# T2R2 東京科学大学 リサーチリポジトリ Science Tokyo Research Repository

## 論文 / 著書情報 Article / Book Information

題目(和文)	
Title(English)	Flexural and Shear Performance of Steel-encased Precast Spun Concrete Piles
著者(和文)	Thusoo Shreya
Author(English)	Shreya Thusoo
出典(和文)	学位:博士(学術), 学位授与機関:東京工業大学, 報告番号:甲第11662号, 授与年月日:2020年9月25日, 学位の種別:課程博士, 審査員:WIJEYEWICKREMA ANIL,河野 進,岩波 光保,竹村 次朗,佐々木 栄一
Citation(English)	Degree:Doctor (Academic), Conferring organization: Tokyo Institute of Technology, Report number:甲第11662号, Conferred date:2020/9/25, Degree Type:Course doctor, Examiner:,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	
Type(English)	Outline

**Tokyo Institute of Technology** 

## Flexural and Shear Performance of Steel-encased Precast Spun Concrete Piles

<sub>by</sub> Shreya Thusoo

Doctoral Committee:

Prof. Susumu Kono Assoc. Prof. Anil C. Wijeyewickrema Assoc. Prof. Jiro Takemura Assoc. Prof. Eiichi Sasaki Prof. Mitsuyasu Iwanami

A dissertation submitted in partial fulfillment of the requirements for the Doctor of Philosophy Degree

August 2020

#### ABSTRACT

The thesis presents a comprehensive study on the flexural and shear performance of steelencased precast spun concrete (SC) piles using large-scale experimental data and analytical modeling. The research mainly focuses on the assimilation of experimental data, improvement of currently available flexural and shear design guidelines, and development of numerical models to simulate the flexural behavior of SC piles. The results from this study are valuable and useful for engineers designing foundations in areas with high seismicity.

The study first focuses on analyzing the test data from previous experiments on 11 SC pile specimens to investigate the bending moment capacity, damage process, and failure criteria for flexural failure. The main parameters include the axial load ratio (0-0.35), steel casing thickness (4.5-6.0 mm), concrete layer thickness (50-68 mm), and filling material (hollow, cement paste, concrete). The test results show that concrete crushing and local buckling of steel are the major factors influencing the bending capacity of SC piles, given that global buckling is not permitted. The damage at failure state is characterized by local buckling of steel between 0-100 mm, concrete between 0-240 mm, all from the base. High curvature demands are seen to be concentrated between 0-125 mm from the base for drift ratios less than 1.5%. Further, it is observed that governing factor changes from concrete strength ratio. It is found that filling the core with a low-cost, low-strength material prevents the spalling of the inner line of concrete and, consequently, increases the drift and ductility performance.

The applicability of stress distribution-based methods given in available guidelines by AIJ (2008), Eurocode 4 (2004), and ANSI/AISC 360-16 (2016) for bending capacity of columns/composite members under axial-flexural loads is investigated. The applicability of strain compatibility-based method in the draft guidelines for SC piles by the AIJ (2020) committee is also examined. For this purpose, a database of 79 bending tests on SC piles, including tests from literature and pile manufacturers in Japan, is organized. The scope of the dataset is defined by characteristic parameters, axial load ratio (-0.4–0.5), section slenderness ratio (36–133), member slenderness ratio (6.0–18.8), concrete compressive strength (81–123 MPa) and steel tensile strength (301–521 MPa). Modifications are proposed to the drafted guidelines for SC piles to give conservative predictions with an error of less than 20% for all tests in the database.

The development of a fiber-based finite element model of SC piles is carried out to simulate the moment-drift behavior under axial-flexural loads up to and beyond the peak response. The model is characterized by a single beam-column element in the damage zone at the base. The stress-strain relationship of fiber elements of steel in the damage zone follows a pipe buckling model. For this, a hysteretic model for steel is developed with a linear falling branch and a constant stress branch after initiation of buckling. The fiber elements of steel in the low damage zone do not undergo buckling. The enhancement of concrete strength due to confinement by steel casing is considered by using a confined concrete model such that the reduction in confinement due to the hollow core is also taken onto account. The sectional behavior is validated by comparison with the moment-drift responses from five simply supported bending tests covering axial load ratios of -0.4 to 0.5 times the section capacity. Whereas the member behavior is validated by comparison with the moment-drift responses from thirteen tests covering simply supported and cantilevered bending tests, hollow and filled-core specimens, and axial load ratios of -0.4 to 0.5 times the section capacity. It is found that the model can simulate the flexural behavior of SC piles for axial load ratios of 0 to 0.5 with good accuracy.

Furthermore, to investigate the performance of SC piles under shear loads, shear tests on 400 diameter SC piles were conducted with the axial load ratio as the main parameter. The objective of these tests is to gather experimental data on the shear behavior of SC piles to investigate the shear capacity, damage process, and failure criteria for shear failure. For the case of SC pile with high compression axial load ratio of 0.5 and shear span to diameter ratio of 0.5, a brittle shear force vs. drift response and shear failure is reported, accompanied by the sudden loss of axial capacity to half of the initial value. From the extent of shear yielding along the cross-section, 1/2 of the area of steel is found to be effective in resisting shear at the failure. Additionally, it is confirmed that the design of SC piles is governed by the bending capacity rather than the shear capacity in most design situations.

#### ACKNOWLEDGEMENT

I would like to express my sincere appreciation and deep gratitude to my supervisors Prof. Susumu Kono and Assoc. Prof. Anil C. Wijeyewickrema for their continuous advice supporting my research and invaluable guidance during my study at Tokyo Institute of Technology.

I would like to express my deep appreciation to the examiners of my dissertation, Assoc. Prof. Jiro Takemura, Assoc. Prof. Eiichi Sasaki, and Prof. Mitsuyasu Iwanami for taking time from their busy schedule to read and give constructive feedback to my thesis. Their helpful comments and suggestions significantly contributed to improving the work and my understanding of the subject.

I would like to thank to the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan for the scholarship and support. I would also like to thank "Seismic Performance of Concrete Pile Work Group" in Architectural Institute of Japan (AIJ) and "Deformation Performance Evaluation of Pile Work Group" in COPITA for their valuable opinions, and the SOFTech Consortium, Japan, and the Tokyo Institute of Technology, Japan for their support in carrying out this research.

My special thanks to Prof. Rajesh Kumar from IIT (BHU), who always encouraged and supported me and also introduce me to the research world. I also would like to thank Prof. David Mukai of University of Wyoming, Dr. Junji Hamada of Takenaka Corporation, Dr. Yoichi Asai and Mr. Kiyoshi Miyahara of Concrete Pile Installation Technology Association (COPITA), Dr. Katsumi Kobayashi of Fujita Corporation, and Dr. Hidekazu Watanabe of Building Research Institute (BRI) for their discussions and invaluable suggestions which have significantly helped me in advancing the research.

Thanks to Dr. Taku Obara, Ms. Chanipa Netrattana, Mrs. Yuki Hayakawa, fellow students and friends at Kono Laboratory who helped me and supported me during my research work. I greatly appreciate what all these people have done for me.

Finally, my sincerest gratitude goes out to my family that always supported and encouraged me to pursue my dream.

### List of Publications

#### Journal papers

- **Thusoo S.**, Obara T., Kono S., Miyahara K. (**2020**); Design models for steel-encased highstrength precast concrete piles under axial-flexural loads. *Engineering Structures*. (Under review, Submitted on 21 May, 2020)
- **Thusoo S.**, Kono S., Hamada J., Asai Y. (**2020**); Performance of precast hollow steel-encased high-strength concrete piles. *Engineering structures*, Vol: 204, 109995.
- **Thusoo S.**, Maithi P.R. and Rai A. (2014); Foam concrete A better replacement to the traditional heavy concrete. *i-manager's Journal on Civil Engineering*, Vol:4, No:1, 1-5.

#### Reports

• Obara T., **Thusoo S.**, Kono S., (**2020**); Chapter 7 SC piles: Moment capacity of steel encased concrete piles. in *Report for the precast concrete pile committee of AIJ*. (Draft)

#### Conference papers

- **Thusoo S.**, Kono S., Hamada J., Asai Y., Mukai D., (**2020**); Experimental investigation of hollow precast steel-encased concrete piles. *17<sup>th</sup> World Conference on Earthquake Engineering (17WCEE)*, scheduled for 13-18 Sept, Sendai, Japan, paper no. C000666.
- Thusoo S., Tanaka H., Otaki T., Kono S., Watanabe H., Hayakawa T., Hirade T., Mukai D., Mukai T. (2018); Analysis of bending behavior of hollow and precast steel encased concrete piles using fiber based models. 11<sup>th</sup> US National Conference on Earthquake Engineering (11NCEE), 25-29 June, Los Angeles, California, ID 394.
- Thusoo S., Tanaka H., Otaki T., Kono S., Watanabe H., Hayakawa T., Hirade T., Mukai D., and Mukai T. (2017); Numerical study on seismic structural performance of steel encased concrete piles. 19<sup>th</sup> Taiwan-Japan-Korea Joint Seminar on Earthquake Engineering for Building Structures (19SEEBUS), 08-09 Sept., Korea, 167p.
- **Thusoo S.**, Modi, K., Kumar, R., Madahar H. (**2015**); Response of Buildings with Soil-Structure Interaction with Varying Soil Types. *XIII International Conference on Structural Engineering, Construction and Management (ICSECM)*, 8-9 April, Dubai, UAE.

#### Extended abstracts

- **Thusoo S.**, Kono S., Obara T., Mukai D. (**2020**); Verification of strength of steel-encased high-strength concrete piles under combined axial and flexure forces using different design codes. *Architectural Institute of Japan Annual Convention*, scheduled for 8-10 Sept., Chiba, Japan, ID. 20244.
- Kasumi F., Kono S., Obara T., Miyahara K., **Thusoo S.**, Mukai D. (**2020**); Axial compression test on SC piles. *Architectural Institute of Japan Annual Convention*, scheduled for 8-10 Sept., Chiba, Japan.
- Obara T., Subedi N., Sayaka A., **Thusoo S.**, Kono S., Hirao K., Imai Y., Mukai D. (**2020**); Experimental study on ultimate shear capacity of steel encased concrete piles (Part 1:

Research background and outline of experiment). *Architectural Institute of Japan Annual Convention*, scheduled for 8-10 Sept., Chiba, Japan.

- **Thusoo S.**, Kono S. (**2020**); Development of numerical models for the steel-encased highstrength concrete piles. *SOFTech Workshop for Young Researchers*, 13 Feb., Tokyo Institute of Technology, Japan.
- **Thusoo S.**, Kono S., Obara T., Asai Y., Hamada J., Kobayashi K. (**2019**); Performance evaluation of earthquake-resistant steel-encased concrete piles based on prestressed concrete member design criteria. *Architectural Institute of Japan Annual Convention*, 3-6 Sept., Ishikawa, Japan, p. 213-214.
- Egawa M., **Thusoo S.**, Obara T., Kono S., Hirao K., Kobayashi K., Mukai D. (**2019**); Study on shear capacity of steel encased precast concrete piles (Part 1: Results of specimen SC1). *Architectural Institute of Japan Annual Convention*, 3-6 Sept., Ishikawa, Japan, p. 227-228.
- Oktiovan Y.P., **Thusoo S.**, Kono S., Mukai D. (**2018**); Analysis of bending behavior of precast concrete piles using fiber based model (Part 1: Description of fiber model), *Architectural Institute of Japan Annual Convention*, 4-6 Sept., Sendai, Japan, p. 609-610.
- **Thusoo S.**, Oktiovan Y.P., Kono S., Mukai D. (**2018**); Analysis of bending behavior of precast concrete piles using fiber based model (Part 2: Results and Discussion), *Architectural Institute of Japan Annual Convention*, 4-6 Sept., Sendai, Japan, p. 611-612.
- Hayakawa T., Tomoshisa M., Watanabe H., Tosauchi Y., Tanaka M., Mizukami D., Fukuda T., **Thusoo S.**, Kishida S. (**2018**); Study on structural performance evaluation for concrete pile system with post-earthquake functional use (Part 19: Section analysis on cast-in-place steel encased concrete piles subjected to varying axial load), *Architectural Institute of Japan Annual Convention*, 4-6 Sept., Sendai, Japan, p. 583-584.
- **Thusoo S.**, Tanaka H., Watanabe H., Kono S., Hirade T., Mukai D., Mukai T., Mizukami D. (2017); Study on structural performance evaluation for concrete pile system with postearthquake functional use (Part 7: numerical analysis of SC piles), *Architectural Institute of Japan Annual Convention*, 31-3 Sept., Hiroshima, Japan, p. 587-588.

## Contents

Chapte	er 1	INTRODUCTION	18
1.1	Bac	kground	18
1.	1.1	Introduction to precast piles	18
1.	1.2	Introduction to precast SC piles	20
1.	1.3	Challenges to the design of SC piles	22
1.2	Obj	jectives and Scope of Research	23
1.3	Org	ganization of the Thesis	24
Chapte	er 2	LITERATURE REVIEW	27
2.1	Intr	oduction	27
2.2	Pre	vious Studies	28
2.	2.1	FEM models for CFTs	29
2.	2.2	Flexural studies on steel-encased precast concrete piles	32
2.	2.3	Shear studies on concrete-filled tubes	37
2.3	Cur	rrent State of Design Codes for Steel-encased Precast Concrete Piles	38
2.	3.1	Flexural capacity	38
2.	3.2	Shear capacity	38
2.4	Flez 39	xure and Shear Design in Codes for Concrete Filled Tubes and Composite Sect	tions
2.	4.1	EN 1994-1-1 2004: Eurocode 4	40
2.	4.2	ANSI/AISC 360-16	43
2.	4.3	AIJ Recommendations for CFT	47
2.	4.4	Other design equations for shear capacity	51
Chapte PRECAS	er 3 ST C	DETAILED ANALYSIS OF FLEXURAL BEHAVIOR OF STEEL-ENCAS ONCRETE PILES BASED ON EXISTING EXPERIMENTAL DATA	ED 53
3.1	Intr	oduction	53
3.2	Exp	perimental Program	54
3.	2.1	Specimen description and materials	54
3.	2.2	Test setup and loading method	60
3.	2.3	Instrumentation and measurements	62
3.3	Exp	perimental Results	65
3.	3.1	Moment-curvature and moment-drift relationships	65
3.	3.2	Damage process and failure modes	75
3.	3.3	Distribution of curvature	80

3.4	Discussion on Experimental Results	82
3.4	4.1 Drift components	82
3.4	4.2 Backbone curve for SC piles	83
3.4	4.3 Comparison of performance	86
3.5	Conclusions	95
Chapte	r 4 AXIAL-FLEXURAL CAPACITY PREDICTIONS BY DESIGN CODES.	97
4.1	Introduction	97
4.2	Steel-encased Precast Concrete Pile Database	97
4.3	Stress Distribution Method	103
4.	3.1 Eurocode 4 (2004)	108
4.	3.2 ANSI/AISC 318-16 (2016)	110
4.	3.3 AIJ-CFT 2008	112
4.	3.4 Summary of results from stress distribution methods	114
4.4	Strain Compatibility Method	115
4.4	4.1 Recommendation for modification to AIJ-SC 2020 guidelines	119
4.5	Summary and Conclusions	123
Chapte	r 5 NUMERICAL MODEL DEVELOPMENT FOR FLEXURAL BEHAVIOR	8.125
5.1	Introduction	125
5.2	Cyclic constitutive model for high-strength concrete	127
5.3	Cyclic constitutive model for steel including buckling	131
5.4	Sensitivity to the length of the damage zone	133
5.5	Validation of the proposed model	134
5.:	5.1 Curvature predictions	135
5.:	5.2 Maximum moment, drift and general hysteresis behavior	138
5.6	Conclusions	146
Chapte	r 6 EXPERIMENTAL STUDY ON THE SHEAR BEHAVIOR OF STEEL-	
ENCASI	ED PRECAST CONCRETE PILES	148
6.1	Introduction	148
6.2	Experimental Program	148
6.	2.1 Specimen description and materials	149
6.	2.2 Test setup and loading method	153
6.	2.3 Instrumentation and measurements	156
6.3	Experimental Results	161
6.	3.1 Specimen SCS1 ( $\eta = 0.093$ )	161

6.	3.2	Specimen SCS3 ( $\eta = 0.5$ )	. 168
6.	3.1	Contribution of shear-flexure deformations	. 168
6.4	Shea	ar capacity predictions using design codes	. 176
6.5	Con	clusions	. 180
Chapte	r 7	CONCLUSIONS AND RECOMMENDATIONS	. 182
7.1	Sum	mary and conclusions	. 182
7.2	Con	tribution to research, limitations and suggestions for future research	. 185
REFEF	RENC	CES	. 188
APPEN	NDIX		. 194

## List of Figures

Figure 1-1 Common precast pile cross-sections
Figure 1-2 Damage to precast piles at pile head in 2015 Kumamoto Earthquake (Image
courtesy: Prof. Susumu Kono, Tokyo Institute of Technology) 19
Figure 1-3 Joints in precast piles
Figure 1-4 A typical jointed precast pile system and the extreme cases of bending moment
and shear forces generated in a strong earthquake
Figure 1-5 Overview of research gaps addressed and flow of the thesis
Figure 2-1 Standard test setup for the performance test of precast piles
Figure 2-2 Different type of damages recorded in two-point bending tests on SC piles; (a)
punching shear under the loading point, (b) fracture in steel casing due to cyclic
fatigue, (c) local buckling inside the constant shear zone and, (d) bending cracks in
concrete on tension side and no local buckling deformations in steel. Images courtesy
of COPITA, Japan
Figure 2-3 General arrangement of the loading system. All dimension in mm
Figure 2-4 Image of real test setup. (Tanaka, 2017 [32])
Figure 2-5 Schematic diagram of loading setup [31]
Figure 2-6 Punching shear failure under the loading point observed in all hollow SC piles.
The three images from the right are the deformation of steel casing, damage to
concrete after removal of steel casing, and zoomed-in image of the concrete damage
[31]
Figure 2-7 Bilinear stress-strain models for (a) concrete and (b) steel
Figure 2-8 Stress blocks for EC4
Figure 2-9 Normalized MN interaction for EC4
Figure 2-10 Variation of flexural strength of filled steel sections with section slenderness.
Figure 2-11 AISC (2016) stress blocks for (a) compact, (b) non-compact and (c) slender
sections
Figure 2-12 MN interaction for compact sections
Figure 2-13 Variation of compressive strength of CFTs with member slenderness 48
Figure 2-14 Stress block for AIJ-CFT 2008

Figure 3-1 Cross-sections of SC piles used in the experiment. All units are in mm 54
Figure 3-2 Different base stub configurations used in the experiment. [81]
Figure 3-3 Schematics of SC pile member and loading setup. All units are in mm. [81]
Figure 3-4 Stress-strain relationship of concrete for A1. [81] 59
Figure 3-5 Uniaxial stress-strain relationship of steel for A1. [81] 59
Figure 3-6 Photograph of specimen A4 inside experimental setup. [81] 61
Figure 3-7 Loading protocol and top drifts at peak loads during each cycle. [81] 62
Figure 3-8 Location of instrumentation used in the experiment. All units are in mm. [81]
Figure 3-9 Schematic diagram showing rotations and deformations in the pile used for
bending moment and base shear calculations. [81]
Figure 3-10 (i) Moment-Drift and (ii) Moment-curvature responses of eleven specimens
with characteristic events in the test history. [81]
Figure 3-11 Images of damage to the steel casing at the end of loading (i) West-side before
removal of steel casing, (ii) West-side after the removal of steel casing, and (iii)
North-West side after scrapping off of crushed concrete. [81]
Figure 3-12 Observed damage in hollow piles A1 and A5 after the end of loading. [81]
Figure 3-13 Observed damage in filled-core A8 after (a) removal of steel casing and (b)
scrapping off crushed concrete. [81]
Figure 3-14 Distribution of curvature along length of piles for A1, A4 and A5. Curvatures
are shown at the first peak positive drift of each cycle as measured by displacement
gauges
Figure 3-15 Distribution of curvature along length of hollow piles at the maximum
moment capacity
Figure 3-16 Comparison of total drift calculated from the flexural displacement gauges
and the main gauge
Figure 3-17 Generalized force-drift backbone curve for SC piles
Figure 3-18 Simplified backbone curves for SC piles for different cases of compression
axial load, steel casing and concrete layer thickness, and core filling. The light plots
in the background show the backbone envelopes obtained from experiments 85

Figure 3-19 Assumed stress block for plastic moment, $M_p$
Figure 3-20 Comparison of moment, drift and curvature performance of 11 specimens.
Figure 3-21 Comparison of load-drift envelopes of A1, A4 and A5
Figure 3-22 Comparison of load-drift envelopes of piles A4 and A7
Figure 3-23 Change in axial and moment capacities with the change in strength of the
steel casing
Figure 3-24 Comparison of hysteretic behavior of hollow and filled piles
Figure 4-1 Comparison of moment-curvature behavior captured for SC piles tested with
different support conditions; (a) $\eta = 0$ and (b) $\eta = 0.18$
Figure 4-2 MN interactions obtained using current SC pile guidelines for all sections in
the database
Figure 4-3 Distribution of data by important test parameters
Figure 4-4 Concrete and steel stress blocks for (a) SC pile section used in (b) $M_p$ , (c) $M_y$
and (d) $M_{cr}$ . Values for the parameters $\gamma$ , $\beta 1$ and $\beta 2$ cab be set as recommended.
Figure 4-5 Comparison of moment capacity prediction by EC4 2004 for varying (a)
slenderness ratio and (b) axial load ratio
Figure 4-6 MN interactions obtained using EC4 2004 guidelines 110
Figure 4-7 Comparison of moment capacity prediction by AISC 2016 for varying (a)
section slenderness and (b) axial load ratio. Predictions assuming compact sections
are also shown111
Figure 4-8 MN interactions obtained using AISC 2016 guidelines 112
Figure 4-9 Comparison of moment capacity prediction by AIJ-CFT 2008 guidelines for
varying (a) member slenderness and (b) axial load ratio. Predictions assuming short
member are also shown
Figure 4-10 MN interactions obtained using AIJ-CFT 2008 guidelines
Figure 4-11 (a) SC section with fiber discretization, (b) concrete, and (c) steel models
used for the stain compatibility method. Material stress-strain relationships from tests
are shown for pile A1 116

Figure 4-12 Comparison of moment capacity prediction by AIJ-SC 2020 guidelines for
varying axial load ratio117
Figure 4-13 MN interactions obtained using AIJ-SC 2020 guidelines 118
Figure 4-14 Comparison of test capacity to predicted moment with different axial load
ratios for 37 specimens (D=400mm) 120
Figure 4-15 Internal stresses in a hollow SC section
Figure 4-16: Predicted moment strength vs. the steel to concrete thickness ratio for 37
specimens
Figure 4-17: Comparison of moment capacity prediction using Proposal 1 121
Figure 4-18: Comparison of moment capacity prediction using Proposal 2 122
Figure 5-1 Fiber-based model for cantilevered tests of SC piles
Figure 5-2 Fiber-based model for simply-supported tests of SC piles
Figure 5-3 HS concrete model with envelope curve based on the model by Muguruma
and Watanabe (1983) [67] modified by Komuro et al. (2004) [72] and hysteresis rules
based on the works of Yassin (1994) 129
Figure 5-4 Hysteresis model for filling material
Figure 5-5 Cyclic steel constitutive model, including steel tube buckling. Instances of
partial strain unloading are shown in the MnP model modified for buckling 133
Figure 5-6 (a) Moment-drift relations for A4 with change in the length of the first element
from the base. (b) % error in prediction of moment capacity in each case
Figure 5-7 Comparison of moment-curvature relations for piles tested in simply-
supported loading conditions
Figure 5-8 Comparison of curvature distribution along the length of piles A1, A4, and A5.
Curvatures are shown at the first peak of each positive drift cycle from both
experiments and analysis
Figure 5-9 Validation of the fiber-based model for the moment vs. drift response for
hollow SC piles tested cyclically with cantilevered support condition
Figure 5-10 Validation of the fiber-based model for the moment vs. drift response for
core-filled SC piles tested cyclically with cantilevered support condition $(cf')$ and
$E_{\rm rate}$ the compressive strength and Voung's modulus of the material filled inside
$f^{L}c$ are the compressive strength and 1 oung s modulus of the material fined inside
the core

Figure 5-11 Validation of the fiber-based model for the moment vs. drift response for
hollow SC piles tested cyclically in simply-supported condition
Figure 6-1 General cross section and elevation of SCS1
Figure 6-2 Stress-strain relationship of concrete for SCS1152
Figure 6-3 Uniaxial stress-strain relationship of steel for SCS1
Figure 6-4 Shear stress-strain relationship of steel for pile SCS1
Figure 6-5 Loading setup
Figure 6-6 Photographs of (a) the whole loading setup, and (b)specimen inside the loading
setup
Figure 6-7 Arrangement '1' of displacement gauges for capturing flexural deformations
for specimens with (a), (b) $l = 600$ mm, and (c), (d) $l = 400$ mm. The arrangement of
gauges on the North-side (positive loading side) are shown in (a) and (c) and the view
from side is shown in (b) and (d) for the same. North-side arrangement was mirrored
on the South-side
Figure 6-8 Arrangement '2' of displacement gauges for capturing flexural deformations
for specimens with (a), (b) $l = 600$ mm, and (c), (d) $l = 400$ mm. The arrangement of
gauges on the South-side (negative loading side) are shown in (a) and (c) and the
view from side is shown in (b) and (d) for the same. South-side arrangement was
mirrored on the North-side
Figure 6-9 Arrangement of displacement gauges for capturing shear deformations for
specimens with (a), (b) $l = 600$ mm, and (c), (d) $l = 400$ mm. The views from the
back of specimen is shown in (a) and (c) and (b) and (d) are the side elevations of the
same
Figure 6-10 Arrangement of axial strain gauges on the steel casing
Figure 6-11 Arrangement of rosette strain gauges on the steel casing
Figure 6-12 Arrangement of axial and rosette strain gauges on the inner wall of concrete
Figure 6-13 SCS1: Shear force vs drift relationship from the test
Figure 6-14 SCS1: Drift ratios captured in the experiment with displacement gauges from
arrangement 1

Figure 6-15 SCS1: Comparison of contribution of shear and flexure deformations to the
total drift at the first peak of all drift cycles
Figure 6-16 SCS1: Specimen at the end of loading 164
Figure 6-17 SCS1: Damage profile at concrete surface after removal of steel casing. 165
Figure 6-18 SCS1: Damage to the outer surface of concrete from the (a) North, and (b)
South and East directions
Figure 6-19 SCS1: Axial strain distribution along height 167
Figure 6-20 SCS1: West-side distribution of maximum principal shear strain along height
at the first peak of positive load cycles
Figure 6-21 SCS3: Shear force vs drift relationship from the test
Figure 6-22 SCS3: Comparison of various drift ratios captured in the experiment using
(a) arrangement 1 and (b) arrangement 2 169
Figure 6-23 SCS3: Comparison of contribution of shear and flexure deformations to the
total drift at the first peak of all drift cycles
Figure 6-24 SCS3: Specimen at the maximum shear capacity and at the end of loading.
Figure 6-25 SCS3: Axial strain distribution along height 173
Figure 6-26 SCS3: East-side distribution of maximum principal shear strain along height
at the first peak of positive load cycles
Figure 6-27 SCS3: (a), (b) Arrangement of rosette strain gauges. Black arrows represent
the direction of shear loads. Red and blue arrows represent the tension and
compression struts, respectively. (c) Strains at the maximum shear capacity.
Direction of strain is the direction of principal axis and size of plot is proportional to
the magnitude of strain174
Figure 6-28 SCS3: Cross-sectional shear strain distribution in steel casing at (a) 0.75%
drift, (b) maximum load capacity, and (c) ultimate load capacity 176
Figure 6-29 Assumed flow of shear stresses in steel according to AIJ guidelines for (a)
SP piles and (b) SC piles
Figure 6-30 Shear force-axial load interactions from various design codes for (a) SCS1
and (b) SCS3
Figure 6-31 Comparison of shear and flexure capacity of members with different shear
span ratios
13

## List of Tables

Table 2-1 General specifications of CFT columns, cast-on-site SC piles, and precast SC
piles
Table 2-2 Summary of the design approaches used in AIJ-CFT, EC4 and AISC codes for
the design of composite members
Table 3-1 Specimen cross sectional and axial load details. [81]
Table 3-2 Mechanical properties of concrete, steel casing and filling materials. [81] 60
Table 3-3 Summary of test results for the yield, maximum and ultimate moment capacities.
Table 3-4 Change in axial and moment capacities with the change in strength of the steel
casing. Here, $f_{y,(n)}$ is the design yield strength and $N_{(n)}$ and $M_{p,(n)}$ are the total axial
load and plastic moment capacites obtained for $f_{y,(n)}$
Table 3-5 Contribution of filling material to the moment capacity of SC pile
Table 4-1 Summary of 79 precast SC pile tests by the sources
Table 4-2: Database summary breakdown with respect to test parameters
Table 4-3 Limit and scope of guidelines 103
Table 4-4 Summary of results for each type of pile test
Table 5-1: Validation of the proposed model for piles in datasets A and B. The moment,
drift and curvature at maximum lateral load are compared
Table 6-1 Specimen cross sectional and axial load details
Table 6-2 Mechanical properties of steel and high-strength concrete
Table 6-3 List of load cycles applied during the tests. Numbers in brackets are the number
of cycles
Table 6-4 Summary of shear capacity predictions from various codes. Values in bracket
are the ratios of experimentally obtained capacity to the calculated capacity 178