TABLE 3—RESULTS OF TYPE III SPECIMENS

(0.96% LONGITUDINAL REINFORCEMENT ONLY)

No. of mesh layers (Nml)	Ast (mm^2)	Confining stress (σ_L, Mpa)	Strength of confined concrete (σ_c, Mpa)	Strength of unconfined concrete (σ_o, Mpa)	Percentage increase in experimental load capacity	Longitudinal strain at peak load in confined column (ε_c,)
0	169.65	0.00	26.65	26.65	-	2.10×10^{-3}
1	169.65	0.81	30.05	26.65	1.0	2.83×10^{-3}
2	169.65	1.66	33.62	26.65	14.85	3.87×10^{-3}
3	169.65	2.53	37.27	26.65	18.81	5.52×10^{-3}

TABLE 4—RESULTS OF TYPE IV SPECIMENS

(1.7% LONGITUDINAL REINFORCEMENT ONLY)

No. of mesh layers (Nml)	Ast (mm^2)	Confining stress (σ_L, Mpa)	Strength of confined concrete (σ_c, Mpa)	Strength of unconfined concrete (σ_o, Mpa)	Percentage increase in experimental load capacity	Longitudinal strain at peak load in confined column (ε_c,)
0	301.6	0.00	26.65	26.65	-	2.20×10^{-3}
1	301.6	0.81	30.05	26.65	(-0.92)	2.92×10^{-3}
2	301.6	1.66	33.62	26.65	10.1	3.66×10^{-3}
3	301.6	2.53	37.27	26.65	16.0	8.00×10^{-3}

TABLE 5—RESULTS OF TYPE V SPECIMENS

(1.7% LONGITUDINAL REINFORCEMENT ONLY)

No. of mesh layers (Nml)	Ast (mm^2)	Confining stress (σ_L, Mpa)	Strength of confined concrete (σ_c, Mpa)	Strength of unconfined concrete (σ_o, Mpa)	Percentage increase in experimental load capacity	Longitudinal strain at peak load in confined column (ε_c,)
0	301.6	0.00, (1.92)*	26.65	26.65	-	4.19×10^{-3}
1	301.6	0.81, (1.92)	30.05	26.65	1.81	4.42×10^{-3}
2	301.6	1.66, (1.92)	33.62	26.65	11.1	8.24×10^{-3}
3	301.6	2.53, (1.92)	37.27	26.65	20.0	12.23×10^{-3}

* Figures in brackets give the uniform confining pressure due to circular ties

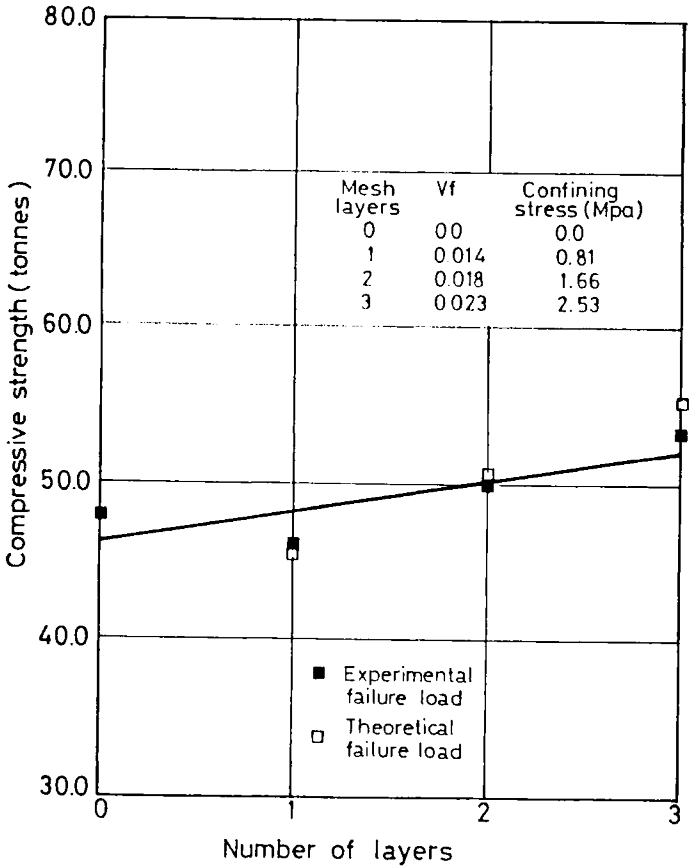

Fig. 1—Compressive strength vs. # of mesh layers

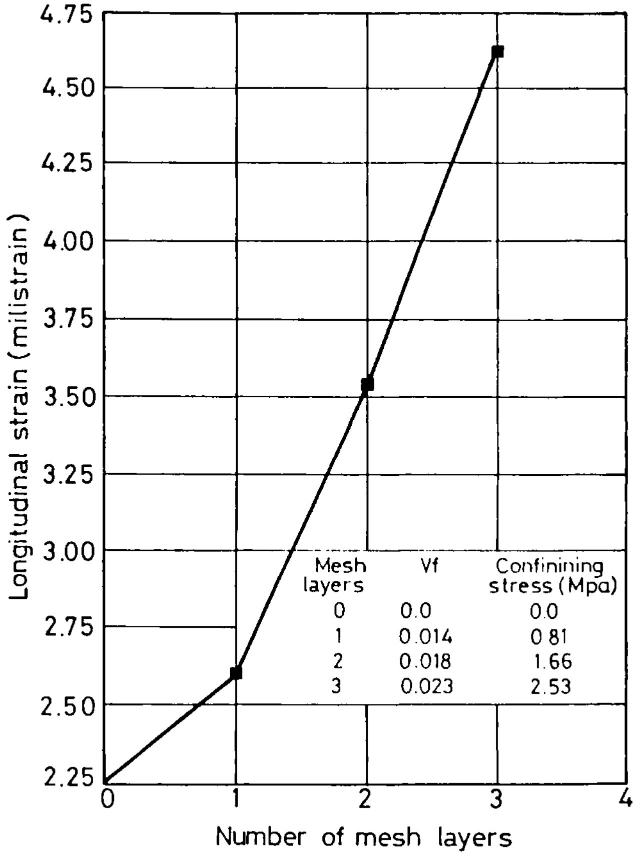

Fig. 2—Longitudinal strain vs. # of mesh layers

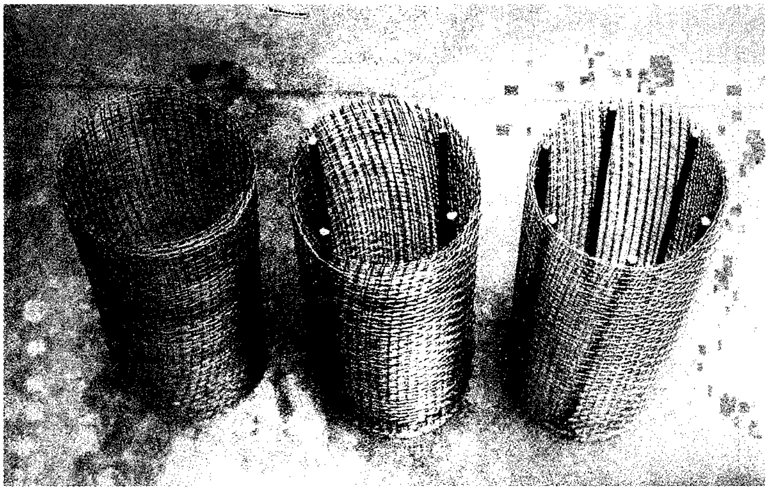

Fig. 3—Mesh framework used for casting of specimens

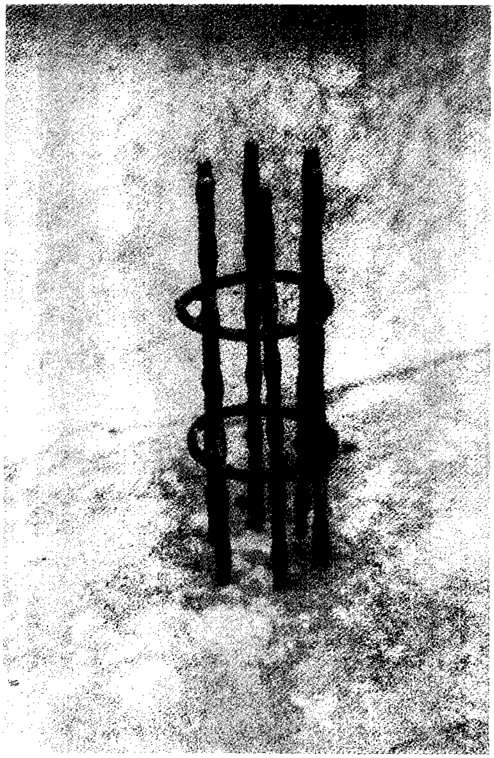

Fig. 4—Longitudinal & lateral reinforcement provided in type V specimens

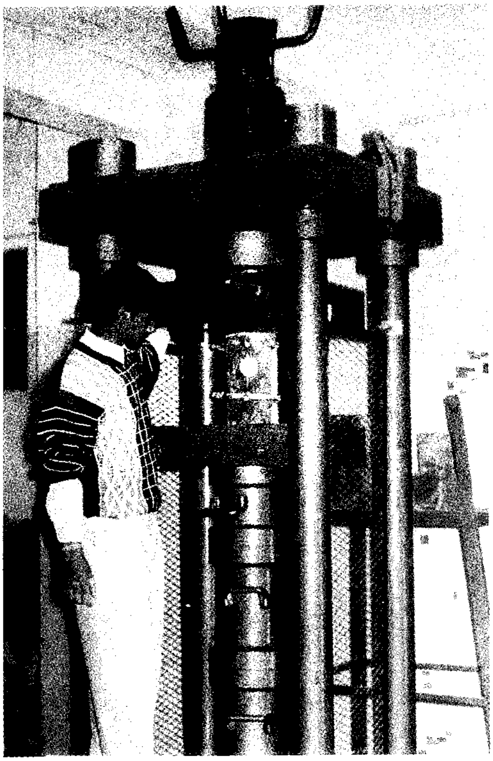

Fig. 5—Specimens under test

Fig. 6—Failure mode of specimens

An Experimental Study on High-Strength Concrete Column Strength Subjected to Eccentric Loads

by Jae-Hoon Lee, Hae-Geun Park and Young-Shik Park

Synopsis: High strength concrete has an advantage of strength capacity and stiffness especially for column elements. This paper is a part of a research plan aimed at verification of basic design rules to high-strength concrete columns. A total 24 column specimens were tested to investigate structural behavior and strength of eccentrically loaded reinforced concrete tied columns. The main variables included in this test program were concrete compressive strength, steel amount, eccentricity, and slenderness ratio. The concrete compressive strength varied from 34.9 Mpa to 70.4 Mpa and the column steel ratios were between 1.1 % and 5.5 %. The eccentricity was selected for the different failure modes, i.e., compression control, balanced point, and tension control. The slenderness ratio varied from 19 to 61. The column specimens with same slenderness ratio but with different concrete compressive strength were constructed and tested. Experimentally obtained column strength were compared with the analytical results by use of an equivalent rectangular stress block, a trapezoidal stress block, and a modified rectangular stress block. And also, the failure mode and concrete ultimate compressive strain were observed and discussed in this paper.

Keywords: Columns (supports); failure; high-strength concretes; strains

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INTRODUCTION

Most experimental studies on reinforced concrete column have been conducted with normal concrete compressive strength under 42 Mpa and many design codes(1,2) have been written according to these experimental results. It was difficult to produce concrete over 42 Mpa of compressive strength due to consistent quality control problems, but recently high strength concrete over 70 Mpa have been easily produced by use of admixtures and superplasticizers. As concrete compressive strength increases, structural behaviors and failure modes may be different from those of normal strength concrete structures due to mechanical material properties such as shapes of stress-strain curve, brittleness, and toughness. Therefore, it may be necessary that the currently used design methods be examined for high strength concrete structures based on experimental results and be modified if needed.

Use of high strength concrete may have advantages especially for columns that a large portion of the sectional area is under compressive stress rather than for beams. Most early researches on high strength concrete columns were concerned with column strength under pure axial loading, and also high strength concrete was applied first to the columns of high-rise buildings which were loaded with small eccentricities. In order to ensure safe and effective use of high strength concrete columns, various researches on structural behavior of high strength concrete columns should be conducted. Recently, various researches on high strength concrete columns have been reported which are concerned with ductility, confinement effect, and cyclic load effect, as well as column strength under pure axial load. The experimental researches on the column strength under eccentric loads, however, are still limited.

STRENGTH ANALYSIS OF COLUMN SECTIONS

Axial Force-Moment Strength Analysis

Since reinforced concrete columns are the structural elements subjected to axial load and bending moment, column strength should be calculated for the combined action. In a practical design process, the column strength is normally checked by axial force-moment interaction diagrams(P-M diagrams). The P-M diagrams have been used also in design of reinforced concrete slender columns in consideration of secondary moment(P-Δ moment) caused by column length effect(P-Δ effect). The column strength is generally checked by comparison of the applied axial load and the total moment with the axial force-moment capacity of the column section. Therefore, the strength analysis of column section may be essential to the practical design of reinforced concrete columns.

Equilibrium and compatibility conditions should be satisfied by use of stress-strain curves of concrete and reinforcing steel in the axial force-moment strength analysis of a column section. In order to obtain the exact concrete stress-strain curve, an experiment may be desirable. However, concrete stress-strain curves proposed by researchers have been used in a practical design process since it is not practical to carry out the experiments in each column design.

Collins et al(3) proposed an analytical method to calculate the axial force-moment strength of high strength concrete column sections. In this method, axial force-moment-curvature analysis using the stress-strain curves of concrete and reinforcing steel should be performed first, and the maximum moment capacity at each axial force level is connected to construct a P-M interaction diagram. This analytical method is excellent for a theoretical concept, but may not be simple. Iteration process should be performed until the maximum moment capacity at a selected axial force level is obtained, since the value of ultimate concrete compressive strain is not defined. Therefore, hand calculation procedure is actually not easy, and computer programming may be also required.

On the contrary, strength analysis using a compressive stress block of which magnitude and location of the resultant compressive force are similar to the actual stress distribution, has been widely used for a practical design because of simple calculation procedure. In case of the high strength concrete structural elements, especially for high strength concrete columns, choice of concrete compressive stress block is the most important part in sectional analysis. CEB-FIP(4) and ACI committee 363(5) reported that the influence of the concrete compressive stress distribution for flexural strength of under-reinforced beams was of less important since it was mainly controlled by the amount of tension steel. And also, it was pointed out that flexural strength of over-reinforced beams and column strength were more dependent on the concrete compressive stress distribution.

Garcia and Nilson(6) performed an analytical study on sectional strength of square column based on a continuous function of concrete stress-strain curve, the equivalent rectangular stress block, and a trapezoidal stress block. It was reported that the predicted strength by the equivalent rectangular stress block showed great difference on the unconservative side when compared with the continuous function for all cases, while the trapezoidal stress block provided values between the continuous function and the rectangular stress block. For relatively large eccentricities, the column strength curves by the rectangular stress block and the trapezoidal stress block were almost distinguishable, however difference between two curves were up to 15 % depending on eccentricity.

Concrete Equivalent Compressive Stress Distribution

Design codes(1,2) have mentioned rectangular, trapezoidal, and parabolic shapes as concrete compressive stress distributions, and have recommended Whitney's equivalent rectangular stress distribution as shown in Fig.1 (a). With the equivalent rectangular stress distribution, the magnitude of compressive force C for a section of width b, is calculated by Eq. (1), and the depth of equivalent rectangular stress distribution a is determined by multiplication of β_1 to the neutral axis c.

$$C = 0.85 f_c' a\, b \tag{1}$$

Since the ascending part of stress-strain curve of high strength concrete is more linear than normal strength concrete is, the trapezoidal stress distribution may be more close to the real stress distribution. Pastor et al(7) introduced a concept of plasticity ratio β originally suggested by Jenson(8), and proposed the trapezoidal stress distribution as Fig.1 (b). β is expressed by Eq. (2) which includes β_1, and the magnitude of compressive force C is calculated by Eq. (3).

$$\beta = 2\,\beta_1 - 1 \tag{2}$$

$$C = \frac{1+\beta}{2}\ \alpha\, f_c'\, b\, c \tag{3}$$

Zia(9) suggested an equivalent rectangular stress distribution as shown in