論 文

[2143] INFLUENCE OF EXISTING CRACKS AND STRAIN RATE ON THE BEHAVIOR OF CONCRETE UNDER CYCLIC COMPRESSIVE LOADING

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ABSTRACT

Experimental investigations on the behavior of cracked concrete under cyclic compressive loading and the effect of strain rate on the overall behavior of concrete are discussed. In order to study the compressive behavior of concrete parallel to cracks, a series of tests was carried out using hollow cylindrical reinforced concrete specimens, in which cracks were introduced by applying tensile strains in the transverse direction of the specimen. The results indicate a reduction in compressive resistance parallel to cracks and the influence of cracks on the compressive plasticity and cyclic response of concrete. Another series of tests was carried out to study the effect of strain rate on the behavior of concrete under cyclic compressive loading, and its influence on the overall behavior is discussed.

1. INTRODUCTION

The finite element method has been used for analyzing reinforced concrete structures for more than twenty years but due to inadequacy of accurate material models for reinforced concrete and lack of agreement in the available models with test results, still the researchers continue their research works for better understanding of the behavior of reinforced concrete and attempting to predict its behavior analytically.

For the prediction of structural response, the designer conceptualizes the real structure as an assemblage of simpler reinforced concrete elements. Therefore it is important to predict the behavior of reinforced concrete elements accurately in order to achieve successful predictions in actual responses of reinforced concrete structures. Prediction of the response of a reinforced concrete element is not that easy due to highly complicated non-linear behavior of its constituent composite materials. This nonlinearity is caused by various contributing factors such as cracking, crushing, shear transfer due to aggregate interlock and dowel action, tension stiffening, bond characteristics, time dependency, yielding of reinforcement, etc. Present researchers have made a great improvement in material modeling and achieved a great success in element analysis[1,2]. It was reported that cracked concrete subjected to high tensile strains in the direction normal to compression direction is weaker in compression than uncracked concrete [3,4,5]. However still the overall behavior of cracked concrete is not fully understood. Therefore recently special attention have been paid for constitutive modeling of cracked concrete. Not only the crack condition but also the strain rate affects the compressive behavior of concrete greatly. Many researchers have studied the effect of strain rate on the behavior of concrete but their main objective was to investigate the effect upon the strength

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and elastic properties of concrete. But to take these parameters into account in constitutive modeling, overall behavior including cyclic response should be investigated. This paper describes the observed behavior of cracked concrete and the effect of strain rate on the overall behavior of concrete.

2. EXPERIMENTAL INVESTIGATION

The objectives of these series of tests were to investigate the influence of co-existing transverse tensile strain on the compressive resistance of concrete parallel to cracks and to study the effect of strain rate on the overall behavior of concrete. To investigate the influence of cracks on the behavior of concrete, the method utilized by Miyahara et al.[4] was adopted in this study.

2.1 DETAILS OF THE TEST SPECIMENS

The series of tests consisted of a total of 10 hollow cylindrical reinforced concrete specimens, each having 300 mm height, 150 mm and 80 mm outer and inner diameters respectively. Type D3 reinforcing bars were arranged in the transverse direction, and in order to arrange them, four D3 bars were used in the longitudinal direction. The reinforcement ratios in the transverse and longitudinal directions were 1% and 0.02% respectively. The geometry of a typical specimen and the arrangement of reinforcements are shown in Fig. 1. The mix proportions of concrete used for series A and B are given in Table 1. Maximum size of aggregate used was 10 mm and high early strength portland cement was used.

2.2 TESTING PROCEDURE

In order to generate tensile cracks in the longitudinal direction of the specimens in series A, uniform pressure was applied radially by pumping water into the rubber tube of the apparatus which was set in the center of the hollow cylindrical specimen as shown in Fig. 2. The pressure apparatus was restrained by a steel frame to avoid possible longitudinal movements and also to prevent any local cracking at top and bottom of the specimen. When the pressure was applied to generate cracks, it could
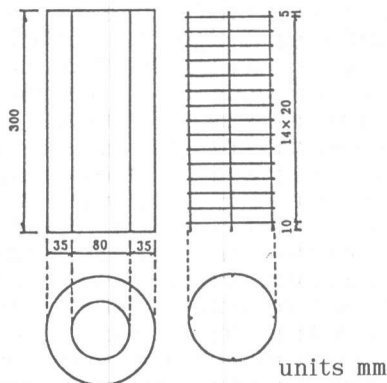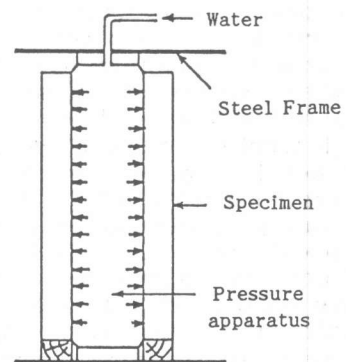

Fig.1 Details of the specimen   Fig.2 Setup for tensile cracking

be seen that initial cracks were mainly generated along the longitudinal reinforcing bars and further increase in pressure resulted widening of the cracks as well as few branch off cracks from the existing cracks under high tensile strains. Average tensile strain "ε_t" in the transverse direction was calculated from the measurements of radial displacements along six diameters. A micrometer was used for the measurements of the radial displacements. After applying predetermined tensile strains in the transverse direction, the specimens were subjected to uniaxial cyclic compressive loading. Loading speed was set in 1 kg/cm². Compressive displacements in the longitudinal direction were measured using PI gauges over the central 250 mm length on vertical surface of the specimen.

In series B, the uncracked concrete specimens were subjected to strain controlled uniaxial compressive loading with rates of straining ranging from .005% to 5%. Experimental data including applied load and compressive displacements were recorded as described previously. Table 2 summarizes the variables such as applied tensile strains ε_t, strain rates for series A and B respectively, and compressive strengths of concrete.

Table 1. Mix proportion of concrete

SERIES	w/c %	s/a %	W kg/m³	C kg/m³	S kg/m³	G kg/m³
A	47	57	220	465	840	647
B	55	54	195	355	932	794

Series A : Specimens $S_1 \sim S_6$
      B : Specimens $T_1 \sim T_4$

Table 2 Test variables

Specimen	f'_c kg/cm³	ε_t micro	Loading rate/ Strain rate
S_1	435	0	
S_2	324	1168	
S_3	358	2390	
S_4	391	4374	1 kg/cm²/sec.
S_5	391	6263	
S_6	391	7971	
T_1	440	–	0.005 %/sec
T_2	440	–	0.05 %/sec
T_3	543	–	0.5 %/sec
T_4	543	–	5 %/sec

3. TEST RESULTS AND DISCUSSION

3.1 Compressive resistance parallel to cracks

Fig. 3 shows the stress-strain curves obtained for uncracked and cracked concrete subjected to uniaxial cyclic compressive loading. In order to facilitate comparison between results, the applied stress was normalized by compressive strength (f'_c). It can be seen that the cracked concrete, subjected to tensile strains in the direction normal to the compression, is weaker in compression than uncracked concrete, and this reduction of compressive stiffness and strength increases with the increase of tensile strain normal to cracks. This degradation of material properties appears at higher stress levels when the co-existing transverse tensile strain is low but in case of concrete with very high co-existing transverse tensile strain, the degradation of material properties appears markedly even at low stress levels. Fig. 4 shows the ultimate strength reduction versus transverse tensile strain. It can be seen that this reduction of strength is greater within the range of transverse tensile strain approximately from 1000μ to 4500μ and beyond that the strength reduction rate decreases.

Fig. 5 shows the total plastic strain corresponds to the maximum compressive strain that the concrete has ever attained, for cracked and
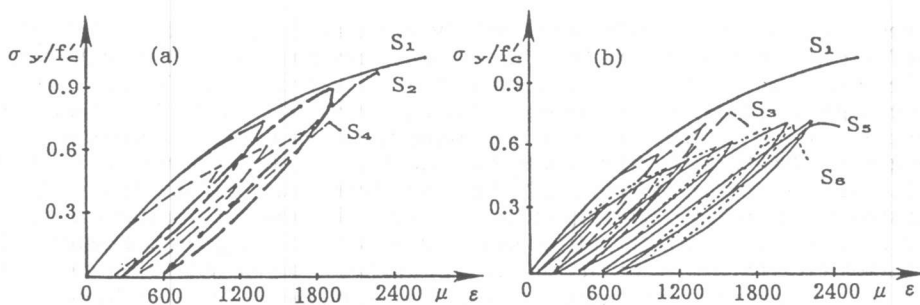
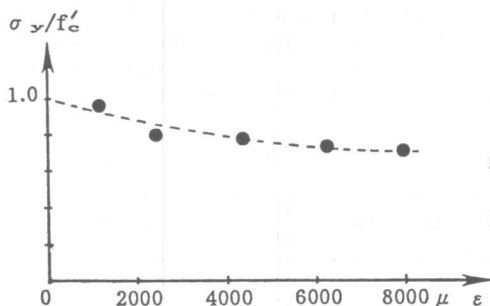Fig.3 Stress-strain relationship of cracked and uncracked concrete

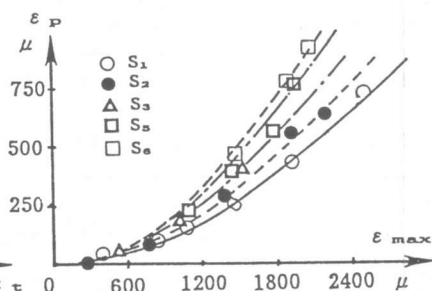Fig.4 Strength reduction vs. transverse tensile strain

Fig.5 Plastic strain vs. maximum compressive strain

uncracked concrete. In this case plastic strain is defined as the total strain which corresponds to zero stress condition. Up to date the compressive plasticity is assumed to be not influenced by co-existing tensile strain in the direction perpendicular to compressive direction. However, the results indicate an increase in plastic strain corresponds to maximum compressive strain with the increase in co-existing transverse tensile strain in concrete. But in the concrete, subjected to very high transverse tensile strains, it can be seen that the rate of increase of plasticity is nearly the same.

In the comparison of the unloading stress-strain relation of cracked and uncracked concrete using a parabolic equation, it was found that a slight increase also in the curvature of unloading path of cracked concrete with the increase in transverse tensile strain and no marked difference among the concrete specimens subjected to very high tensile strains. All these indicate that the influence of cracks on the behavior of concrete between cracks is significant only up to a certain limit of transverse tensile strain. Generally the plasticity is an indication of the accumulated damage in concrete. Therefore, increase in plastic strain corresponding to total maximum compressive strain with increase in transverse tensile strains indicates an increase in the accumulated damage in concrete. Also it can be expected that the degradation of material properties such as strength, modulus of elasticity, etc. with increase in transverse tensile strain could be due to this increase in accumulated damage in concrete within the cracks. When reinforced concrete specimens were subjected to tensile strains by applying radial pressure, it was seen that the number of cracks increased gradually with increasing transverse tensile strain but further increase, resulted mainly

widening of cracks with few branch off cracks from existing cracks under high tensile strains. Therefore very slight increase in accumulated damage in concrete can be expected in this case. Hence the influence of transverse tensile strain will not proportionally degrade the material properties of reinforced concrete subjected to very high tensile strains. This explains the reason for having a certain limit of transverse tensile strain up to which significant influence of cracks on the behavior of concrete and beyond that the influence is almost the same.

3.2 Effect of strain rate on the behavior of concrete.

Many researchers[6,7] have studied the effect of testing speed on the behavior of concrete, but their main objective was to investigate the effect of varying strain rate or the loading speed upon the strength and elastic properties of concrete under monotonic compressive loading. The main purpose of this study is to investigate the influence of loading speed on the behavior of concrete under cyclic compressive loading to study the effect of strain rate on the progress of plasticity and cyclic response of concrete, mainly because this has a great influence in predicting response of concrete under reversed cyclic loading.

Fig. 6 and Fig. 7 show the influence of strain rate upon the strength of two types of concrete under monotonic compressive loading[8]. Type A and type B refer to high and low compressive strength concrete. As reported in previous studies, it can be seen a significant increase in the strength of concrete with increasing strain rate.
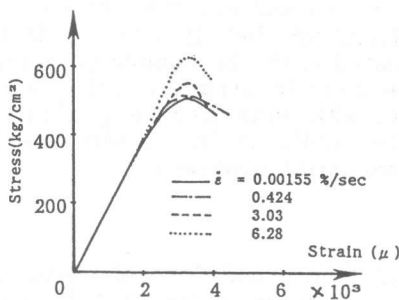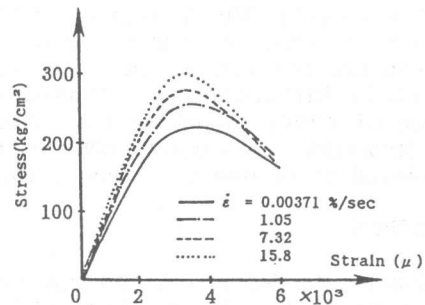

Fig.6 Stress strain relation
of concrete (Type A)

Fig.7 Stress strain relation
of concrete (Type B)

As it can be seen, the average modulus of elasticity has a general tendency to increase with strain rate. With varying strain rate under cyclic compressive loading, similar behavior is observed as seen in Fig. 8. For accurate predictions of cyclic response of reinforced concrete elements, stress - strain relationship of unloading path is also important in material modeling. It can be seen that these inner curves are almost linear when the strain rate is high. But under low strain rates, inner curves become more curved. Fig. 9 shows the plastic strain versus maximum compressive strain relation under different strain rates. The results indicate that the amount of plastic strain decreases as the strain rate increases. This means a part of the total plastic strain measured is a time dependent strain. From these results, it can be concluded that the progress of compressive plasticity is also greatly affected by the length of time involved in the load application as well as the tensile cracks existing in the direction parallel to compressive direction.
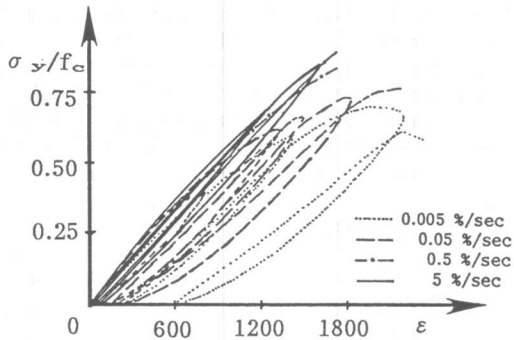
Fig.8 Stress strain curves for concrete
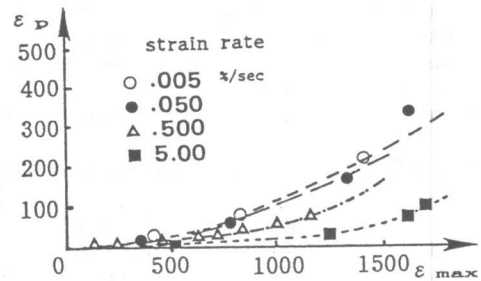under varied strain rates

Fig.9 Plastic strain vs. maximum
compressive strain

CONCLUSION

Cracked concrete subjected to tensile strains in the direction normal to compression direction is weaker in compression than uncracked concrete. The increase in accumulated damage in concrete due to applied tensile strain in the direction perpendicular to compressive direction can be attributed to the degradation of material properties of concrete between cracks. The compressive strength and stiffness of concrete are affected not only by transverse tensile strain but also by strain rate.

From the results, it can be concluded that the compressive plasticity is greatly influenced by transverse tensile strain due to increase in damage of concrete and strain rate. The increase in plastic strain corresponding to maximum compressive strain at low strain rates may be considered to be due to creep deformation of concrete.

REFERENCE

[1] Okamura,H., Maekawa,K. and Izumo,J.," Reinforced Concrete plate Element Subjected to Cyclic Loading, IABSE Colloquium, Delft 1987, Vol.54, IABSE, pp.575-590, 1987.
[2] Cervenka,V.,"Constitutive Model for Cracked Reinforced Concrete", ACI Journal, Proceedings No.82, pp.877-882, November-December, 1985.
[3] Vecchio, F.J. and Collins, M.P., "The Modified Compression Filed Theory for Reinforced Concrete Elements Subjected to Shear", ACI Journal, Proceedings Vol.83, pp.219-231, March-April 1986.
[4] Miyahara, T., Kawakami, K. and Maekawa, K., " Nonlinear Behavior of cracked Reinforced Concrete Plate Element Under Uniaxial Compression", Concrete library of JSCE, No.11, pp.131-144, June 1988.
[5] Kano, T., Gunatilaka, D. and Machida, A., " Behavior of Cracked Reinforced Concrete Under Cyclic Compressive Loading", Proc. of JSCE, pp.278-280, October 1989.
[6] Jones, P.G. and Richart, F.G., "The Effect of Testing Speed on Strength and Elastic Properties of concrete, Proc. of ASTM, Vol.36,pp.380-391, 1936.
[7] Watstein, D.,"Effect of Strain Rate on The Compressive Strength and Elastic Properties of Concrete",ACI, pp.729-744, April 1953.
[8] Mutsuyoshi, H., "Dynamic Properties of Reinforced Concrete Members", Doctoral thesis submitted to the University of Tokyo, 1984.