CRACK RATIO AND SPALL OFF RATIO OF REINFORCED CONCRETE COLUMNS

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The cantilever-type full scale reinforced concrete column test specimens were tested to failure under static reversals in uniaxial and biaxial loadings. The axial load value is about 25% of the 28-day concrete strength. The shear span ratio is 2.2. The equivalent crack area ratios and spall off area ratios are calculated from cracks and spall off diagrams. The behavior of cracking and spalling under the biaxial loadings could simulate well actual earthquake damage features of frame-type buildings in the past earthquakes. According to the crack-spall damage index, if the equivalent crack area ratio is 2 - 2.5% and the equivalent spall off area ratio is 10 - 30 %, the maximum experienced displacement ductility should be around 3.

INTRODUCTION

The earthquake resistant design of reinforced concrete buildings is based on permitting certain degree of damage to structural elements, when they are subjected to severe earthquake excitations. So it becomes necessary to estimate the degree of structural damage in reinforced concrete structures so as to evaluate their post earthquake serviceability. Various damage indices, such as damage ratio (1), flexural damage ratio and dissipated energy (2), slope ratio (3), energy dissipation index (4), etc., have been proposed. Application of these indices is not practical, because they require the use of hysteresis loops recorded during earthquakes. As buildings are not equipped to record load displacement time histories, visual inspection may be the only practical way to evaluate the state of the structural damage. The primary data from visual inspection comprise the information on concrete cracks and spalling. In this paper, relationships between the displacement ductility and the information on cracks and spall off area are examined on the basis of test results.

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TEST SPECIMEN AND TESTING PROCEDURE

Cantilever-type column specimens, shown in Figs. 1 and 2 are used for both the uniaxial and the biaxial lateral loadings. Specimens are approximately full scale models, considered to be representative of the first story interior columns in typical three to five storied buildings in Japan. Table 1 shows the loading paths, the loading displacement ductility steps, strengths of reinforcement and concrete, and the axial load for each test specimen. The lateral load is applied at a height of 1100 mm from the footing block for both the uniaxial and the biaxial loading cases.

The pump for the lateral loading is controlled manually. The applied load is adjusted to follow approximately the prescribed displacement paths. The yielding displacement of the column is defined as the displacement just after the tensile yielding of the longitudinal reinforcement. At the yielding displacement, the displacement ductility is equal to 1.

INSTRUMENTATION AND MEASUREMENT

The axial loads, lateral loads, deflections, rotations and strains are converted into electrical signals by transducers. During each cycle, the loading is temporarily stopped while the output signals are automatically scanned and stored in a computer floppy disk. In addition, signals from displacement and load transducers are displayed by digital volt meters, and recorded in analog form in a X-Y recorder for monitoring to the manual loading.

The displacement at the top of the column is measured at two points each near the corner, to reduce the effect of possible horizontal rotation. Cracks developed during loading are marked with a pencil, so that crack patterns can be followed easily. At the loading stage at which the residual displacement becomes zero, crack patterns and outlines of concrete spall off area are traced with a fiber tip pen on a transparent thin plastics sheet of 500 mm width. Cracks and outlines of the concrete spall off area are divided into small linear segments at adequate intervals by manual operation. Vector data of these linear segments are obtained by a tablet digitizer and stored in a computer floppy disk.

After setting a computer display, which had 640 x 475 pixels on the screen, to 500 pixels representing the column width of 500 mm, crack patterns are drawn with blue lines on the computer display, using vector data of cracks. If concrete spalling data exists, outlines of the spall off area are drawn with red lines on the same display. In order to delete crack patterns, which are included in the spall off area, the inside of the spall off area are painted red. The equivalent crack area is obtained by counting the numbers of blue pixels on the display. The equivalent spall off area is obtained by counting the numbers of red pixels.

TEST RESULTS

Damage In uniaxial loading test, horizontal flexural cracks are mainly observed on loading surfaces and diagonal cracks are mainly observed on non-loading surfaces as shown in Fig. 3(a). In biaxial loading test, horizontal flexural cracks are observed on all surfaces up to the yielding displacement load cycles, as shown in Fig. 3(b). In uniaxial loading test, spalling occurs mainly in the corner parts of the non-loading surface, and in full column width of the loading surfaces. In biaxial loading test, spalling occurs in almost the full column width in both directions. Spalling of concrete cover starts from displacement ductility of 5 in uniaxial loading, compared to that of 3 in biaxial loading.

As the ductility increases to 1, mainly horizontal cracks develop together with a few diagonal cracks. At this ductility, the cracks are seen up to a height of less than one column width. The cracks continue to increase and expand as the displacement increases up to a ductility of 3. Beyond this ductility, the rate of development of new cracks slows down, the some existing cracks are seen to widen further, and shallow concrete spalling begins. At ductility of 5, concrete cover spalling occurs over wide area on all surfaces, and the reinforcement is uncovered. Some of the reinforcements buckle slightly between transverse reinforcements. At ductility of 7, the core concrete, confined with crossties and transverse reinforcement, disintegrates seriously. This leads to opening of end hooks (135 or 180 deg.) of crossties and transverse reinforcement, so that the concrete core is no longer confined.

Hysteresis loops. The yield displacement is defined as the displacement at which the tensile strain of the longitudinal reinforcement reaches around 0.2%, which is a little larger than the initial yield strain. Both in the uniaxial and the biaxial loading tests, the yielding displacement occurs at the top displacement to length ratio of 1/200.

Hysteresis loops under uniaxial loadings are very stable up to very high ductility of the order of 10. After the ultimate load at around ductility of 3, hysteresis loops show very slight strength degradation up to very high ductility. The hysteresis loops of specimen BC-3, subjected to the cross loading paths along the NS and EW axes alternatively, are drawn independently on the NS and EW planes. Specimen BC-6 was subjected to the circular loading paths, so the hysteresis loops are drawn as projected charts on the NS and EW planes. Hysteresis loops under biaxial loading reach the ultimate load at around ductility of 2. After the ultimate, hysteresis loops show rapid strength degradation.

Equivalent crack and spall off area ratios. Equivalent crack area is calculated on the square area of one column width side at the bottom of the column (500 x 500 mm), under the assumption that all cracks have a width of 1 mm. Equivalent crack area ratio is given by the equivalent crack area as a percentage of the whole targeted square area. Fig. 4 shows the relationships between equivalent crack area ratios and ductilities of both LC-type and BC-type specimens. For the BC-type specimens, the crack ratio is seen to increases with ductility up to a value of 3. After that, crack ratios decreases rapidly due to the effect of spalling.

Equivalent spall off area is also calculated on the same area of the column as the crack ratio case. Equivalent spall off area ratio is defined as percentage ratio of the equivalent spall off area to the whole targeted square area. Fig. 5 shows the relationships between equivalent spall off area ratio and displacement ductilities of both LC- and BC-type specimens. The spall off area ratio increases with the increase in ductility.

CONCLUSIONS

1) The biaxial loading gives more serious damage to the concrete columns than the uniaxial loading. The behavior of cracking and spalling of columns under biaxial loading could simulate well the actual earthquake damage features of columns of ordinary reinforced concrete frame-type buildings observed in the past strong earthquakes. The model of the restoring force characteristics and damage index should be based on the biaxial loading test results

2) According to the crack-spall damage index discussed in this study, the following observations can be made:

(1) If the equivalent crack area ratio is less than 1 % and the highest crack height is less than one column width, the maximum experienced displacement ductility should be less than 1.

(2) If the equivalent crack area ratio is from 2 to 2.5% and the equivalent spall off area ratio is from 10 to 30 %, the maximum ductility should be around 3.

(3) If the equivalent spall off area ratio is from 30 to 85 % and/or reinforcing bars are uncovered due to the spalling of concrete cover, the maximum ductility should be around 5.

(4) If the equivalent spall off area ratio is more than 50 % and/or transverse bars become loose and longitudinal bars buckle, the maximum ductility should be more than 5.

REFERENCES

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Table 1 Loading paths, loading steps, strengths of reinforcement and concrete, and axial loads for each test specimen

μ : Displacement Ductility Factor

Spec.	Loading Program		Longitudinal		Transverse		Concrete	Axial Load
	Path	Steps (μ)	σy (kg/cm²)	σu (kg/cm²)	σy (kg/cm²)	σu (kg/cm²)	$_{28}F_c$ (kg/cm²)	(ton) (Ratio)
LC - 1		0.5-1-2-3-4-5-7-14	4000	5820	4020	5760	227	75.9(0.13)
LC - 2		0.5-1-2-3-5-7-10×2						76.7(0.14)
LC - 3		1-2×5-3×5-5×5-7×2						75.9(0.13)
LC - 4		0.5-1-2-3-5-7-10-14						74.9(0.13)
LC - 5								130.2(0.23)
LC - 10		1-2-3-5-7-10-14	3546	5467	3923	5676	246	155.2(0.25)
LC - 11								155.8(0.25)
LC - 12		0.5-1-2-3-5-7-10-14						156.3(0.25)
LC - 13		14	3647	5621	3892	5507	229	146.7(0.26)
LC - 14								76.0(0.13)
BC - 1		1-3-5-10 (N.S-E.W)	3717	5331	3845	5662	251	154.2(0.25)
BC - 2		0.5-1-3-5-7						157.0(0.25)
BC - 3		0.5-1-3-5-7 (N.S-E.W)	3647	5552	3474	5150	274	171.3(0.25)
BC - 4		10 (N.S-E.W)						173.1(0.25)
BC - 5		0.5-1-3-5 (NE.SW-NW.SE)						171.8(0.25)
BC - 6		0.5-1-3-5						171.7(0.25)

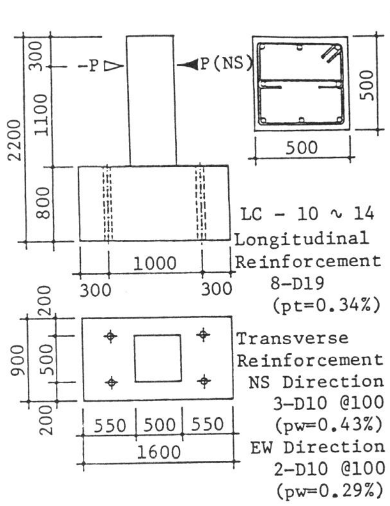

Figure 1 Uniaxial loading test specimen (LC-type)

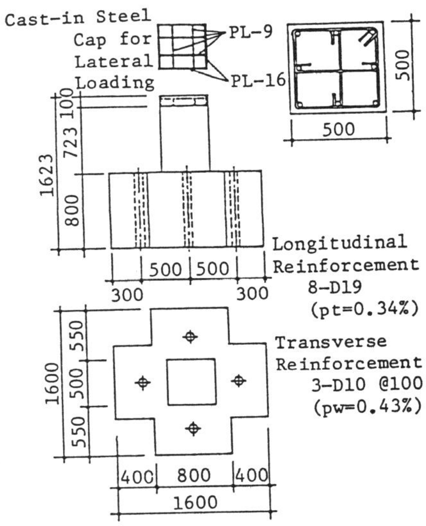

Figure 2 Biaxial loading test specimen (BC-type)

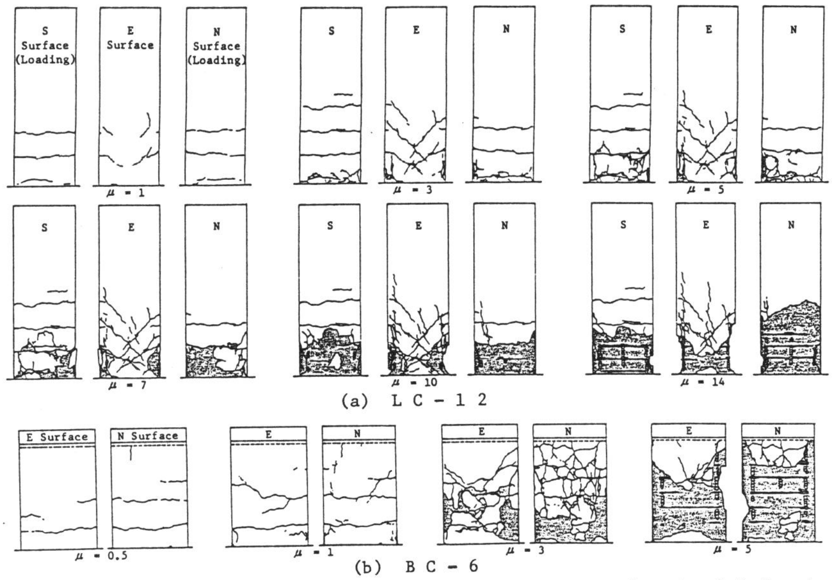

Figure 3 Crack patterns and spall off diagrams of uniaxial loading and biaxial loading

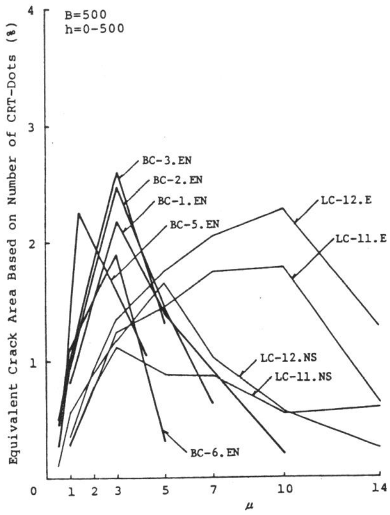

Figure 4 Equivalent crack area ratio and ductility

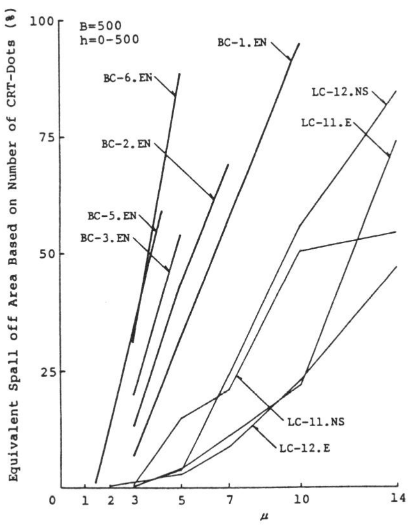

Figure 5 Equivalent spall off area ratio and ductility