Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VI)

6-4-8

DYNAMIC RESTORING FORCE CHARACTERISTICS OF REINFORCED CONCRETE MEMBERS

Motoo SAISHO 1) and Kazuya SENBA 2)

1) Department of Architecture, Kumamoto University, Kumamoto, Japan
2) Structural Department, Kume Architects-Engineers, Minato-ku, Tokyo, Japan

SUMMARY

The effects of loading rate on the restoring force characteristics were investigated by dynamic loading tests of reinforced concrete members. From the test results the empirical formula is presented which predicts the dynamic restoring force characteristics by the use of the static restoring force under the same hysteresis of deformation. Based on the seismic response analyses, which were carried out using the predicted dynamic restoring force, it is shown that the plastic drift of the displacement response of structures is amplified and the possibility to cause the incremental collapse is increased by the effect of loading rate.

INTRODUCTION

When structures are subjected to strong ground motion, the structural members receive dynamic loads whose rate changes irregularly with time. However the restoring force of structures and structural members under seismic load has been studied mainly by the static loading tests. There are many reports of dynamic loading tests to study the loading rate effect on the restoring force of concrete or reinforced concrete members (Ref.1) but the most of all have been studied on the strength of structural material or structural members under constant loading rate except a few papers.(Ref.2-7)

The object of this study is to clarify the influence of dynamic loading, whose rate changes irregularly with time like the seismic load, on the restoring force characteristics of reinforced concrete members. It is also the aim of this study to show the loading rate effects on the seismic response and the aseismic capacity of structures.

DESCRIPTION OF TEST

Specimens As shown in Fig.1, the specimens are cantilevered reinforced concrete members which are designed to fail in flexure. The eight specimens were prepared which are explained in Table 1. The mechanical properties of the reinforcing bar and the mix proportions of the concrete assuming aggregates to be in a saturated and surface dry condition are shown in Table 2 and Table 3.

Test setup Fig.2 shows the general view of test setup. The base of the specimen was fixed at the rigid floor and the universal joint was attached to the top of the specimen. The horizontal load of the specimen was given through

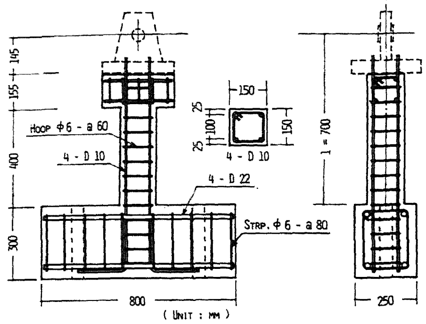

Fig.1 Specimen

the universal joint by an actuator in the dynamic loading tests or by a hydraulic jack in the static loading tests.

Dynamic loading program The dynamic load was given by the use of a closed loop system with a 30 ton actuator controlling the horizontal displacement at the loading point of the specimen. The controlling system of the actuator is explained in Fig.3. There were four types of time history of the applied deformation at the loading point of specimen. They are the monotonic loading (M), the alternated loading with constant amplitude of deformation (C), the alternated loading with gradually increasing amplitude of deformation (I) and the random loading generated by a seismic response analysis (R). The time histories of the recorded deformation (D) are shown in Fig.4.

The strain rate of the specimens, which was measured by wire strain gages attached to the steel bars at the fixed end of the specimen, was about 0.06/sec. -0.08/sec. at the maximum as shown in Fig.5. The loading rate of this test may be in some cases relatively low in comparison with real behavior of reinforced concrete structure but the magnitude of rate is not a problem as mentioned below.

At intervals of ten milliseconds the load and the horizontal displacement at the loading point were measured at the same time using a load cell built in the actuator and a displacement transducer, shown in Fig.2. The measuring system is explained in Fig.3.

Static loading program The static loading tests were also carried out using a hydraulic jack controlled manually to achieve the

Table 1 List of test specimens

Specimen	σc	My	Dy	Hysteresis	Loading
CSM	276(34d)	68.4	0.406	M	Static
CSC	267(54d)	69.6	0.397	C	"
CSI	308(39d)	67.8	0.410	I	"
CSR	281(50d)	68.0	0.409	R	"
CDM	300(32d)	68.4	0.406	M	Dynamic
CDC	281(47d)	68.4	0.406	C	"
CDI	330(32d)	68.1	0.408	I	"
CDR	300(48d)	69.1	0.401	R	"

σc : Concrete compressive strength (kg/cm2)
My : Yield moment (t.cm)
Dy : Deformation at yield moment (cm)

Table 2
Material properties of steel bar (D10)

Yield stress	4.27 t/cm2
Ultimate stress	6.20 t/cm2
Strain at start of strain hardening	0.0202
Strain at ultimate stress	0.222

Table 3 Mix Proportions

Mix components	kg per cubic meter
Cement	360
Water	216
Fine aggregate	836
Coarse aggregate 2.5 to 10 mm	879
Effective water-cement ratio	0.6

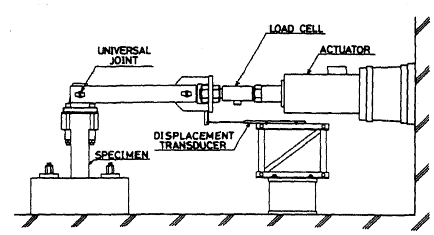

Fig.2 Test setup

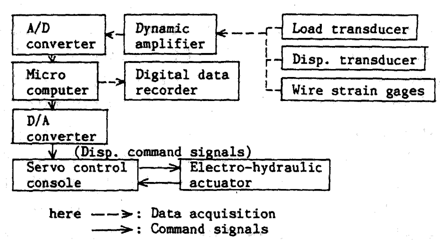

Fig.3 Measuring and controlling system

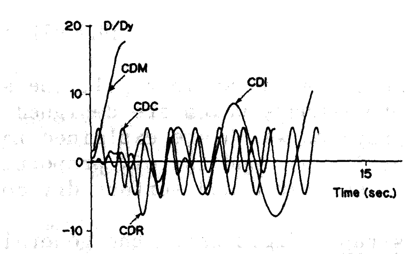

Fig.4 Time histories of recorded deformation

completely static tests. The deformation to be given to the specimens in the static loading tests were equal to the recorded deformation hystereses in the dynamic loading tests shown in Fig.4. In the static loading tests, after a small incremental displacement was given to the specimen by the hydraulic jack and the forced deformation was kept for 30 seconds at least, the load and the deformation were measured. This test process of loading and measuring was repeated until the test ended.

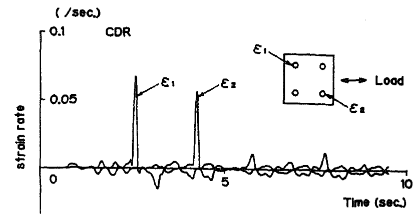

Fig.5 Time histories of strain rate

TEST RESULTS

<u>Loading rate effects</u> The relations between the applied load (F) and the deformation at the loading point (D) of the specimen are shown in Fig.6. In these figures, Dy is the yield deformation (=My L2/3EI, My : yield moment, EI : elastic flexural rigidity) and Fy is the yield load (=My/L). The real lines and the dashed lines show the dynamic test results and the static test results respectively. The effect of loading rate, which is expressed by the difference between the real lines and the dashed lines, is very complicated.

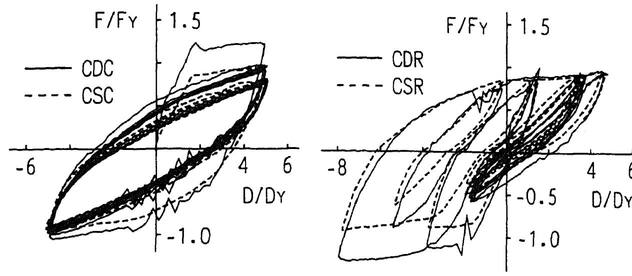

Fig.6
Load-deformation curves of test result

In this study, the value of r, defined in Eq.(1), is introduced to express the effect of loading rate.

$$r = (fd-fs)/fs \qquad (1)$$

where fs = Fs/Fy, fd = Fd/Fy, Fd,Fs : the dynamic and the static restoring force denoted from the reversed point in each cycle in the hysteresis.

To examine the influence of the velocity of the applied deformation (V), the V-r relations are shown in Fig.7. In these figures, the values of r in the case that Fs is smaller than the yield load (Fy) are not included to deal with the inelastic behavior of the members. The figures show that there is no clear relation between the value of r and the velocity of deformation. It has been reported that the dynamic loading effect on the strength of reinforced concrete members is expressed by the strain rate. (Ref.8) But these figures show that the dynamic loading effect on the restoring force of reinforced concrete members is not defined only by the rate of deformation when the velocity of the deformation changes irregularly every moment.

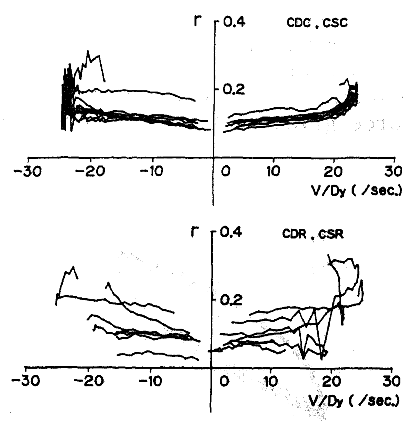

Fig.7
Value of r and rate of deformation

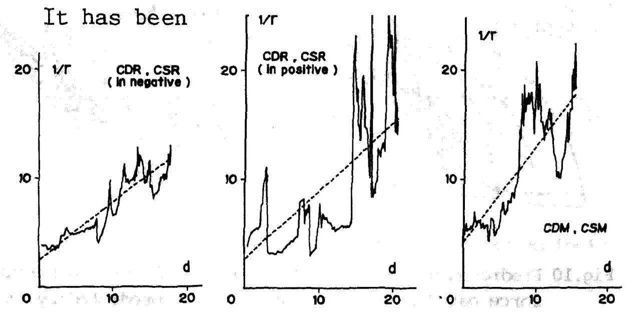

Fig.8 Value of r and accumulated plastic deformation

Prediction of loading rate effects Fig.8 shows the relation between the value of r and d. The value of d is the accumulated plastic deformation normalized by the value of Dy and defined in the positive direction and in the negative direction independently. The dashed lines are the approximate straight lines decided by the use of the least of squares method. Regardless of the hysteresis of deformation and the loading rate, the test results of all specimens can be nearly approximated by the dashed straight lines.

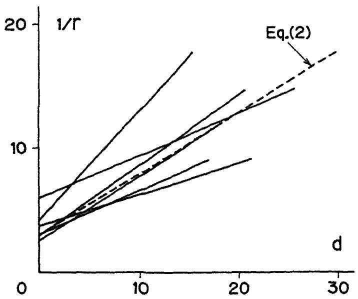

Fig.9 Summarized r-d relation

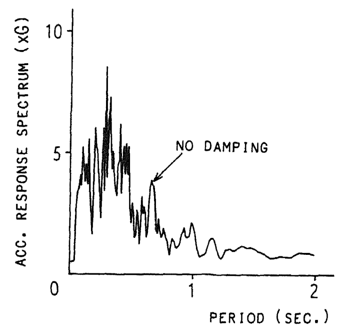

Fig.11 Response spectrum of simulated earthquake

The approximated straight lines are summarized in Fig.9. If the rate of deformation is limited in the values of these tests, we can say from this figure that the effects of loading rate on the restoring force are nearly constant with respect to the velocity of deformation and they are dominated mainly by the accumulated plastic deformation. As the approximated average of these real lines, the dashed straight line is given as shown in Fig.9. This dashed straight line is expressed by Eq.(2).

$$1/r = Ca\ d + Cb \tag{2}$$

in which Ca=0.5, Cb=3.0. Ca and Cb are the constant values decided according to the properties of member and the stress distribution.

By the use of this empirical formula, the dynamic restoring force characteristics are predicted as shown in Fig.10 comparing with the test results. In these figures, it is shown that the approximated dynamic restoring force given by Eq.(2) agrees well with the test results.

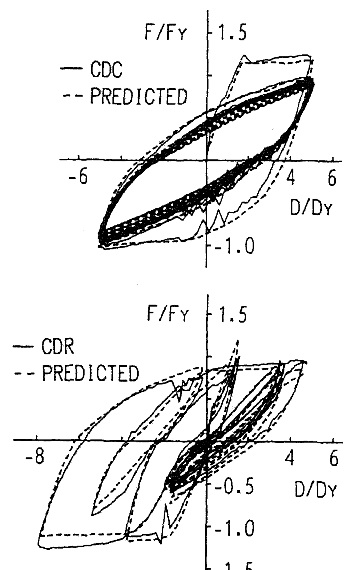

Fig.10 Predicted dynamic restoring force based on static test

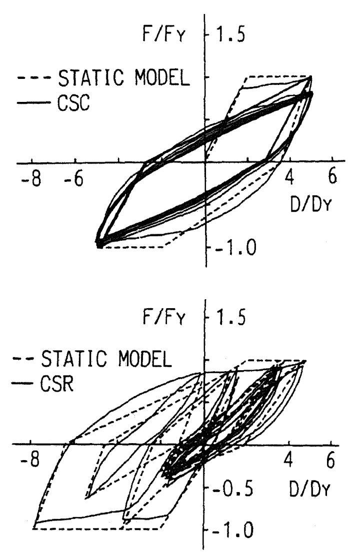

Fig.12 Static restoring force predicted by tri-linear model

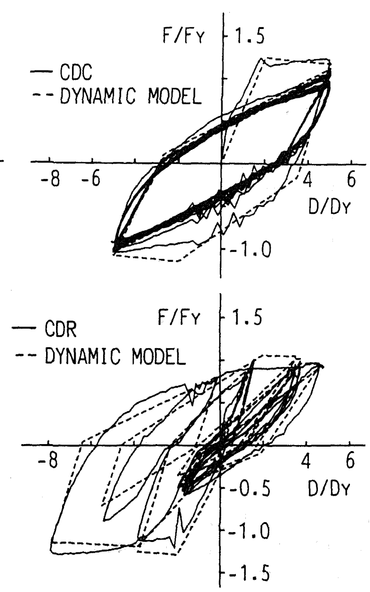

Fig.13 Predicted dynamic restoring force based on tri-linear model

SEISMIC RESPONSE ANALYSIS

Description of analysis On the basis of the dynamic restoring force predicted by Eq.(2), the seismic response of a structural model has been numerically analyzed. The calculated structural model is a single degree of freedom system whose ratio of the horizontal yield strength to the gravity load is 0.2. This model has no viscous damping. The N-S component of the El Centro 1940 earthquake and a simulated earthquake, whose response spectrum is shown in Fig.11, are chosen as the excitations of the analytical model. The former excitation is scaled to a peak acceleration of 500 gal to calculate the fully plastic behavior of the model. The simulated ground motion is used to analyze the effects of the duration of strong ground motion.

Static restoring force and dynamic restoring force The static restoring force characteristics are assumed to be given by the tri-linear model whose hardening ratio is 0.001 and the degrading modulus of stiffness is 0.5. The static restoring forces calculated by the model are compared with the test results as shown in Fig.12, which shows that the test results are nearly predicted by the model. The dynamic restoring force characteristics of analyzed system are also assumed to be given by applying Eq.(2) to the tri-linear model which shows the static restoring force. The predicted dynamic restoring forces are compared with the dynamic loading test results in Fig.13 and it is confirmed that the calculated dynamic restoring forces are agree well with the test results.

Calculated results Fig.14 is the time histories of plastic displacement response and Fig.15 shows the hysteretic restoring forces. We can see a clear difference between the two seismic responses which are calculated based on the static restoring force (SRF) and the dynamic restoring force (DRF). The plastic

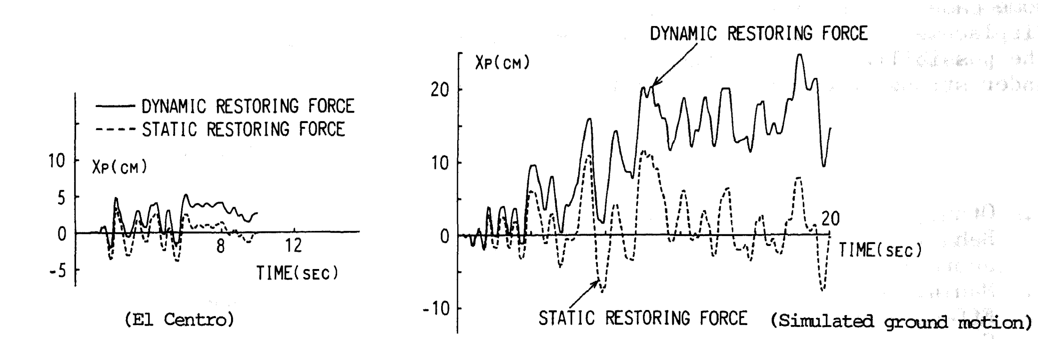

Fig.14 Time histories of plastic displacement response
(natural period=0.3sec.)

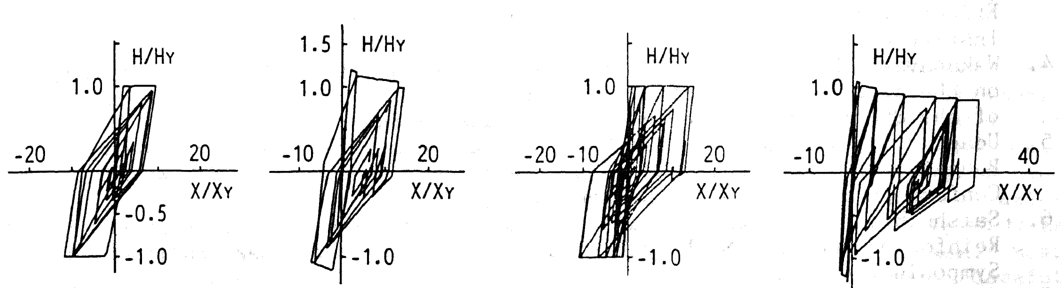

Fig.15 Hysteresis loop of restoring force
(natural period=0.3sec.)

drift of the displacement response which is calculated on the basis of the dynamic restoring force increases gradually with time and shows the tendency to collapse increasingly in comparison with the response based on the static restoring force. To express the influence of natural frequency on the plastic drift behavior the plastic displacement response spectra are shown in Fig.16. The difference between the real line and the dashed line, which is the effect of loading rate on the seismic response, is changed complicatedly according to the natural period. As a whole the seismic displacement response is amplified by the loading rate effect. In some cases the effect of loading rate works to increase the plastic drift remarkably. It may be concluded from these figures that the important and clear effect of the loading rate on seismic response is to cause the plastic drift of displacement response.

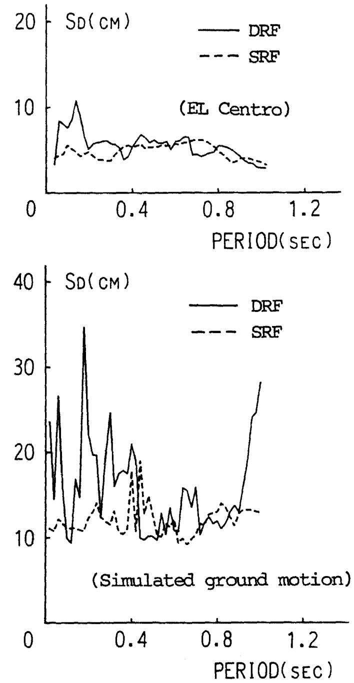

Fig.16 Response spectra of plastic displacement

CONCLUSION

1. The loading rate effect on the restoring force is dominated mainly by the accumulated plastic deformation in each direction but not influenced remarkably by the magnitude of deforming rate and the hysteresis of deformation.
2. The dynamic restoring force including the effect of loading rate is well predicted by Eq.(2).
3. The effect of loading rate on the restoring force, which decreases with the accumulated plastic deformation, results in the drift of the restoring force in one direction. According to this behavior the effect of loading rate works in some cases to increase the plastic drift of the displacement response of structures with time and the possibility to cause the incremental collapse under strong ground motion with long duration.

REFERENCES

1. Otani,S., "Influence of Loading Rate on Behavior of Reinforced Concrete," Concrete Journal, (1983).
2. Mahin,S.A. and Bertero,V.V., "Rate of Loading Effect on Uncracked and Repaired Reinforced Concrete Members," Earthquake Engineering Research Center Report UCB/EERC-72/9, University California, Berkeley, (1972).
3. Kitagawa,Y., Nagataki,Y. and Kashima,T., "Dynamic Response Analysis with Effect of Strain Rate and Stress Relaxation," Trans. of the Architectural Institute of Japan, No 343, (1984).
4. Wakabayashi,M., Nakamura,T., Iwai,S. and Hayashi,Y., "Effects of Strain Rate on the Behavior of Structural Members Subjected to Earthquake Force," Proc. of the 8th World Conference of Earthquake Engineering, (1984).
5. Udagawa,K., Takanashi,K. and Kato,B., "Effects of Displacement Rates on the Behavior of Steel Beams and Composite Beams," Proc. of the 8th World Conference of Earthquake Engineering, (1984).
6. Saisho,M., "Experimental Study on Dynamic Restoring Force Characteristics of Reinforced Concrete Members," Proc. of 7th Japan Earthquake Engineering Symposium, (1986).
7. Eto,H. and Takeda,T., "Study on Aseismic Design of High-rise Reinforced Concrete Buildings (Part 4)," Report of TRI, Ohbayashi Corporation, (1985).
8. Dilger,W.H., Koch,R. and Kowalczyk,R., "Ductility of Plain and Confined Concrete under Different Strain Rate," ACI Journal, (1984).