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FLEXURAL PERFORMANCE OF HIGH STRENGTH LWA CONCRETE COLUMNS

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ABSTRACT. To investigate the structural performance of reinforced concrete columns using light–weight concrete with high compressive strength (about 35MPa), an anti–symmetrical loading test and a compression test were carried out. In the first test, three columns, the parameters of which are the concrete type (light–weight or normal concrete) and the amount of hoops, were loaded cyclically under a constant axial stress. All columns failed by concrete compression at the hinge zone. The maximum strength of light–weight concrete columns is about 10% lower than that obtained for normal concrete. A remarkable decrease in the load of light–weight concrete columns can be observed at large displacement. In the second test, eighteen specimens were tested. Each specimen is designed to be a portion of a column. Test parameters are the similar to the first test. An increment in the compression strength of light–weight concrete caused by hoops is about 50% of that obtained for normal concrete. From the second test results, a stress versus strain model for light–weight concrete is designed and section analysis is carried out. The analytical moment – curvature curves almost fit with the observed curves. The ratio of the maximum moment of light–weight concrete to that of normal concrete is 0.91.

Keywords: High–strength light–weight concrete, Flexural performance, Bending strength, Deformation capacity, Confinement, Axial stress.

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INTRODUCTION

Reinforced concrete (RC) structure has often been used for highrise housing apartments because of its efficiency against the motion caused by ordinary wind and for its fire resistance. It is considered that the number of highrise RC buildings will increase more and more in the future. However, RC structure has a demerit on its own big weight. As buildings become taller, cross sections of members become larger and amount of reinforcements also increases. These factors cause a decrease of useful space, also the worsening of construction site conditions. The use of high-strength and/or light-weight concrete may represent one of the solution for these problems. Nowadays, constructions of highrise buildings using high compressive strength concrete (40–50MPa class) have been more popular in Japan. Light-weight concrete is also watched with special interest.

The first story columns of highrise buildings are requested to have a good deformation capacity and to stand high axial force. It is very important also for light-weight concrete columns to confirm its bending strength and deformation capacity. Because frame type structures are usually designed as strong columns and weak beams, these performances should be clear, even if light-weight concrete is not used at the first story columns.

To investigate the structural performance of light-weight concrete columns, an experiment consisting of two series was carried out. One is an antisymmetrical loading test of columns and the other is a compression test for specimens designed to be a portion of a column. In this paper, the experimental test results are herein reported as well as the results from the section analysis based on the compression test results.

ANTISYMMETRICAL LOADING TEST OF COLUMNS

Test Outline

Three columns were tested. Details of the specimens are listed in Table 1 and the typical specimen is shown in Fig. 1. The cross section of the columns is 250mm width (b) and 250mm depth (D), designed at one third scale of actual size columns. Clear span length (L) is 1000mm. The test parameters are concrete type (light-weight or normal concrete) and the percentage of hoops (p_w = 0.78 or 1.20%). Artificial light-weight aggregate is used as coarse aggregate of light-weight concrete. Weight per unit of volume of light-weight concrete and that of normal concrete at the age of 27 days is 1.96 and 2.27, respectively. The measured compressive strength (σ_B) of both concrete is 39.2MPa.

Table 1 Specimens and materials (Antisymmetrical loading test)

Specimen Name	Concrete Type	Compressive Strength σ_B (MPa)	Axial Force N (kN)	$\eta_0 = N/bD\sigma_B$ for all section	for core section	Hoops Bar Size	p_w (%)	Yield Stress (MPa)
D0781L	Light-weight	39.2	775	0.316	0.461	2-D6@33	0.78	288
D1201L	Light-weight	39.2	775	0.316	0.435	2-D8@33	1.20	353
D0782N	Normal	39.2	775	0.316	0.461	2-D6@33	0.78	288

Main bars: 8-D13 (Yield stress σ_y = 359MPa), Area of tension side bars: a_t = 3.81cm^2

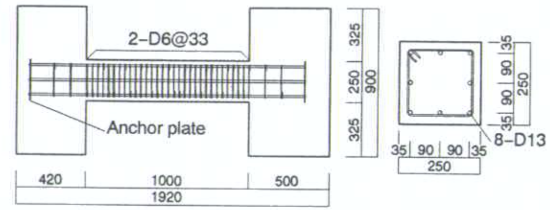

Fig. 1 Column Specimen (D0781L)

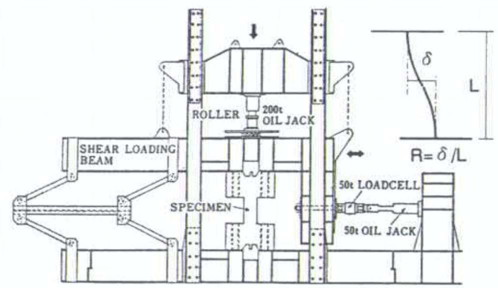

Fig. 2 Antisymmetrical loading system

The specimens were loaded cyclically under a constant axial force (N = 775kN) using the antisymmetrical loading system as shown in Fig. 2. The ratio of axial stress to concrete compressive strength (η_0) is 0.316 for all cross section. The loading was carried out by controlling translational angle (R) that is defined as shown in Fig. 2. The loading history to be applied to all specimens is R = ±1/200, ±1/100, ±1/50, ±1/33 radians twice and ±1/20 radians once. The loading was finished when specimens could not stand axial force. The loads, the relative displacement between the upper and the lower stub and the flexural deformation along a range of 250mm (equal to D) from the ends of columns were measured.

Test Results and Discussions

Failure pattern

Final crack patterns and shear force (Q) versus translational angle (R) curves of each specimen are shown in Fig. 3. The failure progresses until the maximum loads were almost the same among three specimens. First, bending cracks took place at the ends of specimens and they expanded as the displacement became larger. Yielding of main bars were observed at the loading cycle of R = ±1/100 radians. Then the maximum loads were recognized between R = 1/140 ~ 1/100 radians. After that, each specimen showed different failure progresses.

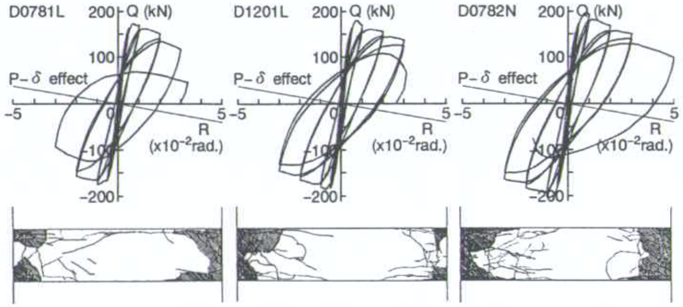

Fig. 3 Final crack patterns and shear force – translational angle curves

Cover concrete of specimen D0781L fell at the loading cycle of R = −1/33. The specimen D0781L could not stand axial force at the second cycle of R = +1/33. Though a remarkable load reduction of specimen D1201L was not recognized until the loading cycle of R = ±1/33, a large portion of cover concrete fell at the loading cycle of R = +1/20 and then specimen D1201L failed. On the other hand, the load reduction of specimen D0782N was not recognized until the loading cycle of R = +1/20. Finally every specimen had a concrete compressive failure at the ends of specimens.

Bending strength and deformation of light-weight concrete columns

Main results obtained from this test are summarized in Table 2. Observed maximum strengths of light-weight concrete columns are about 10% lower than that obtained for normal concrete column. Though the ratio of observed strength to calculated one (see the footnote of Table 2) is 1.10 for normal concrete column, that ratio is 0.96 ~ 1.01 for light-weight concrete columns. Ultimate displacements (defined as shown in Table 2) of light-weight concrete columns are smaller than that obtained for normal concrete.

Table 2 Main results (Antisymmetrical loading test)

Specimen Name	Maximum Strength (kN)		Ultimate	Failure Mode
	Observed	Observed/Calculated*1	Disp.*2(mm)	
D0781L	180.2	0.96	32.1	Concrete compression
D1201L	188.5	1.01	31.4	Concrete compression
D0782N	206.7	1.10	49.9	Concrete compression

*1: Calculated strength $Q = (0.8\, a_t \sigma_y D + 0.5\, N\, D\, (1 - \eta_0)) / (L/2)$
where, a_t: area of tension side bars, σ_y: yield stress of main bar, D: depth of column, N: axial force, η_0: axial force ratio (=$N/bD\sigma_B$), L: clear span length
*2: Observed displacement when the peak load becomes 80% of the maximum load

COMPRESSION TEST

Test Outline

Eighteen specimens were tested. The typical specimen is shown in Fig. 4. The size of cross section is 210 × 210mm or 219 × 219mm, designed to be a core section of column. They do not have main bars and cover concrete to investigate stress versus strain relationship of core concrete. Test zone of the specimens is 250mm central portion (the length is equal to D). The test parameters are concrete type and the percentage of hoops (p_w = 0.00 ~ 1.38% for 250 × 250mm cross section of the columns tested at the previous section). Light-weight concrete, that was used in the previous section, and normal concrete were cast. The measured compressive strength (σ_B) of light-weight concrete and that of normal concrete is 30.9MPa and 31.8MPa, respectively. The relation of these parameters to specimen names is also shown in Fig. 4.

The specimens, p_w of which is 0.30 or 0.78%, were subjected to repeated compressive loading by controlling axial strain (ε). The loading history is ε=0.2, 0.4, 0.8, 1.6, 2.4% twice, 4.0, 8.0% once. Other specimens were loaded monotonically. Compressive load, axial deformation at four parts shown in Fig. 4, and strains of hoops were measured.

Test Results and Discussions

The axial stress (σ) versus axial strain (ε) curves are shown in Fig. 5. The envelope curves of the specimens subjected to repeated loading are also shown in this figure.

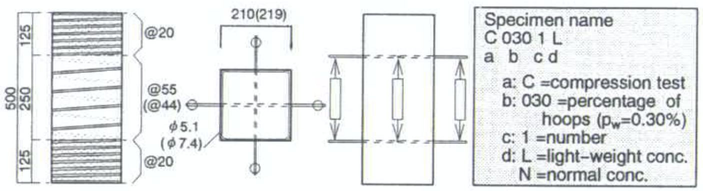

Fig. 4 Specimen for compression test (C0301L, (C0781L))

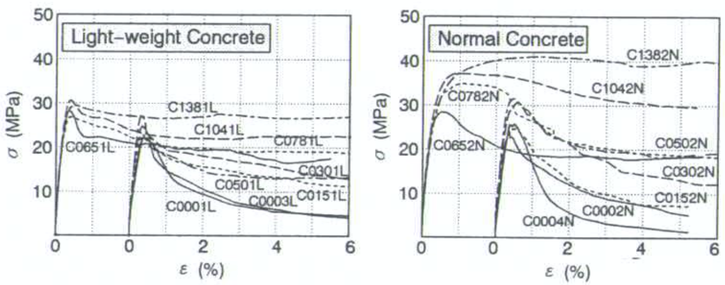

Fig. 5 Axial stress – strain curves

First, vertical cracks were observed at the axial strain of 0.2 ~ 0.3%. Then the load reached the maximum value and surface concrete fell as the axial strain became larger. The failure progresses of light-weight concrete specimens were not different from that of normal concrete specimens. In addition, the curve shape tendency of the specimens subjected to repeated loading is almost the same between light-weight and normal concrete specimens. However, the observed maximum axial stresses of light-weight concrete specimens are much different from those obtained for normal concrete specimens as shown in Fig. 5.

Fig. 6 shows the correlation between the obtained axial strength (σ_m) and the percentage of hoops (p_w). The axial strength is normalized by using concrete compressive strength (σ_B). The difference of the axial strength is observed between light-weight and normal concrete specimens. Lines in this figure are drawn by the least square method. The increment ratio on the strength for light-weight concrete specimens caused by hoops is about 50% of that obtained for normal concrete. Measured strains of hoops when the load reached the maximum value are shown in Fig. 7. The figure shows the difference of confinement effect between light-weight and normal concrete. This deterioration could be explained as light-weight aggregate itself breaks when the specimen becomes the ultimate state.

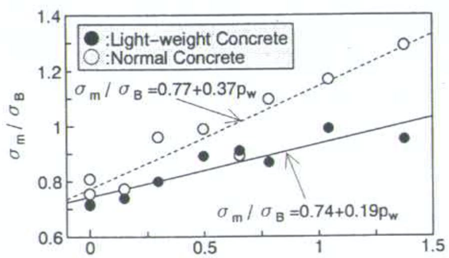

Fig. 6 Correlation between axial strength and p_w

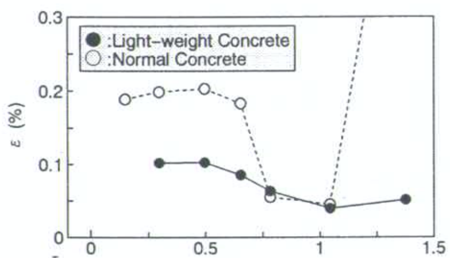

Fig. 7 Measured strain of hoops

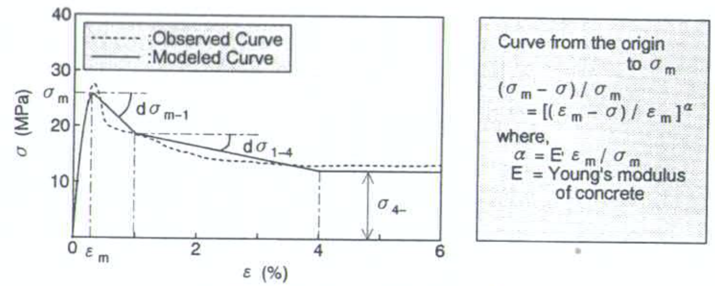

Fig. 8 Stress – strain curve model

The observed stress – strain curves are modeled into four parts as shown in Fig. 8, in order to adopt the curves for section analysis. The first part is the curve from the origin to the axial strength (σ_m). This curve is calculated using the formula [1] as shown in Fig. 8. In the other parts, the observed curve is approximated by three straight lines as shown in Fig. 8. Correlation between $d\sigma_{m-1} / \sigma_m$, σ_{4-} / σ_m and p_w are appreciated similarly as carried out in Fig. 6. No large differences between light-weight and normal concrete can be observed. Therefore, it is supposed that the stress – strain curve can be fixed only by the axial strength in spite of different concrete types.

CORRELATION BETWEEN ANTISYMMETRICAL LOADING TEST AND COMPRESSION TEST

Section Analysis

Section analysis based on the assumption that the plane section remains plain is carried out using stress – strain curves obtained from the compression test results. The adopted hysteretic model [2] for core concrete is shown in Fig. 9. The curve modeled in the previous section is used as a skeleton curve. The straight line, that is drawn from the axial strength point to the point of 2.0% strain and 0MPa stress, is adopted for the skeleton curve of cover concrete, depending on the compression test results for specimens without hoops (Fig. 5). The Ramberg–Osgood model is chosen to represent the hysteretic behavior of main bars.

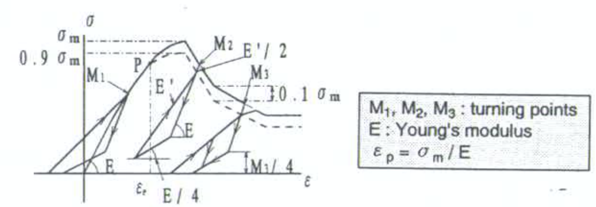

Fig. 9 Hysteretic model of concrete

Fig. 10 shows in the lower line the moment (M) – curvature (ϕ) curves obtained from section analysis, and in the upper line the $M_{ave.}$ – $\phi_{ave.}$ curves observed in the antisymmetrical loading test. $M_{ave.}$ and $\phi_{ave.}$ are the averaged values observed from a range of 250mm at the ends of columns. A good correlation is appreciated between the observed and analytical curves. Black circles on the analytical curves show the point when the strain of cover concrete at the all column surface exceeds 2.0%. It is supposed that the actual cover concrete falls at this point in the antisymmetrical loading test. Both, the remarkable moment reduction points, and the points indicated by the black circles, are located on the same loading cycle curves. Therefore, these analytical points become one of the indexes that express the deformation capacity of columns.

Analytical axial strains (ε_0) are shown in Fig. 11, comparing with the observed ones. The axial strain is the averaged value at the all cross section. Black circles on the analytical curves show the same point as shown in Fig. 10. Though the observed axial strain becomes larger at the last loading cycle, the analytical curves show a good correlation with the observed curves.

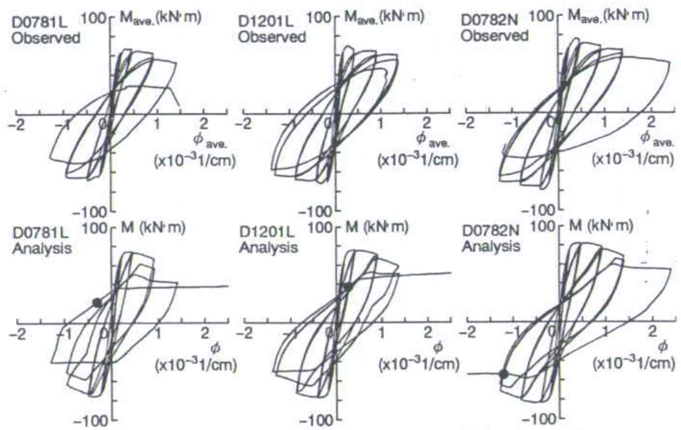

Fig. 10 Analytical moment – curvature curves and the observed curves

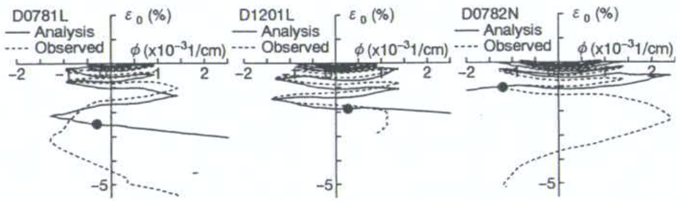

Fig. 11 Analytical axial strain – curvature curves

Table 3 Comparison of the maximum moment

Specimen Name	Observed Value (kN·m)		Analytical Value (kN·m)		Observed / Analytical	
	+	−	+	−	+	−
D0781L	+66.8,	−68.1	+74.9,	−75.1	+0.89,	−0.91
D1201L	+69.8,	−71.6	+76.3,	−76.7	+0.92,	−0.93
D0782N	+76.1,	−78.9	+82.7,	−82.9	+0.92,	−0.95

Bending Strength of Light-weight Concrete Columns

The observed maximum moment for the antisymmetrical loading test and analytical maximum moment in the section analysis are shown in Table 3. While the observed moments are a little smaller than the analytical moments, a difference of the maximum moment between light-weight and normal concrete can be recognized. The observed maximum moment ratio of light-weight concrete to normal concrete column is 0.87, and the analytical ratio is 0.91 in case of specimens D0781L and D0782N with same hoops ratio (p_w=0.78%).

The maximum moment difference between light-weight and normal concrete columns can be recognized using the section analysis that is described in the previous section. Therefore, the same analysis for several axial forces is performed. Correlation between the axial force (N) and the analytical maximum moment (M) is shown in Fig. 12. The moment ratio of light-weight to normal concrete column is 96% in case of axial stress ratio ($\eta_0 = N / bD\sigma_B$) of 0.20. Similarly, the ratio is 91% and 85% in case of η_0 of 0.33 and 0.50, respectively. However, these ratios are obtained from the analysis performed for the specimen with p_w of 0.78%. It is assumed that the ratios become smaller for the specimen with larger hoops ratio, according to the compression test results.

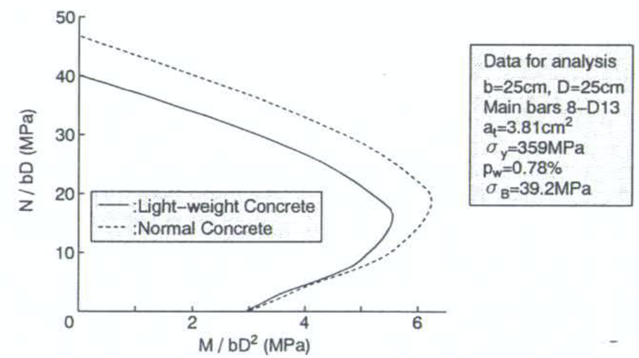

Fig. 12 Axial force versus maximum moment relationship

CONCLUSIONS

1. The bending strength of light–weight concrete columns is about 10% lower than that of normal concrete. The ultimate displacement of light–weight concrete columns is also smaller than normal concrete.

2. The increment of compressive strength ratio for light–weight concrete specimens caused by hoops is about 50% of that for normal concrete. This could be explained as light–weight aggregate itself breaks when the specimen becomes the ultimate state.

3. According to the modeling results of the stress – strain curves for light–weight concrete, it is supposed that the curves can be fixed only by the axial strength in spite of different concrete types.

4. The analytical moment – curvature curves is almost fit with the observed curves. The analytical point when the cover concrete becomes unable to stand the applied stress can be one of the indexes that express the deformation capacity of columns.

5. The analytical maximum moment of light–weight concrete columns is 0.91 of that of normal concrete columns in case of axial stress ratio of 0.33.

ACKNOWLEDGEMENT

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ECOLOGICAL AND ECONOMICAL LWA CONCRETE

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ABSTRACT. In the Laboratory of Technological Mechanics of Concrete of RTU a number of new lighweight concretes are elaborated. There are ligno-concretes made on the basis of the massorganic pollutants of the environment coming out from the cellulose, cardboard and paper industries. They are gas concretes and gas-gypsum with low water/binder ratio made by use the dynamic (vibration, shock) methods of technology. There are foam concretes containing light weight aggregates. Rheological basis of technological processing of all lightweight concretes recorded above are elaborated and main characteristics of their building properties are presented.

Keywords: Ligno-concretes, gas-concretes, foam-concretes, aerated-gypsum, lightweight aggregates, rheology.

Georg Kunnos, Dr.habil.ing., prof., Head of the Lab., published more than 190 sc. papers (including 5 books); 25 authorship certificates. Rheology, its technological applications, concretes.

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Andrey Terentyev, Dr. sci. ing. (Ph.D.), leading researcher, published more than 50 sc.papers; 9 authorship certificates. Mechanics of continua, theoretical and experimental rheology and rheometry, technology of gas-concretes and foam-concretes.

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