# 論文 EFFECT OF NUMBER OF CYCLES ON DAMAGE PROGRESS FOR LARGE SCALE RC COLUMNS UNDER MULTIAXIAL LOADINGS

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### ABSTRACT

To assess the main parameters affecting the damage progress four large-scale specimens with a 560x560 mm section were tested. Number of cycles had little effect on the envelope curves of lateral load - displacement relation up to failure but had some effect on post-peak behavior under large axial force. Analytical results such as moment-curvature and column shortening-curvature relations, obtained using a simple fiber model, matched well the experimental results. Park and Ang's damage index was computed using IDARC, a non-linear frame program and the computed indices predicted the observed damage with a good accuracy.

Keywords: Cyclic loading, Reinforced concrete column, Fiber model, Plastic hinge, Damage index.

# 1. INTRODUCTION

Damage to reinforced concrete columns was and still an important topic for many researchers [1] and [2]. Although numerous promising damage indices have been formulated [3], relatively a few attempts have been made to calibrate them against the observed damage either earthquake laboratory from or tests. Understanding the parameters controlling the damage progress during an earthquake is an important issue to be solved. Sixteen cantilever reinforced concrete columns, constituted of eight large-scale and eight small-scale specimens were tested to investigate failure modes, scale effect as well as the damage progress. Only the last four large-scale specimens from our testing program will be presented in this paper and the results of the other specimens can be found in Refs. [4] and [5]. The behavior of the plastic hinge region was predicted using a fiber model where the confinement effect is taken into account. Progress of concrete damage in a plastic hinge zone was postulated from the strain distribution of external and internal hoops. Using the nonlinear IDARC program [6], the damage progress was assessed using Park at al damage index [7]. Finally, a new damage index is proposed using the cyclic and monotonic curves.

### 2. EXPERIMENTAL PROGRAM

# **2.1. TEST SETUP**

The testing specimens were constituted of four large scales 560x560 mm cross section reinforced concrete columns with 1200mm as a shear span. The specimens were loaded under different axial intensity and horizontal loading path. Figure 1 shows the specimen configuration as well as the loading apparatus. The axial load was kept constant for specimen L1N6B and L2N6B, and was varied for the last two specimens, L2NVB and L2NVC, as a linear combination of the sum of the moments as shown in Figure 2. In order to assess the effect of number of cycles on the bearing capacity the last two specimens were loaded with 2 and 4 cycles for each of the following prescribed rotation angle respectively, 0.25-0.5-0.75-1-2-3-4 and 5%. The loading history is shown in Figure 3 (a) and (b) and the column top movement is shown on the left side of Figure 2. Sixty displacement gauges were provided at the lower part of the specimen to monitor the shear and flexural deformations. Figure 3 (c) shows the placement of these displacement gauges and the shear rebar with strain gauges position, layers. The material characteristics and test variables for this experiment are summarized in Table 1.

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Figure 1: Specimens configuration and loading system



Figure 2: Top view of the loading path and the axial load variation

**Table 1: Test variables** 

	Material			Test variables		
					Slope in	
Specimen	Concrete	Longitudinal	Shear	Axial force	moment-	Lateral
designation	strength	rebar (ratio)	rebar	(axial force	axial force	loading
	f'c (Mpa)	[Fy]	(ratio) [Fy]	level in f'cD <sup>2</sup> )	relation	directions
					(MN/MN.m)	
L1N6B	32.2	12-D25 1.94% 388MPa	D13@100 0.91% 524MPa	Constant (0.6)	0	Uni
L2N6B						Bi
L2NVB				Varied (0-0.6)	6	
L2NVC						

# 2.2. EXPERIMENTAL RESULTS

Since the shear failure was avoided during the design, all four specimens showed a ductile behavior until the test end. As seen in Figure 4, no big difference can be observed on the maximum lateral load between Specimens



Figure 3: Loading history and monitoring zone apparatus

L2NVC and L2NVB. However, a large load drop can be seen for specimen L2NVC, from the 1<sup>st</sup> to the 4<sup>th</sup> negative cycle at a rotation angle of 2% (24 mm). This effect can also be seen on the normalized moment-curvature curve in Figure 5. Besides the moment drop a considerable increase in curvature can be also observed. Here, the curvature was computed for the four zones shown in Figure 3 (c). In Figure 6, normalized load in EW and NS versus the rotation angle envelope curves are shown for both specimens. The two envelope curves are lying on each other for a rotation angle less than 2%. Beyond that point a rapid drop is observed for specimen L2NVC due to the buckling of nearly all the longitudinal reinforcement bars. In the positive cycles of the NS direction, difference was observed at an early stage corresponding to 0.25% of rotation angle due to the effect of number of cycles under high axial load. Besides that, number of cycles had an effect on maximum sustained displacement as shown on the same figure.





Figure 4: Load-displacement relationship





Figure 5: Moment-curvature relationship



Figure 6: Load-displacement envelope curves (continue)



Figure 6: Load-displacement envelope curves







Figure 7: Observed Damage

During the test, concrete cover spalled first followed by buckling of longitudinal corner reinforcement. As test progressed, concrete at the corners started crushing as shown in Figure 7 (a), and gradually load carrying capacity started to reduce as damage penetrated toward the column core. This state can be seen through Figure 8, that shows the strain distribution in east side of shear reinforcement at 1% and 3% rotation angles, respectively at 3 different stirrups location, layers position, through the column height shown in Figure 3 (c). Strain of main shear reinforcement (external stirrups) started to reduce while an increase in strain of auxiliary shear reinforcement (internal stirrups) took place. Nearly the same tendency was found for strain gauges in the other sides. This means that concrete at the peripheral of the core was severally damaged, hence effective concrete area reduced.



(a): At 1% rotation angle



(b): At 3% rotation angle Figure 8: Strain distribution for L1N6B specimen

Taking into account the observed damage and the results found using the shear reinforcement strain distribution; column section was classified in distinguished areas. These areas are shown in Figure 7 (b) and classified from 1 to 4. Number attributed to each area indicates its crashing order.

### **3.** ANALYTICAL RESULTS

The behavior of a plastic hinge was predicted using a simple fiber model. Section analysis was carried out assuming Bernoulli's theory for concrete and longitudinal steel. The column cross section was subdivided into concrete fiber elements and reinforcing steel fiber elements and the section response was obtained by integrating all fiber element stresses and stiffness. Steel fiber element followed Nakamura's stress-strain relation, whereas concrete fiber element followed Popovic's stress-strain relation. The enhanced strength,  $f'_{cc}$ , due to confinement is expressed [8] as follows.

$$f_{cc}' = f_c' + \kappa \rho_h f_{hy}$$
(1)  

$$\kappa = 11.5 \alpha \left(\frac{d}{C}\right) \left(1 - \frac{s}{2D_{core}}\right)$$
(2)

where  $f'_c$  is the cylinder compressive strength without confinement,  $\kappa$  , the coefficient of strength enhancement due to confinement,  $\rho_h$ ,  $f_{hv}$ , d, and C the volume ratio, yield strength, diameter, and unsupported length of shear reinforcing bars, respectively, s the distance between adjacent shear reinforcement, and D<sub>core</sub> the width of confined concrete. The coefficient,  $\alpha$ , was added to the original equation by the authors to take into account the effects of strain gradient. Value of  $\alpha$  was taken greater or equal to 1.0 to increase the strength and ductility of confined concrete. The optimum values used in the analysis, are those giving the best fit between the prediction and the test results in term of vertical strain,  $\varepsilon_o$ , and the normalized curvature,  $D\phi_{ns}$ , where D is the depth of the column and  $\phi_{ns}$  is the curvature in the NS direction. The analytical and the experimental curvature were computed using a plastic hinge length equal to D, that correspond to zone 2, 3 and 4 in Figure 3 (c). The obtained results are shown in Figure 9 for the four specimens, where a good agreement can be observed. Good agreement was also observed for the Moment-Curvature curves that are not shown



Figure 9: Analytical and experimental axial strain results (continue)



Figure 9: Analytical and experimental axial strain results



Figure 10: Load-displacement and damage progress assessed using IDARC program

#### 4. DAMAGE EVOLUTION

The best known and most widely used of all cumulative damage indices is that of Park and Ang (1985). This consists of a simple linear combination of normalized deformation and energy absorption:

$$D = \frac{\delta_m}{\delta_u} + \beta_e \frac{\int dE}{F_y \delta_u}$$
(3)

where:  $\delta_m$  = maximum deformation under earthquake,  $\delta_u$  = ultimate deformation under monotonic deformation,  $F_{y}$  = calculated yield strength, dE = incremental absorbed hysteretic energy, and  $\beta_e =$  a positive parameters. Values of the damage index are such that  $D \ge 1.0$  signifies complete collapse or total damage. The advantage of this model is its simplicity, and the fact that it has been calibrated against a significant amount of observed seismic damage. Using the non-linear IDARC program [6], load displacement curve and the damage progress of specimen L1N6B were computed and shown in Figure 10. A good agreement for load-displacement relation is observed between the experimental and the analytical prediction. It can also be seen on the same figure, that the damage rate increased more rapidly after cycle number 8, which correspond to 2% rotation angle corresponding to excessive concrete crushing followed by the buckling of the longitudinal reinforcement, already discussed in section 2.2. At the end of the cyclic loading, the total damage was D=0.417, corresponding using Park et al classification to "severe damage" range, which is more or less consistent with the observed one in term of classification. However, the value itself, which is considered here low, did not reflect the real state of the specimen that was near collapse. One of the reasons that can contribute to such low value is that, specimens that were included in formulating Eq. 3 were under low or moderated axial load and not under a high axial load as in our case. As a consequence, a new damage index was proposed based on the monotonic and cyclic curves. It is formulated as follows:

$$DI^{(+)} = \sum \left( 1 - \frac{F_{ci}^{(+)}}{F_{mi}^{(+)}} \right)$$
(4)

where:  $F_{ci}$  is the applied load at the prescribed displacement "i" on the cyclic curve and  $F_{mi}$  is the corresponding load on the monotonic curve at the same displacement "i". The computed damage for specimen L1N6B using the proposed damage index reflects well the observed damage as it can be seen through Figure 11 and Figure 12. In this case the column damage was the average between the computed negative and positive damage that



Figure 11: Observed damage



Figure 12: Assessed damage for L1N6B

gave DI = 0.72 at the end of the test. This value is more realistic compared to the one found using Eq. 3.

# 5. CONCLUSIONS

The following conclusions can be drawn from the test results and analytical study:

- Number of cycles did not have a noticeable influence on the lateral load-displacement relation and the moment-curvature relation in terms of envelope curves and peak values until the rotation angle reached 2 %. After a rotation angle of 2 %, specimen with four cycles at a prescribed rotation angle (L2NVC) showed a large drop in lateral load carrying capacity and rapid progress in curvature at a plastic hinge region although a specimen with two cycles (L2NVB) did not show this degradation until a rotation angle of 3 %.
- Progress of concrete damage in a plastic hinge zone was postulated from the strain distribution of external and internal hoops. External hoops mainly confined the core concrete at an early loading stage but lost its contribution after concrete at core corners started to crush. Once the corner concrete started to crush, strain of external hoops reduced and strain of internal hoops

increased. During this transition, concrete area carrying external load reduced accordingly.

- ✤ Using a simple fiber model, the analytical results simulated with enough precision the experimental ones, shortening-curvature and moment-curvature, by adjusting a coefficient added to Sakino's equation, Eq. 1 and 2, that takes into account the concrete strength enhancement.
- The inelastic IDARC program successfully predicted the horizontal loading capacity for specimen L1N6B. The proposed damage index was found to reflect with a good agreement the observed damage for specimen L1N6B.

#### ACKNOWLEDGEMENT

The authors are thankful to M. Ando and Y. Arai, students at Kyoto University for their help during the test. Sincere thanks are extended to Prof. T. Kaku and Prof. H. Kuramoto at Toyohashi University of Technology who gave us continuous support and suggestions throughout the experiment. The authors also acknowledge TOPY Industries Limited, NETUREN Corporation Limited, and KOBE steel Limited for donating experimental materials.

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