VERIFICATION OF STRENGTH OF STEEL-ENCASED HIGH-STRENGTH CONCRETE PILES UNDER COMBINED AXIAL AND FLEXURE FORCES USING DIFFERENT DESIGN CODES

Design Codes SC piles AIJ CFT
Eurocode4 ANSI/AISC AIJ SC

Members ○Shreya THUSOO[1] Susumu KONO[1]
Taku OBARA[1] David MUKAI[2]

1. Introduction

Since the development of steel-encased concrete (SC) piles in 1972 and standardization in 1979[1)], the use of SC piles at the pile-pile cap connection in construction of mid to high-rise buildings has become widespread in Japan. The extensive and unexpected damages[2)] reported in PHC and PRC piles after the 1995 Hyougoken-Nanbu earthquake further propelled the use of SC piles to increase resistance against large bending moments and axial forces. However, the applicability of current guidelines for the design of SC piles has not been verified for design in severe earthquakes when SC piles endure axial loads from -0.5 to 0.7 times the section capacity[3)].

Several large-scale tests were carried out on SC piles[4)] under combined flexure and axial forces. This paper compares the strength obtained from these tests with the predictions from SC pile guidelines by AIJ committee[5)] (AIJ-SC), CFT member guidelines by AIJ[6)] (AIJ-CFT), and composite member guidelines in Eurocode 4[7)] (EC4) and AISC[8)].

2. Axial-flexural capacity predictions of current design codes

Currently, there are no official guidelines for the design of SC piles. However, various guidelines are available for the design of composite steel-concrete members that may be followed to estimate the moment capacities of SC piles. The specimens used in this study do not fall into the scope of the available codes (AIJ-CFT, EC4, and AISC) 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 following sections summarize the related provisions of each code.

Strain compatibility method: AIJ-SC (2017)

The moment capacity of precast SC piles is currently estimated using strain compatibility method with the assumption of linear strain distribution. An elastic-perfectly plastic stress-strain relation 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. No limits for stability against pile slenderness, local buckling, or global buckling have been suggested. Based on the approach used in the AIJ-SC guideline, a lower bound model was also developed. Here, the steel model is kept the same, while the concrete model is changed to the model by Muguruma et al.[9)] of HS concrete for the unconfined concrete. The obtained moment curvature relations are shown in **Fig. 1** and comparison of moment capacities predicted by these models with test is summarized in **Table 1**.

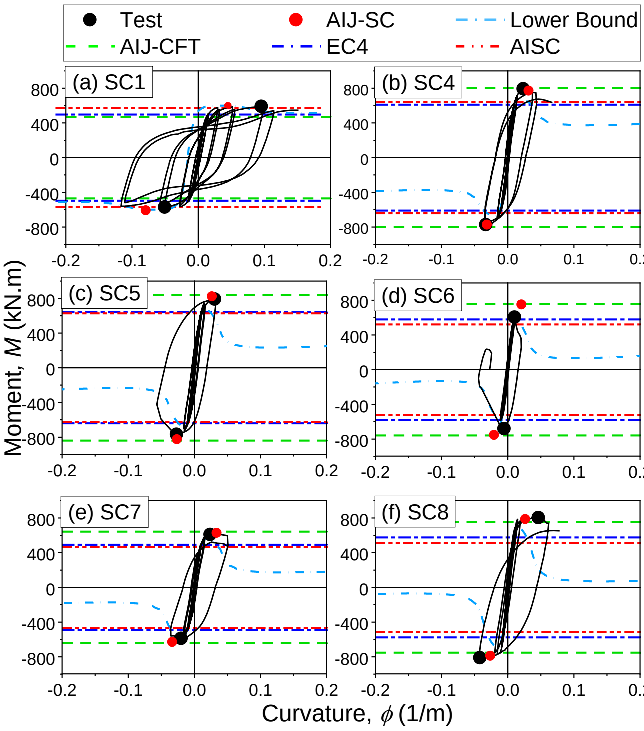

Fig. 1 Moment curvature relations obtained from test showing the maximum moment capacity. Moment capacitates obtained using lower bound, and AIJ-SC models and AIJ-CFT, EC4, and ANSI/AISC guidelines are also shown.

Table 1 Moment capacity prediction using various codes

	Axial load ratio	Test	Test/Cal				
		kNm	AIJ-SC	Lower bound	AIJ-CFT	EC4	AISC
SC1	0.0	608	1.00	1.03	1.29	1.18	1.07
SC4	0.18	803	1.02	1.09	0.99	1.24	1.23
SC5	0.26	817	0.99	1.09	0.97	1.16	1.30
SC6	0.35	789	0.86	1.03	0.86	0.94	1.25
SC7	0.20	815	0.99	1.04	0.97	1.25	1.34
SC8	0.28	651	1.13	1.22	1.14	1.31	1.67
Avg			1.00	1.09	1.04	1.18	1.31
SD			0.08	0.07	0.14	0.11	0.17

Stress distribution method

In this section, the stress distribution methods, as given in the AIJ-CFT (2001), EC4 (2004), and ANSI/AISC (2016) for composite columns under axial (compression)-flexure loads are briefly

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小原 拓, ムカイデビッド

discussed and used to determine the bending moment capacity of specimens. All three codes outline the method to generate the MN interaction curve. The bending capacity for an axial load value can be calculated from this interaction.

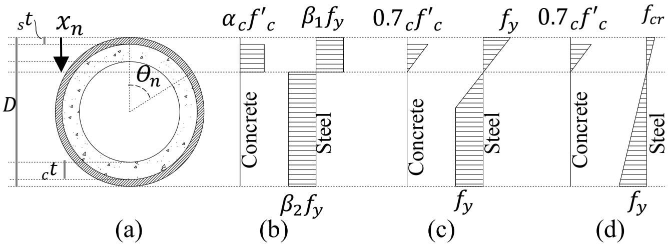

***Fig. 2** Concrete and steel stress blocks for (a) SC pile section used in (b) AIJ-CFT, EC4, and AISC for calculation of M_p and AISC for calculation of (c) M_y and (d) M_{cr}. Each code specifies a different value for the parameters $\boldsymbol{\alpha}$, $\boldsymbol{\beta_1}$ and $\boldsymbol{\beta_2}$.*

AIJ-CFT (2001): The AIJ-CFT calculates the bending strength for three different categories of member slenderness, l_k/D. Here, l_k is the effective buckling length of the column. For columns with $l_k/D < 4$, no reduction in section strength is assumed, and the interaction is obtained for a fully plastic section (**Fig. 2b**). For columns with $l_k/D > 12$, equations for MN interaction are given in the code. The equations are based on the idea of superimposing interactions of a long concrete member and a long steel member. Both interactions individually consider appropriate reductions in strengths due to buckling. For columns with intermediate l_k/D, an interpolation scheme is detailed in the code. For the six SC specimens, $l_k/D = (2*1.2)/0.4 = 6$, and hence, the ultimate bending strength is given by using the interpolation scheme.

EC4 (2004): The EC4 approach is to obtain the section interaction (assuming a fully plastic section, shown in **Fig. 2b**) and to check whether the applied loads satisfy the criterion defined in the code. Second-order and concrete confinement effects are taken into account. The plastic resistance to compression is reduced by using a factor for buckling which depends on the member slenderness. Buckling is taken care of by not permitting axial loads greater than the reduced resistance.

AISC (2016): The ANSI/AISC classifies the sections into compact, noncompact, and slender sections based on the section slenderness ratio, $D/_st$. A higher $D/_st$ ratio leads to a slenderer section causing a reduction in strength due to buckling and 2^{nd} order effects. This reduction is considered in the interaction by using different stress blocks (**Fig. 2b–2d**). Further, the obtained interaction curve is modified based on the ratio of steel to concrete strength. Using the AISC criteria, the six SC specimens fall into the category of noncompact sections.

Comparison of the bending strengths obtained using the three composite member codes are summarized in **Table 1** and are also shown in **Fig. 1**. It is seen that the predictions from AISC and EC4 are highly over-safe. This implies that the factors used to reduce section strengths to member strengths are too strict. However, further investigation would be needed to find relevant factors. On the other hand, the predictions by AIJ-CFT (plastic stress distribution method) are very close to the results from AIJ-SC (strain compatibility method). However, both these models give unsafe predictions with test strengths being less than 0.9 times the predicted capacity for members under axial load ratio more than 0.27 times section capacity. The lower bound model underestimated strength in all the cases as expected.

3. MN interactions

MN interaction curves were generated for all the models using the procedures described in previous sections. The obtained curves for specimens SC1 are shown in **Fig. 3**. Test results for SC4 and SC5 piles, which had a similar section to SC1 are also shown. The AIJ-SC and AIJ-CFT interactions are similar in the tension-controlled region but divert in the compression-controlled region, where AIJ-CFT interaction is similar to the AISC simplified curve. Similar trends were seen in all cases.

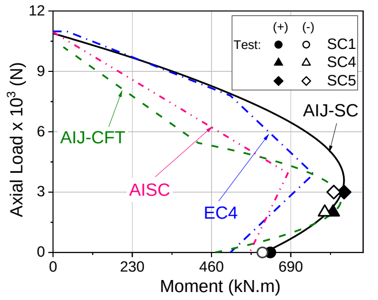

***Fig. 3** MN interactions obtained using various codes for SC1, SC4 and SC5 piles.*

4. Conclusion

For the prediction of the bending capacity of SC piles under combined axial-flexural loading, the strain compatibility model in AIJ-SC guidelines is most suitable out of the available design codes (AIJ-CFT, EC4 and AISC) for composite members.

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1 Tokyo Institute of Technology
2 University of Wyoming

1 東京工業大学
2 ワイオミング大学