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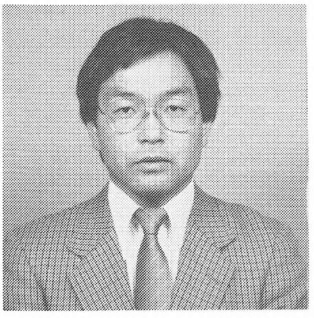
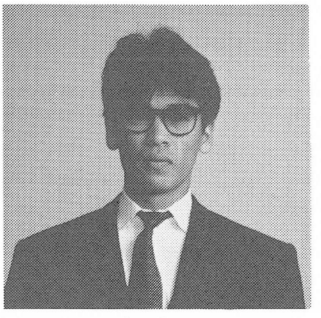
DYNAMIC NONLINEAR EARTHQUAKE RESPONSE OF REINFORCED CONCRETE STRUCTURES BASED ON STRAIN RATE EFFECT





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SYNOPSIS

It has been recognized that behaviors of reinforced concrete members under dynamic loading are different from those under static loading due to strain rate effect of materials (1,2,3,4). This paper describes the effects of strain rate of reinforcing steels on the dynamic response of reinforced concrete structures subjected to earthquakes motions. In order to obtain accurately the dynamic response of reinforced concrete members subjected to earthquake motions, the new force-displacement model was proposed based on the effects of strain rate of reinforcing steels. The dynamic responses, especially accelerations, calculated using the proposed force-displacement model resulted in satisfactory agreement with the measured responses. Furthermore, the influences of strain rate on real reinforced concrete structures subjected to actual earthquakes were clarified using the proposed force-displacement model.

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1. INTRODUCTION

In the past studies on reinforced concrete members subjected to earthquake motions, the experiments for reinforced concrete members have generally been conducted under static loading based on the assumption that behaviors of reinforced concrete members under dynamic loading are equal to those under static loading. Furthermore, the dynamic responses of reinforced concrete structures subjected to real earthquakes have been calculated using the mechanical properties obtained from the static tests and assuming a suitable damping factor. However, each part of concrete and reinforcing steels of reinforced concrete structures subjected to an earthquake have a high magnitude of strain rate because an earthquake is a dynamic load with a repetition of loading. Previous studies have indicated that the strengths of reinforced concrete members under monotonic and reversed dynamic loading were about 20 % higher than those under static loading due to strain rate effect of reinforcing steels (1,2,3,4). It was also reported from the shaking table tests using reinforced concrete members that the response displacement calculated on the basis of the static load-displacement relationship agreed in general with the measured responses except the fact that the maximum values of the measured response accelerations were higher than the calculated values by about 20 % due to strain rate effect (6,7). Moreover, it was observed that the dynamic loads obtained from the shaking table tests using steel members increased remarkably due to strain rate effect compared with the static ones (8).

All these facts indicate that the dynamic response of reinforced concrete structures during severe earthquakes can not be obtained accurately by means of the static load-displacement characteristics. Therefore, in order to calculate accurately the dynamic response of reinforced concrete members subjected to dynamic loading, it may be necessary to modify partially the static load-displacement characteristics considering the increase of the restoring force of the member due to strain rate effect. However, the study on the above problems has not yet been conducted, and the influence of strain rate effect on response behaviors of actual reinforced concrete structures has never been also clarified.

The objective of this paper is to clarify the influence of strain rate effect on the dynamic response behaviors of reinforced concrete members subjected to earthquake motions. To fulfill the above objective, the results of intense simulated earthquake tests using a shaking table were compared with the ones of the dynamic response analysis based on the static load-displacement characteristics. From the comparison, the defect of the static load-displacement model was brought up. To solve this problem, the dynamic load-displacement model was proposed considering strain rate effect of reinforcing steels. Furthermore, the influence of strain rate on the actual reinforced concrete structures subjected to real earthquakes were clarified by means of the proposed load-displacement model.

2. SIMULATED EARTHQUAKE MOTION TESTS

The specimens, of which cross section was 10x15 cm and heights were 60 cm (shear span ratio:a/d=8) and 40 cm (a/d=5.5), were used in the tests shown in Fig.1. Two types of deformed bars, one being 6 mm and the other being 10 mm, provided the longitudinal reinforcements. Plain 2 and 3 mm round bars were used for the closed ties. The amounts of the longitudinal reinforcement and the tie were determined to represent actual reinforced concrete bridge piers. All specimens were made with concrete having a design compressive strength of 300 kgf/cm^2 (29.4 MPa) at 28 days. The maximum size of coarse aggregate was 12.5 mm. Table 1 describes the properties of the specimens. 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 5.5 kgf/cm^2 (0.539 MPa).

The base acceleration history of the motion was patterned after the EL Centro-NS 1940 and the TAFT-NS 1952 earthquakes. To excite the specimens into an inelastic range (about three or four times of the yield displacement), the original time scale was compressed by a factor of 4 and the maximum base acceleration was amplified to 2.0 g. For each specimen, the free vibration test was conducted at first to measure the natural frequency and the initial damping factor, and then the simulated base motion test was carried out. The absolute acceleration at the center of the mass and the base acceleration were measured by accelerometers. The displacement at the mass with respect to the base was measured by linear voltage differential transducers, and the strains of the reinforcing steels at the root of the column were measured by wire strain gages. All the data obtained during the experiments were recorded on the data recorder, and then were transformed into digital data through the A/D converter. The time interval of sampling for transforming analog data into digital data was 0.0012 sec.

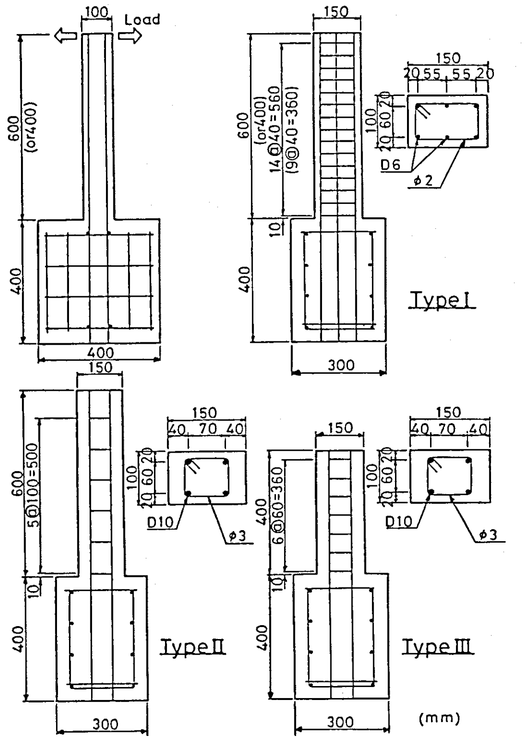


Fig.1 Details of test specimens

Table 1 Properties of specimens

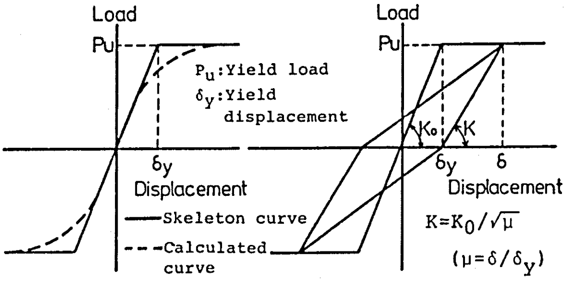
Speci-men No	Type of Speci-men	Height (cm)	Type of Bar, Tensile Re-inforcement Ratio (%)	Shear Rein-forcement Ratio (%)	Type of Earth-quake	Compressive Strength of Concrete (kg/cm^2)
S−1	I	60	3XD6, 0.79	0.1	EL Centro	270 (26.5)
S−2	II	60	2XD10, 1.18	0.09		
S−3	III	40	3XD6, 0.79	0.1		
S−4	III	40	2XD10, 1.18	0.09		
S−5	I	40	3XD6, 0.79	0.1	Taft	300 (29.4)
S−6	I	60	3XD6, 0.79	0.1		

( ):MPa

3. INELASTIC RESPONSE ANALYSIS BASED ON STATIC LOAD-DISPLACEMENT RELATIONSHIP

3.1 Static Load-Displacement Relationship

In determining the static load-displacement relationship, moment-curvature relationship for each section of the column under a constantly increasingly load was calculated by means of the discrete element technique (9), and then the displacement at the mass was calculated by integrating the curvature of each section along the longitudinal axis. The calculated load-displacement curve was further idealized by two lines as a skeleton curve. One was the line which express the elastic state, and the other was the line in the range after yielding, passing through the maximum point of the load and being parallel to the displacement coordinate axis (Fig.2(a)). The degrading bilinear model (10) was used as a hysteresis rule shown in Fig. 2(b). Table 2 describes the yield loads, the yield displacements used for the static load-displacement model of each specimen and the initial damping factors. Fig.3 shows the static load-displacement model described above and the measured load-displacement relationship obtained from the static cyclic loading tests (4). The agreement in Fig.3 was apparently good on the whole and the model for the load-displacement behavior was considered to be accurate enough to use in the response analysis.



(a) (b)

Fig.2 Load-displacement model

The response at the centroid of the mass to the simulated earthquake motions was calculated regarding the specimen as the single degree-of-freedom system. The Newmark's method (β=1/6) was used to integrate the equation of motion numerically, with a time interval of 0.0012 sec. The base accelerations measured from the tests and the damping factors obtained from the free vibration tests at the initial uncracked stage (Table 2) were used in the analysis. Two kinds of damping characteristics were assumed in the analysis. One was an equivalent viscous damping equal to the initial damping factor through the analysis, and the other was no initial damping after the yield displacement. The reason why the two kinds of damping were assumed is that the viscous damping in reinforced concrete members is hardly produced but the hysteretic damping is dominant after the yield displacement (4).

Table 2 Properties for static restoring force model

Specimen No	Yield Load (Pu), (Kgf)	Yield Displacement (δy), (cm)	Initial Damping Factor (%)
S−1	560 (5.49)	0.55	1.7
S−2	614 (6.02)	0.58	1.3
S−3	796 (7.80)	0.27	1.4
S−4	874 (8.57)	0.28	1.7
S−5	796 (7.80)	0.27	1.4
S−6	560 (5.49)	0.55	1.7

Note:1) ( ):KN
2)Yield Load was taken as load when the strain at the compressive extreame fiber of concrete reached 0.0038.
3)Initial Damping Factor was obtained from free vibration tests

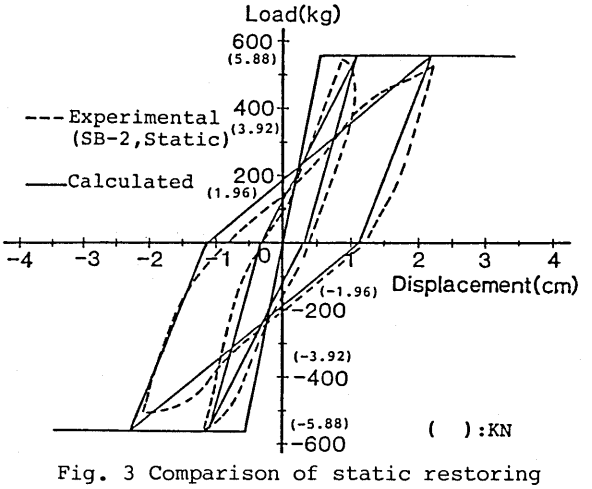
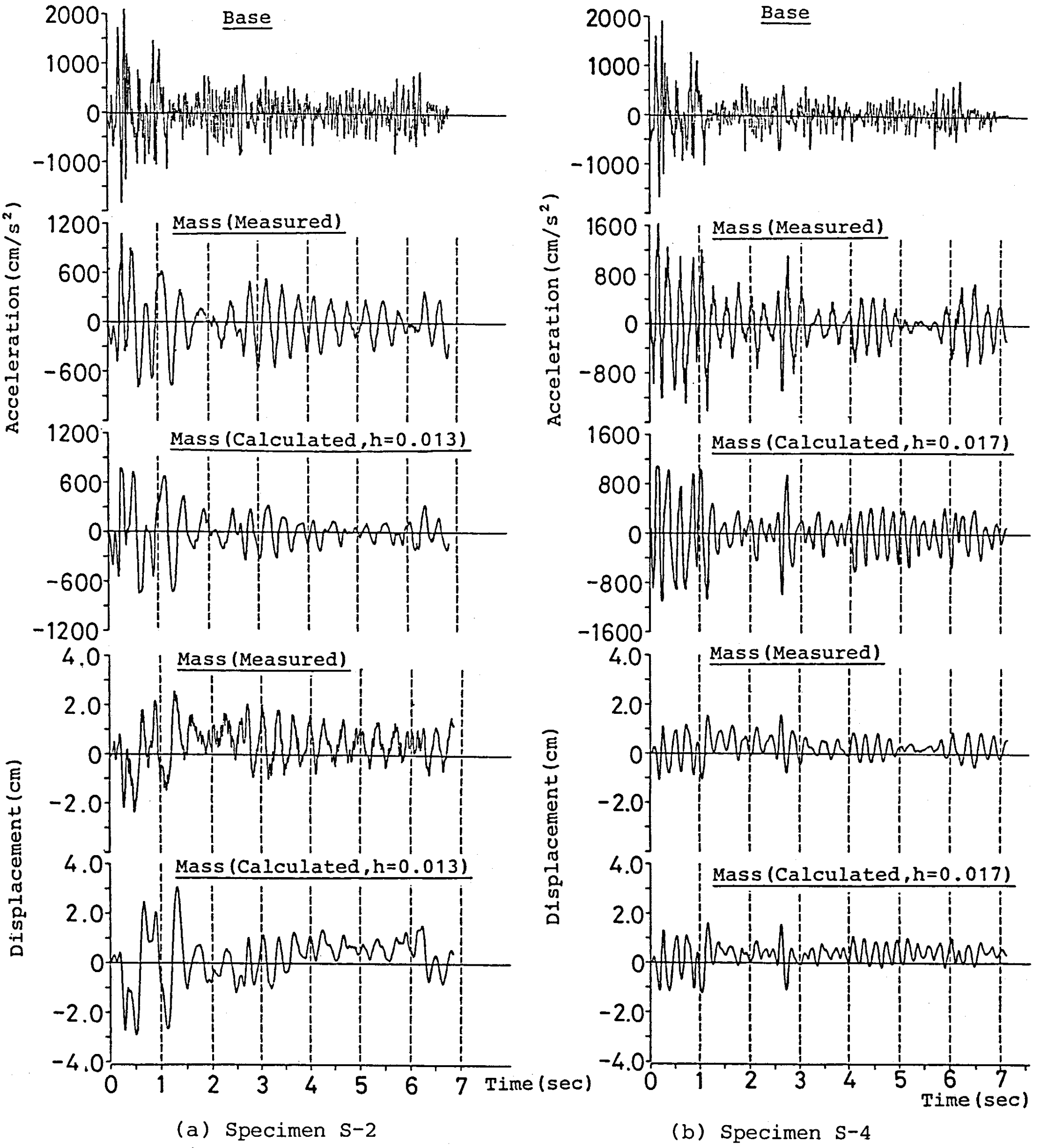


Fig. 3 Comparison of static restoring force model with experimental results

3.2 Problem in Response Analysis Based on Static Load-Displacement Model

Figure 4 shows the measured and calculated response histories. In the case of the calculation, the damping factors indicated in Table 2 were used through the analysis. The calculated responses agreed in general with the measured ones during the tests, as shown in Fig.4. However, the peak points of the measured acceleration were



(a) Specimen S-2 (b) Specimen S-4

Fig.4 Measured and calculated response (static model)

smaller than those of the calculated ones. Table 3 shows the maximum values of the measured and calculated responses for each specimen. It is evident that the maximum values of the measured accelerations are about 20 % higher than those of the calculated ones. These results indicate that the calculated response acceleration based on the static load-displacement model is underestimated. The same results were reported by Takeda and Okada, et al. (6,7).

It has been clarified from the dynamic cyclic tests of reinforced concrete members that the peak restoring force in the load-displacement relationship under dynamic cyclic loading became higher than those under static cyclic

Table 3 Maximum response values obtained from experiments and analyses (static model)

Speci-men No.	Measured Response						Calculated Response (1)						Calculated Response (2)					
	Displacement (cm)			Acceleration (gal)			Displacement (cm)			Acceleration (gal)			Displacement (cm)			Acceleration (gal)		
	Plus	Mi-nus	Aver-age	Plus	Mi-nus	Aver-age	Plus	Mi-nus	Aver-age	Plus	Mi-nus	Aver-age	Plus	Mi-nus	Aver-age	Plus	Mi-nus	Aver-age
S−1	2.9	2.7	2.8	779	826	802	2.6	2.6	2.6	702	659	681	2.3	2.5	2.4	702	688	695
S−2	2.6	2.4	2.5	1077	798	938	3.4	2.9	3.1	772	722	747	3.1	2.9	3.0	772	753	763
S−3	1.6	1.4	1.5	1465	1141	1303	0.8	3.1	1.9	936	948	942	0.7	2.9	1.8	1002	955	978
S−4	1.6	1.1	1.3	1633	1409	1521	1.8	1.6	1.7	1075	1028	1051	1.6	1.3	1.4	1075	1092	1083
S−5	1.6	0.8	1.2	1104	1304	1204	1.9	0.9	1.4	948	936	942	1.2	1.3	1.3	974	962	968
S−6	1.5	1.5	1.5	821	810	815	2.0	1.1	1.5	682	659	671	1.9	1.1	1.5	682	700	691

Note:1)Calculated Response (1):without initial damping after yield displacement
2)Calculated Response (2):with initial damping through analysis
3)Mass acceleration measured by accelerometers mounted on both sides (plus and minus) of mass.
4) S−1～S−4 : EL Centro, S−5～S−6 : Taft

loading due to strain rate effect of reinforcing steels (4). Therefore, the reason for the increase of the response acceleration may be attributed to the same phenomenon as described above. In order to clarify this reason in detail, the time histories of the response acceleration, displacement and the strain and the strain rate of the reinforcing steel at the root of the column were investigated shown in Fig.5. The segment A-A in Fig.5 shows the maximum value of the calculated acceleration using the static load-displacement model. Noting the points of a,b,c and d in which the acceleration took a peak, the reinforcing steel yielded at first in the point of a, then the acceleration became larger than the segment A-A. Afterward, the strain entered into a large plastic range (the point of b and c), then the large acceleration was produced again. Furthermore, when the strain of the reinforcing steel entered into a larger strain range as not experienced before (the point of d), the acceleration also became larger than the segment A-A which indicates the maximum value of the calculated acceleration based on the static load-displacement model. That is, it was confirmed that a high magnitude of strain rate was produced in the points of a,b,c and d in which the acceleration became larger than the calculated values using the static model. The same phenomena were observed from all the test results.

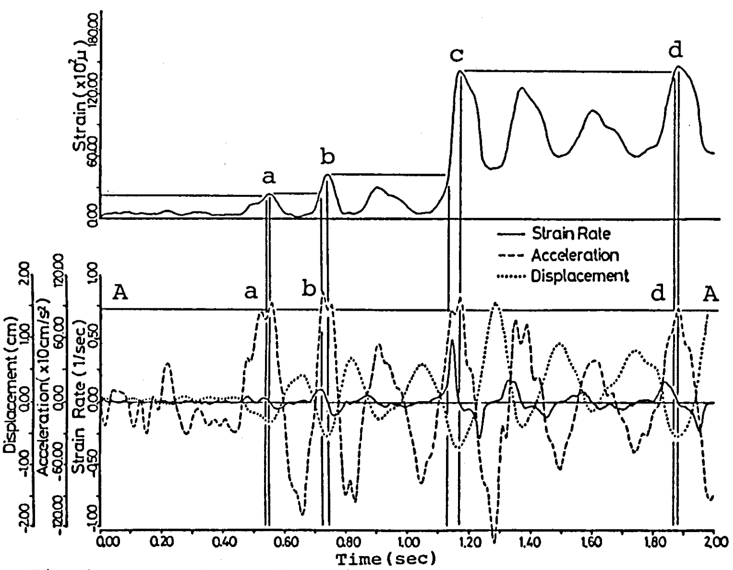


Fig.5 Measured acceleration, displacement, strain and strain rate of reinforcing steels (Specimen S-5)

It has been already recognized from the previous study that the stress of a reinforcing steel under dynamic cyclic tensile loading increased with increasing strain rate when the strain reached the yield strain or entered into a large strain range as not experienced before (4). From this fact, it can be concluded that the reason why the measured peak accelerations became larger than the calculated ones using the static model is because the restoring force of the reinforced concrete member increased due to strain rate effect of the reinforcing steels. That is, under severe earthquake motions as well as under dynamic loading, the strength of reinforced concrete members increased compared with the static strength. Therefore, in order to obtain accurately the dynamic response of reinforced concrete structures subjected to earthquake motions, the load-displacement model based on strain rate effect of reinforcing steels is required.

4. NEW DYNAMIC RESTORING FORCE MODEL BASED ON STRAIN RATE EFFECT OF REINFORCING STEEL

As described above, in order to calculate accurately the dynamic response of reinforced concrete members subjected to severe earthquake motions, it is necessary to modify the static load-displacement characteristics considering the influence of strain rate effect of reinforcing steels. In this Chapter, the new dynamic load-displacement model was proposed taking strain rate effect of reinforcing steels into account, and the validity of the proposed model was examined by comparison of the experimental results with the calculated values using the proposed model. The strength of concrete may also increase with loading rate. Since the longitudinal reinforcement ratio of the specimens used in this study is relatively small, however, the influence of the increase of the strength of concrete on the strength of the member is very small. Therefore, only the influence of strain rate effect of reinforcing steels was taken into account to establish the new dynamic load-displacement model.

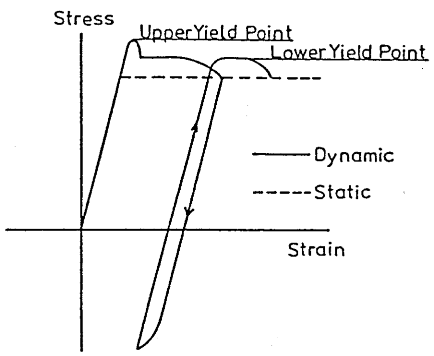


Fig.6 Stress-strain relationship of reinforcing steel under dynamic cyclic loading

The new dynamic load-displacement model was determined on the basis of the following assumptions.

(1) Restoring force of the reinforced concrete member used for the dynamic load-displacement model depends on the increase of the upper and lower yield stress of the longitudinal reinforcing steels due to strain rate effect. When the restoring force attains the static yield strength at the first time, the increase of the upper yield stress of the reinforcing steels is applied for the dynamic model. In the case of reloading over the static yield strength at the second cycle, the increase of the lower yield stress is

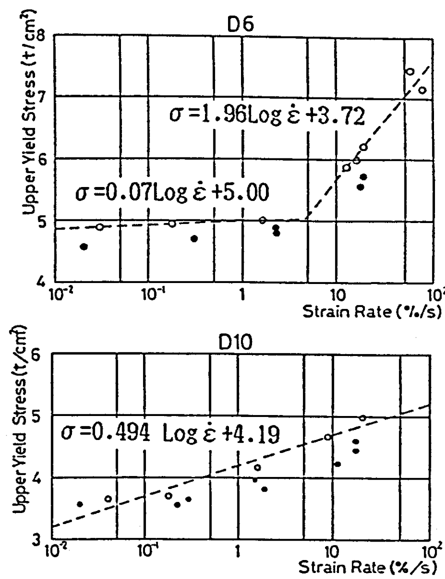


Fig.7 Upper yield point and strain rate relationship

applied for the dynamic model. Furthermore, in the case of reloading more than three cycles at the same displacement, the static yield stress is used (see Fig.6).
(2) When the restoring force is smaller than the static yield strength, the influence of strain rate effect is not considered.
(3) In determining the dynamic model, the static load-displacement model is modified step by step by the increase of the flexural restoring force of the member due to the increase of the yield stress of the reinforcing steel.
(4) The hysteresis rule in dynamic model is generally the same one as used in the static model.

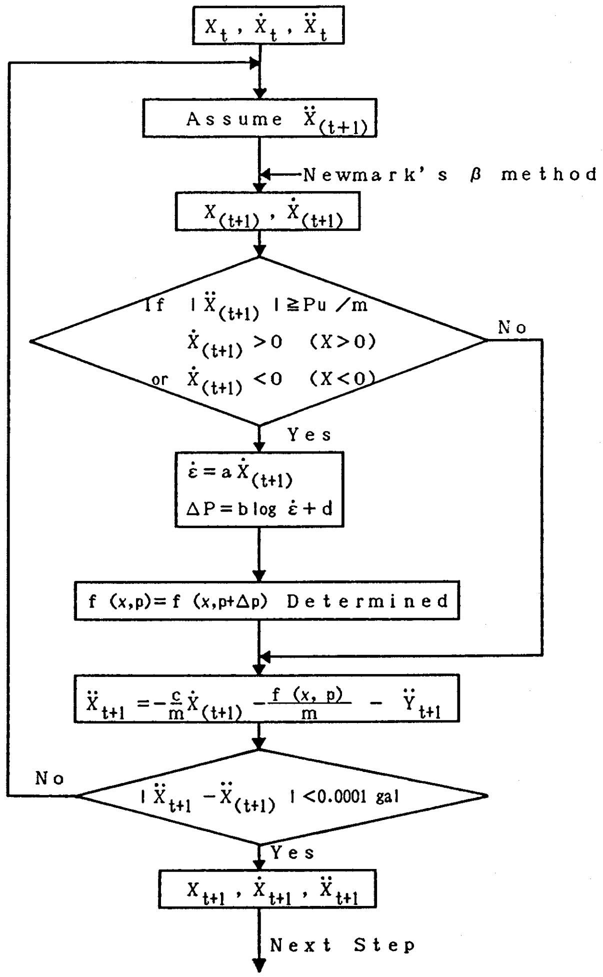
The procedure for establishing the dynamic load-displacement model is as follows; the relation between the displacement at the centroid of the mass and the strain of the reinforcing steel at the root of the column can be calculated by the flexural theory. This relation is indicated in Eq. (1) before the reinforcing steel attains the yield strain,

$$\varepsilon = a * X \text{----------} (1)$$

in which ε=strain of the longitudinal reinforcing steel, X=displacement at the centroid of the mass, a:constant. The relation between the displacement rate and the strain rate can be obtained by differentiating Eq. (1) with respect to time t as indicated in Eq. (2),

$$\dot{\varepsilon} = a * \dot{X} \text{----------} (2)$$

in which $\dot{\varepsilon}$=strain rate, $\dot{X}$=displacement rate. It is assumed that Eq. (2) can be also applicable to the displacement after yielding of the reinforcing steel. The relations between the upper and lower yield stress and the strain rate of the reinforcing steels used in this study is shown in Fig.7 which has been already obtained from the dynamic tensile tests of reinforcing steels (2,4). Once the displacement rate is given, the strain rate is determined by Eq. (2), and then each yield stress is obtained from Fig.7. Consequently, it becomes possible to calculate the dynamic restoring force of the reinforced concrete member considering the increase of the yield stress of the reinforcing steel due to strain rate effect. The dynamic restoring



Note: X_t , $\dot{X}_t$, $\ddot{X}_t$: displacement, velocity and acceleration of mass relative to ground
$\ddot{Y}_t$: base acceleration
f (x, p) : dynamic restoring force
m : weight of mass
c : initial viscous damping factor

Fig 8 Procedure of determination of dynamic model force (P) and the logarithm of strain rate is a linear relation as indicated in Eq.(3) because the yield stress and the logarithm of strain rate relationship is linear as shown in Fig.7,

$$P=b*Log(\dot{\varepsilon})+d \text{---------}(3)$$

in which P=dynamic restoring force considering strain rate effect, b,d:constant.

The dynamic restoring force of the specimen considering strain rate effect can be calculated as described above if the displacement rate at time t is given, and then the static yield strength in the skeleton curve is changed to the dynamic restoring force. Such a modification is carried out step by step at each time after the restoring force reaches the static yield strength in the skeleton curves. Figure 8 shows the procedure of the determination of the dynamic load-displacement model. This procedure was included in the nonlinear earthquake response analysis. Figure 9 shows the dynamic load-displacement model. The rule of the hysteresis curve is generally the same one used in the static model except the point directed in the next reloading. This point was determined from the co-ordinate given by the maximum load and the maximum displacement experienced in the previous cycle, as shown in Fig.9.

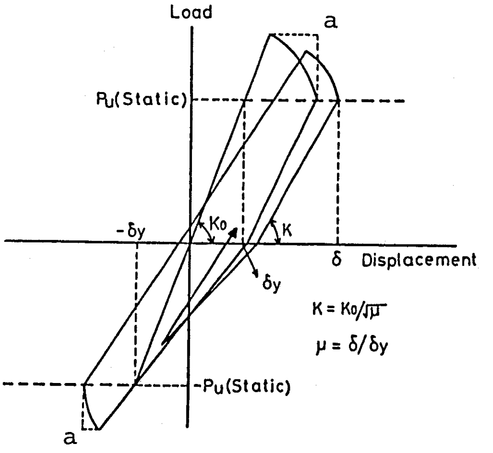


Fig.9 Dynamic load-displacement model

Figure 10 shows the hysteresis curves obtained from the dynamic cyclic loading tests (4) and the dynamic load-displacement model in which the measured displacement rate at each time was used. As shown in Fig 10, the dynamic load-displacement curves using the proposed model show satisfactory agreement with the measured ones. Consequently, in order to estimate

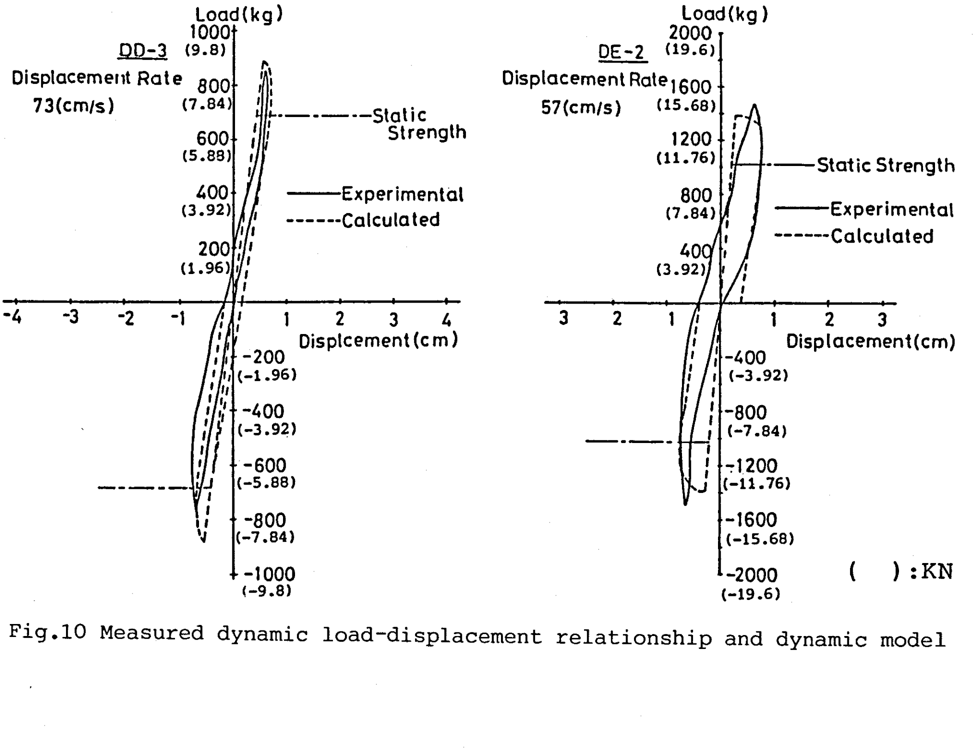
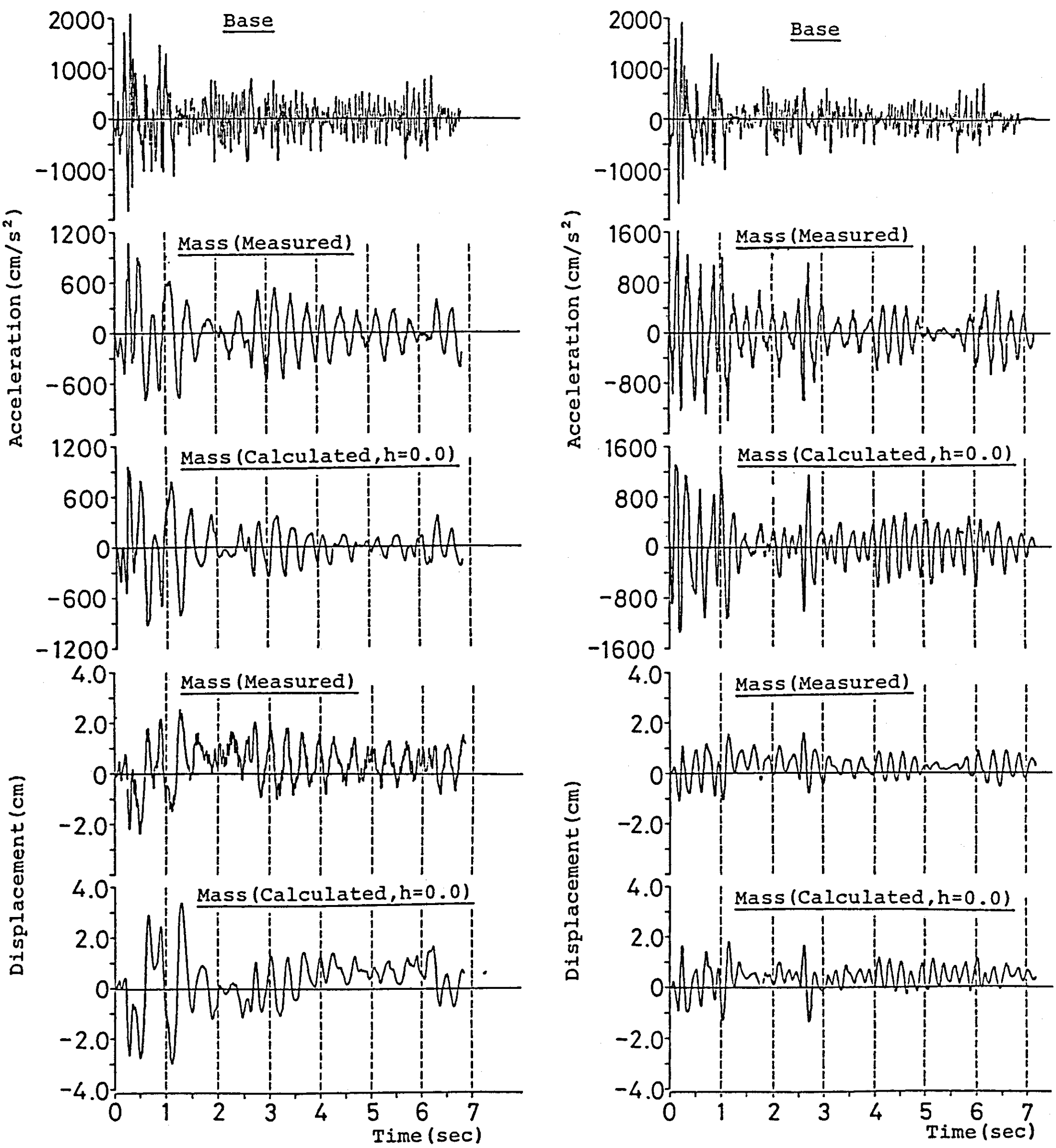


Fig.10 Measured dynamic load-displacement relationship and dynamic model

accurately the dynamic behaviors of reinforced concrete members subjected to dynamic cyclic loading, it is necessary to use the proposed dynamic model.

5. INELASTIC RESPONSE ANALYSIS BASED ON NEW DYNAMIC LOAD-DISPLACEMENT MODEL

In this chapter, the results of the response analysis using the proposed new dynamic load-displacement model are described. The method of the response analysis was the same one as used in 3.1. Figure 11 shows the time histories of the measured base acceleration, response acceleration, response displacement,



(a) Specimen S-2 (b) Specimen S-4

Fig.11 Measured and calculated response (dynamic model)

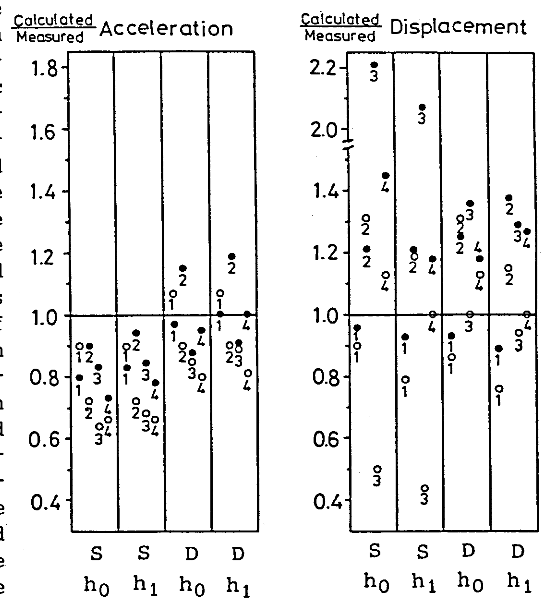
Table 4 Maximum response values obtained from experiments and analyses (dynamic model)

Speci-men No.	Measured Response						Calculated Response (1)						Calculated Response (2)					
	Displacement (cm)			Acceleration (gal)			Displacement (cm)			Acceleration (gal)			Displacement (cm)			Acceleration (gal)		
	Plus	Mi-nus	Aver-age	Plus	Mi-nus	Aver-age	Plus	Mi-nus	Aver-age	Plus	Mi-nus	Aver-age	Plus	Mi-nus	Aver-age	Plus	Mi-nus	Aver-age
S−1	2.9	2.7	2.8	779	826	802	2.5	2.5	2.5	832	804	818	2.2	2.4	2.3	832	828	830
S−2	2.6	2.4	2.5	1077	798	938	3.4	3.0	3.2	964	917	940	3.0	3.3	3.2	965	946	956
S−3	1.6	1.4	1.5	1465	1141	1303	1.6	1.9	1.8	1242	1004	1123	1.5	1.8	1.7	1298	1042	1170
S−4	1.6	1.1	1.3	1633	1409	1521	1.8	1.3	1.6	1313	1342	1328	1.6	1.4	1.5	1329	1415	1372
S−5	1.6	0.8	1.2	1104	1304	1204	1.6	1.3	1.5	1004	983	993	1.2	1.4	1.3	1045	995	1020
S−6	1.5	1.5	1.5	821	810	815	2.1	1.1	1.6	750	806	778	2.0	1.1	1.6	750	843	797

Note: 1) Calculated Response (1): without initial damping after yield displacement
2) Calculated Response (2): with initial damping through analysis
3) Mass acceleration measured by accelerometers mounted on both sides (plus and minus) of mass.
4) S−1∼S−4 : EL Centro, S−5∼S−6 : Taft

the calculated response acceleration and response displacement based on the dynamic load-displacement model without the initial damping after the yield displacement. Note that each peak of the calculated response acceleration using the proposed dynamic model results in satisfactory agreement with that of the measured acceleration, whereas the calculated response acceleration based on the static model was smaller than the measured one. Table 4 indicates the maximum values of the measured and calculated responses. Figure 12 shows the ratios of the maximum values of the calculated response acceleration and displacement to those of the measured ones obtained from the specimen S-1 through S-4. From Table 4 and Fig.12, it is apparent that the maximum values of the calculated acceleration by means of the dynamic model are almost equal to those of the measured one while the maximum values of the calculated acceleration using the static model are about 20 % smaller than the measured ones. That is, the problem in the static model could be solved by using the proposed new dynamic model.

Fig.13 shows the restoring force-displacement relationships obtained from a) the simulated earthquake tests, b) the response analysis by means of the static model with the initial damping through the calcula-



Note: 1) 1∼4: specimen number.
2) ○: response value in plus, ●: response value in minus.
3) S: static model, D: dynamic model.
4) h_0: no damping after yield displacement
h_1: considering initial damping through analysis

Fig.12 Comparison of maximum response values

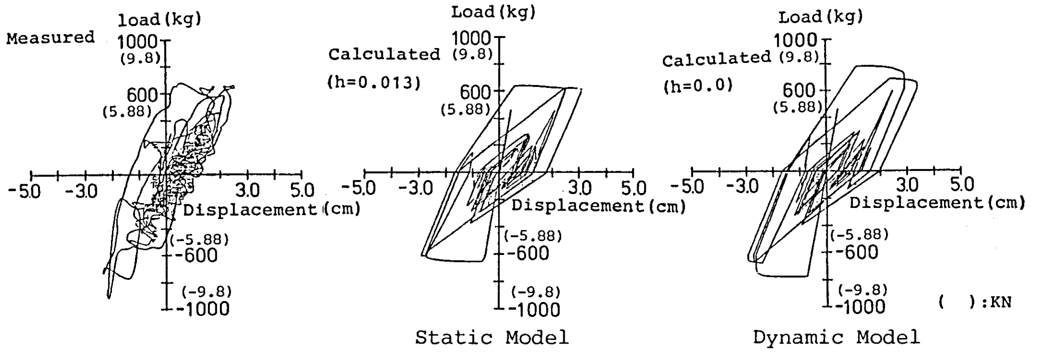


Fig.13 Measured and calculated restoring force-displacement relationship (Specimen S-2)

tion, and c) the response analysis by means of the dynamic model without the initial damping after the yield displacement. In this case, the measured restoring force was determined by the product of the measured absolute acceleration and the weight of the mass. The shape of the calculated restoring force from the dynamic model agrees generally with that of the measured one compared with the calculated restoring force from the static model.

It has been recognized that the calculated response displacement with the initial damping through the analysis agreed in general with the measured one compared with the case of no damping (6). However, how the initial damping is taken into account in the response analysis has not yet been thoroughly clarified though the influence of the damping on the response results was very large. It has been also recognized that the damping produced in reinforced concrete members was not viscous damping dependent on the loading rate but the hysteretic damping caused by the hysteresis curves (4). Therefore, it is doubtful that the initial damping, assumed to be the equivalent viscous damping, should be considered through the response analysis after the yield displacement. As shown in Fig.12, comparing the maximum response displacements calculated by the static model with the initial damping through the calculation (marks of S and h1) with those calculated by the dynamic model without the initial damping after the yield displacement (marks of D and h0), the maximum response displacements in both models are almost equal, and agree satisfactory with the measured values. That is, the dynamic model without the initial damping after the yield displacement has the same effects on the response displacements as the static model with the initial damping through the calculation.

As described above, the problem in the response analysis by means of the static model could be solved by using the proposed new dynamic load-displacement model, and this model is good to obtain accurately the dynamic responses of reinforced concrete members. In other words, it can be concluded that the proposed new dynamic model should represent accurately the actual behaviors of reinforced concrete members subjected to earthquake motions.

6.APPLICATION OF DYNAMIC LOAD-DISPLACEMENT MODEL TO ACTUAL REINFORCED CONCRETE STRUCTURES

It was confirmed that the proposed dynamic load-displacement model was a very effective method to obtain the dynamic responses of the reinforced concrete members. However, as the small test specimens were used in the simulated earthquake tests, the natural periods of the test specimens were smaller than those of the actual structures, and the amplitude of the base accelerations used in the tests was larger than that of actual earthquakes. Thus, the influence of strain rate effect on the dynamic response behaviors may be overestimated because the strain rate of the test specimen become larger compared with that of actual structures. Therefore, it is necessary to investigate the influence of strain rate effect on the actual reinforced concrete structures subjected to actual earthquake motions using the proposed method.

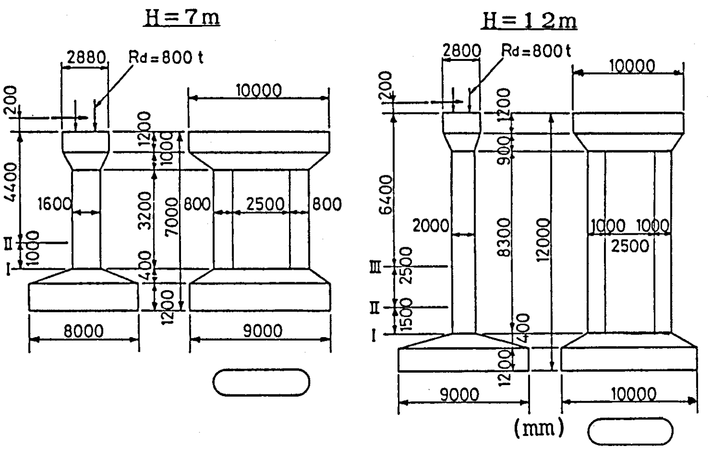


Fig.14 Details of reinforced concrete bridge piers

Table 5 Properties of piers

Type of Pier	Yield Load (tonf)	Yield Displacement (cm)	Weight of Mass (ton)	Natural Frequency (s)
H= 7m	270 (2646)	1.80	857 (8403)	0.48
H=12m	284 (2783)	4.98	898 (8796)	0.80

( ):KN

Two types of actual single-column-type reinforced concrete piers, generally used in Japanese bridges, were used for the response analysis. These heights were 7m and 12m, and the natural frequencies were about 0.5 and 0.8 sec, respectively. The general view and the details of these piers are indicated in FIg.14 and Table 5, respectively. The response analysis was conducted assuming that the piers were a single degree of freedom system. The weight of the mass was the sum of the weight of a span of the girder and the one third of the weight of the pier (13). The static model and the proposed dynamic model were used in the calculation. In this case, the static skeleton curves of these piers were determined from the load-displacement relationship calculated by Ohta (12). As the relation between the strain rate and the yield point of the reinforcing steels used in these piers was unknown, the results of the dynamic tensile test of D19 (deformed bar of diameter 19 mm), which has been already carried out by the authors (2), were used for the dynamic model. The influence of using such a test results on the calculated results is considered to be very small because the relation between the strain rate and the yield point of reinforcing steels doesn't generally differ so seriously with the kind of the reinforcing steel. The EL CENTRO-NS 1940 and the TAFT 1952 N-S earthquakes with the original time scale and the maximum base acceleration of 326 gal were used for the response analysis.

Table 6 indicates the calculated results. The maximum response velocities in the piers of H=7m and H=12m were 40-60 and 60-70 cm/s, respectively. Noting the maximum response accelerations for each pier, the maximum values using the dynamic model are apparently 10-20 % higher than those using the static model. That is, the response acceleration of the actual reinforced concrete structures subjected to earthquake motions becomes considerably larger than that calculated based on the static load-displacement characteristics.

Table 6 Calculated results

Type of Earth-quake	Pier	Displacement (cm)			Velocity (cm/s)			Acceleration (gal)		
		Plus	Mi-nus	Aver-age	Plus	Mi-nus	Aver-age	Plus	Minus	Average
EL Centro	H= 7m	7.5	5.1	6.3	58	46	52	386 (1.25)	373 (1.21)	379 (1.23)
	H=12m	10.7	9.5	10.1	70	70	70	369 (1.19)	367 (1.18)	368 (1.19)
Taft	H= 7m	5.6	4.7	5.2	41	44	42	378 (1.19)	372 (1.20)	375 (1.22)
	H=12m	9.0	9.8	9.4	58	73	66	337 (1.09)	362 (1.17)	349 (1.13)

Note:1)without initial damping after yild displacement
2)( ):ratio of acceleration using dynamic model to that using static model

The influences of the increase of the response acceleration on the reinforced concrete structures are considered as follows. As the actual yield point of reinforcing steels used in general are obviously higher than the nominal values, the actual strength of the structure or the member also becomes larger than the design strength. The increase of the strength described above and of the response acceleration due to strain rate effect may have bad influences on reinforced concrete structures and members. For example, shear force larger than the calculated value in design must act on the structure during earthquake. The followings are pointed out about the mechanical properties of reinforced concrete members under dynamic loading (2,4). That is, the shear strength of reinforced concrete members subjected to dynamic loading increases considerably with increasing loading rate compared with the increasing rate of the flexural strength due to dynamic loading. However, shear failure has a tendency to occur easily because the shear strength after yielding of reinforcing steels decreases suddenly. Therefore, it is necessary to take care to design safely for shear. Moreover, larger forces due to the increase of the response acceleration act on the secondary structures (for example, the shoes at the top of the pier, the tank in the roof of the building and the apparatuses and instruments placed in the building) besides the substantial structure. It is also necessary to take notice of the earthquake resistant design for these structures.

7. CONCUSIONS

In order to clarify the influence of strain rate on the dynamic response behaviors of reinforced concrete members subjected to earthquake motions, the simulated earthquake tests and the response analysis using the new dynamic load-displacement model were conducted. It is concluded that;

(1)It was recognized that the calculated response acceleration, based on the static load-displacement model, of reinforced concrete members subjected to earthquake motions was underestimated because the restoring force of the member increased due to strain rate effect of the reinforcing steels.
(2)The dynamic load-displacement model was proposed based on the increase of the restoring force of the member due to strain rate effect of reinforcing steels. It was confirmed that the proposed dynamic model could simulate satisfactory the dynamic load-displacement characteristics obtained from the dynamic cyclic loading tests of reinforced concrete members.
(3)The response acceleration calculated by means of the proposed dynamic model resulted in satisfactory agreement with the measured response acceleration, while that calculated by means of the static model was smaller than the measured one. That is, the problem in the response analysis based on the static model could be solved by using the proposed dynamic model.

(4)It was observed that the dynamic model without the initial damping after the yield displacement had the same effects on the response displacement as the static model with the initial damping through the analysis. From the test and the calculated results, it can be concluded that the proposed dynamic model represent accurately the actual behaviors of reinforced concrete members during earthquake motions. Therefore, it is necessary to use the dynamic model to obtain the dynamic response of the reinforced concrete structures.
(5)In order to clarify the influence of strain rate effect on actual reinforced concrete structures during real earthquakes, the proposed dynamic model was applied to actual structures. Consequently, it was recognized that the response acceleration of actual reinforced concrete structures also became considerably larger than that calculated based on the static load-displacement model.

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