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Effects of Sub-Standard Detailing of Transverse Reinforcement on the Behavior of Square RC Columns

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ABSTRACT

The arrangement and detailing of transverse reinforcement of columns have a governing effect on the performance of reinforced concrete (RC) columns, particularly under seismic actions. Both strength and ductility characteristics are remarkably effected by the changes of the detailing of the transverse reinforcement. Ductility is among major features of structural members for exhibiting a satisfactory seismic performance. While the research on seismic behavior of columns is generally conducted on code-complying configurations and detailing of transverse reinforcement, and columns with non-code-complying detailing are generally considered as non-ductile, actually the columns, which partially comply with the code requirements, may also have a certain amount of ductility. Therefore, in this study, 6 short square columns with different detailing of transverse reinforcement (either code-complying or non-code-complying) were tested under concentric compression. Additionally, 1 short square column without transverse reinforcement was tested as a reference specimen. According to the test results, significant enhancement on ductility ratio and energy dissipation capacity was obtained even for the columns with non-code-complying transverse reinforcement detailing (i.e. in terms of hook angle and hook length). Experimental axial stress-strain relationships were also compared with the predictions of several available analytical models.

1. INTRODUCTION

During the past years, many researchers have conducted analytical and experimental studies on the behavior of confined concrete by transverse reinforcement (Kent and Park 1971; Sargin et al. 1971; Priestley et al. 1981; Park et al. 1982; Sheikh and Uzumeri 1982; Mander et al. 1988a, 1988b; Saatcioglu and Razvi 1992; Cusson and Paultre 1994; Saatcioglu et al. 1995; Hoshikuma et al. 1997; Ilki et al. 2004; Kazemi and Morshed 2005; Ilyas and Rizwan 2006; Vintzileou and Stathatos 2007; Lee at al. 2013). However, according to the literature survey of the authors, the effects of the detailing of the transverse reinforcement (i.e. hook angle and hook length) on strength and ductility are not examined.

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For the assessment of existing structures, several approaches including the detailing of transverse reinforcement used for confining concrete are suggested by EN 1998-3 (2005), ASCE 41-06 (2006), Turkish Seismic Code (TSC) (2007). According to related codes, a considerable part of existing structures in Turkey are not fully convenient in terms of the detailing of transverse reinforcement. To accept the structural elements of these structures as unconfined may be lead to unrealistic assessment and uneconomic strengthening solutions. Therefore, an extensive analytical and experimental research program on this subject is under progress at the Structural and Earthquake Engineering Laboratory (STEEL) of Istanbul Technical University, Turkey.

In this paper, as a part of the research in STEEL, the tests on the square RC columns confined with transverse reinforcements are presented. The inspected detailing are the hook angle (90, 112.5 and 135º), and hook length (40 and 80 mm) of the transverse reinforcement with a spacing of 50 mm. The effects of these detailing on stress-strain relationship, strength and ductility are examined. The dimensions of the square RC columns are 250(width)x250(depth)x500(height) mm. Longitudinal reinforcement is not used to determine the effectiveness of the transverse reinforcement directly. Instead of the longitudinal reinforcement, wooden slats of marginal strength are used to connect the transverse reinforcements. The unconfined concrete strength of the square specimen tested at the similar period with the confined specimens is determined as 35.6 MPa.

It should be noted that the test results of 6 rectangular specimens (250(width)x375(depth)x500(height) mm) are presented in Saribas et al. (2013). The main parameters of the study are the hook angle (90, 112.5 and 135º), and the spacing (50 and 100 mm) of transverse reinforcement with a hook length of 40 mm.

2. SPECIMEN PRODUCTION AND MEASUREMENT SYSTEM

For this study, 6 reinforced concrete columns and 1 concrete column were constructed using medium strength concrete (nominal concrete strength at 28 days is 30 MPa). The column specimens with the height of 500 mm have square cross-sections of 250x250 mm. Ready mixed concrete was used to produce the column specimens. The concrete mix-proportions are given in Table 1. For mixture, ordinary Portland cement was used. The water/cement ratio of the mixture was 0.60.

Table 1. Mix-proportions of concrete (kg/m^3)

Cement	Water	Gravel	Stone powder (Washed)	Sand	Stone Powder	Chemical Additives
385	232	776	262	688	283	3.85

The column specimens were produced in Structural and Earthquake Engineering Laboratory (STEEL) of Istanbul Technical University. For the confinement, the deformed bars with 8 mm diameter were used as the transverse reinforcement. In order to determine the properties of these bars under tension, two bars were tested and the stress-strain relationships obtained are illustrated in Fig.1. The average yield strength of the transverse steel (f_{yh}) was determined as 557 MPa. It should be emphasized that for observing the effects of transverse reinforcement directly, longitudinal steel bars were not used. To locate and keep the positions of the transverse reinforcements, four longitudinal wooden slats of negligible strength were utilized (Fig. 2). To prevent direct loading of the wooden slats, a clear cover of 10 mm was formed at the bottom and top faces of the specimens (Fig. 2). The clear cover of concrete was 20 mm (from the outside of the transverse reinforcement). The reinforcement detailing of the RC columns are shown in Fig. 2. The spacing of the transverse reinforcement was 50 mm for all RC specimens. The specimen production steps can be seen in Fig. 3.

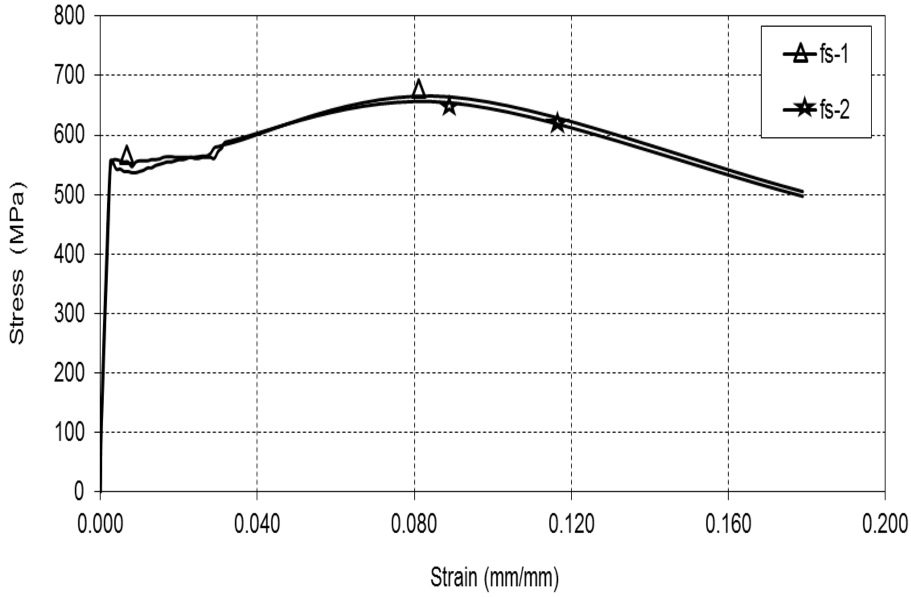

Fig. 1 Stress-strain relationships of transverse reinforcement

The general characteristics of the column specimens are given in Table 2. The specimens were symbolized with cross-section type (S)-hook angle (135,112.5 or 90^{o})–hook length (40 or 80 mm)-type of transverse reinforcement (N, deformed bars)-spacing of transverse reinforcement (s50). For example, S-135-80-N-s50 denotes a specimen with a square cross-section, hook angle is 135°, hook length is 80 mm, transverse reinforcement type is deformed and spacing of the transverse reinforcement is 50 mm. In this table, f_{co} is the unconfined compressive strength of a column specimen, f_{cc} is the confined compressive strength of the specimen, ϕ is the hook angle of the transverse reinforcement, and l is the hook length of the transverse reinforcement. The volumetric ratio of the transverse reinforcement (ρ_{sh}) of each column specimen was 0.013.

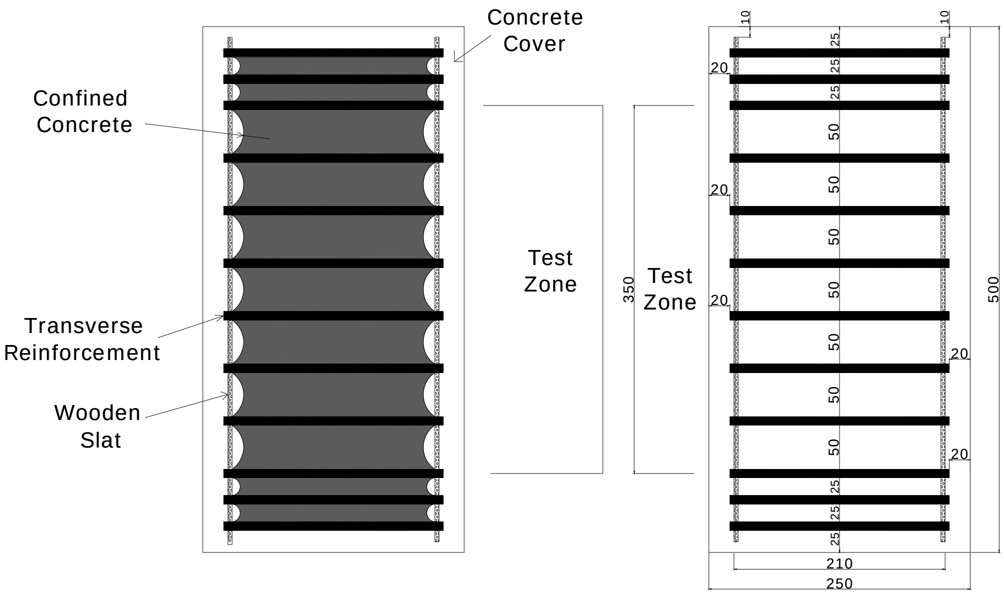

Fig. 2 Transverse reinforcement detailing (all dimensions are in mm)

Fig. 3 Specimen preparation

Table 2 General characteristics of the specimens

Specimens		f_{cc} / f_{co} (MPa)	ϕ (°)	l (mm)
Ref	S-Ref	1.00	-	-
First Group	S-90-40-N-s50	1.07	90	40
	S-112.5-40-N-s50	1.11	112.5	40
	S-135-40-N-s50	1.05	135	40
Second Group	S-90-80-N-s50	1.10	90	80
	S-112.5-80-N-s50	1.26	112.5	80
	S-135-80-N-s50	1.01	135	80

Table 3 Design assessment of the specimens (EN 1998-1-1 (2004) and TSC (2007))

Specimens		EN 1998-1-1 (2004)				TSC (2007)			
		ϕ =135 (°)	l≥80 (mm)	s≤70 (mm)	ρ_{sh}≥0.007	ϕ =135 (°)	l≥80 (mm)	s≤83 (mm)	ρ_{sh}≥0.013
First Group	S-90-40-N-s50	-	-	√	√	-	-	√	√
	S-112.5-40-N-s50	-	-	√	√	-	-	√	√
	S-135-40-N-s50	√	-	√	√	√	-	√	√
Second Group	S-90-80-N-s50	-	√	√	√	-	√	√	√
	S-112.5-80-N-s50	-	√	√	√	-	√	√	√
	S-135-80-N-s50	√	√	√	√	√	√	√	√

-: non- code-complying
√: code-complying

The specimens were tested under monotonic compressive loads by utilizing an Instron Satec 1000 RD universal testing machine. The testing machine has a load capacity of 5000 kN. The tests were performed under displacement control with a rate of 0.4 mm/min. Before the tests, a preload of 94 kN (4% of the unconfined compressive strength) was applied to each specimen. In order to record the compression shortening of the specimens during the tests, linear variable displacement transducers (LVDTs) and strain gages were utilized.

A total of 8 LVDTs were used to obtain average axial strains of the specimens, Fig. 4. Four of the LVDTs were located in the mid-height of the specimen, with a gauge length of 200 mm. The other LVDTs were positioned between the upper and lower loading plates, with a gauge length of 500 mm. The experimental data were recorded by means of a TML-TDS-303 data logger and a 50 channel TML-ASW-50C switch box.

Two strain gauges were used to measure the strains of the transverse reinforcement, these strain gages were positioned on the transverse reinforcement at mid-height (Fig. 5). The gage lengths of the strain gages were 5 mm.

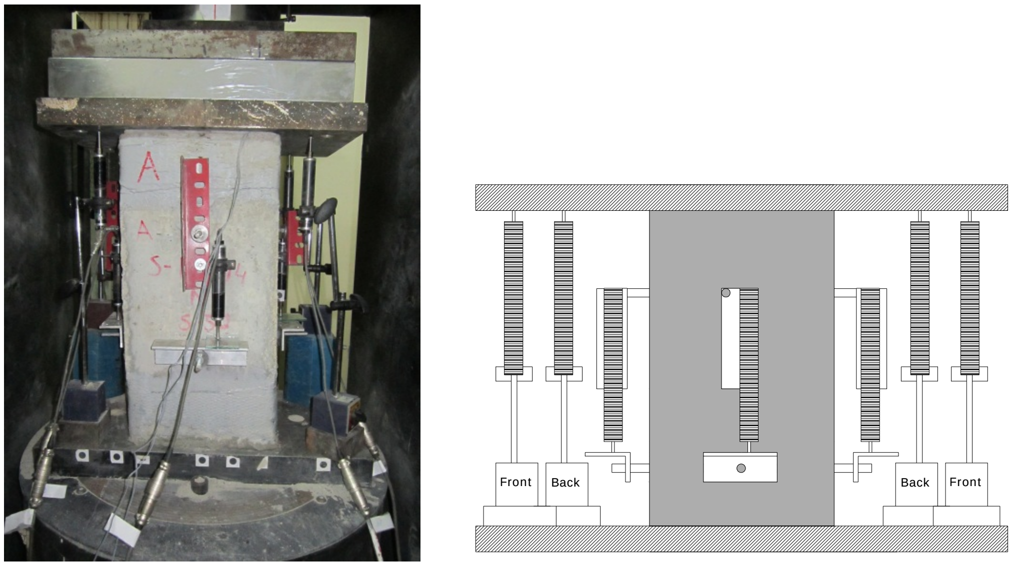

Fig. 4 General appearance of the test setup

Fig. 5 Transverse reinforcement with strain gauges

3 TEST RESULTS

The experimental results are presented with the axial stress – strain relationships. The average strains were determined from the readings of the LVDTs with the gauge lengths of 200 mm (up to peak) and 500 mm (after peak). In order to understand the contribution of the transverse reinforcement and the effect of the test variables on the axial behavior of the RC columns, the stress-strain relationships are presented in Fig. 6 for the first group specimens and in Fig.7 for the second group specimens. In these figures, σ_c is the concrete stress and f_{co} is the compressive strength of unconfined specimen. It should be noted that the stress values in the axial stress – strain relationships of each confined column are normalized with the compressive strength of the unconfined square column (f_{co}=35.6 MPa). Several quantitative results obtained from Figs. 6 and 7 are presented in Tables 4 and 5 for the first and second group specimens, respectively. It should be mentioned that the test of each specimen was terminated at a strain corresponding approximately to 50% loss in strength. In these tables; f_{cc}, ε_{cc}, E_{cc}, $\varepsilon_{0.5fcc}$, μ, and E are the compressive strength of confined specimen, axial strain at peak stress, modulus of elasticity, axial strain at a stress corresponding to 50% loss in strength, ductility and energy dissipation capacity of the specimens, respectively. In order to understand the relative increments in these parameters due to the confinement, the values of the parameters were divided by the corresponding values of the unconfined specimen (S-Ref) (Table 6). In Table 6, the parameters of the unconfined specimen were denoted with the subscript of "ref".

Analyzing the test results (Figs. 6 and 7 and Tables 4-6) leads to the following outcomes:

(a) The stress-strain relationships of the columns vary in the post-peak region depending on the values of the hook angle and hook length. After peak, the stress is decreasing in different rates depending on the hook angle and hook length. As the hook angle or hook length is increasing, the decrement rate is decreasing. For the columns with the hook length of 40 mm, this rate is higher than for the columns with the hook length of 80 mm. In other words, when the hook length is 80 mm, the adverse effect of deficiency in terms of the hook angle is less.

(b) The effects of the test variables on deformability are quantified in Tables 4-6 through the axial strain at a stress corresponding to 50% loss in strength ($\varepsilon_{0.5fcc}$), ductility (μ) and energy dissipation capacity (E). Ductility is defined as the ratio of the strain at 85% of the strength in the post-peak region to the strain at peak stress. Energy dissipation capacity is calculated as the area of the axial stress-axial strain relationship plotted between 0-$\varepsilon_{0.5fcc}$ axial strains. It is seen that due to the confinement of the transverse reinforcement these factors take higher values with respect to the unconfined case. For the constant hook length, these factors take larger values as the hook angle is increasing. This state is observed for the constant hook angle as the hook length is increasing. As seen in Tables 4-6, and as expected the enhancements in these factors for the hook length of 80 mm is higher than those for the hook length of 40 mm.

In accordance to the assessment procedure of TSC (2007), with exception of S-135-80-N-s50 specimen the other specimens are considered as unconfined. However, as seen in Tables 4-6 that even if the detailing of the transverse reinforcement (hook angle and hook length) are not fully satisfying related code requirements in terms of detailing aspects, the existence of the transverse reinforcement provides significant ductility and energy dissipation capacity to the RC columns. Consequently, the contribution of the transverse reinforcement with non-code-complying detailing should be taken into account during the assessment of existing structures.

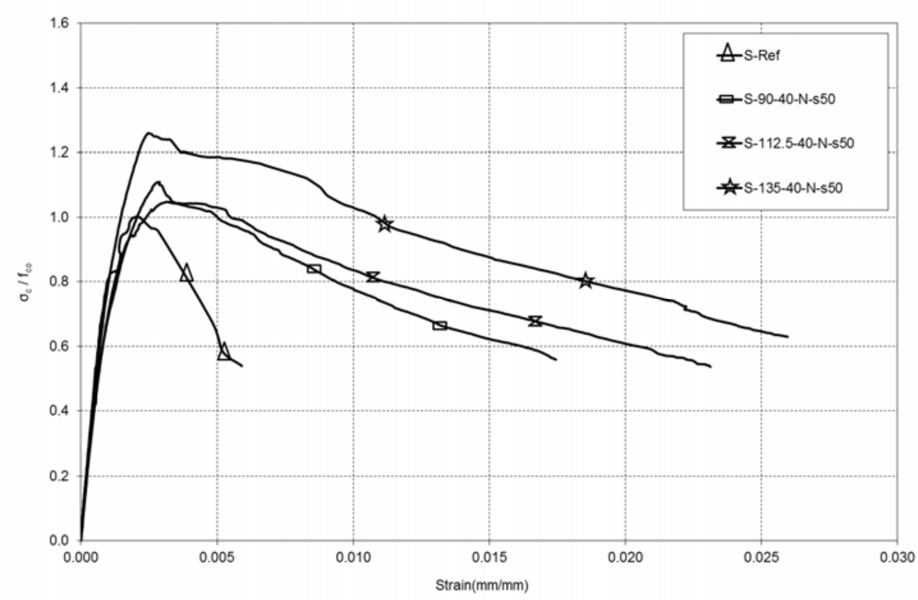

Fig. 6 Stress – strain relationships of the first group specimens

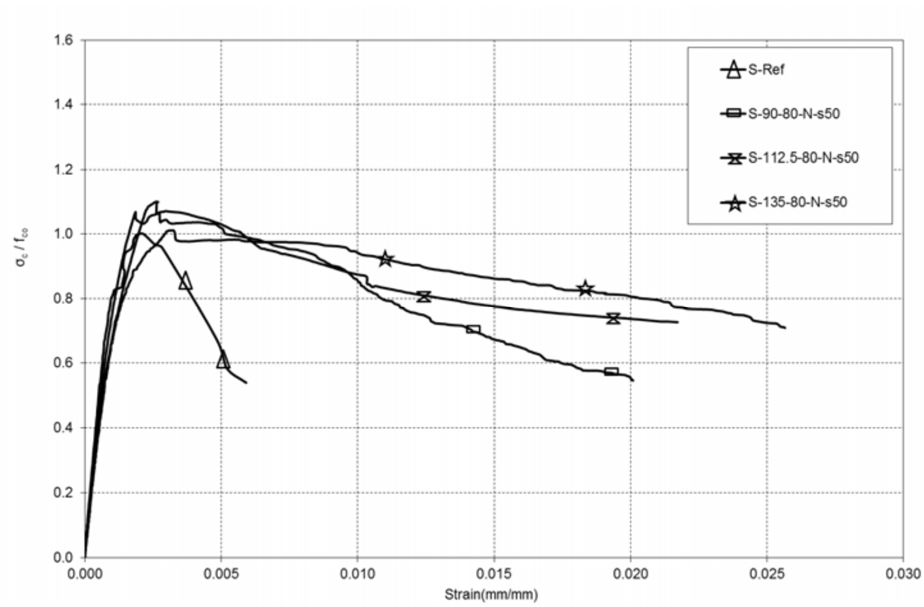

Fig. 7 Stress – strain relationships of the second group specimens

It is observed that the specimens with different hook angle and hook length failed in a similar manner. The appearances of S-135-40-N-s50 and S-135-80-N-s50 after the tests are presented in Fig.8. Before the peak loads, no cracks were visible. Around the peak load, vertical cracks started to form. Then, while the deformations were increasing, new cracks formed and the spalling of cover concrete was observed. Due to the widening of the existing cracks and crushing of the concrete, the specimens failed. It should be mentioned that no hoop fracture observed.

Table 4 Test results of the first group RC column specimens

Specimens	f_{cc} / f_{co} (MPa)	ε_{cc} (mm/mm)	E_{cc} (MPa)	$\varepsilon_{0.85fcc}$ (mm/mm)	$\varepsilon_{0.5fcc}$ (mm/mm)	μ	E (MPa)
S-Ref	1.00	0.0023	31900	0.0037	0.0057	1.9	0.176
S-90-80-N-s50	1.07	0.0026	28400	0.0044	0.0095	2.2	0.208
S-112.5-80-N-s50	1.11	0.0023	26300	0.0059	0.0175	2.9	0.280
S-135-80-N-s50	1.05	0.0022	31950	0.0090	0.0258	4.4	0.420

Table 5 Test results of the second group RC column specimens

Specimens	f_{cc} / f_{co} (MPa)	ε_{cc} (mm/mm)	E_{cc} (MPa)	$\varepsilon_{0.85fcc}$ (mm/mm)	$\varepsilon_{0.5fcc}$ (mm/mm)	μ	E (MPa)
S-Ref	1.00	0.0023	31900	0.0037	0.0057	1.9	0.176
S-90-80-N-s50	1.10	0.0024	28400	0.0067	0.0181	3.3	0.315
S-112.5-80-N-s50	1.26	0.0027	28900	0.0093	0.0270	4.1	0.390
S-135-80-N-s50	1.01	0.0023	27400	0.0144	0.0320	7.3	0.700

Table 6 Increments in several parameters

Specimens	$\varepsilon_{0.85fcc}$ / $\varepsilon_{ref,0.85fco}$	$\varepsilon_{0.5fcc}$ / $\varepsilon_{ref,0.50fco}$	μ / μ_{ref}	E / E_{ref}
S-Ref	1.0	1.0	1.0	1.0
S-90-80-N-s50	1.2	1.7	1.2	1.2
S-112.5-80-N-s50	1.6	3.1	1.5	1.6
S-135-80-N-s50	2.4	4.5	2.3	2.4
S-90-80-N-s50	1.8	3.2	1.7	1.8
S-112.5-80-N-s50	2.5	4.7	2.2	2.2
S-135-80-N-s50	3.9	5.6	3.8	4.0

Fig. 8 Appearances of S-135-40-N-s50 and S-135-80-N-s50 after the tests

3.1 Comparison of Test Results with the Mathematical models

The stress-strain relationships of the RC column specimens obtained from the tests are compared with the predicted relationships obtained from the mathematical models proposed by Mander et al. (1988a), Saatcioglu and Razvi (1992), Ilki et al. (2004). It should be noted that the unconfined compressive strength is taken as 35.6 MPa determined from the test of the unconfined column. As seen in Figs. 9 and 10, the model proposed by Ilki et al. (2004) could predict the stress-strain relationship of S-135-80-N-s50 successfully. It is observed that as the transverse reinforcement detailing of these columns are not sufficient, the model proposed by Ilki et al. (2004) could not predict the stress-strain relationships of these columns. The models proposed by Mander et al. (1988a) and Saatcioglu and Razvi (1992) overestimated the stresses on the descending branches (Figs. 9 and 10). This indicates that a model reflecting the influences of the parameters of the hook angle and hook length is required to predict the behavior of the RC columns confined with the transverse reinforcement. Such a model may contribute to a more potentially realistic assessment of existing buildings with improper transverse reinforcement detailing.

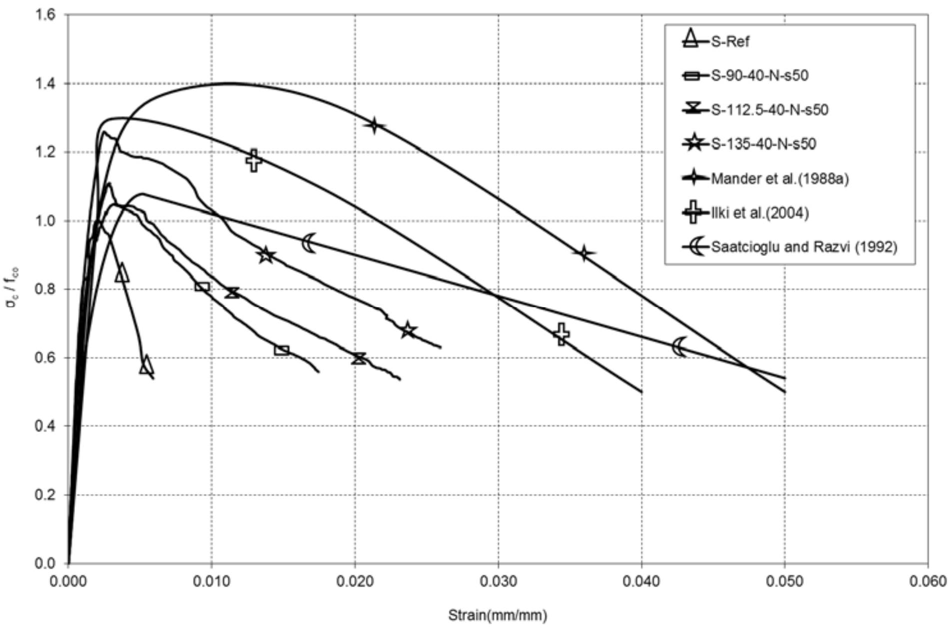

Fig. 9 Predicted stress-strain relationships for the first group specimens

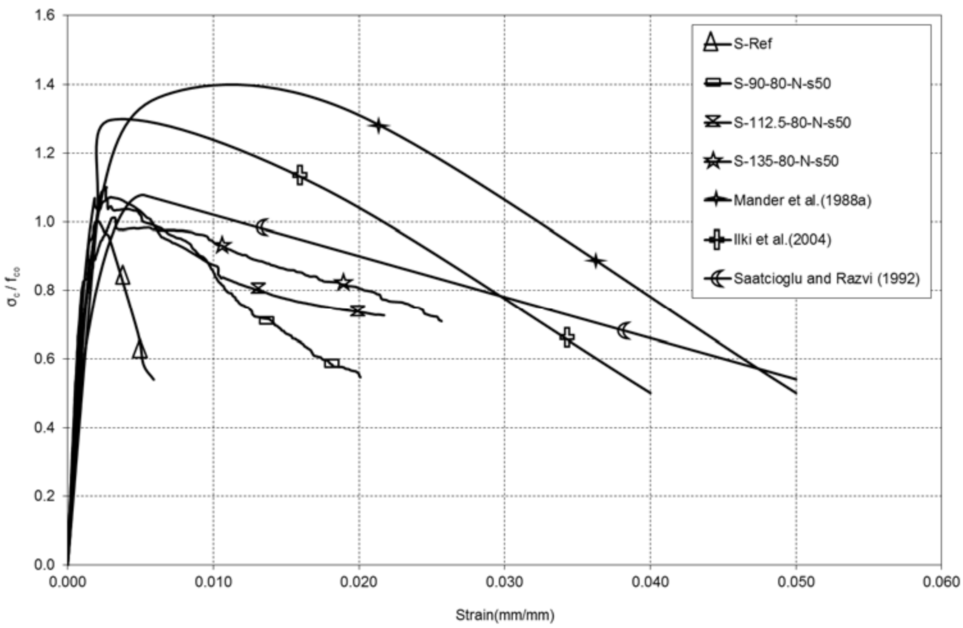

Fig. 10 Predicted stress-strain relationships for the second group specimens

3. CONCLUSIONS

In this paper, an experimental study investigating the effects of the transverse reinforcement detailing of RC columns on the axial performance is outlined. The effects of the hook angle and hook length of the transverse reinforcement on the compression behavior of the columns are investigated.

(a) The test results showed that the RC columns with the non-code-complying reinforcement transverse detailing may exhibit significantly ductile behavior with respect to the behavior of the unconfined concrete column. Consequently, the contribution of the transverse reinforcement with non-code-complying detailing should be taken into account during the assessment of existing structures through proper modeling approaches.

(b) It is observed that the stress-strain relationships of the columns with non-code-complying reinforcement transverse detailing are not predicted by the models since the relationships proposed were based on the test results on columns proper hook angle and length. Consequently, a model incorporating the effects of the hook angle and length is needed.

It is clear that these findings should be validated through tests on columns subjected to reversed cyclic lateral loads as well as axial loads.

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