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Energy dissipation of reinforced concrete beams under reversed cyclic loading

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ABSTRACT: In this study, energy dissipation properties of reinforced concrete beams under reversed cyclic loading were discussed. Non-dimensional total dissipated energy until the ultimate state was defined, and the effects of longitudinal reinforcement ratio and shear reinforcement ratio on that was investigated. The differences in the accumulating process of dissipated energy due to the different loading histories were also discussed. In addition, an example of damage index based on the hysteretic dissipated energy for evaluating the seismic damage of reinforced concrete members was indicated.

1 INTRODUCTION

The evaluation of seismic damage of concrete structures is very important in order to take early countermeasures, such as repair and strengthening, for the deteriorated structures after severe earthquakes. The degree of seismic damages in concrete structures is related closely to the maximum response deformation and the hysteretic dissipated energy of their constitutive members. In case of cyclic loading, however, the latter seems to be more predominant. From this reason, it is essential to make clear the accumulating process of dissipated energy under reversed cyclic loads in order to make an accurate evaluation of seismic damages in concrete structures.

The main object of this study is to investigate the effects of longitudinal reinforcement ratio and shear reinforcement ratio on the accumulation process of dissipated energy until the ultimate state of reinforced concrete beams under different loading histories.

2 OUTLINE OF LOADING TESTS

All of the tested beams were identical in size, that is, width = 10cm, full depth = 20cm and total length = 160cm as shown in Fig.1. Three levels of longitudinal reinforcement ratio (p), 1.43, 2.26 and 3.28%, and three levels of shear reinforcement ratio (ρ_w), 0.63, 0.95 and 1.26%, were selected. The value of ρ_w=0.63% corresponded to the minimum required one prescribed in Standard Specification for Design and Construction of Concrete Structures (JSCE, 1986). The design compressive strength of concrete (f_{ck}) was 39.2MPa for all of the specimens. The yield strength of longitudinal bars and stirrups was approximately 340MPa and 500MPa, respectively.

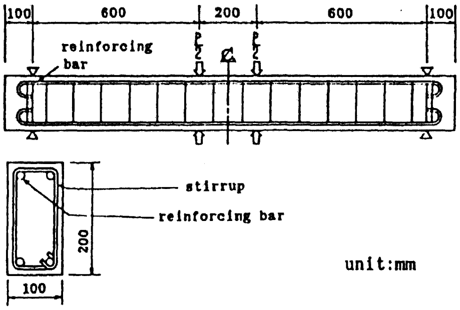

Fig.1 Dimensions of tested beams

All of the beams were simply supported and loaded under symmetrical two points load with a/d=3.4 (a:shear span length, d:effective depth). Two types of loading history were adopted. The one (Series-A) was reversed cyclic loading with each one load reversal at the deflection amplitude of δy, $2\delta y$, $3\delta y$, --- (δy:yield deflection). The other (Series-B) had five load reversals at each deflection amplitude.

3 TEST RESULTS AND DISCUSSIONS

3.1 *Definition of the ultimate state and non-dimensional dissipated energy*

It is necessary to define the ultimate state of members when the seismic damage of concrete structures should be evaluated. In this study, the ultimate state of a member was defined as the point at which the reduction in load carrying capacity from the maximum load reached to 20% of the maximum load.

Non-dimensional dissipated energy at each deflection amplitude (Ed') was defined as

$$Ed'=Ed/(Py'*\delta y') \qquad (1)$$

where Ed is the energy dissipated in each deflection amplitude, Py' is the calculated yield load of each beam and $\delta y'$ is the calculated yield deflection of each beam, in order to eliminate the effect of difference in the maximum load carrying capacity among each specimen. Non-dimensional total dissipated energy until the ultimate state ($\Sigma Ed'$) was calculated by summing each Ed'-value up to the ultimate state. In this case, the energy dissipated within the cycle at which the member reached to its ultimate state was included in the $\Sigma Ed'$-value.

3.2 *Energy dissipation in Series-A beams*

In Fig.2 are shown some examples of non-dimensional dissipated energy (Ed') at each deflection amplitude.

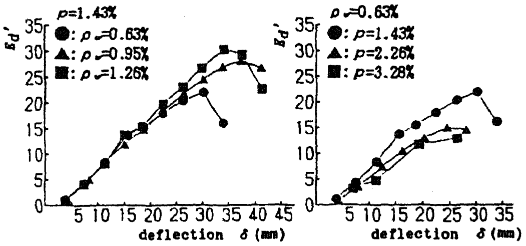

Fig.2 Non-dimensional dissipated energy (Series-A)

The Ed'-value increased almost linearly with increasing the deflection amplitude until the ultimate state, where the Ed-value began to decrease. The increasing ratio of the Ed'-value was influenced by the longitudinal reinforcement ratio, p, and it became smaller with increasing the p-value, while the effect of the shear reinforcement ratio was not significant. On the other hand, the deflection amplitude at which the Ed'-value began to decrease became larger with increasing the shear reinforcement ratio, ρw. In other wards, the shear reinforcement ratio determined the deflection amplitude at the ultimate state of the members subjected to load reversals well into the post-elastic range.

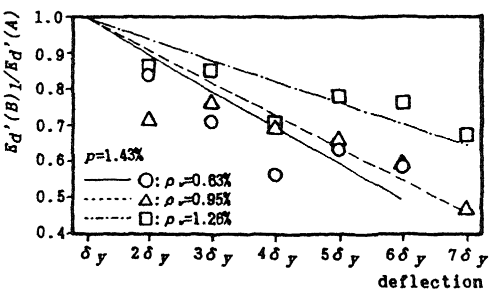

Fig.3 Relationship between $Ed'(B)1/Ed'(A)$ and applied deflection amplitude

3.3 *Energy dissipation in Series-B beams*

In Series-B, the energy dissipated in the first cycle at each deflection amplitude was affected by the previous load cycles. The ratio of $Ed'(B)1/Ed'(A)$, where $Ed'(B)1$ is non-dimensional energy dissipated in the first cycle at each deflection amplitude in Series-B beams and $Ed'(A)$ is non-dimensional energy dissipated in the corresponding load cycles in Series-A beams, decreased approximately linearly with increasing the deflection amplitude as seen in Fig.3, although scattering existed in the experimental data. This decreasing ratio was affected by the shear reinforcement ratio and became larger with decreasing the ρw-value. In this case, the effect of longitudinal reinforcement ratio was not significant.

From these results, the equation representing the relationship between $Ed'(B)1$ and $Ed'(A)$, which was a function of shear reinforcement ratio and deflection amplitude, was given as bellow.

$$Ed'(B)1/Ed'(A)=1-\alpha*[(\delta/\delta y)-1] \qquad (2)$$

where δ is more than δy and α is a parameter affected by shear reinforcement ratio.

In this study, $\alpha=0.112$, 0.082 and 0.056 was obtained for $\rho w=0.63$, 0.95 and 1.26%, respectively.

On the other hand, the energy dissipated in each cycle at the same deflection amplitude of Series-B beams was affected by the number of repeated cycles (N), and the ratio of $Ed'(B)N/Ed'(B)1$, where $Ed'(B)N$ is non-dimensional dissipated energy in Nth cycles at each deflection amplitude, decreased with increasing N-value as shown in Fig.4. This decreasing ratio was influenced by the given deflection amplitude. At the deflection amplitude of $\delta=\delta y$, the Ed'-value at the fifth cycle reduced to approximately 20% of that at the first cycle. At the deflection amplitude of more than $2\delta y$, on the other hand, the Ed'-value at the fifth cycle reduced to at most 80% of that at the first cycle. In this case, the effect of longitudinal reinforcement ratio and shear rein-

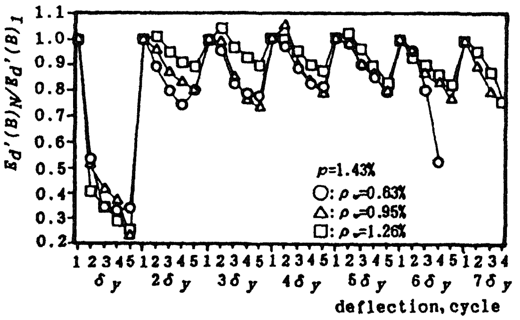

Fig.4 Relationship between $E_d'(B)_N/E_d'(B)_1$ and the number of repeated cycles

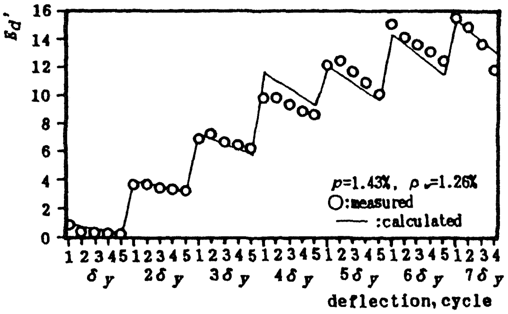

Fig.5 Comparison between the measured and the calculated E_d'-values (Series-B)

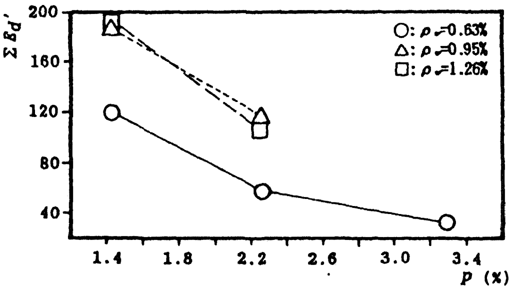

Fig.6 Effect of longitudinal reinforcement ratio on $\Sigma E_d'$-values

forcement ratio was not significant.

From these results, the relationship between $E_d'(B)_N$ and $E_d'(B)_1$, which was given as a function of the number of the repeated cycles, were proposed as bellow.

$$E_d'(B)_N/E_d'(B)_1 = 1-0.8*(N-1)/4 \quad (\delta=\delta_y) \quad (3)$$

$$= 1-0.2*(N-1)/4 \quad (\delta>=2\delta_y) \quad (4)$$

where N is the number of load reversals not more than 5 at each deflection amplitude.

Fig.5 shows an example of the comparison between the measured and the calculated E_d'-values of a Series-B beam, where the latter was obtained from the equations (2) to (4) using the E_d'-values of the corresponding Series-A beam. This figure indicates that the E_d'-values in Series-B beams could be well estimated by using the proposed equations if the energy dissipation properties under the fundamental loading process, in this case such as Series-A, was given.

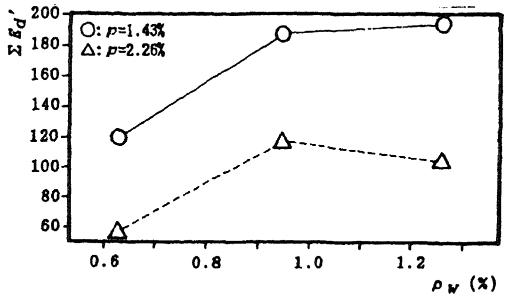

Fig.7 Effect of shear reinforcement ratio on $\Sigma E_d'$-values

3.4 *Total dissipated energy until the ultimate state*

Fig.6 and Fig.7 show the effects of the longitudinal reinforcement ratio and the shear reinforcement ratio on the non-dimensional total dissipated energy until the ultimate state ($\Sigma E_d'$) of Series-A beams, respectively.

$\Sigma E_d'$-value decreased with increasing the p-value, while its decreasing ratio reduced with increasing the p-value. On the other hand, $\Sigma E_d'$-value increased with increasing the ρ_w-value, although its increasing ratio decreased with ρ_w-value. These tendencies were also observed in Series-B beams. From these results, the equation representing the $\Sigma E_d'$-values of the beams was proposed as bellow, assuming that $\Sigma E_d'$-values were in inverse proportion to longitudinal reinforcement ratio and expressed by a logarithmic function of shear reinforcement ratio.

$$\Sigma E_d' = a*\ln(1+\rho_w)+b*(1/p) +c*\ln(1+\rho_w)/p+d \quad (5)$$

where p and ρ_w are in percent, and a, b, c and d are experimental coefficients.

From the regression analysis of the experimental data, the values of the coefficients were obtained as a=44.54, b=123.27, c=266.89 and d=-69.89 for Series-A beams and a=449.50, b=205.93, c=-116.78 and d=-171.35 for Series-B beams. The $\Sigma E_d'$-values calculated by the equation (5) were compared with the measured ones in Fig.8. This figure indicates that the $\Sigma E_d'$-values of Series-A

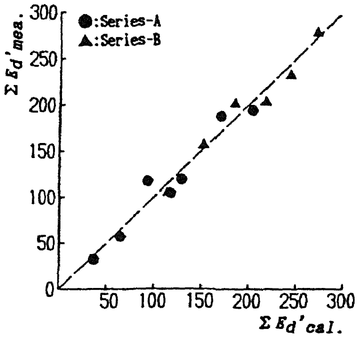

Fig.8 Comparison between the measured and calculated $\Sigma Ed'$-values

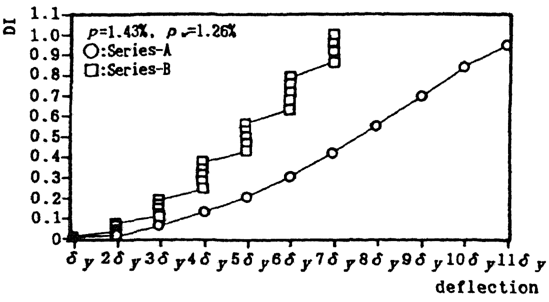

Fig.9 Changes of damage index (DI)

and Series-B beams could be well estimated by the proposed equation.

3.5 *Index for the evaluation of seismic damage based on the hysteretic dissipated energy*

If the total dissipated energy until the ultimate state ($\Sigma Ed'$-value) of a reinforced concrete member was known, the degree of damage could be estimated by comparing that with the actual dissipated energy under a practical earthquake. However, the $\Sigma Ed'$-value of a member is different according to the loading histories as seen in this study. From this reason, the following assumption was introduced in order to evaluate the damage of a member subjected to different loading histories.

When a member is subjected to more than two loading cycles at the same deflection amplitude, the real damage of that member after the second loading cycle is assumed to decrease with increasing the loading cycles (N). If the damage of a member could be represented by the non-dimensional dissipated energy, the above assumption could be expressed by the following equations.

$$Ed''(N)=f(N)*Ed'(N) \qquad (6)$$

$$f(N)=(1/N)*[\{1+(\beta-1)*N\}/\beta] \qquad (7)$$

where $Ed''(N)$ is the assumed non-dimensional dissipated energy at the Nth loading cycle of the same deflection amplitude, $f(N)$ is the reducing factor for the Nth cycle and β is an experimental coefficient.

Here, the index evaluating the seismic damage is defined as

$$DI=\Sigma Ed''(N)/\Sigma Ed'(A) \qquad (8)$$

where DI=0 indicates no damage and DI=1 represents the total failure, then the degree of damage of a member subjected to different loading histories could be estimated by using the equations (2) to (8) if the total non-dimensional dissipated energy until the ultimate state under a fundamental loading history, such as Series-A, was already known.

As for the value of the coefficient β, β=1.1 for p=2.26% and β=1.9 for p=1.43% was obtained in this study by applying DI=1 to the experimental data.

An example of the changes of DI in Series-A and Series-B beams was shown in Fig.9. It is indicated that the damage of the beams subjected to many load reversals at the same deflection amplitude as Series-B in this study could be well estimated by the above mentioned method and that Series-B beams failed at smaller deflection amplitude than Series-A beams due to many load reversals at each deflection amplitude.

4 CONCLUSIONS

Dissipated energy of reinforced concrete beams was influenced significantly by longitudinal reinforcement ratio, shear reinforcement ratio and number of load reversals at each deflection amplitude. The changes in dissipated energy according to the applied deflection amplitudes and the number of load reversals as well as the total dissipated energy until the ultimate state of reinforced concrete beams under gradually increased reversed cyclic loads could be well estimated by the equations proposed in this study. In addition, an example of damage index for evaluating the seismic damage of reinforced concrete members was indicated. However, the experimental coefficients in these equations were decided by the limited experimental data. Therefore, further investigations are necessary as for the applicability of these equations to the existing concrete structures.

REFERENCE

Japan Society of Civil Engineers. 1986. *Standard Specification for Design and Construction of Concrete Structures: Part 1 [Design]*. Japan