Fracture Mechanics of Concrete and Concrete Structures -
Assessment, Durability, Monitoring and Retrofitting of Concrete Structures- B. H. Oh, et al. (eds)
 ISBN 978-89-5708-181-5

Effect of Fracture Behavior and Height-to-Diameter Ratio on High-Strength Concrete Core Specimens' Compressive Strength

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ABSTRACT: Compressive strength of cylindrical concrete specimen increases as the height-to-diameter ratio decreases. While this fact is dealt with through strength correction factors, as shown in ASTM C42 and JIS A 1107, these coefficients cannot be applied to high-strength concrete over 40MPa. Based on compressive strength tests, this study estimates the strength correction coefficients and examines the fracture behavior of high-strength concrete cores of compressive strength in the range of 30-100MPa. Concrete core specimens of 100mm diameter were cut into different lengths with respect to the following height-to-diameter ratios 1.0, 1.25, 1.5, 1.75 and 2.0. Strains along the horizontal and axial directions were measured during testing. The compressive strength, which is the maximum load divided by the cross section area, increased similarly to the coefficients shown in JIS A 1107. From the strain distribution along the horizontal direction, a restraining strain area was observed near both loading surfaces for all concrete strength grades during all loading stages until reaching maximum load. The critical stress, corresponds to when specimen's volume starts to increase, was 85% of the compressive strength for all concrete strengths and all height-to-diameter ratios. Compressive strength of concrete core specimens increases when height-to-diameter ratio decreases. It is effected by the critical volume change stress.

1 INTRODUCTION

To determine compressive strength of structural concrete, concrete core specimens are taken from structural members. Generally, compressive strength tests are carried out on core specimens of 100mm diameter and 200mm height. However, in some cases, when drilling core specimens are accidentally sawed short with low height-to-diameter ratios, resulting in high values of core concrete strength that do not reflect actual strength of structural concrete. Because of such inversely proportional relationship between the compressive strength of short cores and their height-to-diameter ratios, strength correction factors are recommended, as in ASTM C42[1)] and JIS A 1107[2)]. These correction factors are valid for cores of concrete strength below or equal to 40MPa and cannot be applied to cores of higher concrete strength. For cores of concrete strength above 70MPa, measured compressive strengths show that the correction factors may become larger[3)] than those listed on ASTM C42 and smaller[4)] than those listed on JIS A 1107.

Based on compressive strength tests, this study estimates the strength correction coefficients and examines the fracture behavior of high-strength concrete cores of compressive strength in the range of 30-100MPa. Concrete core specimens of 100mm diameter were cut into different lengths with respect to the following height-to-diameter (H/d) ratios 1.0, 1.25, 1.5, 1.75 and 2.0. Strains along the horizontal and axial directions were measured during testing to verify the fracture behavior under different height-to-diameter ratios.

2 MATERIALS AND METHODS

2.1 *Materials and Mix Proportions*

High-strength concretes of different mix proportions were prepared, as listed in Table 1. Ordinary Portland Cement conforming to JIS R 5210 was used for the strength grades of 30MPa, 45MPa, 60MPa and 80MPa. Moderate Heat Portland Cement conforming to JIS R 5210 was used for the strength grade of 100MPa. Sand and crushed stone were used for the aggregate of all concretes. Water reducing agent was used for the strength grade of 30MPa and super-plasticizer was used for the strength grades of 45MPa, 60MPa 80MPa and 100MPa. For the strength grades of 30MPa and 45MPa, water to cement ratio was decided aiming to reach the target strength at age of 28days. For the strength grades of 60MPa, 80MPa and 100MPa, water to cement ratio was decided aiming to reach the target strength at age of 56days.

Table 1. Mix proportions of concrete.

Strength grade	Water to Cement ratio (%)	Cement (kg/m^3)		Water (kg/m^3)	Sand (kg/m^3)	Coase Aggregate (kg/m^3)	Admixture	
							Water Reducing Agent	Super plasticizer
30MPa	61.0	292	OPC	178	880	940	2.92	—
45MPa	45.0	378	OPC	170	833	934	—	3.78
60MPa	37.5	453	OPC	170	780	926	—	4.67
80MPa	28.0	607	OPC	170	710	867	—	8.19
100MPa	27.0	630	MHPC	170	715	851	—	9.77

2.2 *Wall shape mock-up*

To prepare concrete core specimens of different height-to-diameter ratios, a wall shape mock-up was made for each strength grade. The mock up was 1,800mm long, 1,200mm high and 325mm wide. After placing concrete into plywood forms, they were at the age of 14days for the strength grades of 30MPa, 45MPa, 60MPa, and 80MPa, and 21days for the strength grade of 100MPa.

Concrete cores were drilled into mock-ups 1week before the compressive strength test. After drilling, concrete cores were sawed into lengths each of the following ratios H/d=1.0, 1.25, 1.5, 1.75 and 2.0 and grounded on both ends. Figure 1 shows the mock-up size and concrete core drilling locations. Figure 2 shows specimens' lengths from concrete cores.

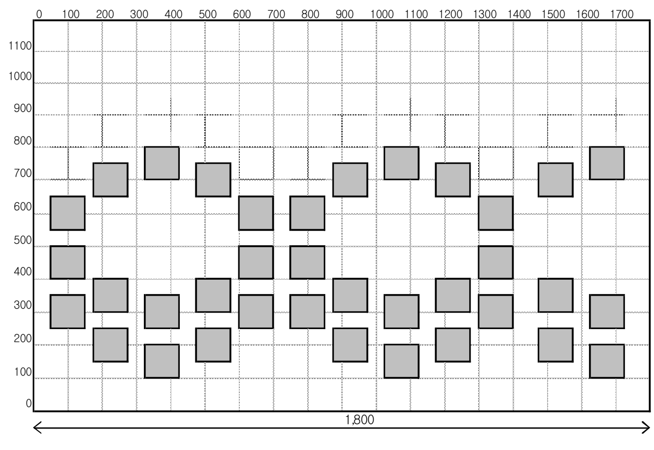

Figure 1 Wall shape mock-up size and core drilling locations

2.3 *Compressive Strength Test*

The compressive strength test was carried out conforming to JIS A 1108 at two testing centers A and B to compare their compressive strength results. At the testing center A 7 specimens were examined for all ratios H/d and all compressive strength grades, measuring only the compressive strength. At the testing center B 3 specimens were examined for each of the following ratios H/d=1.0, 1.5 and 2.0and for each of the following compressive strength grades 30MPa, 60MPa and 100MPa, measuring the compressive strength and strains along the horizontal and axial directions. At the testing center A specimens were kept into water until the test. At testing center B specimens were kept into the water until 2days before testing and after adhering strain gauge they were kept at room dry condition. The loading rate was kept at about $0.6N/mm^2/sec$ during the compressive strength test.

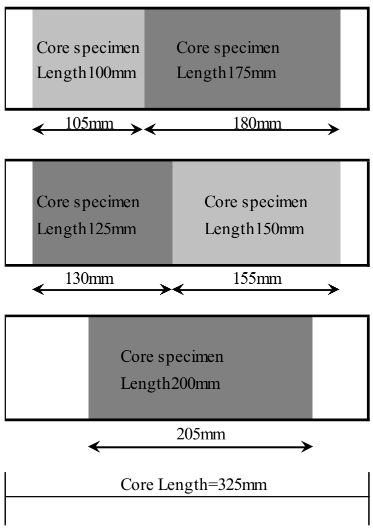

Figure 2 Concrete core length and specimen size

2.4 *Strain Measurement*

Axial direction strain was measured by strain gauges placed on two opposite sides of each specimen at its mid-height. Horizontal strain distribution was measured by strain gauges placed on two opposite sides of each specimen along its height as shown in Figure 3. Strain gauge length was 60mm for any strain measurement, and all strains were measured every 1second during testing.

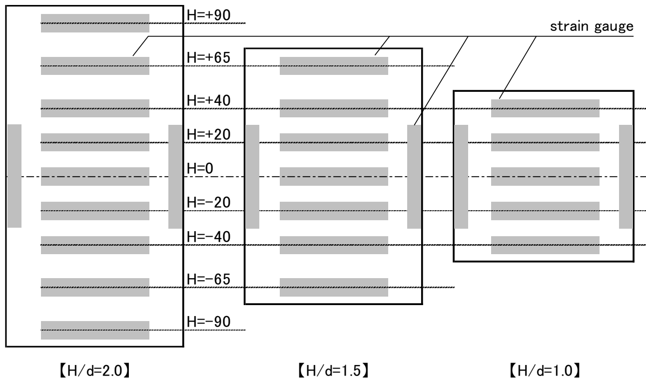

Figure 3 Strain gauge distribution layout

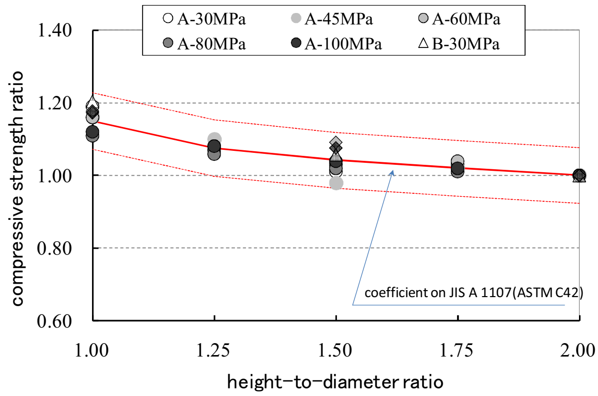

Figure 4 Compressive strength ratio respective to height-to-diameter ratio

3 RESULTS AND DISCUSSION

3.1 *Compressive strength*

Compressive strengths measured at the testing center A and B are listed in Table 2. For both testing centers, the compressive strength increased as the height-to-diameter ratio decreased at any strength grade. The compressive strength ratio, which is the ratio of the compressive strength of each specimen to the compressive strength at H/d=2.0 of the same strength grade, was calculated for each strength grade regarding each testing center and compared to the strength correction coefficients listed on JIS A 1107. Compressive strength ratios and strength correction coefficients listed on JIS A 1107 are shown in Table 2*. The compressive strength ratio respective to height-to-diameter ratio is shown in Figure 4. The compressive strength ratio increases as height-to-diameter ratio decreases, similarly to the correction coefficients on JIS A 1107 at any strength grade. From this experimental compressive strength test results, the compressive strength ratio of any strength grade up to 100MPa is within an error range with an accuracy of 95%. That means the strength correction coefficients listed on JIS A 1107(ASTM C42) are valid for high-strength concrete up to 100MPa.

3.2 *Horizontal direction strain distribution*

Horizontal direction strain distributions at 1/3 of maximum load, 2/3of maximum load, 80% of maximum load and 95% of maximum load are shown in Figure 5.

(1)Strain distribution at 1/3 of maximum load

At 1/3 of maximum load, specimens behaved elastically in general, horizontal direction strain distribution uniformly increased for strength grade 30MPa, and for grade 60MPa as well. For strength grade 100MPa, strains near the loading surfaces were smaller than that at the mid-height. This fact means that strain restraining occurred at loading surfaces with loading plates of the testing machine.

(2)Strain distribution at 2/3 of maximum load

At 2/3 of maximum load, horizontal direction strain distribution uniformly increased for the specimens of H/d=1.5 and 2.0, but strains near the loading surfaces were smaller than those at the mid-height in the case of H/d=1.0 for the strength grade 30MPa. For the strength grade 60MPa, strains near the loading surfaces were smaller than those at the mid-

Table 2. Result of Compressive strength and Compressive strength ratio.

*For the values in parentheses

	grade 30MPa		grade 45MPa		grade 60MPa		grade 80MPa		grade 100MPa		Coefficient on JIS A 1107
	center A	center B	center A	center B	center A	center B	center A	center B	center A	center B	
H/d=2.0	27.3	29.2	40.9	–	55.8	57.3	67.8	–	84.9	84.6	
	(1.00)	(1.00)	(1.00)	?	(1.00)	(1.00)	(1.00)	?	(1.00)	(1.00)	1.00
H/d=1.75	28.0	–	41.7	–	57.9	–	68.8	–	86.8	–	
	(1.03)	–	(1.02)	–	(1.04)	–	(1.01)	–	(1.02)	–	1.02
H/d=1.5	27.7	30.9	40.2	–	57.4	62.5	69.1	–	88.7	91.0	
	(1.01)	(1.06)	(0.98)	?	(1.03)	(1.09)	(1.02)	?	(1.04)	(1.08)	1.04
H/d=1.25	29.1	–	44.9	–	60.4	–	71.9	–	91.4	–	
	(1.07)	–	(1.10)	–	(1.08)	–	(1.06)	–	(1.08)	–	1.08
H/d=1.0	32.5	35.2	47.3	–	64.5	67.4	75.5	–	94.9	99.2	
	(1.19)	(1.20)	(1.16)	–	(1.16)	(1.18)	(1.11)	–	(1.12)	(1.17)	1.15

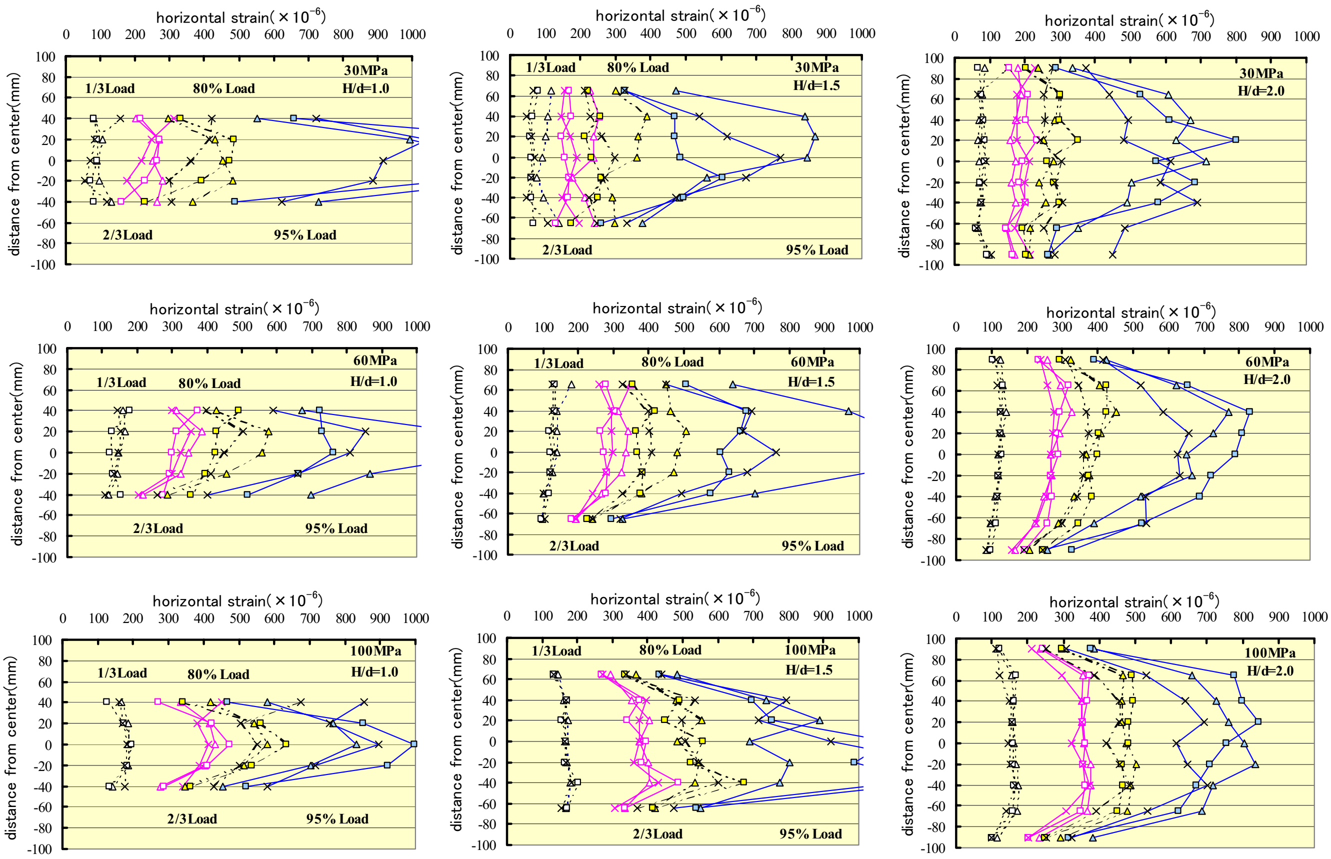

Figure 5. Horizontal direction strain distributions during testing

height. For the strength grade 100MPa, strains at the mid-height increased significantly than those of other parts.

(3)Strain distribution at 80% of maximum load

At 80% of maximum load, horizontal direction strains near the loading surfaces were smaller than those at the mid-height for all H/d ratios of the strength grade 30MPa. For the strength grade 60MPa and 100MPa, horizontal direction strains at the mid-height increased significantly than those of other parts.

(4)Stress when strain restraining occurs

From the horizontal direction strain distribution, strain restraining behavior near the loading surfaces occured at 2/3 to 80% of maximum load for the strength grade 30MPa, and the corresponding stress was about 25MPa. For the specimens of the strength grade 60MPa, strain restraining behavior near the loading surfaces occured at 2/3 of maximum load, and the corresponding stress was about 40MPa. For the specimens of the strength grade 100MPa, strain restraining behavior near the loading surfaces occured at 1/3 of maximum load, and the corresponding stress was about 30MPa. The phenomenon of strain restraining near the loading surfaces is caused by the friction between both loading surfaces of specimens and loading plates, and occurs at the stress range of 20-40MPa irrespective to the compressive strength grade.

3.3 *Critical volume change stress*

Using axial direction strain and horizontal direction strain, volume strain(ε_{vol}) of specimens can be calculated, as shown in Formula (1).

$$\varepsilon_{vol} = 2 \times \varepsilon_h + \varepsilon_v \qquad (1)$$

Where, ε_h: *Horizonal direction strain at mid−height*
ε_v: *Axial direction strain*

During compression testing, volume strain decreases at first, but when the stress exceeds a critical point, then the volume strain starts to increase. The critical point of stress is called critical volume change stress. From measured axial direction strains and horizontal direction strains at the mid-height, critical volume change stress was calculated for all specimens. Figure 6 shows the relationship between critical volume change stress and compressive strength. From Figure 6, critical volume change stress increases proportionally to the compressive strength. Critical volume change stress is approximately 0.848 of the compressive strength for any H/d of any strength grade. The phenomenon, which is the variation of the compressive strength of concrete core specimens related to the height-to-diameter ratio, is affected by the critical volume change stress.

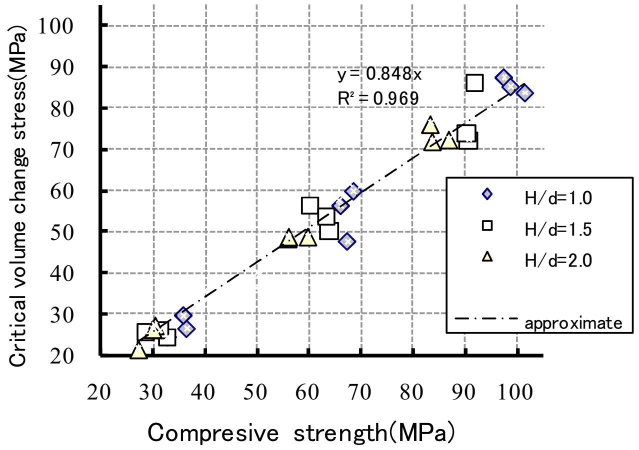

Figure 6. Critical volume change stress respective to Compressive strength

3.4 *Fracture of specimens*

Specimens' fracture is discussed in terms of horizontal strain ratio, which is the measured horizontal direction strain divided by the axial direction strain. Figure 7 shows the distribution of the horizontal strain ratio at 85% of maximum load (critical volume change stress) and 99% of maximum load.

(1)Strain restraining at loading surfaces

From all specimens, distributions of horizontal strain ratios near both loading surfaces of each specimen are constant despite the loading level being at 85% or 99% of maximum load. This fact means strain restraining at both ends of specimens remains until destruction at any ratio H/d and at any compressive strength grade.

(2)Strain ratio distribution for strength grade 30MPa

For the strength grade of 30MPa, at mid-height of the specimen, horizontal strain ratio relative to H/d=1.0 is larger than the one of H/d=1.5 and H/d=2.0 at 85% of maximum load. At 99% of maximum load, at mid-height of the specimen, horizontal strain ratio relative to H/d=1.0 is larger than the one of H/d=1.5 and H/d=2.0. The increment of horizontal strain ratio at specimens' mid-height within 85% to 99% of maximum load increases when H/d decreases. Thus, it is considered that stress of smaller H/d specimens increases as horizontal strain increases, because of the influence of strain restrain at loading surfaces.

(3) Strain ratio distribution for strength grade 60MPa

For the strength range at 60MPa, at the mid-height of specimens, the horizontal strain ratio is the same for all H/d at 85% of maximum load. At 99% of maximum load, at the mid-height of specimens, horizontal strain ratio does not much differ for H/d=1.0, H/d=1.5 and H/d=2.0. The increment of horizontal strain ratio at the mid-height of specimens within 85% to 99% of maximum load is also the same for H/d=1.2, H/d=1.5 and H/d=2.0. Thus, strain increment after critical volume change stress cannot be the reason of stress increase as H/d decreases.

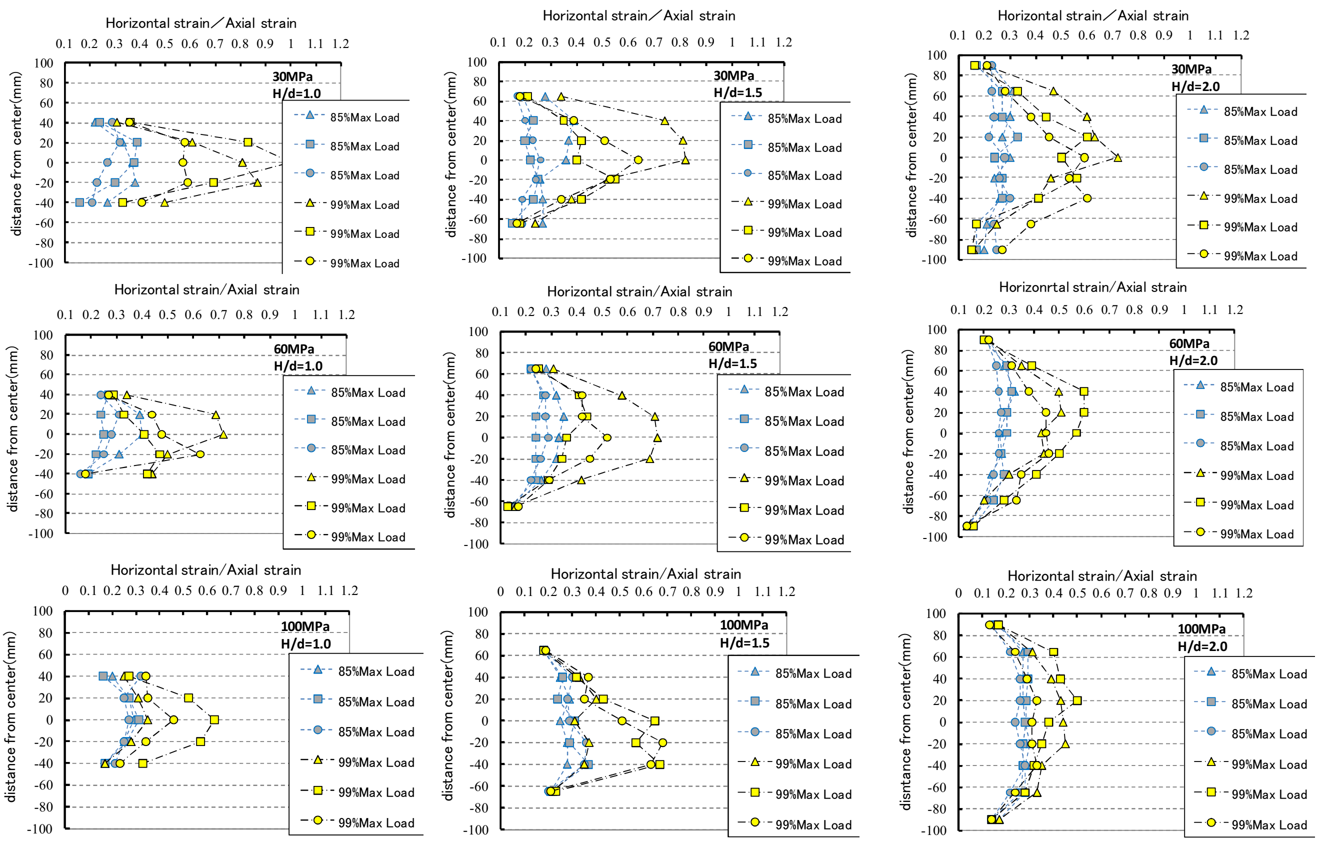

Figure 7 Distribution of the ratios of the horizontal strain divided by the axial strain

(4) Strain ratio distribution for strength grade 100MPa

For the strength grade of 100MPa, at the mid-height of specimens, horizontal strain ratio is the same for all H/d at 85% of maximum load. At 99% of maximum load, the horizontal strain ratios at the mid-height of 2 specimens of H/d=1.5 are larger those of other specimens of H/d=1.0, H/d=1.5 and H/d=2.0. Mid-height horizontal strain ratios within 85% to 99% of maximum load are almost the same for H/d=1.2, H/d=1.5 and H/d=2.0, except 2 specimens of H/d=1.5. Thus, strain increment after the critical volume change stress cannot be the reason of stress increase as H/d decreases. Because horizontal strain increases as much as axial strain increases at strength grade 100MPa, it is assumed that the fracture mode is different from the one relative to the strength grade 30MPa.

4 CONCLUSION

Based on compressive strength tests, this study estimates the strength correction coefficients and examines the fracture behavior of high-strength concrete cores of compressive strength in the range of 30-100MPa. Concrete core specimens were cut into different lengths with respect to the following height-to-diameter ratios 1.0, 1.25, 1.5, 1.75 and 2.0. Strains along the horizontal and axial directions were measured during testing. The following results are drawn.

1) Compressive strength ratio increases as height-to-diameter ratio decreases, similarly to the correction factors on JIS A 1107 from the strength grade 30MPa to 100MPa. Strength correction coefficients listed on JIS A 1107(ASTM C42) are valid for high-strength concrete up to 100MPa.
2) From the horizontal direction strain distribution, strain restraining behavior near the loading surfaces occurs at 2/3 to 80% of maximum load for the strength grade 30MPa, and at 2/3 of maximum load of the strength grade 60MPa, and at 1/3 of maximum load of the strength grade 100MPa. Strain restraining near the loading surfaces is caused by the friction between the loading surfaces of specimens and loading plates, and occurs at the stress level of 20 to 40MPa irrespective to the compressive strength grade.
3) Critical volume change stress is approximatly 0.85 of the compressive strength for all H/d and all strength grades. Compressive strength of concrete core specimens increases when height-to-diameter ratio decreases. It is effected by the critical volume change stress.
4) From the distribution of the horizontal strain ratio, strain restraining at the both ends of specimens remains until destruction for all H/d and all compressive strength grades.
5) It is considered that the stress of smaller H/d specimens can largely increase as horizontal strain increases, because of the influence of strain restrain at loading surface for the strength grade 30MPa. Strain increment after critical volume change stress cannot be the reason of the stress increase as H/d decreases at the strength grade 60MPa and 100MPa. It is assumed that the fracture mode is different from the one relative to the strength grade 30MPa, because horizontal strain increases as much as axial strain increases at the strength grade 100MPa.

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