Workshop for Young Researchers
Feb. 13, 2020 Tokyo Tech

Development of numerical models for steel-encased high-strength concrete piles

Thusoo Shreya[1], Kono Susumu[2]

[1]Tokyo Institute of Technology, thusoo.s.aa@m.titech.ac.jp
[2] Tokyo Institute of Technology, kono.s.ae@m.titech.ac.jp

Abstract— **Results from tests on six steel-encased concrete pile specimens under cyclic, combined axial-flexure loading are presented. The bending capacity is verified against various available design codes for composite members. A computationally efficient fiber-based model is proposed and validated against test results.**

I. Introduction

The applicability of current guidelines for the design of steel-encased concrete (SC) piles has not been verified for design in severe earthquakes when an SC pile is expected to endure axial loads from -0.5 to 0.7 times the section capacity[1]. Furthermore, there is an imminent need for models that, in addition to strength, can also predict member ductility. This is important for the development of a performance-based design framework targeted for SC piles.

II. Test Program

In a previous study[2], the authors have tested six precast hollow/filled SC pile specimens made of high-strength (HS) concrete under combined axial-flexure loading. Fig. 1 shows the general cross-section of the specimens. High levels of axial loads were applied as given in Table 1 to study the behavior under severe earthquake conditions. Table 1 also summaries the other specimen details. The core of SC8 was filled with low-cost material (cement paste).

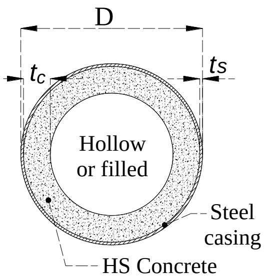

FIG. 1 General cross-section

TABLE I
SPECIMEN DETAILS AND MATERIAL PROPERTIES

Pile	Outer dia.			Axial load ratio	Concrete		Steel		Core Filling	
	D	$\frac{t_c}{D}$	$\frac{t_s}{D}$	η	f'_c	$_cE$	f_y	$_sE$	$_ff_c$	$_fE$
	mm				MPa	GPa	MPa	GPa	MPa	GPa
SC1	400	0.17	0.015	0.00	115	45.6	505	212	-	-
SC4	400	0.16	0.015	0.18	111	44.2	505	212	-	-
SC5	400	0.17	0.015	0.26	115	45.6	505	212	-	-
SC6	400	0.13	0.015	0.35	115	45.6	505	212	-	-
SC7	400	0.16	0.011	0.20	115	45.6	453	207	-	-
SC8	400	0.17	0.015	0.27	122	46.7	408	201	27.4	9.95

III. Test Results

Fig. 2 shows the moment-curvature relationships obtained from the tests. The characteristic points on the hysteresis curves are also shown. It is seen that as axial load increases, the moment capacity and stiffness also increase; however, the curvature ductility decreases.

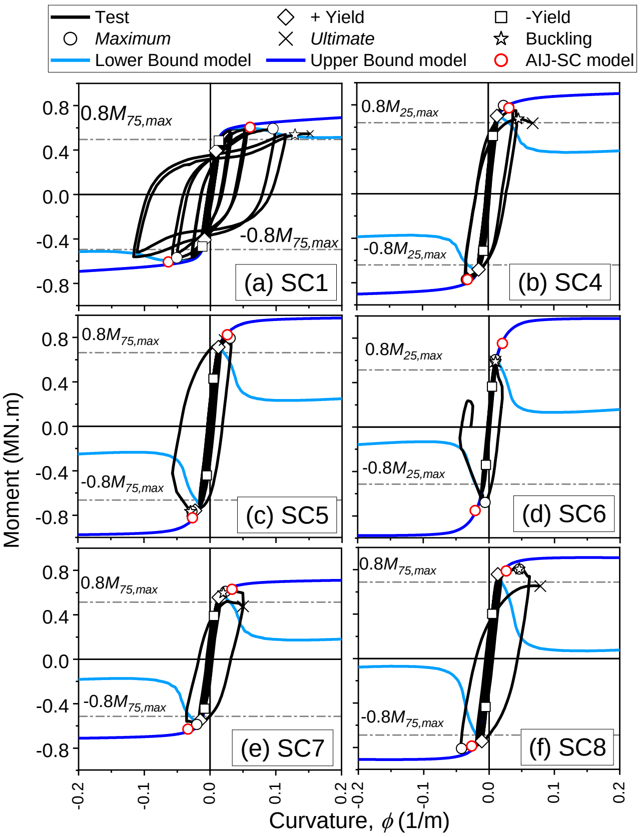

FIG. 2 Moment-Curvature relationships of specimens

Fig. 3 shows the damage sustained at the end of loading, and after removal of the casing and scraping off loose concrete in SC1 and SC5 specimens. In specimen SC1 with low axial load, the governing failure mode was concrete crushing leading to local buckling at the compression face, whereas, in specimen SC5 with lower axial load, local buckling was the governing failure mode which was caused by the high compressive axial load. The bulge in steel casing caused by local buckling was found to occur at around 50 mm height from the base in all the specimens. From the distribution of curvature along the pile height, it was seen that the distribution remained linear after 125 mm (0.31D) from the base making 0-125 mm the zone of concentrated plastic damage.

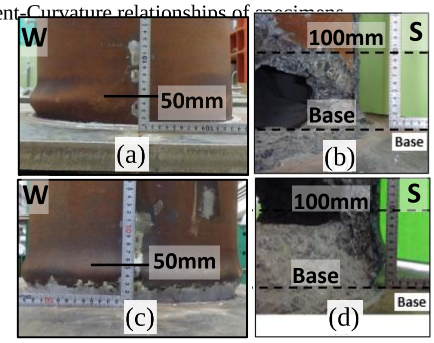

FIG. 3 Damage in (a), (b) SC1 pile and (c), (d) SC5 pile; (a), (c): at the end of loading; (b), (d): after scrapping off loose concrete.

IV. Axial-Flexural Capacity Predictions of Current Design Codes

A. AIJ-SC guidelines

The moment capacity of precast SC piles is currently estimated using strain compatibility method with the assumption of linear strain distribution[3]. An elastic-perfectly plastic stress distribution is used for both concrete and steel. In case of both hollow-core and filled-core sections, the concrete is assumed to be unconfined with the ultimate strain, ${}_c\varepsilon_{cu} = 0.5\%$ and the strength of filling (if present) is ignored. Comparison of the bending strength obtained using AIJ-SC guidelines with the test results is shown in Fig. 2. Based on the approach used in the AIJ-SC guideline, lower bound and upper bound models were also developed. While keeping steel model the same, concrete model was changed to the model by Muguruma et al.[4] and Komuro et al.[5] of HS concrete for the unconfined and confined concrete, respectively. The comparison of moment capacities predicted by these models with test is summarised in Table II and the obtained moment curvature relations are shown in Fig. 2.

B. CFT codes

The current specimens do not fall into the scope of the available codes (AIJ-SRC (2001), EC4 (2004), and AISC (2016)) for composite member design in axial-flexure loads. Despite this the different approaches given in these codes for determination of member bending capacities were used to study their applicability. The plastic stress distribution method given in each code was followed. The results are summarized in Table II. It is seen that the predictions from AISC and EC4 are highly underestimated. This implies that the factors used to reduce section strengths to member strengths are too strict. On the other hand, the predictions by AIJ-SRC (plastic stress distribution method) are very close to the results from AIJ-SC (strain compatibility method). This might be because the full section strengths were used in both these models.

TABLE II
MOMENT CAPACITY PREDICTION USING VARIOUS MODELS (TEST/CAL)

	Upper Bound	Lower Bound	AIJ-SC	AIJ-SRC	EC4	AISC	Fiber Model
SC1	0.97	1.03	1.00	0.94	1.22	1.07	1.03
SC4	0.92	1.09	1.02	0.99	1.29	1.23	0.99
SC5	0.86	1.09	0.99	0.96	1.27	1.30	0.93
SC6	0.68	1.03	0.86	0.84	1.12	1.25	1.09
SC7	0.91	1.04	0.99	0.97	1.27	1.34	0.97
SC8	0.75	1.22	1.13	1.12	1.48	1.67	0.98
$\bar{x}$	0.85	1.09	1.00	0.97	1.28	1.31	1.00
σ_{sd}	0.10	0.06	0.07	0.07	0.10	0.17	0.05

V. ADVANCED FIBRE-BASED NUMERICAL MODEL

The current guidelines tend to give a reasonable estimate of ultimate section capacity but cannot be used to simulate (1) the post-peak behaviour, (2) the energy content, (3) the drift capacity, and (4) the ductility capacity. Hence, a computationally efficient fibre-based model is proposed to overcome these shortcomings. The cyclic constitutive model for concrete uses the model by Komuro et al.[5] for compression side envelope, linear softening in the tension side envelope and Yassin's model for the hysteresis. Confinement is reduced by a factor depending on diameter of the hollow core. The cyclic constitutive model for steel consists of the Menegotto-Pinto (MnP) model modified for buckling. The buckling model is derived from two previous studies[6,7] on hollow steel tubes and was integrated with the MnP model in *OpenSees*. It is proposed to have a single element in the damage zone to avoid convergence issues. The buckling model was assigned to steel only in the damaged zone.

A. Validation of the proposed model

Fig. 4 shows the moment-drift relations obtained from the proposed model for the six specimens. The model can predict moment-drift behavior very well. The comparison of predicted moment capacities with the test is summarised in Table II. The error in moment prediction is less than ±9%.

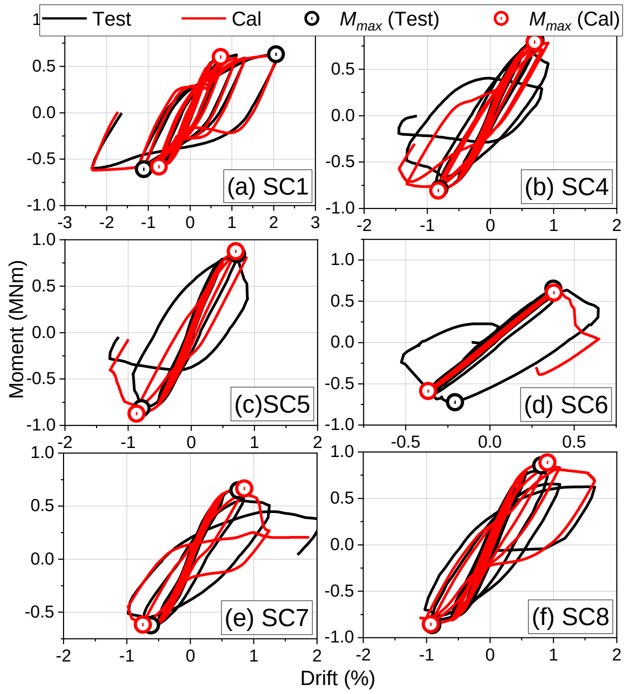

FIG. 4 Comparison of moment-drift relationship obtained using the proposed model with test results.

VI. CONCLUSION

For the prediction of bending capacity of SC piles under combined axial-flexural loading, the strain compatibility model in AIJ guidelines is most suitable out of the available design codes for composite members. For the prediction of drift capacity, a computationally efficient fiber-based model is proposed and successfully validated.

ACKNOWLEDGMENT

This work was supported financially by JSPS and JST Program on Open Innovation Platform with Enterprises, Research Institute and Academia.

REFERENCES

[1] Kobayashi K. What is clarified or not clarified about seismic performance of concrete piles? [In Japanese]. AIJ Struct. Sect. (Basic Struct. Panel Discuss. Mater., 2017, p. 1–10.
[2] Thusoo S, Kono S, Hamada J, Asai Y. Performance of precast hollow steel-encased high-strength concrete piles. Eng Struct 2020.
[3] Architectural Institute of Japan. Guidelines for seismic design of reinforced concrete foundation members (Draft) [In Japanese]. 2017.
[4] Muguruma H, Watanabe F, Iwashimizu T, Mitsue R. Study on improving the ductility of high-strength concrete by lateral confining [In Japanese]. JCI, Proc. 5th Annu. Conf., 1983, p. Vol. 5, 317-320.
[5] Komuro T, Imai K, Muramatsu A, Korenaga T, Watanabe F. Compressive properties of reinforced concrete columns using high strength concrete with compressive strength of 100-180N/mm^2 [In Japanese]. J Struct Constr Eng (Transactions AIJ) 2004;69:77–84.
[6] Denavit MD, Hajjar JF. Nonlinear Seismic Analysis of Circular Concrete-Filled Steel Tube Members and Frames. J Struct Eng ASCE 2011;138:1089–98.
[7] Bai Y, Lin X, Mou B. Numerical modeling on post-local buckling behavior of circular and square concrete-filled steel tubular beam columns. Int J Steel Struct 2016;16:531–46.