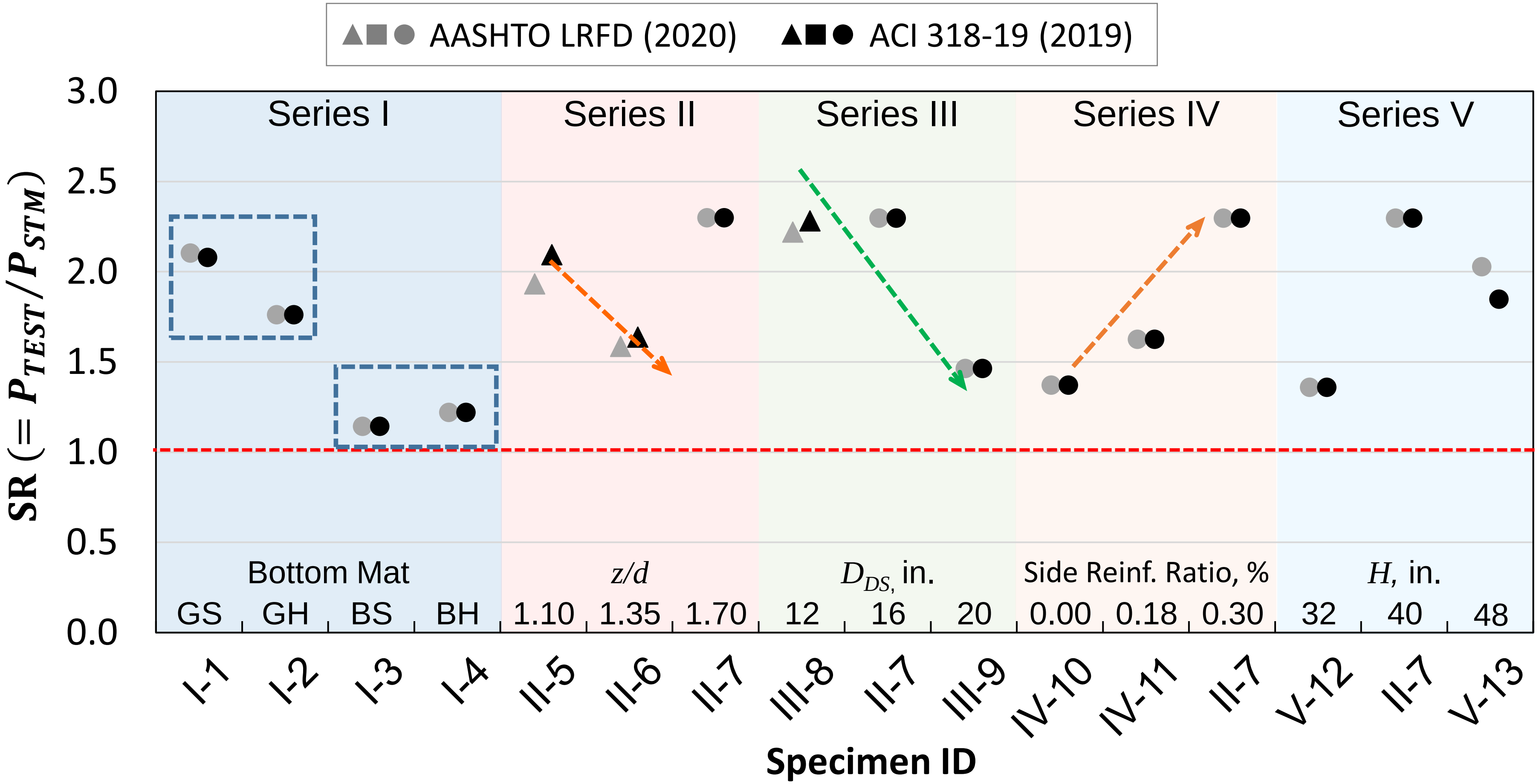
Design Criteria	AASHTO LRFD (2020)	ACI 318-19 (2019)
① Bearing at CCC node below the column ② Bearing at CTT node above the shaft	$F_{n,n} = f_{cu}A_{cn} = (m\nu f_c')A_{cn} = F_{n,b}$ where $m = 1.0$ (conservatism) $\nu = 0.85$ CCC Node $= 0.85 - \frac{f'_c}{20\ ksi}$ CTT Node m: confinement modification factor ν: concrete efficiency factor	$F_{nn} = f_{ce}A_{nz} = (0.85\beta_c\beta_n f_c')A_{cn} = F_{n,b}$ where $\beta_c = 1.0$ (conservatism) $\beta_n = 1.0$ CCC Node $= 0.6$ CTT Node β_c: confinement modification factor β_n: nodal zone coefficient (≈ concrete efficiency factor)
③ Ties	$F_{n,tie} = A_{st}f_y(l_{ad}/l_d)^* = T_x\ or\ T_y$	$F_{nt} = A_{st}f_y(l_{ad}/l_d)^* = T_x\ or\ T_y$
④ Strut strength	N/A	~~$F_{ns} = f_{ce}A_{cs} = (0.85\beta_c\beta_s f_c')A_{cs} = F_s$~~

Note) A_{st}: Total steel area of longitudinal reinforcement in the bandwidth, $f_{y,}$: Yield strength of longitudinal reinforcement, $l_{ad}/l_d \leq 1.0$

➡ $P_{STM} = \min(F_{n,n}, F_{n,tie})$ or $\min(F_{nn}, F_{nt})$ **according to each code provision**

3D Strut-and-Tie Method

■ Evaluation



	AASHTO LRFD (2020)	ACI 318-19 (2019)
Min.	1.145	1.145
Max.	2.299	2.299
Mean	1.702	1.708
CoV	0.227	0.230

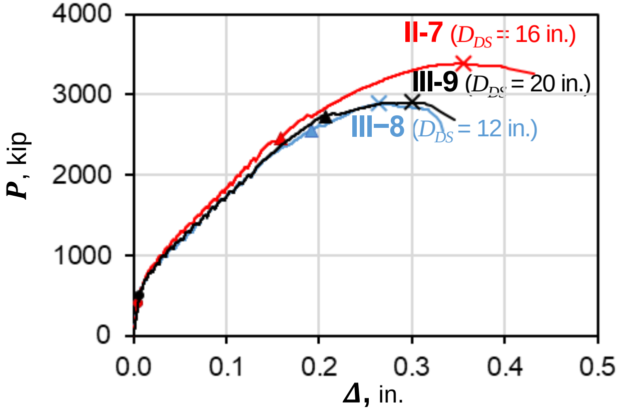
Note) CoV (Coefficient of Variation)
= Mean / Standard Deviation

△ : Bearing strength at node above drilled shaft □ : Bearing strength limit at node beneath column ○ : Tie yielding

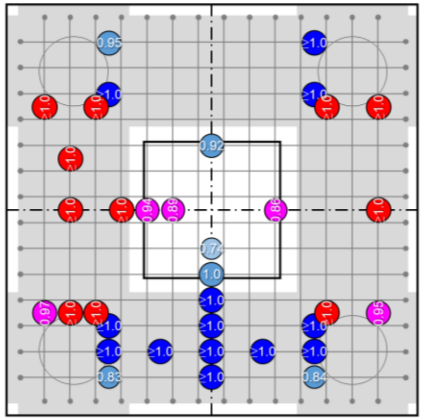
Summary and Further Study

▪ Valuable Findings from the Evaluation

- <u>Controlling failure mechanism:</u>
  - – Tie yielding governed most cases
  - – Discrepancy with the experimental observation



II-7 Cutting Section



I-2 Strain Distribution

- Most brittle failure (IV-10) → the <u>least safety margin</u> (undesirable)
- <u>Excessively conservative assumptions</u>
  - – Unit confinement factor
  - – Nodal strength checks at bearing face only

Summary and Conclusions

- **Potential Refinements to Improve Accuracy and Dispersion**

1) Contribution of steel outside the bandwidth

2) Downgrade of the strength for the case of unsatisfied amount of side face reinforcement

3) Confinement effect from massive concrete surrounding by nodal region

4) 3D Nodal geometry necessary
   → Nodal capacity at the strut-to-node interface
   → Available development length

Acknowledgements

Questions?

E-mail: hyunsu.kim@utexas.edu

Publications from this study:

Kim et al., "Effects of Reinforcement Details on Behavior of Drilled Shaft Footings," ACI Structural Journal (Submitted)

Kim et al., "Effects of Geometric Parameters on Behavior of Drilled Shaft Footings" (in-progress)

Kim et al., "Three-Dimensional Strut-and-tie Method for Drilled Shaft Footings" (in-progress)