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Prediction of Structural Behavior of RC Columns Confined with High Strength Steel Bars

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ABSTRACT: Higher compressive strength of concrete is desired as the building height increases. High strength concrete inherently shows brittle behavior after reaching its maximum compressive strength. The effect of high strength concrete can be significantly improved by the use of high strength and large size reinforcing bars. Lateral confinement using high strength steel is thought to be an effective countermeasure to compensate for rapid decrease in the descending branch of stress-strain relationship of high strength concrete. The yield strength of transverse reinforcement is limited in the current design codes to prevent possible sudden concrete failure due to over reinforcement. This paper presents the effects of the yield strength of transverse reinforcement and compressive strength of concrete on the structural behavior of reinforced concrete columns. A total of twenty five RC cylindrical specimens were tested. Four parameters were considered in this investigation: compressive strength of concrete, the yield strength of transverse reinforcement, percentage of transverse steel, and spacing. Test results indicated that the structural behavior of RC cylinders confined with high strength transverse reinforcement was strongly influenced by compressive strength of concrete. The high strength lateral reinforcement in high strength concrete did not reach its yield strain and the confining effect of the high strength steel bars in high strength concrete was small compared to the effect of the high strength steel bars in normal strength concrete. Based on the experimental observations, an equation was proposed to predict compressive stress vs. compressive strain of RC columns confined with high strength transverse reinforcement. The proposed equation predicted the structural behavior of RC columns with reasonable agreement.

1 INTRODUCTION

In the last four decades, the compressive response of concrete confined with steel spirals or hoops have been researched extensively. Richart et al (1928) has been demonstrated that lateral confinement increases compressive strength, deformability, and energy absorption capacity of concrete. Early experimental and analytical researches to use steel spirals of hoops as confining materials in columns were performed by Barmer(1943) and Hognested et al(1955). These attempts were followed by many experimental studies to investigate the effects of percentage of lateral reinforcement (Iyengar et al(1970), Sargin et al(1971), Sheikh and Uzumeri(1980), Mander et al(1988), Yong et al(1988), Nishiyama et al(1993)) spacing of lateral reinforcement (Muguruma et al(1979, 1983), Sheikh and Uzumeri(1980), Somes(1980), Mander et al(1988), Sheika and Toklucu (1993), Nishiyama et al(1993)) configurations of transverse steel(Iyengar et al(1970), Burdette and Hilsdort(1971), Sheikh and Uzumeri(1980)), distribution of longitudinal steel (Mander et al(1988)), and compressive strength of concrete on the compressive response of concrete columns(Muguruma et al(1979, 1983, 1990, 1991), Ahmad and Shah (1982, 1985), Martinez et al(1984)). Hognested et al(1955) simulated concrete section between the maximum compression fibre. Several researches have examined the response of concrete specimens with different types of confining reinforcement by maintain all over variables at constant level. Circular spiral configuration was typically found to be the most effective whilst rectangular hoops without cross tie were the least effective(Iyengar et al 1970). Burdette and Hilsdorf(1970) tested concrete prisms with various configurations of transverse reinforcement. From these test results, it was concluded that flexural rigidity of lateral reinforcing bars in rectangular hoop configuration was found to be important parameter in confining concrete. Moehle and Cavanagh(1985) indicated that the columns with indeterminate hoops or cross ties to support mid side longitudinal bars, performed superior to the column having no support for the intermediate longitudinal bars. The model developed by Mander *et al*. is based on the works by Popovics(1973) and Elwi *et al*.(1979) using the energy balance approach for steel confinement. The model is widely accepted and adopted by many design codes.

The number of high-rise reinforced concrete (RC) buildings is steadily increasing since 1980’s. The use of high strength concrete is indispensible for high-rise RC construction to cope with high axial compressive stress in the vertical members resulted both from gravity load and from the overturning moment due to lateral load. The effect of high strength concrete can be significantly improved by the use of high strength and large size reinforcing bars. Consequently higher strength is desired as the building height increases. On the other hand, high strength concrete inherently shows brittle behavior after reaching its maximum compressive strength.

The yield strength of transverse reinforcement gives an upper limit to the confining pressure. The stress in transverse steel increases with the increase in axial compressive strain in concrete. The confining pressure provided by transverse steel is dependent not only on its yield strength but also on the inherent lateral expansion capability of plain concrete, i. e., Poisson’s ratio. Lateral confinement using high strength steel is thought to be an effective countermeasure to compensate for rapid decrease in the descending branch of stress-strain relationship of high strength concrete. However, the test results in the literature(Martinez et al(1984), Nishiyama et al(1993), Watanabe et al(1980)) indicated that the high strength transverse reinforcement might not reach its yield strain when it was used to confine high strength concrete. For high strength concrete, the increase in yield strength of transverse steel up to a certain level increase the strength and ductility of concrete. Beyond that level the increase in yield strength of transverse steel does not necessarily enhance the strength and ductility of concrete. In addition, the test results of Ahmad and Shah(1982, 1985) demonstrated that for the same concrete grade, steel stress at peak was essentially the same regardless of the yield strength of spirals. This means that the increase in the yield strength of spirals did not influence the compressive strength of the confined concrete. However, an increase in the yield strength did influence the slope of the descending branch(Assa (1996)).

This paper presents the results of an experimental and analytical study on the performance of concrete cylinders confined with steel spirals. Twenty-four 150 x 300 mm concrete cylinders are tested under pure compression. Applied load, axial strain, and lateral strain are recorded to monitor the stress-strain behavior, ultimate strength, and corresponding strain of the tested specimens. The experimental results are then compared with some of the existing confinement models available in the technical literature. In addition, a new analytical model to predict the behavior of concrete confined with transverse steel was proposed.

2 EXPERIMENTAL STUDY ON CONFINED CONCRETE

2.1 Test program

2.1.1 Test specimens

In order to investigate the effects of the yield strength of transverse reinforcement and compressive strength of concrete on the structural behavior of reinforced concrete columns, twenty five RC cylindrical specimens were tested. Four parameters were considered in this investigation: compressive strength of concrete, the yield strength of transverse reinforcement (472MPa, 880MPa, and 1,430MPa), and percentage of transverse steel, and spacing. The effect of each parameter has been investigated by keeping the other parameters at a constant level. No cover concrete was provided in all specimens. The target strength of concrete was varied from 20MPa to 100MPa. Bar diameter of spirals were 4.5 mm in all specimens. The target spacing of spirals were varied from 25mm to 65mm. All specimens were tested under monotonic concentric compression. Table 1 gives the details of the specimens. The cement used for all specimens was normal Portland cement. At least three 100 x 200 mm cylinders for each

Table 1. Test results of specimens (Cha et al (2011))

Group	Specimens	f_c' (MPa)	Spirals	
			f_{wy} (MPa)	s (mm)
C-25	P25-1	28.3	-	-
	NS25-1	28.3	472	25
	NM25-1	28.3	472	45
	NL25-1	28.3	472	65
	HS25-1	28.3	880	25
	HM25-1	28.3	880	45
	US25-1	28.3	1430	25
	UM25-1	28.3	1430	45
	UL25-1	28.3	1430	65
C-50	P50	44.4	-	-
	NS50	44.4	472	25
	NM50	44.4	472	45
	NL50	44.4	472	65
	HS50	44.4	880	25
	HM50	44.4	880	45
	US50	44.4	1430	25
	UM50	44.4	1430	45
	UL50	44.4	1430	65
C-100	P-100	100.3	-	-
	NS100	100.3	472	25
	NL100	100.3	472	65
	HS100	100.3	880	25
	HM100	100.3	880	45
	US100	100.3	1430	25
	UL100	100.3	1430	65

concrete strength were also cast with the specimens and tested on the same or next day of specimens testing. Table 1 shows the compressive strength of the plain cylinders.

2.1.2 Measurements

Axial deformation of specimen was measured using three linear variable differential transducers(LVDTs) at the central zone of the specimen as shown in Figure 1. The measuring length of vertical LVDTs was 200mm as shown in Fig.1, whereas the measuring length of lateral LVDTs was the diameter of the cylinder, 150mm. In addition, lateral deformation was also measured using three transducers. The strain in the spiral steel was measured using five wire strain gages placed approximately at three loops as shown in Figure 1. The specimens were loaded using universal test machine with a load capacity of 3,000kN. The load applied to the specimens was monitored using a load cell and all measurement data were collected by a system of data logger and store directly to a computer. All specimens were tested under monotonically increasing axial compression.

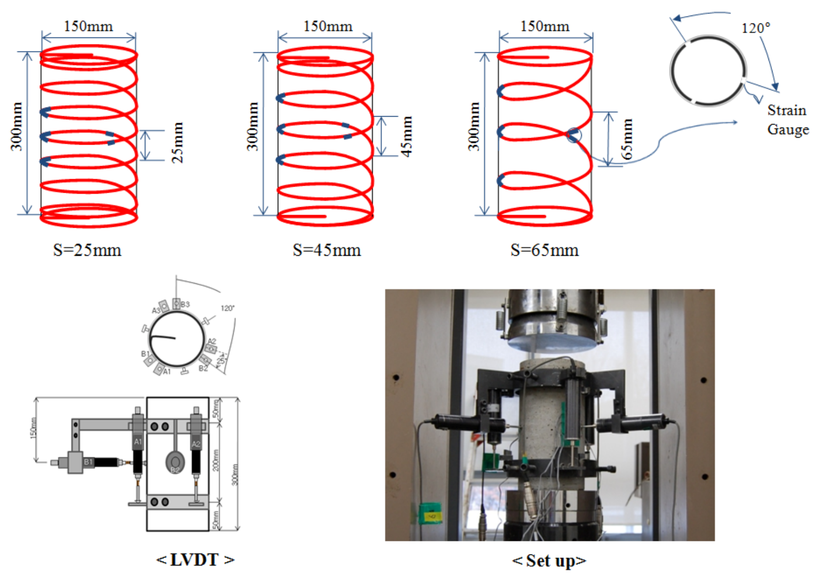


Figure 1. Location of wire strain gages and transducers (Cha et al (2011)).

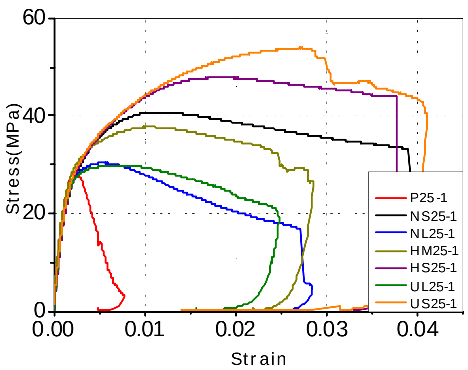
2.2 Test results

Two different basic failure modes were observed in the tested specimens : (1) bulging of the cylinders at certain location along its length followed in most cases by rupture of one or more spiral loops and (2) the formation of a shear plain. These failure modes were found to be highly dependent on the compressive strength of concrete and hoop spacing.

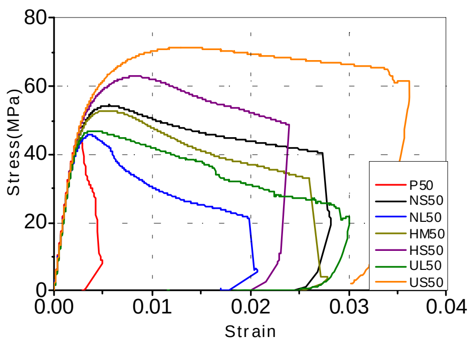
Figure 2 shows the axial stress vs. strain curves of the confined cylinders tested under monotonic loading. The curves were grouped for showing the effects of the compressive strength of concrete on the response.

Test results indicated that the structural behavior of RC cylinders confined with high strength transverse reinforcement was strongly influenced by compressive strength of concrete. The stiffnesses of unconfined specimen and other confined specimens are almost identical in the elastic range. With further increase in the axial compressive strain, the stress-stain curve of concrete becomes nonlinear. The typical failure of the specimens confined with the steel spirals initiated at the mid-height of the specimens. The effect of spiral confinement can be observed in the compressive stress-strain curves of in Fig. 2. The peak stress, the corresponding strain and the area under the stress-strain curve (energy absorption capacity) tend to increase as the amount of spirals increases. Test results also indicated that the confining effect of lateral reinforcement (f_{cc}’ / f_c’, rate of the compressive strength of concrete confined with lateral reinforcement to that of plain concrete) decreased as the compressive strength of plain concrete (f_c’) increased. The high strength lateral spiral (f_{wy} = 880MPa) reached its yield strain when the compressive strength of concrete (f_c’) was 28.3MPa, while it did not reach its yield strain when the compressive strength of concrete (f_c’) was 100.3MPa. On the other hand, all of the ultra high strength lateral spirals (f_{wy} = 1,430MPa) not only in normal strength concrete (f_c’=28.3MPa) but also in high strength concrete (f_c’=100.3MPa) did not reach its yield strain.

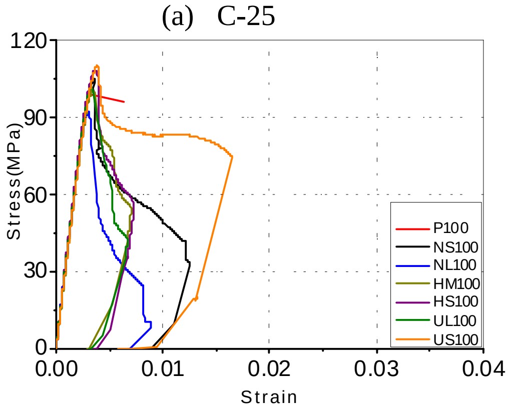
The strength of concrete and spacing of spirals affect the lateral deformation significantly. The lateral strain at a given level of axial strain increase with the increase in concrete strength as shown in Fig. 3.



(a) C-25



(b) C-50

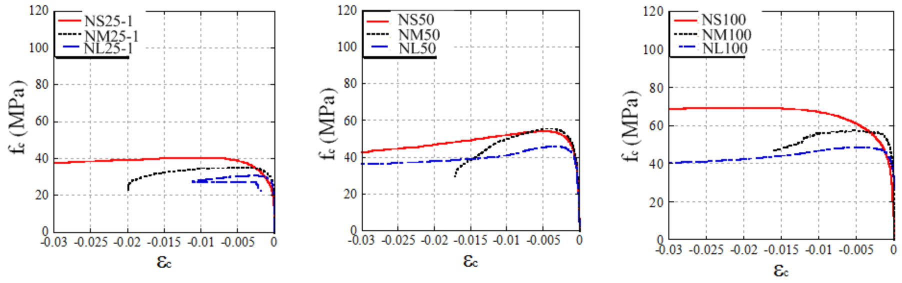


(c) C-100

Figure 2. Axial stress vs. axial strain response of specimens.

3 POISSON’S RATIO OF CONFINED CONCRETE

Three trends could be observed from the stress vs strain response of test specimens; (1) regardless of the spacing of spirals, the Poisson’s ratio increased with the increase in concrete



(a) C-25 (b) C-50 (c) C-100

Figure 3. Axial stress vs. lateral strain response of specimens (Cha et al (2011)).

strength, (2) the Poisson's ratio increased with the increase in spacing of spirals for all concrete strength, and (3) the Poisson's ratio increased with the increase in axial strain. Based on the test results, Eq. (1) was proposed to evaluate the Poisson's ratio (v)in the lateral direction.

$$v = 2.97\left(\frac{\rho_s f_{wy}}{f_c'}\right)^{0.41} \tag{1}$$

$$\rho_s = \frac{\pi d_s A_{sp}}{s \cdot \pi \cdot (d_s/2)^2} \tag{2}$$

where, f_c' is the compressive strength of concrete, ρ_s is the ratio of volume of spirals to volume of confined concrete core, f_{wy} is the yield strength of spirals, d_s is the diameter of core concrete, s is the spacing of spirals, and A_{sp} is the sectional area of steel stirrup. The lateral strain, ε_l, at the maximum stress can be calculated by substituting the Poisson's ratio of Eq.(1) into Eq. (3).

$$\varepsilon_l = \frac{1}{E}\left((1-v)\, f_r - v f_1\right) \tag{3}$$

where, f_r is the lateral stress, calculated by $2\,A_{sp} f_{wy}/(d_s s)$, E is the secant modulus of elasticity for concrete, and f_1 is the longitudinal stress of concrete.

If the ε_l is known, the stress, f_l, of transverse reinforcement at the maximum stress can be calculated by using the stress vs. strain curve of steel bars. In this study, the calculated stress of transverse reinforcement f_l was substituted into widely accepted equations, such as Mander et al's equation(1988) or Razvi and Saatcioglu's equation(1999).

$$f_{cc} = f_c'\left(2.254\sqrt{1+\frac{7.94 f_{lewy}}{f_c'}} - \frac{2 f_{lewy}}{f_c'} - 1.254\right) \tag{4}$$

$$f_{cc} = f_c' + 0.67(f_l)^{-0.17}\left(0.15\sqrt{\frac{b_c}{s}\frac{b_c}{s_1}}\right) f_l \tag{5}$$

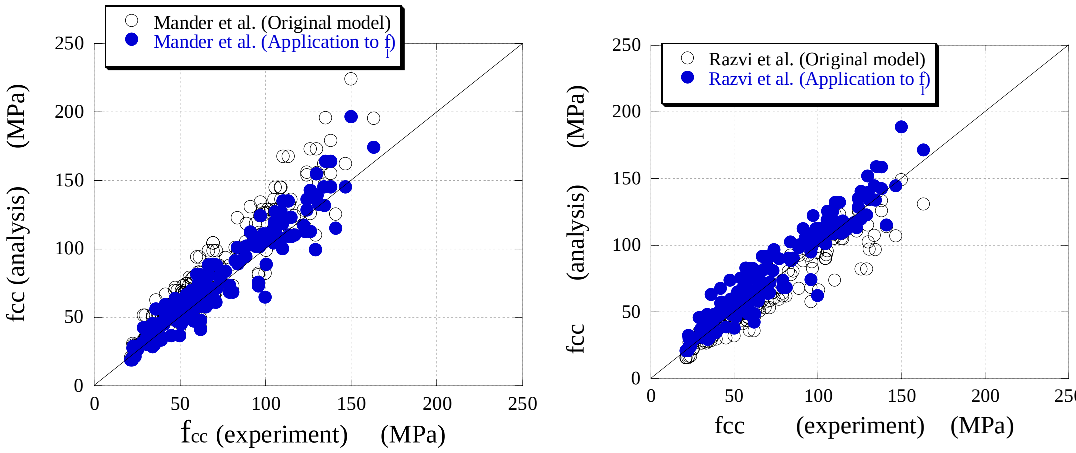
where, f_{lewy} is the effective lateral stress, b_c is core dimension, s_1 is the spacing of longitudinal reinforcement, laterally supported by corner of hoop or hook of crosstie. Figures 4(a) and (b) compare the observed and calculated compressive strengths of confined concrete by Eq.(4) and Eq.(5), respectively. In Fig. 4, the open circles represent the predicted results using yield strength of transverse reinforcement, while solid circles represent the predicted results using Eq.(3). As shown in Fig. 4, the accuracy of the current equations to calculate the compressive strength of the confined concrete was increased by using the proposed effective stress of transverse reinforcement.

4 CONCLUSIONS

Based on the analytical and experimental results, the following conclusions are drawn:

1) High strength transverse reinforcement in high strength concrete does not reach it's yield strain.

2) An equation was proposed to predict the effective stress of transverse reinforcement at failure. The accuracy of the current equations to calculate the compressive strength of the confined concrete was increased by using the proposed method to calculate the effective stress of transverse reinforcement.



(a) Mander et al's equation (b) Razvi and Saatcioglu's equation

Figure 4. Comparison between predicted and observed compressive strength of concrete.

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