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SEISMIC PERFORMANCE OF FULL SCALE REINFORCED CONCRETE COLUMNS CONTAINING COAL ASH

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SUMMARY

Two types of static loading tests using full scale concrete columns containing high volume coal sash were carried out in the laboratory.
The first one was the monotonic compressive loading tests of unreinforced full scale concrete columns to clarify the mechanical properties of concrete containing coal ash. In these tests, considered parameter was a mix property for concrete containing coal ash. Three types of mix properties, normal concrete, concrete containing coal ash as a replacement of fine aggregate, and high fluidity concrete containing coal ash as a partial replacement of cement were prepared.
The second one was the seismic loading tests of reinforced concrete columns which were designed as the flexural- shear failure type, subjected to lateral reversal loadings under the constant axial load, to clarify the seismic performance of those columns. In these test, considered parameter was specified design compressive strength of concrete while mix properties of concrete was common in all test specimens.
From results of full scale columns, it is anticipated that there is strong possibility of using concrete containing high volume coal ash for reinforced concrete building structures.

INTRODUCTION

The amount of industrial by-products, such as coal ash produced by coal-fired power plants, continues to increase with the demand for more electricity. It is said that total quantities of coal ash produced in Japan will be more than 10,000,000 tons in a couple of years (Japan Coal Ash Association : JCAA 1995)[1]. Utilization of coal ash is a very urgent objective. At present, approximately 60% of coal ash is utilized as cement material or admixture. The remainder is thrown away in landfill although they include good properties, corresponding to Japanese Industrial Standard (JIS) for fly ash. Utilization of the large quantity of coal ash to concrete manufacturing is not only effective in increasing the use percentage of the waste

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material, but also able to reduce the consumption of other natural material, such as aggregates that has been nearly depleted. In order to consume a large quantity of coal ash, the mechanical characteristics of concrete containing high volume coal ash have been investigate recently through the small size cylinder test(Malhotra 1993)[2], (Tanigawa 1995)[3]. It has been clarified that mechanical properties and durability of hardened concrete containing high volume coal ash were not so different from normal concrete without coal ash. The mechanical characteristics of reinforced concrete(RC) members containing high volume coal ash should be investigated in order to utilize to building structural members. It is necessary to investigate the seismic performance of RC members containing coal ash, because Japan is located in the most active seismic area in the world.

From the above point of view, authors have clarified the seismic performance of RC members containing high volume coal ash through the seismic loading tests using small scale RC beams and RC columns[4,5,6]. For the early realization of the utilization of coal ash to building structures, it is necessary to ensure the validity of the seismic performance using full scale model when concrete contained high volume coal ash.

Three full scale test specimens were prepared for the seismic loading tests while they were designed as flexural failure types.

MONOTONIC COMPRESSIVE LOADING TESTS

Test parameters

Coal ash used in this study consisted of both fly ash and cinder ash. Used coal ash in this study was produced in Misumi Coal-fired Power Plant located in Shimane Prefecture and Shin-Onoda Coal-fired Power Plant in Yamaguchi Prefecture, Japan. The physical properties of the coal ash from the both the coal-fired plants are shown in Table 1. Coal ash from Shin-Onoda Coal–fired Plant was used in the full scale RC columns described in the next section. The physical properties of coal ash were corresponded to 1 ~3 class of JIS for fly ash.

Table 1 Physical properties of used coal ash

Coal-fired Power Plant	Moisture (%)	Loss on ignition(%)	Density (g/cm^3)	Blaine (cm^2/g)
Misumi	Less than 0.1	2.3	2.16	2,840
Shin-Onoda	Less than 0.1	3.2	2.13	3,200

Considered parameters in this study were mix property for concrete containing coal ash and specified concrete strength. Four mix properties of concrete consisted of normal concrete(NC), containing coal ash as a partial replacement of fine aggregate(CA20, CA40), and high fluidity concrete containing coal ash as a partial replacement of cement(HF). The properties of CA20, CA40 and HF were selected as the most practical case, based on the preliminary mixing tests in the laboratory. The ratios of the coal ash as the replacement for fine aggregate were 20% and 40% for CA20, CA40, respectively, and the ratio of the coal ash as the replacement for total amount of cement and coal ash was about 50% for HF. Specified compressive strength of concrete at 28day, Fc, were $27N/mm^2$(MPa) and $36N/mm^2$(MPa). Number of the full scale concrete columns for Fc27 was five, including two normal concrete columns NC and number of the columns for Fc36 was four. In design for workability, the air content was 4.5% and slump was 18cm for NC and CA type, slump flow was 65cm for HF type. Summaries of mix properties for concrete in this paper are shown in Table 2. The maximum size of used coarse aggregate, that was crash stone, was 20mm. The fine aggregate was the mixture of pit sand and fine sand. Concrete were supplied by the local ready-mix concrete plants near the laboratory.

Compressive strength σ_B of concrete were obtained by compressive tests using $\phi \times h$=100mm×200mm cylinders. Those cylinders, which were placed in the air after casting, were demolded at the age 3 days. The demolded cylinders were exposed to the air in the laboratory where full scale concrete columns were placed. When the compressive strength of concrete reached to the specified strength, Fc, loading tests of the full scale concrete columns were carried out. The properties, tensile strength σ_t and Young's modulus Ec , were almost similar regardless of coal ash content in concrete.

Table 2 Summary of mix properties for concrete

Test column	Fc (N/mm^2)	W/C (%)	Unit(kg/m^3)				
			W	C	FA		CoA
					S	CA	
NC	36	43	187	435	748	0	921
CA20		50	180	360	591	121	1,022
CA40		55	180	330	475	247	1,016
HF		51	175	285	694	285	789
NC*	27	52	186	358	810	0	927
CA20		60	180	300	569	124	1,062
CA40		60	180	300	452	259	1,051
HF		70	175	250	697	300	791
FS27CA	27	56	180	320	600	124	1,023
FS36CA	36	45	180	400	577	124	983
FS36NC	36	41	180	439	725		947

Fc; specified concrete strength, W; water, C; cement, FA; fine aggregate, S; sand, CA; coal ash, CoA; coarse aggregate
* 3 test columns were performed
NC,CA20,CA40,HF for monotonic loading
FS27CA,FA36CA,FS36NC for seismic loading

Details of full scale concrete columns without reinforcing bars are shown in Fig. 1. The section of the concrete column was 800mm square and its length was 1,600mm. Length to depth ratio(2.0) of the columns was the same as that of the concrete cylinders. Concrete was cast into the metal form from the perpendicular direction to the column length.

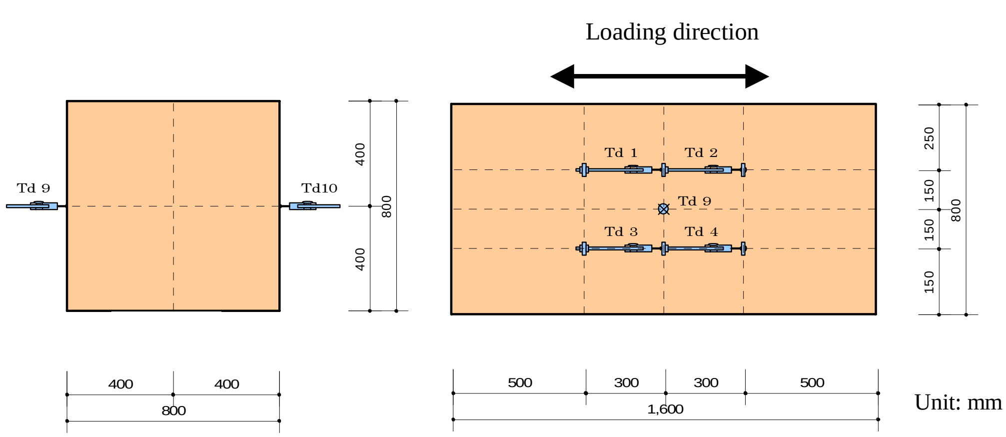


Fig.1 Details of full scale concrete columns

Loading procedure

The full scale concrete columns were subjected to compressive load monotonically up to the failure with the strong testing machine of Hiroshima University. The maximum compressive capacity of the testing machine was 30MN. Strain rate of loading was set as the same as that of cylinder tests. The test setup is

Fig.2 Test setup

shown schematically in Fig.2. While the columns were set in the testing machine laterally as shown in the figure, the gravity force acting in the perpendicular direction of the compressive load was ignored in this study because the weight of the concrete columns (approximately 2.5tonf) were relatively very low in comparison with the maximum compressive strength of the columns (over 1,500 tonf). Although the ignorance of the column weight may lead to somewhat conservative test results, the direct comparisons between the results for nine concrete columns can be made.

The electric strain gages were mounted on the surface of the concrete in both parallel and vertical directions of the loading to measure the elastic characteristics of the full scale concrete columns, Young's modulus Ec and Poisson Ratio ν. All columns were also instrumented with Linear Variable Displacement Transducers (LVDTs) to measure strains after cracking or near the maximum strength of the columns. The representative compressive strains of the concrete columns were obtained from an average of the strains measured by the strain gages or the LVDTs. The stresses of the concrete columns were obtained form the pressure gage of the strong testing machine. All instruments were connected to a computer through a data logger.

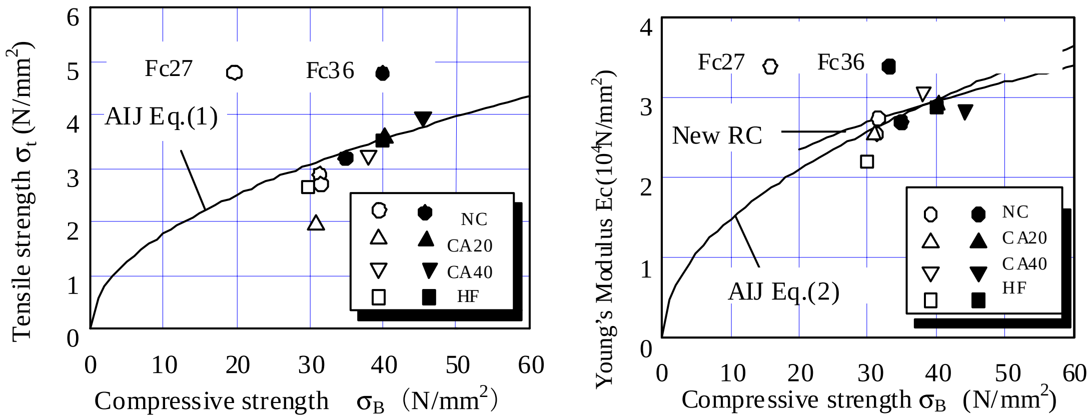
TEST RESULTS

Test results from cylinder tests

The relationships between the tensile strength σ_t ,Young's modulus Ec and the compressive stress σ_B at the age 28 day from cylinder tests are shown in Fig.3 (a) and (b). Young's Modulus Ec were calculated as the equivalent stiffness at the 1/3 compressive strength σ_B. The proposed equations and range in the RC standard[7] of the Architectural Institute of Japan(AIJ) are also inserted in theses Figures. The mechanical properties of the hardened concrete containing high volume coal ash can be estimated by using the existing equations for normal concrete.

$\sigma_t = 0.56\sigma_B^{0.5}$ (1)

$Ec = 21000(\sigma_B /20)^{0.5}$ (2)



(a) Tensile Strength (b) Young's Moludus

Fig.3 Mechanical properties of concrete

Test results from full scale loading tests

The comparison of the maximum strength σ_{MAX} of the full scale concrete columns and the compressive strength σ_B of the cylinders are shown in Fig.4. Average of the ratios of six coal ash concrete columns CA and HF is 0.86, although that of three normal concrete columns NC is 0.78. It is indicated that the size effect of coal ash concrete have less influence on the maximum stress than those of the normal concrete.

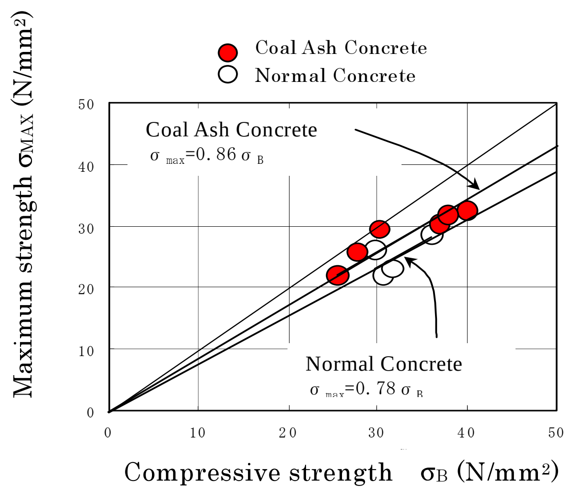


Fig.4-Maximum strength

According to the many researches for the size effect, the main reasons of the size effect are the difference of the materials, for example maximum size of the aggregate or grain distributions in the concrete between the small size specimens and the full scale specimens.

SEISMIC LOADING TESTS

Descriptions of specimens

Three full scale reinforced concrete (RC) columns have been assigned for seismic loadings under constant axial loads. Three full scale columns consisted of a column without coal ash FS36NC and two columns containing coal ash FS36CA and FS27CA. Mix property of concrete containing coal ash was chosen to be the same as that of CA type whose the ratio of the coal ash as the replacement for fine aggregate were 20% in Table 2. Specified strength of concrete, Fc, were 27N/mm^2 for FS27CA and 36N/mm^2 for FS36NC and FS36CA, respectively. RC columns had a clear height of 2,400mm with a cross section of 800mm×800mm. Each column had the heavily reinforced stubs at the top and bottom ends. Configurations of three RC columns were common. All columns were designed as the flexural failure type according to the RC standard[7] while the ratios of the flexural strength Q_{CM} to the shear strength Q_{CS} were approximately 1.2. All columns were reinforced with D25 longitudinal bars and the total longitudinal reinforcement ratios were 1.26%. FS27CA was reinforced with D16 transverse bars whose yield strength was 358 N/mm^2 and the transverse reinforcement ratio was 0.50%. FS36NC and FS36CA were reinforced with U10.7 transverse bars that were high strength reinforcing bars manufactured by Ulbon, whose yield strength were 1,497 N/mm^2 and the transverse reinforcement ratio was 0.30%. Those hoops and sub-ties were butt-welded at the manufacturer. Details of the full scale concrete columns are shown in Fig.5. Table 3 and Table 4 show the experimental parameters for three RC columns and the mechanical properties of used materials, respectively. In design for workability, the air content was 4.5% and slump was 18cm as same as the specimens for compressive test.

Table 3 Mechanical properties of concrete

Test column	Test Age(day)	σ_B (N/mm2)	σ_t (N/mm2)	Ec (N/mm2)	ν
FS27CA	36	27.1	2.5	2.10×10^4	0.177
FS36CA	33	33.3	2.8	2.40×10^4	0.169
FS36NC	28	43.6	3.3	3.03×10^4	0.170

σ_B; compressive strength σ_t; tensile strength Ec; Young's Modulus, ν;Poisson's Ratio

Table 4 Mechanical properties of steel

Test column	*FS27CA*	*FS36CA,FS36NC*
Longitudinal	16-D25 (σy=378N/mm^2)	16-D25 (σy=364N/mm^2)
Transverse	D16@100 (σy=358N/mm^2)	U10.7@150 (σy=1,497N/mm^2)

σy ; yield strength

Test setup and procedure

The seismic shear tests for the full scale RC columns were conducted using the large scale structural testing frame of the High-tech Research Center in Fukuyama University. The test setup is shown in Fig.6. The top and bottom RC stubs of the columns were post-tensioned to the L-shape loading beam and the strong steel base with the high tension bolts, whose tension force were 200kN per a bolt.

The lateral loading system displaced the full scale column in a double bending condition with the point of inflection occurring at its midheight. The shear span ratio was M/QD=1.5. The pantograph system was connected between the L-shape loading beam and the reaction frame to provide restraint against accidental rotation of the loading beam. All columns were subjected to simulated seismic loadings according to the predetermined drift angles, attempting two cycles for the each peak drift angle levels of R=0.0625%, 0.125%, 0.25%, 0.5%, 1% and 2% under the constant axial loads N. After the positive drift angle R=2%, lateral loads were increased monotonically up to the failure. Drift angle R is found from the dividing the lateral displacement δ of the top of the column by the clear height of the column. During the lateral loading under displacement control, the constant axial load was maintained automatically. Applied axial forces were 1.73MN (0.1Fc/bD) for FS27CA and 4.61MN (0.2Fc/bD) for FS36NC and FS36CA, respectively because the RC columns were designed for the low rise RC buildings. The computer controlled hydraulic jacks whose maximum capacities were 10MN and 5MN in the vertical and lateral directions respectively were used in the two directional loading system.

Measurement system

All RC columns were instrumented with the number of LVDTs to measure the lateral displacements to evaluate the flexural deformation modes and to measure curvatures of the hinging regions at the column ends. The electric strain gages were mounted on the surface of the longitudinal and transverse reinforcing bars. Both jacks for the vertical load and the lateral load were equipped with load cells at the load points.

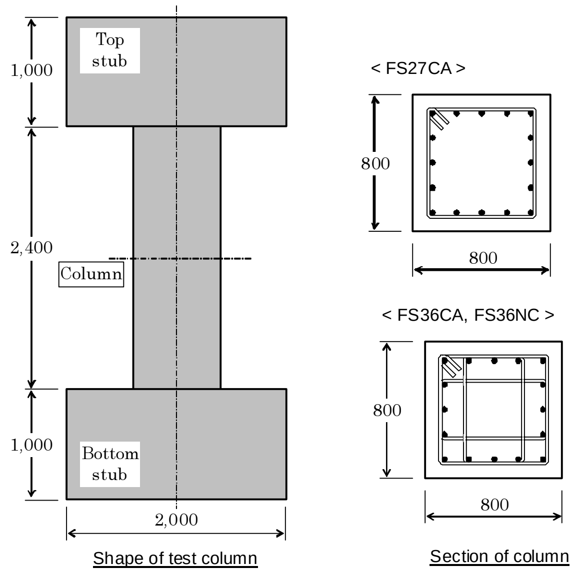


Fig.5 Details of the full scale concrete columns

Fig.6 Test setup

TEST RESULTS

Elastic characteristics

Prior to the lateral loadings, axial forces were applied to the columns through the L-shape beam to evaluate the elastic characteristics of the full scale RC columns. The relationships between Young's

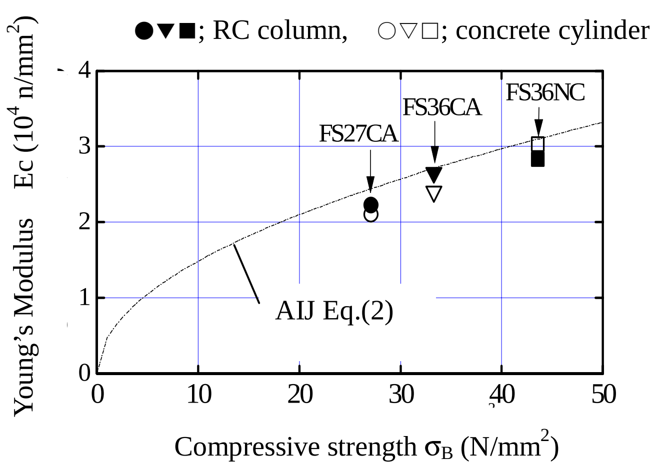


Fig.7 Young's Modulus Ec

modulus Ec obtained from the strains of the column surfaces before cracking and the compressive strength σ_B from cylinder tests at the test day are shown in Fig.7. In those figures, Ec from the cylinder tests and the proposed equation (1) from AIJ are also inserted.

Crack patterns

Crack patterns of the all columns at failure stages are shown in Fig.8. The flexural cracks started to be observed at the drift angle R=0.125% in the region close to the top and bottom ends of the columns. The shear crack started to occur on the way to the drift angle R=1%. And shear cracks penetrated through the column width at the drift angle 2% and width of these shear cracks became wide. Spalling of the cover concrete at the compression side were observed at the drift angle over R=2%.

Apparent plastic hinges were fully formed at the top and bottom ends of ***FS36CA*** and ***FS36NC***. The lengths of the hinging regions *lp* were approximately equal to the depth D of the column sections.

In ***FS27CA***, bond splitting cracks along the corner longitudinal bars and the buckling of the longitudinal reinforcing bars were observed in the hinging regions of the columns at the final stage. Subsequently, cover concrete spalled in wide range at the both ends of the column. The buckling of the longitudinal bars were not observed through the restrains of the high strength hoops and sub-ties to in ***FS36NC*** and ***FS36CA***.

FS27CA ***FS36CA*** ***FS36NC***

Fig.8 Crack patterns at the failure stages

Remarkable differences of the crack propagations and the crack patterns between ***FS36CA*** and ***FS36NC*** were not observed through the tests, regardless of the existence of coal ash contents. There was no influence of coal ash content on the crack patterns.

Shear force-drift angle hysteresis loops

Relationship between the normalized shear force Q/Q_{CM} and the drift angle R of the full scale RC columns are shown in Fig.9. Stiffness degradations of all columns started to degrade at the drift angle R=0.25% and the strength reached at the maximum strength at the drift angle R=0.5%.

The general shapes of shear force-drift angle hysteresis loops were the flexural types in the all columns. The hysteresis loops were stable until the drift angle R=2%. These phenomena indicate the excellent energy absorption capacity. The slight pinching behaviors due to the influence of the high level of shear force were observed in ***FS36CA*** and ***FS36NC***. No strength degradations due to the reversal loading at the same drift angle were observed in ***FS36NC*** and ***FS36CA***, but, slight strength degradations due to the Pdelta effects of the axial loads were observed after the maximum strength. In ***FS27CA***, strength of degraded largely due to the bond deteriorations and the buckling of the longitudinal bars after drift angle R=2%. Neither the rapid strength decay nor the rapid stiffness degradation was observed through the tests of all columns until the drift angle R=2%. In all columns axial loads were maintained even when drift angles R became quite large over 5%.

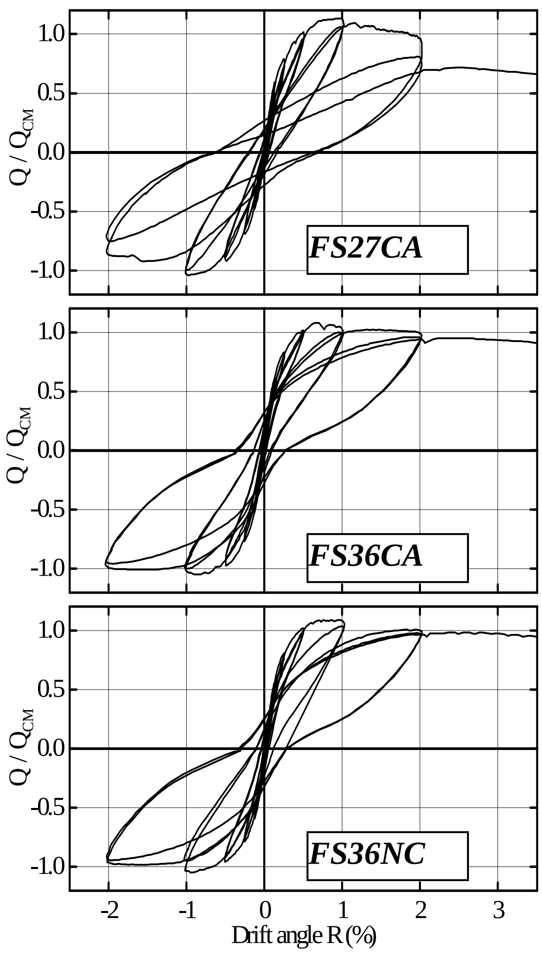


Fig. 9 Lateral hysteresis loops

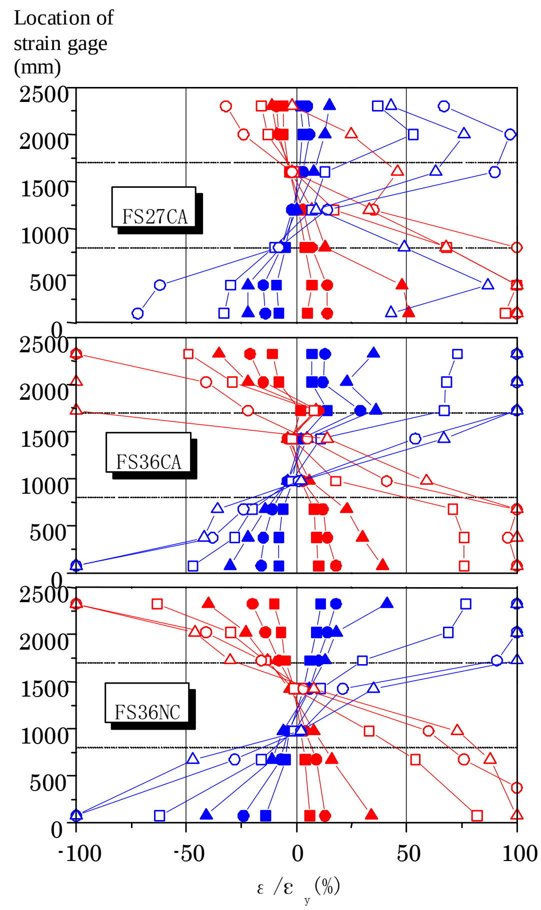


Fig.10 Strains in longitudinal reinforcements

Strains in reinforcements

Measured strains normalized by the yield strain from tensile tests of longitudinal reinforcements at the peak of the drift angle are shown in Fig.10. Yielding of the reinforcing bars occurred in the region approximately equal to the depth D of the column sections on the way to the drift angle R=1% in all columns. Yielding did not occur in transverse reinforcements in ***FS36CA*** and ***FS36NC*** even when drift angle R=2% because the strength of transverse reinforcement were more than 1400N/mm^2. In ***FS27CA*** yielding in the transverse reinforcement occurred at the drift angle R=2% due to the propagations of the diagonal cracks in the central region of the column.

Comparison between calculated and observed maximum strength

Comparisons between the measured maximum strength and the calculated ultimate strength of the full scale RC columns are shown in Table 6. Calculated results for the ultimate flexural strength and the ultimate shear strength were obtained by using Equations shown in footnote in Table 6, respectively. There are good agreements between test results and calculated strengths in each column. Difference of concrete strength σ_B between ***FS36NC*** and ***FS36CA*** did not have a large influence on the calculated strength while the characteristics of tensile reinforcing bars dominated the behavior of the flexural members. From the same reason size effects on the maximum strength were not observed in all columns.

Table 6 Measured and calculated maximum lateral strength

Test column	Test results Q_{Exp} (kN)	Calculated results Q_{CM} (kN)	Q_{CS} (kN)	Test / Cal. Q_{Exp} / Q_{CM}	Q_{Exp} / Q_{CS}
FS27CA	1,375	1,216	1,337	1.13	1.03
FS36CA	1,997	1,851	1,939	1.08	1.03
FS36NC	2,083	1,917	2,091	1.09	1.00

Ultimate flexural strength; $Q_{CM} = M_U / h$ .... (1)

$$M_U = 0.8\, a_t\, \sigma_Y\, D + 0.5\, N\, D\, [1 - N / (bD\sigma_B)]$$

Ultimate shear strength (lower limit); $Q_{CS} = (\tau_U + 0.1\,\sigma_0)\, b\, j$ .... (2)

$$\tau_U = \frac{0.092 k_U k_P (180 + \sigma_B)}{(M/Qd) + 0.12} + 2.7\sqrt{p_W\, \sigma_{WY}} \qquad \sigma_0 = N / bD$$

a_t; *area of tensile reinforcing bar,* b, D, j; *width, depth and lever arm of section,* h; *height of lateral loading point,* k_U, k_P; *coefficients related to section,* M/Qd; *shear span ratio,* N; *axial load,* p_W; *ratio of hoop,* σ_B; *compressive strength of concrete,* σ_{WY}; *yield strength of hoop,* σ_Y; *yield strength of longitudinal reinforcing bar*

It is confirmed that those equations for normal concrete are applicable to estimate the ultimate flexural strength and the ultimate shear strength for RC members containing high volume coal ash.

CONCLUSIONS

Two type of loading tests of full scale columns containing high volume coal ash were performed. From test results it was indicated that,

Compressive tests for concrete columns

1) Elastic characteristics of the full scale concrete columns are approximately the same as those of the cylinders.

2) Size effects have less influence on the maximum stress of coal ash concrete than those of the normal concrete.

Seismic tests for reinforced concrete columns

1) Elastic characteristics of RC columns can be estimated by the existing equations regardless of the existence of coal ash contents.

2) Remarkable differences of the crack propagations and the crack patterns were not observed regardless of the existence of coal ash contents.

3) The equations of the ultimate flexural strength and shear strength for normal concrete were applicable to RC columns containing high volume coal ash.

It is anticipated that there is strong possibility of utilizing concrete containing high volume coal ash for building structural members.

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