CONCRETE LIBRARY OF JSCE NO. 6, DECEMBER 1985

BEHAVIOR OF REINFORCED CONCRETE MEMBERS SUBJECTED TO DYNAMIC LOADING

(Reprint from Transactions of JSCE, Vol. V-2, No.354, 1985)

Hiroshi MUTSUYOSHI

Atsuhiko MACHIDA

SYNOPSIS

Dynamic analysis and earthquake resistant design for reinforced concrete structures have been commonly conducted on the basis of the assumption that the characteristics under dynamic loading are equal to those under static loading. It has hardly been clarified, however, whether the fundamental properties of reinforced concrete structures under dynamic loading are equal to those under static loading. The objective of this paper is to establish the differences between the mechanical properties of reinforced concrete members under dynamic loading and static loading. In order to investigate the dynamic behavior of reinforced concrete members and to clarify the effect of the strain rate on the properties of reinforced concrete members, dynamic tensile tests on reinforcing steels were carried out, and small scale reinforced concrete specimens were tested under dynamic loading, steady-state dynamic base motion and static cyclic loading.

H. Mutsuyoshi is a research associate of Construction Engineering at Saitama University, Urawa, Japan. He received his Doctor of Engineering Degree in 1984 from the University of Tokyo. His research interests include seismic design of reinforced concrete structures, response behavior of reinforced concrete structures during earthquakes and dynamic properties of reinforced concrete members. He is a member of ACI, JSCE and JCI.

A. Machida is a professor of Construction Engineering at Saitama University, Urawa, Japan. He was awarded the JSCE prize (Yoshida Prize) in 1979. He received his Doctor of Engineering Degree in 1976 from the University of Tokyo. His research interests include test methods for properties of concrete, behaviours of reinforced concrete structures under seismic load and seismic design of reinforced concrete structures. He is a member of several research committees on concrete and reinforced concrete at JSCE and JCI.

---

1. INTRODUCTION

Many studies have been conducted on the properties of reinforced concrete structures subjected to earthquakes. The dynamic analysis and the earthquake resistant design for reinforced concrete structures have generally been carried out on the basis of the assumption that the properties of reinforced concrete members under dynamic loading are equal to those under static loading. However, each part of the concrete and the reinforcing steel of reinforced concrete structures subjected to an earthquake will have a high magnitude of strain rate because an earthquake is a dynamic load with a repetition of loading. It is therefore necessary to clarify whether the fundamental properties of reinforced concrete structures under dynamic loading are equal to those under static loading.

Previous tests have indicated a logarithmic increase in the compressive strength and modulus of elasticity of concrete and in the yield point of reinforcing steel with increasing strain rates(1,2). It is also well known that the properties of reinforced concrete members under monotonic dynamic loading or impact loading are different from those under static loading due to the strain rate effect of the concrete and the reinforcing steel(3,9). On the other hand, it is recognized that the influence of the loading rate under dynamic cyclic loading on the load-displacement characteristics of reinforced concrete members is considerably small compared with that under monotonic dynamic loading(5,7). The loading rates used in past studies on the dynamic cyclic tests, however, were limited to very small magnitudes, compared with the response velocity under severe earthquakes, because of the limitation of the capacity of the loading equipment or the dimensions of the test specimens. It is apparent, therefore, that the influence of the loading rate or strain rate, which can occur in actual reinforced concrete structures during severe earthquakes, on the behaviors of reinforced concrete members has not yet been satisfactorily clarified.

The objective of this paper is to establish the fundamental properties of reinforced concrete members subjected to dynamic loading with high loading rates at severe earthquakes. In order to investigate the dynamic behavior of reinforced concrete members and to clarify the effect of strain rate on the properties of reinforced concrete members, dynamic tensile tests on reinforcing steels were carried out, and small scale reinforced concrete specimens were tested under various types of loading, such as monotonic dynamic loading, dynamic cyclic loading, steady-state dynamic base motion and static cyclic loading.

2. INFLUENCE OF STRAIN RATE ON STRESS-STRAIN CHARACTERISTICS OF REINFORCING STEEL

2.1 Outline of Experiment

The stress-strain characteristics of reinforcing steels depend on the magnitude of the strain rate. It has also been clarified that the extent of the influence of strain rate on the stress-strain characteristics differs with the material and the type of the reinforcing steel(1). Therefore, dynamic tensile tests were conducted for the reinforcing steels which are used in the dynamic loading tests of reinforced concrete members.

The specimens used for the tests were such that two plates were welded to the ends of the bar, as shown in Fig. 1. The specimens were tested with a 50 tonf hydraulic jack with a servo valve which was programmed to impose uniform strain

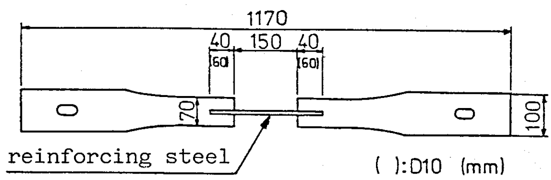

Fig.1 Test specimen for reinforcing steel

Table 1 Test results of dynamic tensile tests of reinforcing steels

		Specimen No.	Strain Rate(1)[1)] (%/s)	Strain Rate(2)[2)] (%/s)	Elastic Modulus[2)] (GPa)	Stress (MPa)		
						Upper Yield	Lower Yield	Ultimate
D6	Monotonic	1	0.05	0.03	225	480	480	570
		2	0.5	0.18	216	485	485	584
		3	4.6	1.66	206	492	468	574
		4	34.0	12.8	206	577	495	616
		5	40.0	16.0	216	587	498	620
		6	51.9	18.6	225	609	501	615
	Reversed	7	0.05	0.02	186	448	448	549
		8	0.5	0.30	206	461	451	568
		9	5.0	2.30	206	480	470	570
		10	5.3	2.32	196	470	463	571
		11	47.6	17.4	196	545	483	588
		12	53.0	18.8	196	561	512	607
D10	Monotonic	13	0.05	0.04	186	349	349	527
		14	0.5	0.18	176	364	364	549
		15	4.7	1.64	186	411	388	561
		16	28.4	9.05	186	462	412	564
		17	32.0	—	—	433	394	571
		18	51.9	20.7	167	488	401	550
	Reversed	19	0.05	0.02	167	352	351	517
		20	0.55	0.29	167	359	350	544
		21	0.49	0.22	176	351	342	521
		22	4.8	1.53	186	390	370	553
		23	5.0	1.91	186	376	373	550
		24	49.0	17.1	186	453	399	582
		25	47.5	17.2	186	438	391	590
		26	48.0	17.3	176	417	379	566

Note
1):Measured by displacement transducer
2):Measured by strain gauge

rates in the specimens. The strain caused in the specimens was measured by two different methods, using a wire strain gage of length of 2 mm and using a displacement transducer of length of 50 mm attched to the specimen. Using this system, the specimens were tested at the constant strain rates of 0.05, 0.5 and 50.0 %/sec, and the resulting stress-strain relationships were recorded on a data recorder.

Two loading methods were used in the dynamic tensile tests. One was monotonic tensile loading in one direction and another was cyclic tensile loading in one direction. In the cyclic tensile loading, the specimens were unloaded to the point of zero force after the strain of the reinforcing steel reached 2.0, 4.0, and 10.0 %, and ten cycles of tensile loading with reversal were repeated from the point of zero force to each of the strain levels described above. Table 1 shows the test results.

2.2 Experimental Results

Figure 2 shows an example of stress-strain relations obtained from the monotonic tensile tests. Figure 3 quantitatively indicates the influences of strain rate on the yield stress. Both the yield stress and the ultimate strength increase with increasing strain rate as long as the strain remains in the plastic range. Particularly, a significant increase was observed in the yield stress, which amounted to about 25 % for a strain rate of 20 %/sec. However, increasing the rate of strain had a negligible effect on the initial stiffness of the specimens. These results are almost the same as those previously reported.

Figure 4 shows an example of the stress-strain relationships obtained from the cyclic tensile tests. The envelope curves of the stress-strain relationship at the first cycle of every strain level almost agree with the ones obtained from the monotonic tensile tests when both the strain rates are the same value. That is, the yield stress and the ultimate strength under dynamic cyclic

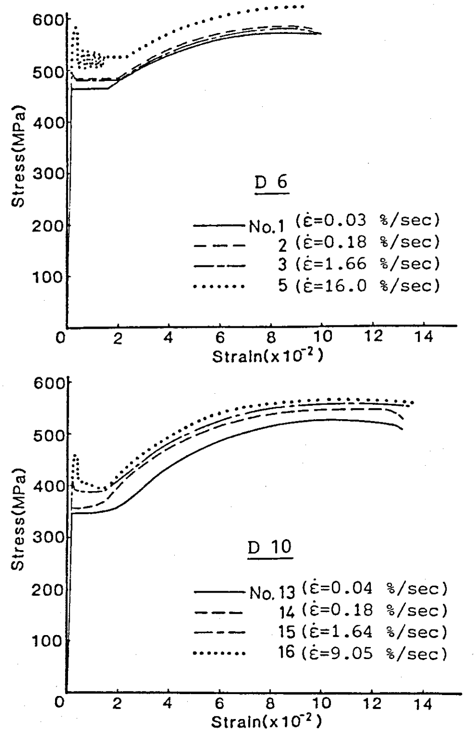

Fig.2 Stress-strain relationships (dynamic monotonic load)

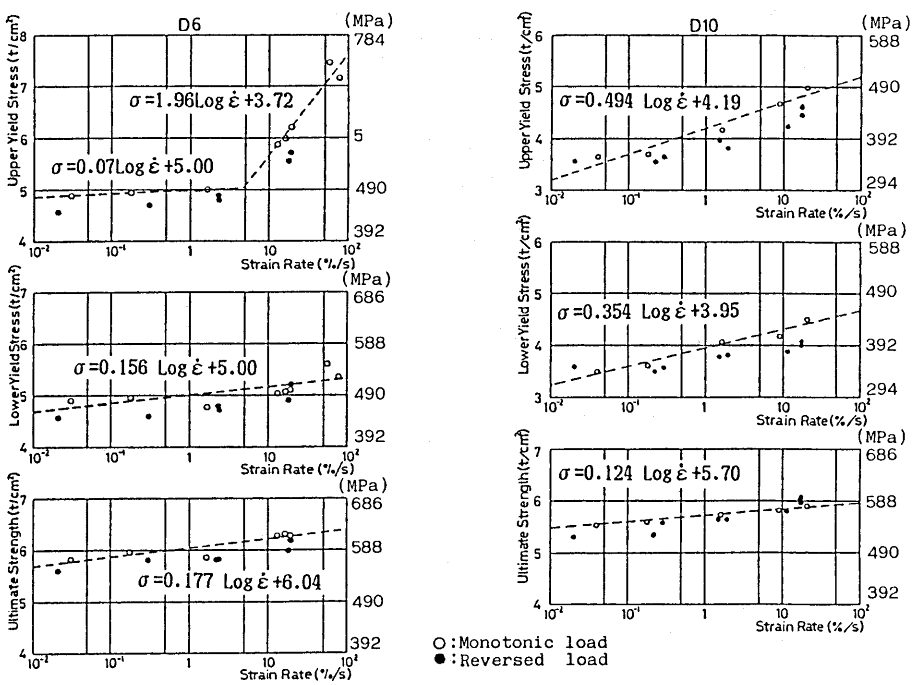

Fig.3 Influence of strain rate on yield stress and ultimate strength

loading also increase with increasing strain rate. However, the stress at the point at which the strain begins to decrease in one cycle (hereafter, this point will be called the turning point) doesn't increase but almost coincides with the statically loaded stress. The strain rate at the turning point of the stress-strain curves under dynamic cyclic loading is considered to be negligibly small. For this reason, the influence of the strain rate on the stress at the turning point may be considerably small. Furthermore, it was also observed in all specimens under cyclic tests that the stress at the turning point has a tendency to decrease with increasing the number of repetitions of tensile loading.

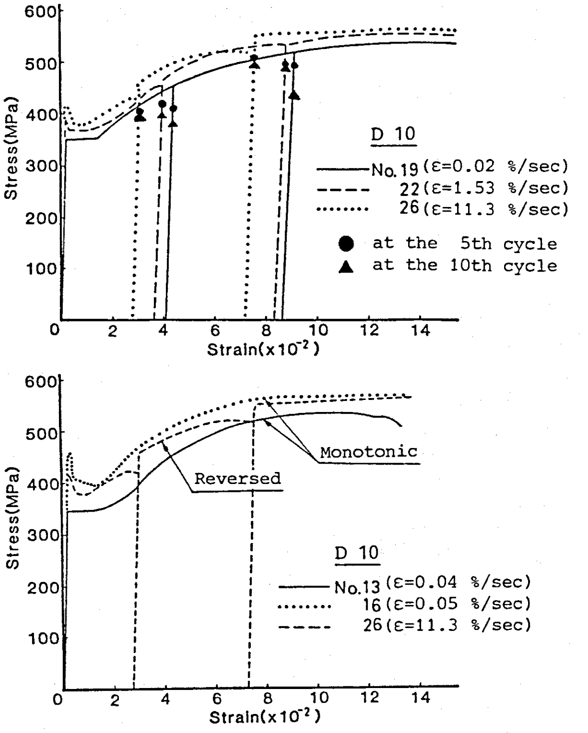

Fig.4 Stress-strain relationships (dynamic cyclic load)

3. LOAD-DISPLACEMENT CHARACTERISTICS OF REINFORCED CONCRETE MEMBERS SUBJECTED TO DYNAMIC LOADING

3.1 Test Program

The specimens, of which cross section was 10x15 cm and heights were 60 cm and 40 cm, were used in the tests, as shown in Fig 5. The shear span ratios of these specimens were 7.0 and 4.5, respectively. Table 2 describes the properties of the specimens. Two types of loading methods were used in the dynamic tests, one being monotonic dynamic loads in one direction and the other being dynamic cyclic loads operated with sine waves. Dynamic loads were applied at the top of the specimen and the loading rates of 0.1(or 0.05), 10 and 100(or 50) cm/sec were adopted as the dynamic loads.

The reason for the adoption of the loading rates described above is as follows; the loading rate of 0.1(or 0.05) cm/sec corresponds to that of the static tests conducted in general, and the loading rate of 100 cm/sec was determined from the maximum response velocity and the strain rate which can occur in actual reinforced concrete structures subjected to severe earthquakes. For example, when a typical reinforced concrete pier of a single column type, of which height is about 7 m, natural frequency is 0.5 sec and yielding displacement is about 2 cm, is subjected to a severe earthquake of a maximum base acceleration of 350 gal, the maximum response velocity calculated by Umemura's spectrum(13) is about 100 cm/sec. Based on these values, the time for the displacement at the top of the pier to reach the yielding displacement can be estimated to be about 0.02 sec. On the other hand, in case of the specimens

Table 2 Properties of specimens for dynamic tests

Specimen	Type	Tensile Reinf. Ratio (%)	Shear Reinf. Ratio (%)	Nominal Loading Rate (cm/s)	Loading Method	Compressive Strength of Concrete (MPa)
DA-1	I	0.8	0.1	0.1	Monotonic	26.0
DA-2				100.0		
DB-1				0.1	Reversed	35.3
DB-2				10.0		
DB-3				100.0		34.6
DC-1	II	1.18	0.09	0.1	Monotonic	28.9
DC-2				100.0		
DD-1				0.1	Reversed	37.8
DD-2				10.0		
DD-3				100.0		38.3
DE-1	III		1.50	0.05		21.9
DE-2				50.0		

and the loading rate used in this test, in which the yielding displacement of the specimens is about 0.7 cm and the average displacement rate obtained from the dynamic tests is about 80 cm/sec, it takes about 0.01 sec to reach the yielding displacement. That is, the loading rate of 100 cm/sec is high enough to investigate the effect of the loading rate. The displacement amplitude at the top of the specimen and the frequency for the dynamic cyclic loading were determined so that the displacement rates could satisfy the loading rates mentioned previously(see Table 3). The displacement amplitudes were taken as always equal to the integral multiples of the yield displacement, and the number of the repetitions at a certain displacement was 10 cycles. The loading program is shown in Fig. 6.

When the dynamic cyclic load is applied at the top of the specimen, the inertia force, which is given as the product of the acceleration in the loading direction and the mass of the equipment fixed at the top of the specimen (including the mass of the equipment fixed in the exterior of the load cell at the tip of the actuator) and the column of the specimen, is produced horizontally. In addition to this horizontal inertia force, a vertical inertia force is also produced because the actuator moves up and down in a vertical line, so that the vertical inertia force is applied to the specimen as an eccentric load. Such an eccentric

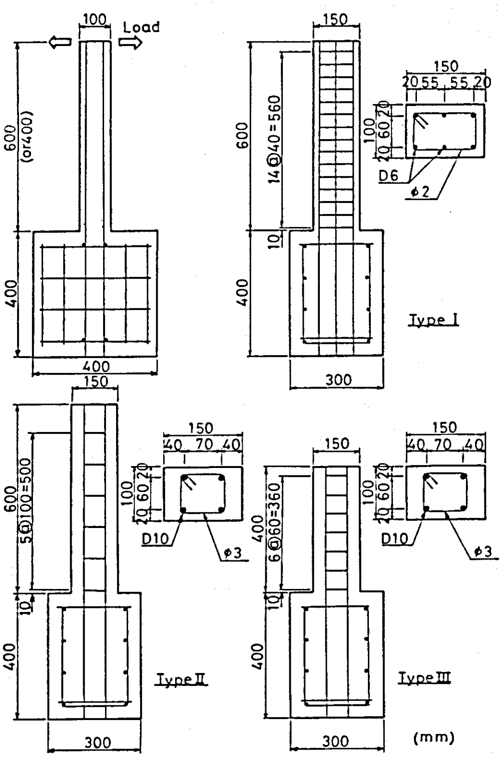

Fig.5 Details of test specimens for dynamic tests

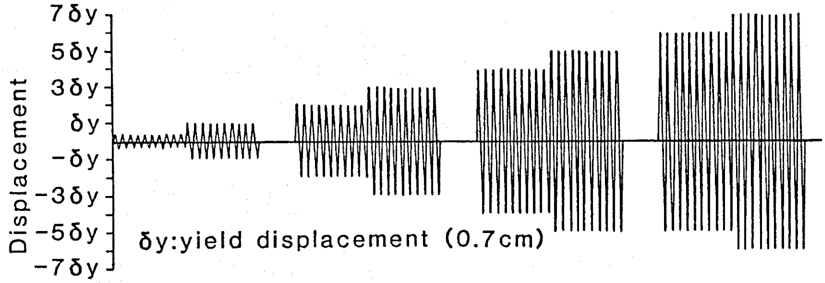

Fig.6 Loading program (specimen DB)

load in the loading rate of 100 cm/s is very large and significantly influences the behavior of the specimen. Therefore, the actuator was fixed horizontally, and a device capable of rotating and moving up and down was installed at the tip of the actuator so that the vertical inertia force would not be produced. The loading system for the dynamic loading tests is shown in Fig.7.

Table 3 Example of input frequency for dynamic cyclic tests (specimen DB)

Nominal Loading Rate (cm/s) \ Displacement (cm)	—	δy	2δy	3δy	4δy	5δy	6δy	7δy
	0.2	0.7	1.4	2.1	2.8	3.5	4.2	4.9
0.1	0.08	0.023	0.011	0.008	0.006	0.005	0.004	0.003
10.0	8.0	2.3	1.1	0.8	0.6	0.5	0.4	0.3
100.0	30.0	22.7	11.4	7.6	5.7	4.5	3.8	3.2

(HZ)

3.2 Measuring System and Procedure of Processing Data

Figure 8 shows the system for measuring data and the procedure for processing data. All the data obtained from the experiments were recorded on the data recorder, and were transformed into digital data through the A/D converter. In transforming analog data into digital data, the time interval of sampling was determined so that the number of the sampled data at one measuring point was about 60 in one hysteresis curve.

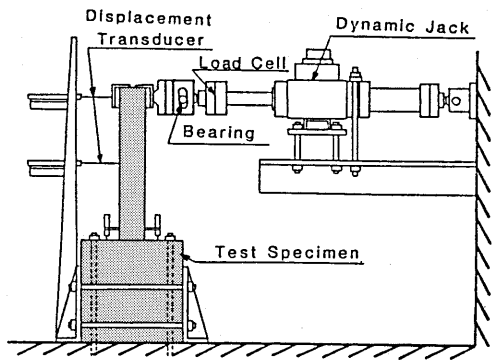

Fig.7 Loading system for dynamic test

In order to obtain the resisting force under dynamic cyclic loading at high loading rates, the horizontal inertia force described previously cannot be disregarded. Therefore, the influence of this horizontal inertia force was taken into account using Eq. (1),

$$Pt = Pot - (W1 + W2 + W3) \times \ddot{X}t \quad \text{-----(1)}$$

in which Pt=the resisting force acting on the specimen at time t; Pot=the force measured by the load cell at time t; W1=the mass of the equipment fixed at the top of the specimen; W2=the mass of the equipment fixed in the exterior of the load cell at the top of the actuator; W3=(the mass of the column)x33/140; $\ddot{X}$t=the acceleration at the top of the specimen at time t. The force given by Eq. (1), that is Pt, is regarded as the dynamic load in the dynamic cyclic loading tests.

Since high frequency waves due to the noises of the loading apparatus and the measuring instruments were included in the data, disorder of the wave was observed for the loading rates of 100 cm/sec and 50 cm/sec. In order to obtain the real data, the high frequency waves were eliminated from the digitized data using Hanning's digital filter. In this case, the number of applying the filter was determined so that the fourier spectrum of the dynamic loads calculated by Eq. (1) is almost equal to that of the displacement obtained from the experiments.

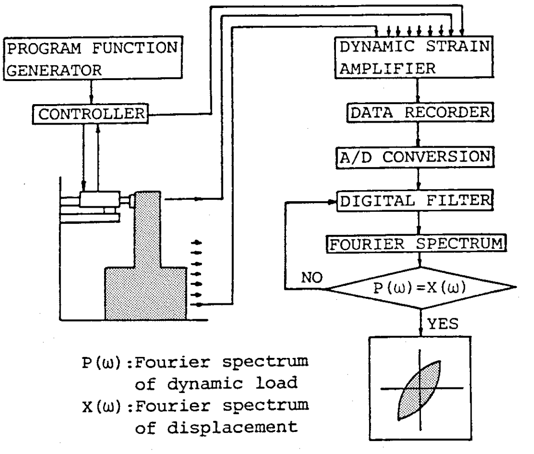

Fig.8 Measuring system and procedure of processing data

3.3 Influence of Loading Rate on Load-Displacement Characteristics under Monotonic Dynamic Loading

Figure 9 indicates the load-displacement curves obtained from the monotonic dynamic loading tests. The initial stiffness, the yielding strength and the maximum strength under dynamic loading are considerably higher than those under static loading. In order to clarify these causes, the yielding strength and the maximum strength of the specimen were calculated using the yield stresses determined from the measured strain rate of the reinforcing steel at the root of the column and Fig. 3. In this case, the strength of the concrete may also increase with loading rate. Since the longitudinal reinforcement ratio of the specimens used in this study is very small, however, the influence of the increase of the strength of concrete on the strength of the specimens is small. Therefore, only the change of the stress-strain relationship of the reinforcing steel due to strain rate effect was taken into account to calculate the strength of the specimens. Table 4 indicates the experimental results and the calculated value. The calculated values agree well with the observed ones. That is, the strength of reinforced concrete members under the monotonic dynamic loading depends considerably on the loading rates, and it is possible to calculate the strength

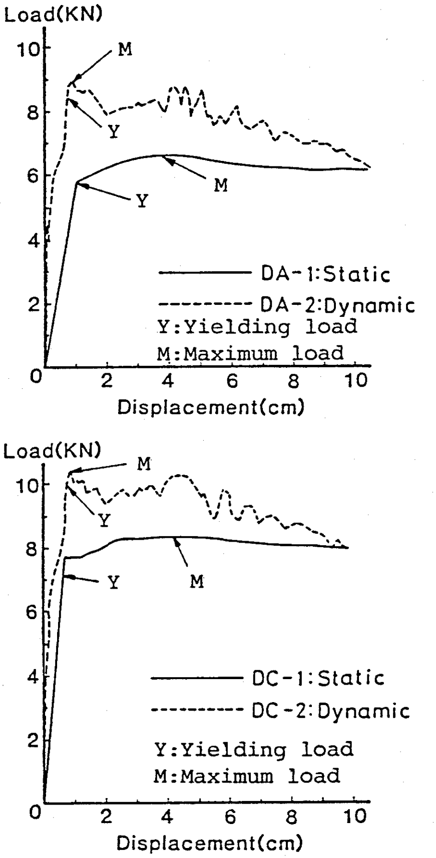

Fig.9 Load-displacement curves obtained from monotonic dynamic tests

Table 4 Measured and calculated values

Specimen No.	Yielding Load (KN) [1)]		Maximum Load (KN)		Measured Displacement Rate (cm/s)	Strain [2)] Rate (%/s)
	Measured	Calculated	Measured	Calculated		
DA-1	5.79	5.50	6.62	6.13	0.1	0.02
DA-2	8.33	7.61	8.85	7.86	76.0	28.0
DC-1	7.15	7.29	8.33	7.66	0.1	0.04
DC-2	9.97	9.82	10.23	10.12	77.0	25.0

1) Load at yielding of longitudinal bar.
2) Measured by strain gauge at yielding of longitudinal bar.

of the reinforced concrete members by considering the increase of the stress of the reinforcing steel due to the strain rate effect.

3.4 Influence of Loading Rate on Load-Displacement Characteristics under Dynamic Cyclic Loading

Figure 10 shows the hysteresis curves obtained from the dynamic cyclic loading tests on specimens of DD-1,2,3 and DE-1,2 indicated in Table 2. These hysteresis curves are the ones for the first cycle of every displacement amplitude, and the loading rates are 0.1, 10, 100, 0.05 and 50 cm/sec, respectively. Figure 11 shows the skeleton curves obtained from these hysteresis curves.

In regard to the load-displacement characteristics in the loading rates of 0.1(or 0.05) and 100(or 50) cm/sec, the peak loads of the hysteresis curves of 100(specimen DD-3) and 50(DE-2) cm/sec are about 20 % higher than those of 0.1(DD-1) and 0.05(DE-1) cm/sec when the displacement is in the range of dy to 2dy (dy:the displacement at the top of the specimens when the reinforcing steel attains the yield strain; dy were 0.5, 0.55, 0.6, 0.45, 0.45 cm for DD-1, DD-2, DD-3, DE-1 and DE-2, respectively). Since the displacement rate under dynamic cyclic loading becomes zero at the turning point of the hysteresis curves, the strain rate of the reinforcing steel is also considered to be almost zero at that point. Consequently, it is expected that the peak loads at the turning point of the hysteresis curves do not increase compared with the dynamic monotonic loads. In order to clarify the reason for the peak loads becoming higher under dynamic cyclic loading in spite of such an expectation, the time histories of the load, the displacement and the strain of the reinforcing steel at the root of the column were investigated.

Figure 12 indicates the time histories mentioned above. In the case of a loading rate of 100(or 50) cm/sec, the strain of the reinforcing steel at the root of the column progresses from the elastic range into the plastic range when the displacement passes the yield displacement and turns back at the first cycle. At the moment when the strain of the reinforcing steel passes the yield strain, a high magnitude of strain rate is produced, as shown in Fig. 12. In the case of DD-3, for example, the strain rates at the yielding of the reinforcing steels were 11 %/sec in one direction and 16 %/sec in the opposite direction, and in the case of DE-2, the strain rate reached about 23 %/sec. It is evident that the upper yield stress increases by about 20 % when the strain rate is in the range of 15 %/sec to 20 %/sec (see Fig.3). From these facts, it can be concluded that the peak loads of the hysteresis curves increase for higher loading rate even under cyclic loading, mainly because the yield stress of the reinforcing steel increases due to the strain rate effect. However, the differences of the peak

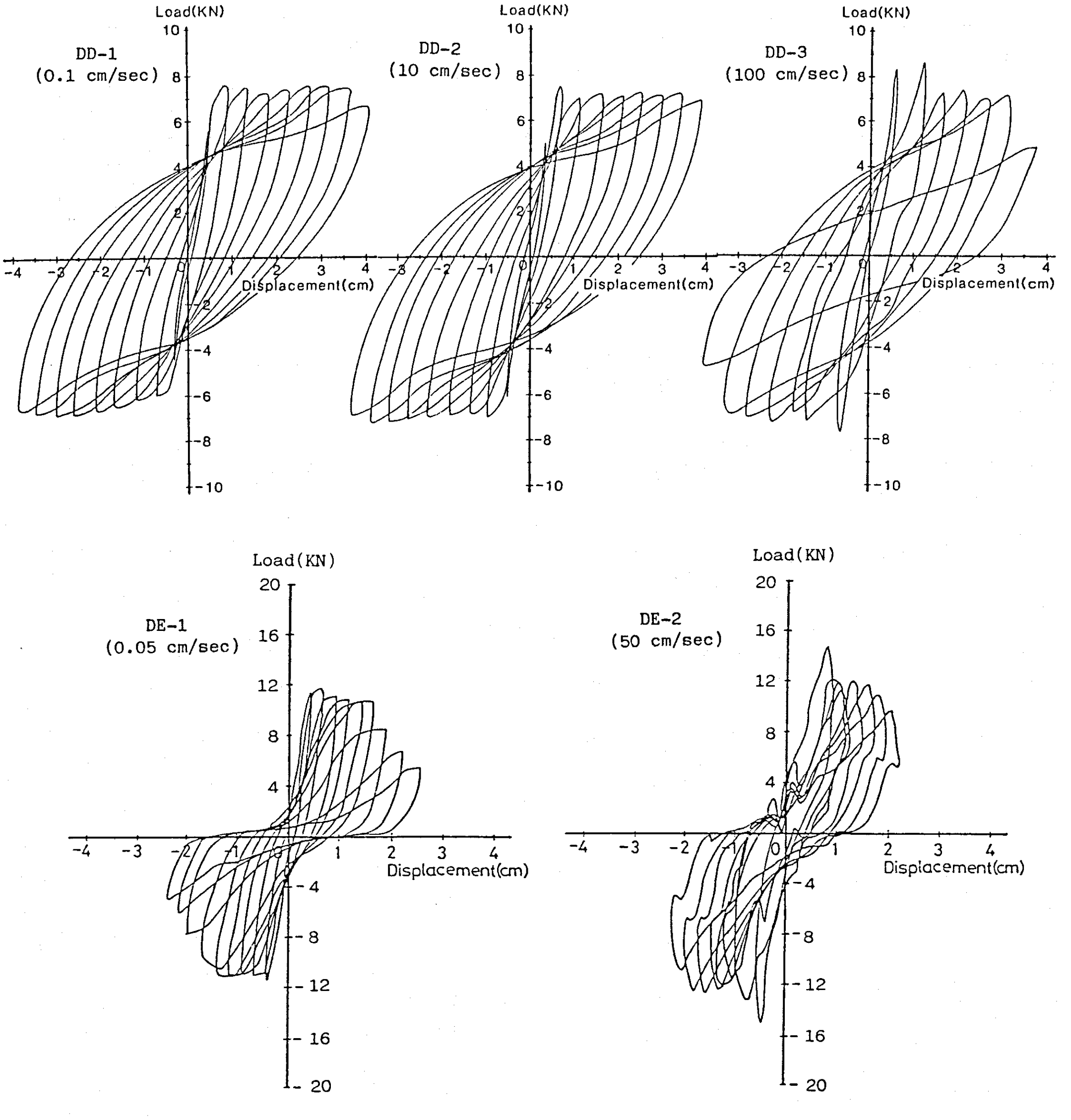

Fig.10 Load-displacement curves obtained from dynamic cyclic tests

loads after the second cycle between the loading rates of 0.1(or 0.05) and 100(or 50) cm/sec are hardly discernible. This is because the strain of the reinforcing steel after the second cycle does not follow the same stress-strain path as experienced at the first cycle, as shown in Fig. 13.

The hysteresis curves of the loading rates of 10 cm/sec(DD-2) show almost the same shape as those of the loading rates of 0.1 cm/sec(DD-1), and the maximum strengths obtained from both curves also indicate almost the same value. In other words, the differences of the load-displacement curves are not recognized between the loading rates of 0.1 and 10 cm/sec. At the moment when the strain of the reinforcing steel at the root of the column passed the yield strain, the magnitude of the strain rate was only about 2.0 %/sec. Therefore, it is

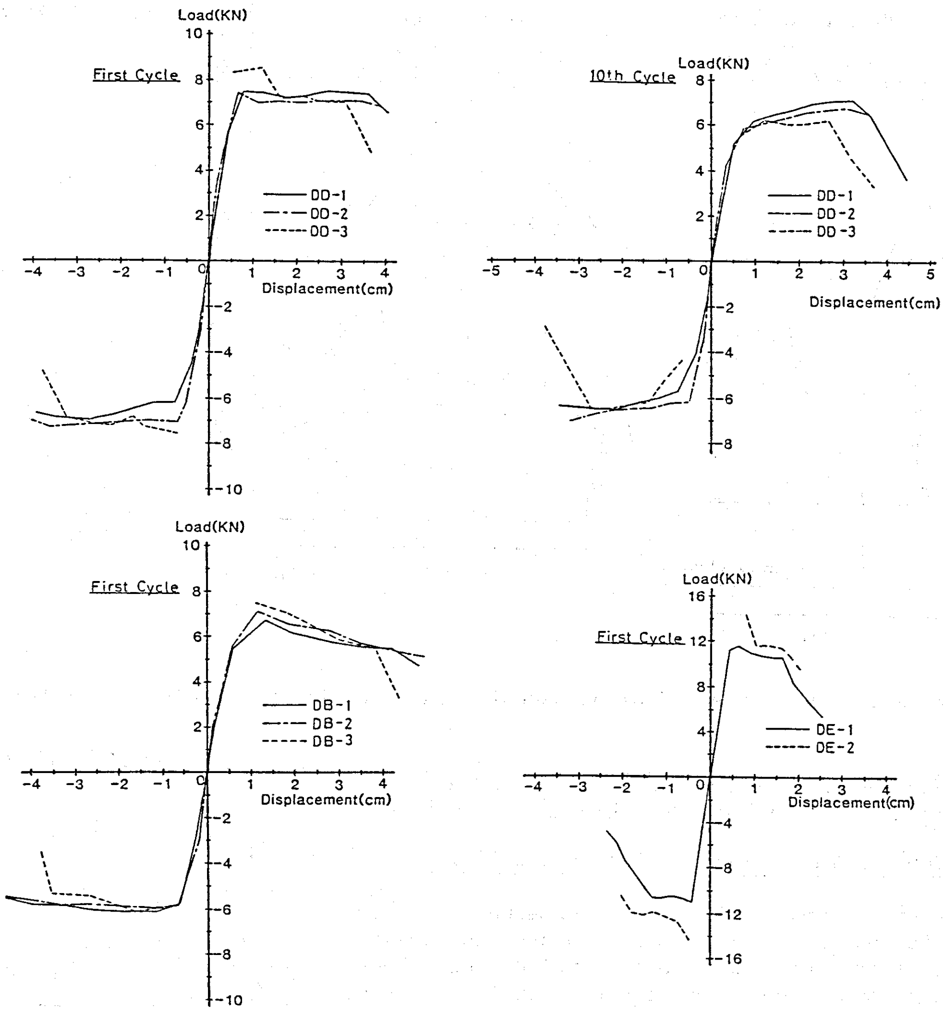

Fig.11 Skeleton curves obtained from dynamic tests

considered that the influence of such a strain rate on the strength of the reinforced concrete member is negligible (see Fig. 3).

When the displacement is larger than 2dy, the hysteresis curves become almost the same shape regardless of the loading rate, and the peak loads also indicate the same value. Since the strain of the reinforcing steel reaches the range of strain hardening when the displacements become larger than 2dy, the increase of the stress due to strain rate effect is considerably small compared with the yield stress (see Fig. 2). Consequently, the strengths of the reinforced concrete members hardly depend on the loading rate in the range of large displacements.

However, it should be pointed out that the load and the ductility decrease suddenly after the maximum strength in the loading rate of 100 cm/sec (DB-3 and DD-3). This fact will be discussed more in detail in Chapter 6.

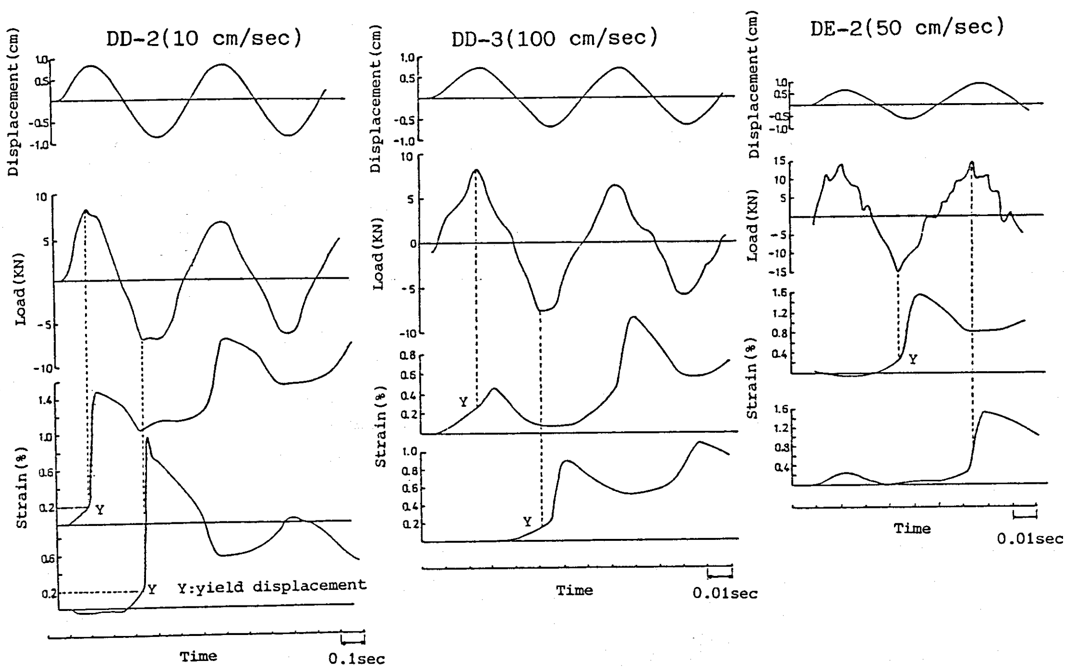

Fig.12 Time histories of displacement, load and strain of reinforcing steel

4. LOAD-DISPLACEMENT CHARACTERISTICS UNDER STEADY-STATE BASE MOTION AND STATIC CYCLIC LOADING

4.1 Shaking Table Test and Static Cyclic Test

In order to confirm the results obtained from the dynamic loading tests described above, the shaking table tests and the static cyclic tests were carried out. The specimens used in the shaking table tests were the same specimens as shown in Fig. 5. Table 5 describes the properties of the test specimens. Six specimens were tested statically, and eight specimens were tested dynamically. In every test, a weight of 833 kgf was installed at the top of the specimen in such a way that this weight is able to rotate around its central axis to eliminate the inertia force due to rotation. The axial stress caused by the weight was 5.5kgf/cm.

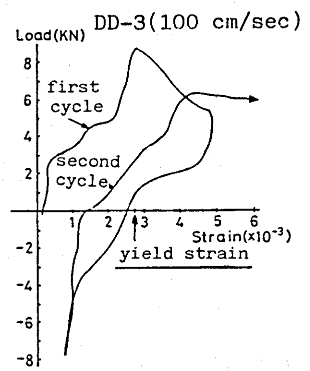

Fig.13 Relation between dynamic load and strain of reinforcing steel (specimen DD-3)

In the shaking table tests, the specimen was fixed on the shaking table at the base, and the shaking table was operated with sine waves. The frequency of the shaking table was decreased stepwise with the measured displacement at the top of the specimen in order that the frequency of the shaking table should be nearly equal to the natural frequency of the specimen, which was obtained from the calculated load-displacement characteristics. That is, the specimens were tested dynamically in a state of the near resonance. The shaking table test was carried out continuously up to failure for each of the specimens.

Table 5 Properties of specimens for shaking table tests and static tests

Specimen	Tensile Reinforcement Ratio (%)		Spacing of Stirrups (cm)		Shear Reinforcement Ratio (%)	Number of Cycles	Loading Method	Failure Mode
SA−1	2XD6	0.53	$\phi 2$	8	0.05	64	D	Flexure
SA−2				4	0.1	105	S, D	
SB−1	3XD6	0.79	$\phi 2$	8	0.05	169		
SB−2				4	0.1	237		
SB−3				3	0.14	565		
SC−1	2XD10	1.18	$\phi 3$	20	0.05	481		Shear
SC−2				10	0.09	1002		
SC−3				8	0.12	1205	D	Flexure

D:Shaking table test, S:Static test

In the static tests, the specimen was fixed at the base, and the reversal horizontal force, which produced a constant horizontal displacement amplitude, was cyclically applied. The number of the repetitions of static loading at a certain displacement was kept the same as the one obtained from the shaking table test. The static loading was continuously always controlled to impose a constant displacement rate of 0.2 cm/sec.

When such a single degree-of-freedom specimen, as shown in Fig. 5, is subjected to steady-state base motion, the equation of dynamic equilibrium is

$$m\ddot{y} + f(y,\dot{y};t) = -m\ddot{u} \quad \text{-----(2)}$$

in which $y,\dot{y},\ddot{y}$=the displacement, velocity and acceleration of the mass relative to the ground, respectively; m= mass; $\ddot{u}$= ground acceleration. The function $f(y,\dot{y};t)$ indicates the resisting force of the specimen, and this force is generally denoted as $(c\dot{y}+ky)$, in which c= viscous damping coefficient, k= elastic stiffness. In this study, the resisting force under the shaking table tests, that is $f(y,\dot{y};t)$ or $-m(\ddot{y}+\ddot{u})$, is defined as the dynamic load.

4.2 Comparison of Load-Displacement Characteristics Under Shaking Table Tests and Static Cyclic Tests

The load-displacement characteristics obtained from the static tests and the shaking table tests are considerably influenced by the number of loading repetitions. To eliminate this influence, the number of loading repetitions at a certain displacement were made not different from each other, as described previously. Figure 14 shows the hysteresis curves obtained from both tests. As these curves are the ones for the first cycle of every displacement amplitude, they are not influenced by the number of the loading repetitions at the same displacement amplitude. When the displacements at the top of the specimen are between dy and 3dy, in which dy is about 0.7 cm, the hysteresis curves obtained from the static tests show a slightly reversed-S shape while those obtained from the shaking table tests show a spindle shape. However, both hysteresis curves become almost the same shape in larger displacements (3dy-6dy). The influences of the loading rates under steady-state base motion on the load-displacement characteristics are considerably small compared with those under dynamic cyclic

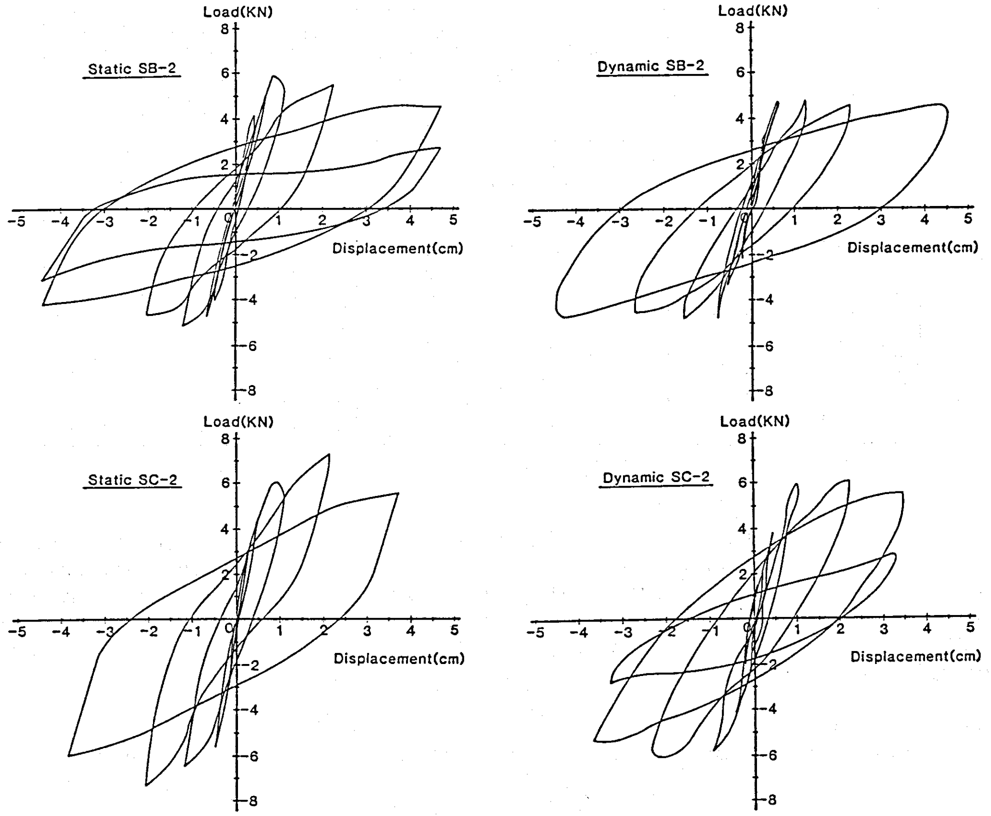

Fig.14 Hysteresis curves obtained from shaking table tests

loads of 100 cm/sec. The reason for this may be considered to be that the maximum loading rate under the shaking table test is about 20 cm/sec, which is much slower than 100 cm/sec. Therefore, the differences between the load-displacement characteristics under the shaking table tests and the static cyclic loading tests are hardly discernible even in the case of the yielding displacement.

5. INFLUENCE OF LOADING RATE ON DAMPING

The damping of reinforced concrete structures subjected to dynamic loading has not yet been completely clarified. A viscous damping, which is generally used, produces a damping force in proportion to velocity relative to the ground. If such a damping force is actually produced, the shape of the dynamic hysteresis loops and the magnitude of the force at the point where the velocity reaches the maximum value in a hysteresis loop must change, depending on the magnitude of the loading rates. In this Chapter, the characteristics of the damping of the reinforced concrete member were investigated using the results obtained from the dynamic cyclic loading tests.

Figure 15 shows the relationship between the displacement and the dissipated energy, i.e., the area within the hysteresis curve at the first cycle of every displacement. As shown in Fig. 15, the dissipated energy increases linearly in

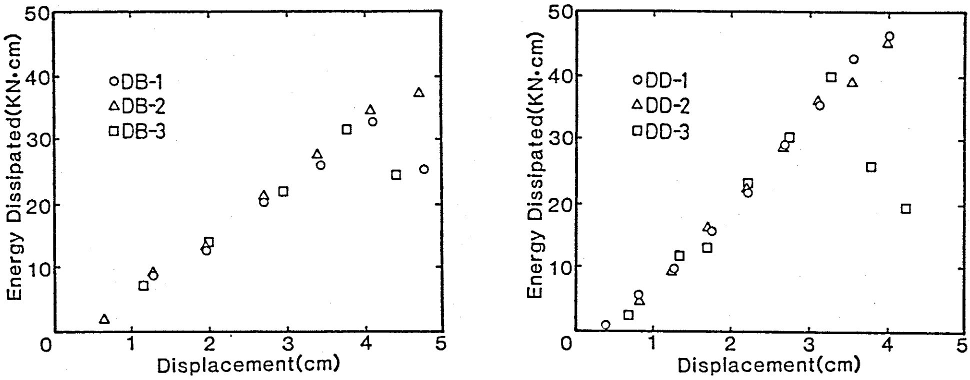

Fig.15 Relation between dissipated energy and displacement

proportion to the magnitude of the displacement. However, the rate of increase of the dissipated energy and the amounts of the dissipated energy at a certain displacement are almost independent of the loading rate. Figure 16 shows the relationship between the input frequency and the equivalant damping factor (heq) at the first cycle of every displacement. If viscous damping is produced in reinforced concretes, the equivalent damping factor should vary with the input frequency. However, the values of the equivalent damping factor at the same displacement amplitude are same regardless of the magnitude of the input frequency. These results show the viscous damping force is insignificant in the reinforced concrete members. Figure 17 shows the relation between the displacement and the equivalent damping factor at the first and the 10th cycle in the loading rates of 0.1, 10 and 100 cm/sec. It is recognized that the equivalent damping factors have a tendency to decrease as the number of the loading repetitions increases. That is, the damping of the reinforced concrete members is influenced by not only the magnitude of the displacement amplitude but also the number of the loading repetitions.

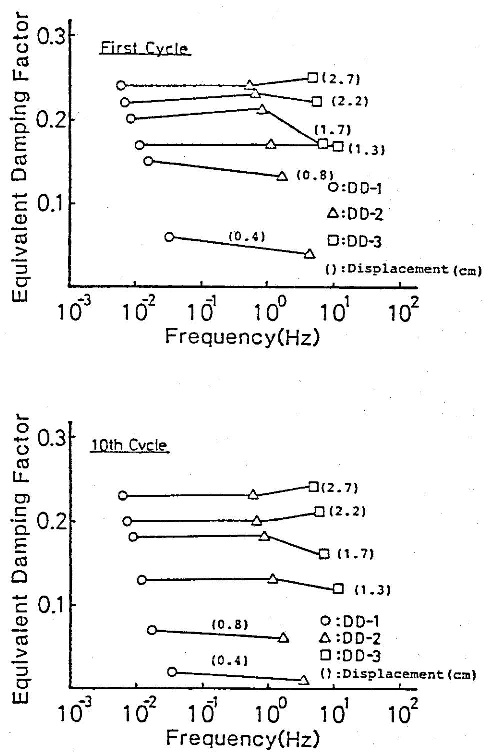

Fig.16 Equivalent damping factor and frequency

6. DISCUSSION ON ULTIMATE FAILURE MODE

It was observed in the dynamic cyclic loading test that the ultimate failure

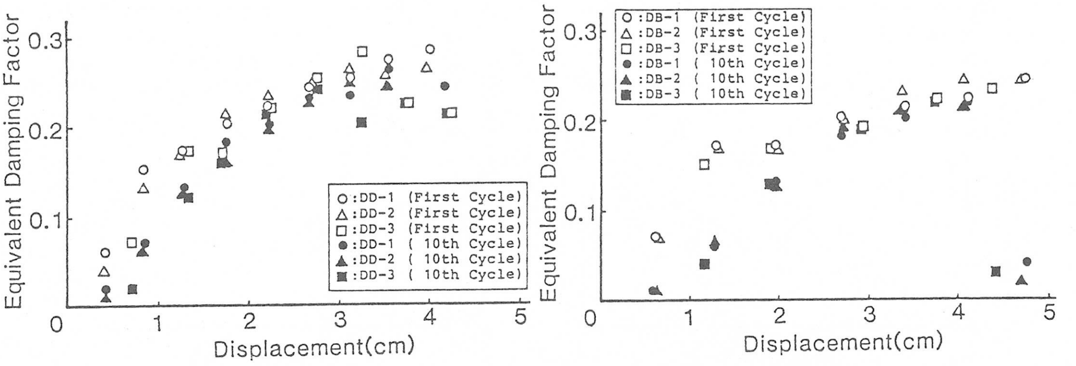

Fig.17 Equivalent damping factor and displacement

mode changed due to the loading rate. That is, specimens DD-1 and DD-2, in which the loading rate were 0.1 and 10 cm/sec, respectively, showed a typical flexural failure, while specimen DD-3 in the loading rate of 100 cm/sec showed a final diagonal tension failure after the reinforcing steel yielded, as shown in Photo. 1. Therefore, the tendency for the load to decrease suddenly in the ultimate state was recognized from the skeleton curves in the loading rate of 100 cm/sec (DD-3), as shown in Fig 11.

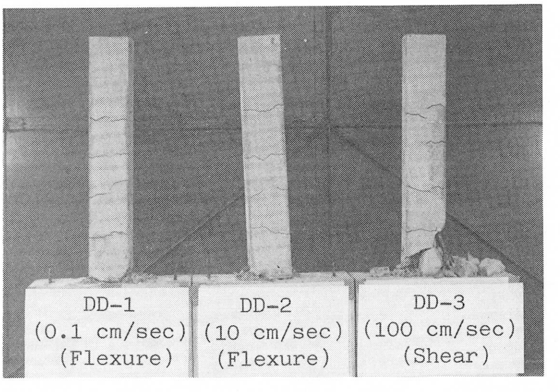

Photo.1 Ultimate failure mode (specimen DD)

Specimens DB-1, DB-2 and DB-3 showed flexural failure regardless of loading rate. However, the same phenomenon as described above, in which the load in the loading rate of 100 cm/sec (DB-3) decreased more rapidly than those in the loading rates of 0.1 and 10 cm/sec (DB-1 and DB-2), was observed.

From these facts, the properties of reinforced concrete members subjected to cyclic loads with high loading rates can be summarized as follows: the load increases at the yielding displacement due to strain rate effect of the reinforcing steel (DD-3 and DE-2), and then the load decreases suddenly and the ductility becomes smaller after the maximum strength (DB-3 and DD-3). Furthermore, the ultimate failure mode may change due to the magnitude of the loading rate (DD-3).

These results are very important for the seismic design of actual reinforced concrete structures because the ductility of reinforced concrete members may decrease with increases in loading rate.

7. CONCLUSIONS

In order to clarify the influence of loading rates on the properties of reinforced concrete members, dynamic tensile tests on reinforcing steels were carried out, and small reinforced concrete specimens were tested under dynamic loading, steady-state base motion and static cyclic loading. It is concluded that;

(1)The yielding strength and the maximum strength of the reinforced concrete members under the monotonic dynamic loads increase considerably with increases in the loading rate. The reason for this can be attributed to the strain rate effect of the reinforcing steel. It is therefore possible to calculate the strength of the reinforced concrete member under the monotonic dynamic loads by considering the increase of the stress of the reinforcing steel due to the strain rate effect.

(2)The peak loads of the hysteresis curves under dynamic cyclic loading become higher than those under static cyclic loading when the displacement is in the range of dy to 2dy. However, the differences of the peak loads due to the loading rate after the second cycle are hardly discernible. Furthermore, when the displacement is larger than 2dy, the hysteresis curves become almost the same shape, and the peak loads also indicate the same value regardless of the loading rate. It is possible to explain these phenomena clearly using the stress-strain relations of the reinforcing steel under dynamic tensile loading.

(3)The influences of the loading rate on the load-displacement characteristics under steady-state base motion are considerably small compared with those under dynamic cyclic loads of 100 cm/sec. The reason for this is considered to be that the maximum loading rate under the shaking table test is much smaller than the loading rate of 100 cm/sec. Therefore, the restoring force of the reinforced concrete member even under base motion may change according to the magnitude of the acceleration and the frequency characteristics of the ground motion.

(4)It was confirmed that the damping of reinforced concrete members was almost independent of the loading rate, and that viscous damping in reinforced concrete members is insignificant. Therefore, the damping of the reinforced concrete member can be evaluated from the static cyclic test.

(5)When the loading rate became higher, it was observed that the load decreased more suddenly and the ductility became smaller after reaching the maximum strength. The ultimate failure mode may change due to the magnitude of the loading rate.

ACKNOWLEDGMENT

The research was supported by the Grant-in-Aid for Scientific Research from the Japanese Ministry of Education. The authors would like to express their sincere thanks to Professors H. Okamura, K. Kobayashi, H. Aoyama, T. Katayama and S. Otani at University of Tokyo. A part of this study was conducted as the joint research by Saitama University and the Public Works Research Institute, Ministry of Construction, Japan.

REFERENCES

(1)Iwai, S., N. Yoshida, T. Nakamura and M. Wakabayashi:Effects of loading rate on the performance of structural elements, Proceedings of AIJ, Vol. 314, 1982,

(in Japanese).
(2)Manjoin, M.J. :Influence of rate of strain and temperature on yield stresses of mild steel, Journal of Applied Mechanics, Vol.11, 1944.
(3)Mogami,T. and J. Kobayashi:Experimental study on strength and deflection of reinforced concrete members under high rate loading," Annual Meeting of Japan architectual Association, 1979, (in Japanese).
(4)Mutsuyoshi,H. and A. Machida:Dynamic properties of reinforced concrete piers, Proceedings of the 6th Japan Earthquake Engineering Symposium, 1982.
(5)Iwasaki,T., R. Hagiwara and T. Koyama:Dynamic behavior of a reinforced concrete bridge pier subjected to cyclic loadings, Proceedings of the 6th Japan Earthquake Engineering Symposium, 1982.
(6)Mutsuyoshi, H. and A. Machida, :Properties and failure of RC members subjected to dynamic loading,: Transactions of JCI, Vol.6, 1984.
(7)Mahin, S.A. and V.V. Bertero:Rate of loading effects on uncracked and repaired reinforced concrete members, Report No.EERC 72-9, Earthquake Engineering Research Center, Univ. of California at Berkeley, 1972.
(8)Takeda,T., N.N.Nielsen and M.A.Sozen:Reinforced concrete response to simulated earthquakes, Proc. of ASCE, ST12, Vol.96, 1970.
(9)Aoyagi,Y.:Fundamental studies on RC beam subjected to impact loading, Cement Gijutsu Nenpo, Vol.19, 1966, (in Japanese).
(10)Mutsuyoshi, H. and A. Machida:Dynamic properties of reinforced concrete piers, 8th WCEE, Vol.6, 1984.
(11)Kotsubo, S.:Vibration in civil engineering, Morikita Publisher Co.
(12)Ohsaki, Y. :Introduction to spectral analysis of earthquake, Kajima Institute Publishing Co., Ltd.
(13)Shibata, A.: Analysis of earthquake resistant structure, Morikita Publisher Co.