論文 Localization Effects and Fracture Mechanics of Concrete in Compression

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ABSTRACT: The distribution of vertical strain inside concrete specimens subjected to uniaxial compression has been measured to examine the failure mechanism and localization effects. From the tests, localization in uniaxial compression occurred when $H/D \geq 2$. By considering the parameters, such as height-depth ratio (H/D), cross-section size and shape of specimens, it has been found that, when the localization occurs, the fracture length depends only on the width of the cross-section. The fracture energy in compression, which is calculated based on the obtained complete load-deformation curve and the fracture volume, has found to be constant for the same properties of concrete.
KEYWORDS: fracture mechanics, localization effects, size effects, fracture energy in compression, compressive fracture length

1. INTRODUCTION

It is now generally accepted that tensile failure is localized to a limited zone. Many researchers have studied the localization behavior in tension and useful results had been obtained [1]. The localized behavior in tension is modeled by stress-crack width relationship based on the tensile fracture energy (G_F). A uniaxial description of the properties is sufficiently realistic, because no major lateral deformations take place.

On the other hand, material models for compressive failure of concrete are normally based on a uniaxial compressive stress-strain curve obtained from tests, where uniform deformation of the concrete specimens is assumed. This assumption is reasonable for the ascending branch of the stress-strain curve, but not necessarily accurate for the descending branch. As it was found that the deformation after the peak stress is localized to certain zones [2], so descending branch of the stress-strain curve becomes size dependent as the measured strain depends on the gage length and position of the gage. Anyway, though many studies were carried out [3] [4], the localization behavior and fracture zone of concrete in compression have not yet been clarified. The compressive failure is more complex than tensile failure, as it is always accompanied by significant lateral deformations. The lateral deformations are mainly caused by splitting cracks, which form and expand during the failure process. In addition to these cracks, localized shear bands may also form. Thus, the fracture process in compression is not only determined by localized cracks, as in tension, but in a realistic manner both the local and the continuum components of compressive softening have to be taken into account. It is necessary to study the behaviors of concrete under compression by considering also the localization of cracks and fracture energy of concrete in compression, in order to be able to analyze the post-peak behavior of concrete.

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In this paper, by considering the parameters of height-depth ratio, shape and size of specimen, the compressive fracture length and fracture energy in compression of concrete under uniaxial compressive stress have been determined based on the experimental results. The concretes having compressive strength ranged from 40 to 50 MPa with the maximum size of aggregate of 20 mm were used in the tests. In all tests, the high early strength cement was used.

2. EXPERIMENT

The experiment was conducted to examine the effects of the parameters such as height-depth ratio, size and shape of the specimens on the failure of specimens relating to compressive fracture length and compressive fracture energy. The details of the experimental program are listed in Table 1.

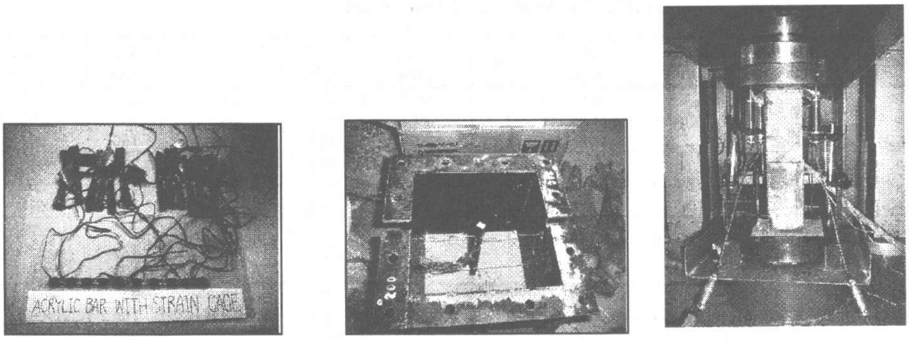
Table 1 Experimental program

Specimen	Cross-section mm×mm	Height mm	H/D	Designation
Prism	200×200	800	4	PS20-80
		400	2	PS20-40
		200	1	PS20-20
	200×100	800	4	PR20-80
		400	2	PR20-40
		200	1	PR20-20
	100×100	400	4	PS10-40
		200	2	PS10-20
		100	1	PS10-10
Cylinder	ϕ 200	800	4	C20-80
		400	2	C20-40
		200	1	C20-20
	ϕ 100	400	4	C10-40
		200	2	C10-20
		100	1	C10-10

**Average cylinder compressive strength at 7 days for all case is 45 MPa with the maximum size of aggregate 20 mm.*

All specimens were cast by using the same mix proportion of concrete with the average cylinder compressive strength of 45 MPa and the maximum size of aggregate 20 mm. The tops of specimens were capped by cement paste to ensure the smooth horizontal surface while loaded. Specimens were demolded after one day and were cured in water for 7 to 8 days before tested. The compressive strength tests of concrete cylinder ϕ 100×200 mm taken from the same batch of specimen were also conducted.

The technique of measuring strain inside concrete specimen by embedding acrylic resin square bar studied by Nakamura and Higai [3] was found effective and was used in this experiment. The acrylic resin square bar with cross-section of 10×10 mm, attached by strain gages was installed vertically at the position coincide with the specimen axis before casting of concrete. The strain gages were attached to the bar vertically to measure the longitudinal local strain at the interval of 40 mm (or 20 mm in case of 100 mm height specimen). The total average strain of specimen was measured externally by the use of deflection gages set between loading plates while specimen was loaded in the testing machine. The reduction of the friction between concrete specimen and loading platen interfaces was done by placing friction reducing pads set consists of two teflon sheets inserted by silicon grease. All the data were recorded through the data logger. The installation of strain gages and the test set up is illustrated in Figure 1.



(a) Acrylic bar with strain gages (b) Installation of acrylic bar (c) Loading set up

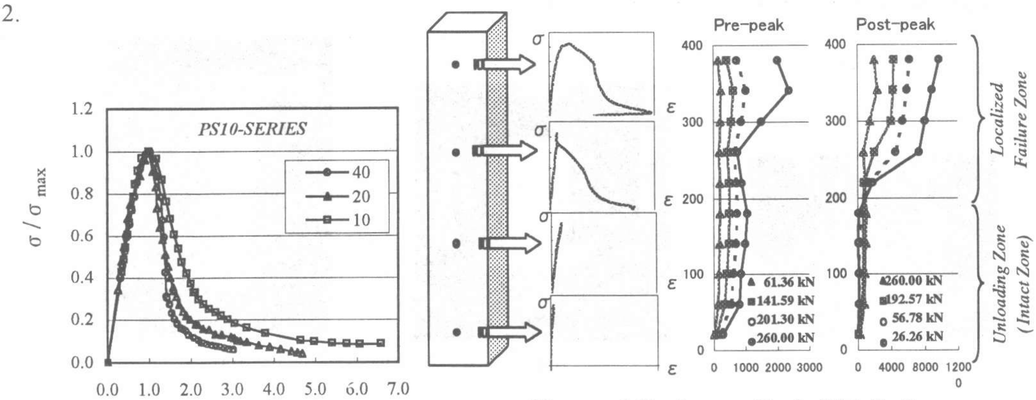
Figure 1 The installation of strain gages and the test set up

The post-peak load-deformation curves were captured by the one directional repeated loading in the stress descending range. The initiation and the propagation of cracks were also visually observed.

3. RESULTS AND CONSIDERATION

3.1 TEST RESULTS

After compiling all the test results, the load-deformation curves measured externally in dimensionless form, together with the distribution of the local vertical strain are plotted as an example shown in the Figure 2 for PS10-SERIES specimen. All test results are summarized as shown in Table 2.



Measured Strain **Strain Distribution (at different loading level)**

Figure 2 Typical results from the tests (PS10-SERIES)

As mentioned above, the attempt to reduce the friction between specimen and loading platens was done by using friction-reducing pads. The test results show that the ratios of the maximum stress of specimen to its compressive cylinder strength, σ_{max}/f_c', are almost constant with the average value of 0.71, when $H/D \geq 2$, which means the friction was effectively removed by the friction-reducing pads. In the case of $H/D = 1$, the average of σ_{max}/f_c' is 0.58. The reason why this low value is obtained is because specimens failed in splitting mode, which is explained in details in section 3.2.

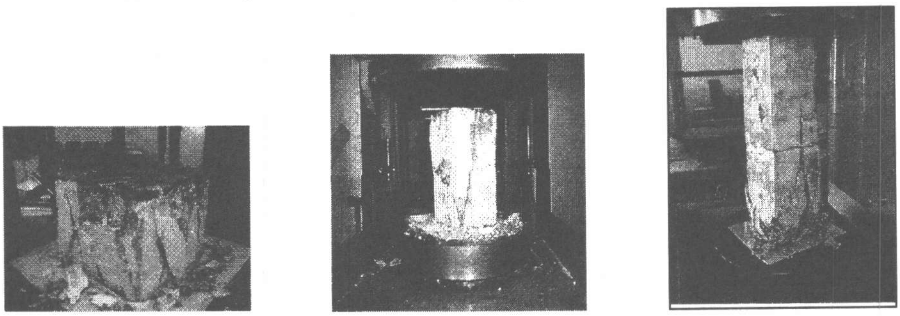
Table 2 Summary of test results

	Specimen	Section mm	A_C mm^2	H mm	H/D	σ_{max} MPa	f_c' MPa	σ_{max} / f_c' %	L_p, mm	A_{curve} kN-mm
PRISM	PS20-80	200×200	40,000	800	4	30.1	47.5	63.3	218	1,120
	PS20-40			400	2	29.7	43.5	68.3	253	1,533
	PS20-20			200	1	23.7	39.6	59.8	160	576
	PR20-80	200×100	20,000	800	4*	30.5	39.4	77.2	233	910
	PR20-40			400	2	35.7	43.5	82.1	240	563
	PR20-20			200	1	37.6	50.4	74.6	200	628
	PS10-40	100×100	10,000	400	4	30.5	46.7	65.4	175	226
	PS10-20			200	2	39.4	50.4	58.2	180	176
	PS10-10			100	1	25.7	47.3	54.3	100	193
CYLINDER	C20-80	ϕ 200	31,416	800	4	34.3	47.5	72.3	220	1,147
	C20-40			400	2	28.1	43.5	64.6	190	656
	C20-20			200	1	22.5	50.4	44.6	200	-**
	C10-40	ϕ 100	7,854	400	4	30.5	45.6	66.9	153	167
	C10-20			200	2	31.2	39.9	78.1	149	154
	C10-10			100	1	20.0	39.6	50.5	100	172

**For PR20-SERIES, D = 200 mm was used.*
*** Result not available.*

3.2 CRACKING PATTERN

From the observation of the occurrence of cracks on tested specimens, it can be seen that, for short specimen, H/D = 1, specimens were failed by the splitting from the top to the bottom of specimen and the observed value of compressive fracture length, L_p, are, almost all cases, equal to H. As for the longer specimen, H/D = 2 and 4, lots of small visual vertical cracks were observed over some regions when the peak was reached. At the final state, in the post peak region, i.e. $0.1P_{max}$, the small cracks were coalesced forming a large crack band. That means the localization occurred just in the case of H/D ≥ 2, hence the later sections discussing about L_p and G_{Fc} will refer to only the results of specimens having H/D ≥ 2. It can also be clearly seen from the cracking pattern of specimen at the final state shown in Figure 3.



H/D = 1 H/D = 2 H/D = 4

Figure 3 Cracking patterns of tested specimens (PS10-SERIES)

3.3 COMPRESSIVE FRACTURE LENGTH, L_p

It can be seen from the stress-strain curve of each gage embedded inside the same specimen, as shown in Figure 2, that the localization occurred in some part of the specimen. The failure occurred from the top of specimen down to approximately 180 mm, whereas the bottom part showed unloading behavior. Based on the local stress-strain curve obtained, the compressive fracture length of each specimen was determined and summarized as shown in Table 2. The effects of experimental parameters are discussed as the followings.

(1) Height-depth ratio

Figure 4 shows that, for the same cross-section specimens, the variation of H/D of specimen causes no change to L_p. In other words, the change in height of specimen has no effects on L_p.

(2) Size and shape of specimen

From Figure 4, it can be further observed that, regardless of the results of H/D = 1, when the specimen having the same D, the shapes of specimen, i.e. square, rectangular and circular, have small effect on L_p. Nevertheless the higher values of L_p are observed when the widths of specimens become larger.

(3) Formulation of L_p

It was found that the height of specimen and shape of specimen have virtually small effects on L_p, instead the width of specimen showing remarkable effect on L_p. By considering Figure 5 (a), almost constant value of L_p/D^* equal to 1.5 was obtained, where D^*, the equivalent width, is the square root of the area of the cross section.

Finally, the following relation can be proposed,

$$L_p = H \leq 1.5D^* \quad ; H/D < 2 \tag{1}$$
$$= 1.5\,D^* \quad ; H/D \geq 2 \tag{2}$$

or, as depicted in Figure 5 (b).

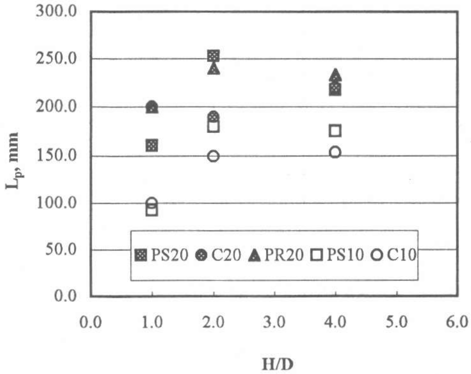


Figure 4 The variation of L_p with the H/D, size and shape of specimens

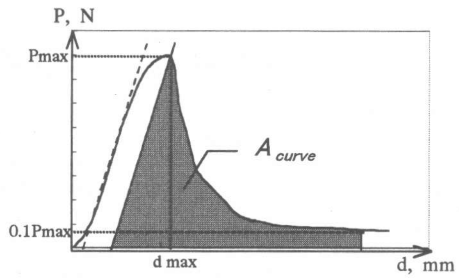
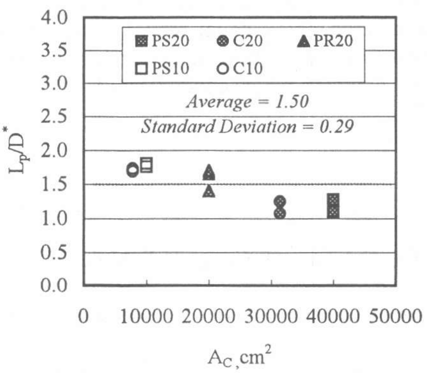
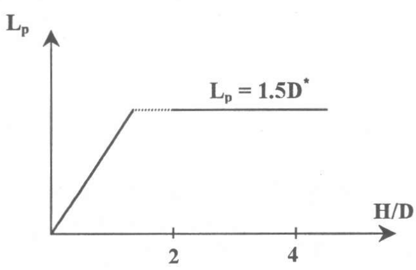


Figure 6 Area under load-deformation curve



(a) Experimental results



(b) Proposed formulation

Figure 5 Relation of L_p and equivalent width of the specimen

It should be noted that the proposed relation is obtained within the range of compressive strength 40-50 MPa, while the maximum size of aggregate is 20 mm.

3.4 FRACTURE ENERGY IN COMPRESSION, G_{Fc}

In this research, fracture energy in compression (G_{Fc}) is calculated by dividing the area under load-deformation curve up to $0.1P_{max}$, A_{curve}, by the fracture volume, V_p. The value of A_{curve} is illustrated in Figure 6. The fracture volume is calculated by L_p times cross-sectional area, A_C.

Considering Figure 7, it is found that, regardless of volume of specimen, V_c, the value of G_{Fc} divided by $f_c'^{2/3}$ are almost constant with the average value of 10.8×10^{-3} and the coefficient of variation of 14%. Therefore, when the localization in compression occurs, the following relation can be obtained,

$$G_{Fc} = 10.8\times10^{-3} f_c'^{2/3} \quad (3)$$

where, the unit of G_{Fc} is N/mm^2, and MPa for f_c'.

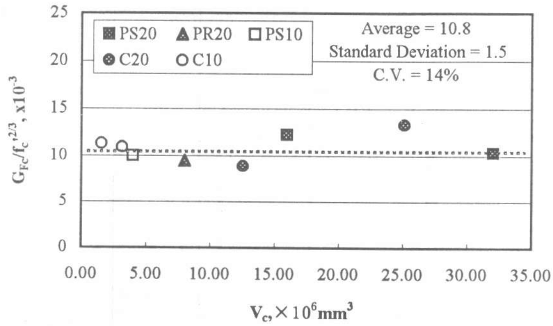


Figure 7 Relationship of $G_{Fc}/f_c'^{2/3}$ with concrete volume

4. CONCLUSIONS

The test results show that the localization in compression occurred when specimen of $H/D \geq 2$ was loaded under uniaxial compression. It can also be further observed that, in case of the localization occurred, the H/D, height and shape of specimen have no significant effects on L_p while the width of specimen is found to play an important role on L_p. The relation of L_p equal to 1.5 times of the equivalent section width is obtained. Furthermore, it is found that the fracture energy in compression is not depending on the size of specimen and found to be constant when concrete with the same property was used.

REFERENCES

1. Bažant, Z. P. and Oh, B. H., "Crack Band Theory for Fracture of Concrete," Materials and Structures, Vol.16, No.93, 1983, pp. 155-177.

2. Santiago, S. D. and Hilsdorf, H. K., "Fracture Mechanisms of Concrete under Compressive Loads," Cement and Concrete Research, Vol. 3, 1973, pp. 363-388.

3. Nakamura, H. and Higai, T., "Compressive Fracture Energy and Fracture Zone Length of Concrete," JCI-C51E Seminar on Post-Peak Behavior of RC Structures Subjected to Seismic Loads, Vol.2, Oct. 1999, pp. 259-272.

4. Markeset, G., "Failure of Concrete under Compressive Strain Gradients," Dr.Eng thesis 1993:110, Norwegian Institute of Technology, Trondheim, 1993.