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VISUAL SIMULATION FOR DYNAMIC RESPONSE OF REINFORCED CONCRETE COLUMNS SUBJECTED TO EARTHQUAKE MOTION

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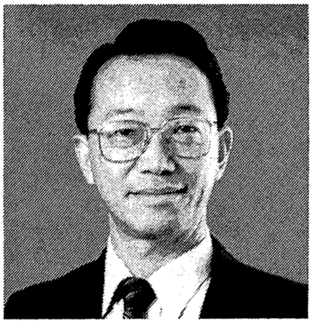

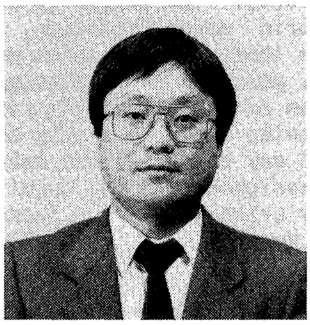

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SYNOPSIS

In order to generate the dynamic response of reinforced concrete structures in a visual manner without a shaking table test, a simulated dynamic response visualization system has been successfully developed. It utilizes a computer-controlled video tape recorder in a pseudo-dynamic testing. By playing the tape, the visual dynamic response can be observed in real time scale, although the experiment is carried out using pseudo-dynamic testing. Visual dynamic simulations of four types of reinforced concrete columns during severe earthquake motion have been carried out using this system, demonstrating that it is a useful means of visualizing the characteristics of ongoing seismic failure.

Keywords : reinforced concrete columns, pseudo-dynamic testing, visual simulation, dynamic response, video tape recorder

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1. INTRODUCTION

Pseudo-dynamic testing is an experimental method in which the dynamic response of a structural system during earthquake motion is obtained by a combination of sequential loading and on-line computer analysis. The pseudo-dynamic testing method was developed by Hakuno, et al.[1] and since then has been used in much research work[2]. The method is also referred to as computer-actuator on-line testing, hybrid experimentation, and the on-line computer test control method[3]. Since loading and on-line computer analysis are carried out alternately at each step, pseudo-dynamic testing takes much longer to yield the seismic displacement than an actual seismic movement would. However, pseudo-dynamic testing has following advantages over shaking table tests: (1) The method can treat specimens of any size; (2) The natural period of the structural system can be arbitrarily assigned; and (3) Ongoing seismic failures can be observed in detail because they arise slowly and loading can be stopped at any time if necessary. On the other hand, since pseudo-dynamic testing is a discrete quasi-static loading method, the dynamic response of the structural system cannot been observed on a real time scale.

In this study, the development of a simulated dynamic response visualization system which generates the dynamic response of a reinforced concrete structural system without shaking table tests was described. The system is based on a computer-controlled video tape recorder(VTR) and pseudo-dynamic testing methods. Using this system, the visual dynamic simulation of four types of reinforced concrete column during a severe earthquake was carried out.

2. FEATURES OF PSEUDO-DYNAMIC TESTING AND VISUALIZATION OF DYNAMIC RESPONSE

As shown in Figure 1, pseudo-dynamic testing (PD testing) was carried out using an acceleration record of an earthquake digitized in 0.02 second intervals (Δt). Since loading is applied according to the analyzed response displacement at each Δt in PD testing, the time required to obtain the designated response displacement at each Δt varies as a result of the conversion process. Also, a reinforced concrete specimen deforms greatly, so the specimen must be connected to the actuator through a hinge to ensure accurate loading. Since it is difficult to avoid longitudinal looseness at the hinge, however, a feedback control system as shown in Figure 2 was introduced. This controls the displacement of the specimen using a displacement transducer attached directly to the specimen. Using this system, the time taken for the displacement to converge is different at each Δt due to the varying number of iterations required, and this is one of

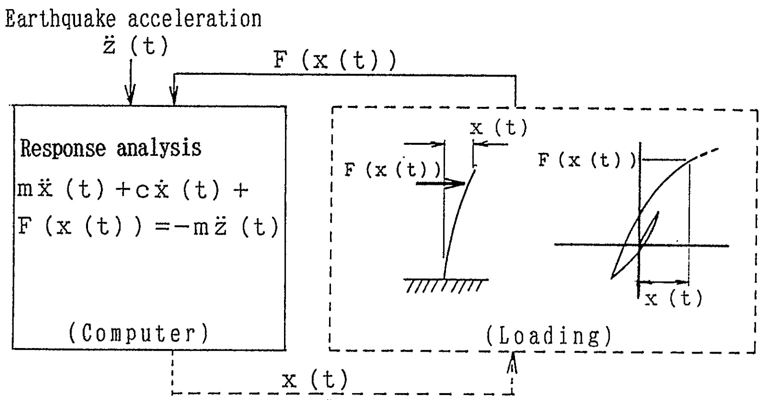


Fig.1 - Conceptual procedure for pseudo-dynamic testing

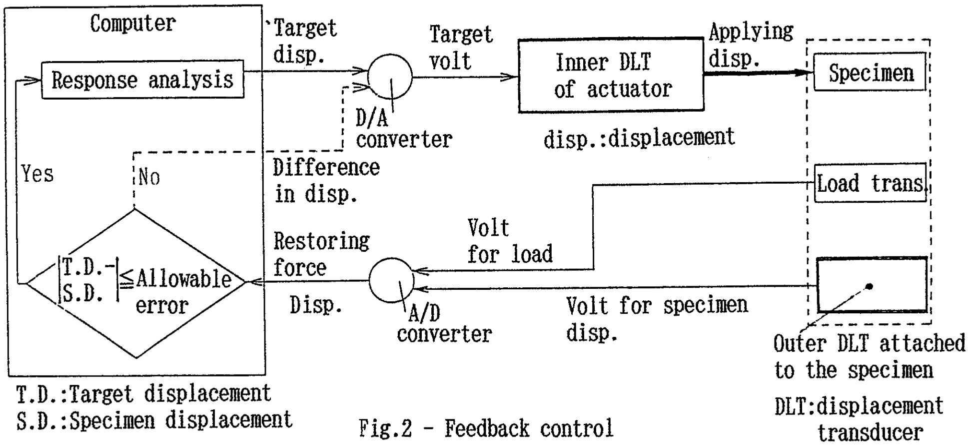


Fig.2 - Feedback control

the obstacles to visual simulation of the dynamic response using PD testing.

The authors have combined PD testing with a computer-controlled VTR to make movies of the dynamic response of a specimen during an earthquake. The simulated dynamic response of the specimen can be visualized in real time scale as the earthquake progresses by playing the tape.

3. RECORDING USING COMPUTER CONTROLLED VIDEOTAPE RECORDER

Repeated stopping and starting of the VTR is necessary during PD testing. Furthermore, the recording duration of one shot must be very short corresponding to the short interval between each digital value in the earthquake motion. There is also the restriction that the total recording time must coincide with the original earthquake duration. In the recording method the authors adopted, the video camera was kept on continually and recording was controlled by switching the VTR on and off. The switch signal used to start the VTR was 5 volts while a pause was marked by 0 volt; these signals were transmitted by the computer on line. The VTR for professional use was adopted due to requirement for durability of the recording parts and for the fact that the VTR facilitated a connecting terminal for remote control. The video timer used in this system has a 0.001 second resolution and, like the VTR, has a connector for remote control. By using this timer, each time corresponding to the time of the earthquake acceleration record could be shown on the monitor.

A videotape records images at the rate of 30 frames per second. When the recording time of the VTR is controlled by signals from the computer, the number of frames fluctuates by one or two from this target frame rate. If there were four frames or fewer in one shot, the picture often could not be recorded at all. Thus, it was concluded that the minimum possible recording time for one shot was 0.2 second, corresponding to six frames. The time taken to cause the recording of six frames, that is, from the pause state to the end of recording, was about 6.5 seconds. The authors adopted a VTR system in consideration of publicity, but a laser disc recorder might be more suitable because it would reduce the minimum recording time and result in fewer fluctuations in the number of frames. Photo 1 shows the video apparatus used in this system.

The visibility of cracks on the monitor is influenced by the quality of the video camera and the lighting conditions. If white poster color is applied to the concrete surface, the minimum crack which can be identified on the monitor

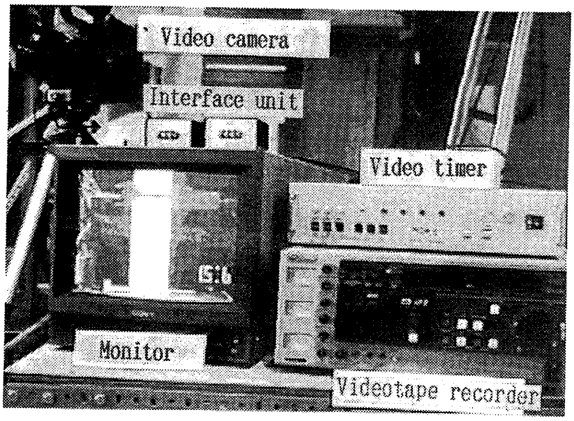


Photo.1 - Video apparatus

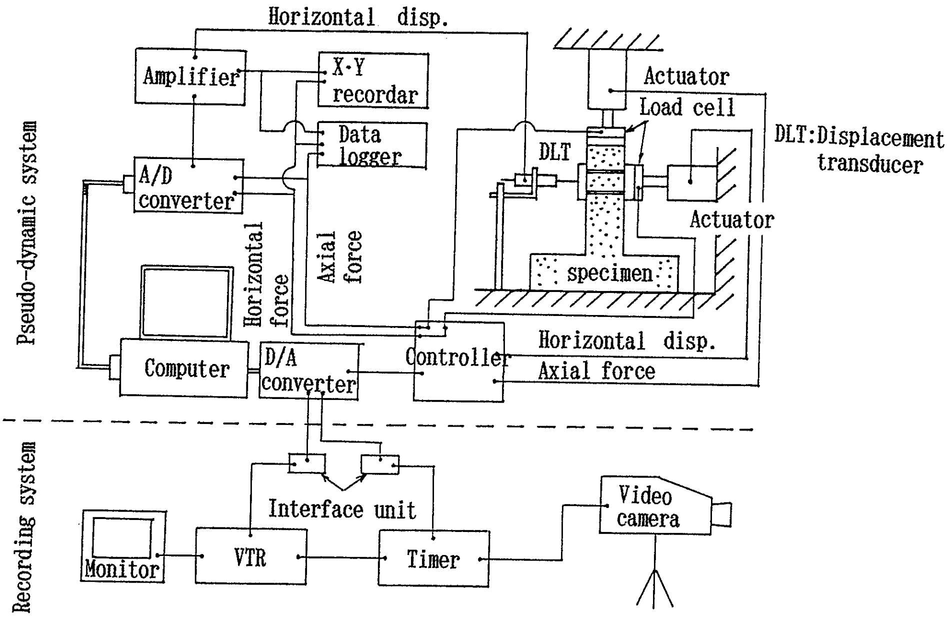


Fig.3 - Pseudo-dynamic loading system with recording system

has a width of 0.1mm in a 50cm× 50cm object area under laboratory lighting conditions.

The combined PD loading and video recording system is shown in Figure 3. The PD loading system was designed to maintain the status quo while the video recording system is in operation.

4. VERIFICATION OF THE SYSTEM

In order to verify the propriety of the combined PD and video recording system, a test using an H-shaped steel column was carried out as shown in Figure 4[4]. The stiffness of the column within the elastic range in a static loading test

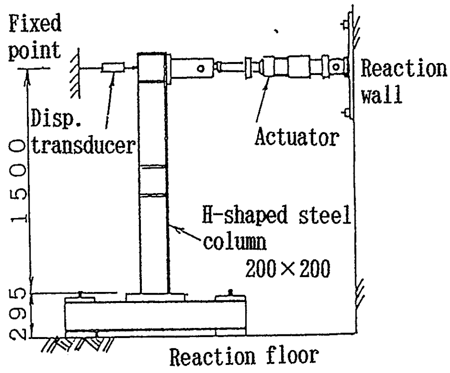


Fig.4 - Loading condition of H-shaped steel column

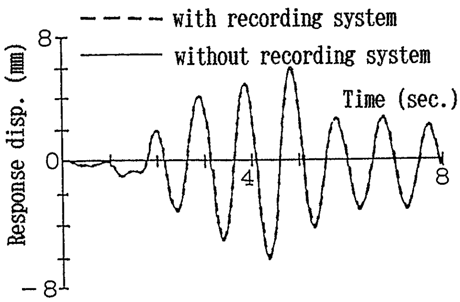


Fig.5 - Response displacement of H-shaped steel column

was 4.81 kN/mm. An initial part of the wave of the El-Centro 1940 (NS) for eight seconds was used in the PD test. Δt was 0.02 second and the natural period of the column was assumed to be 1.0 second. The maximum acceleration was made 0.11 m/s^2 in order to keep the loading within the elastic range of the column. The video recording system was set up such that the VTR recorded for 0.2 seconds for every 0.2 seconds of the El-Centro record, so the total recording time would be eight seconds corresponding to the actual duration of the record.

Figure 5 shows the response displacement-time curves for the H-shaped steel column obtained from these experiments. The curve obtained from the experiment with the video recording system coincides exactly with that taken without the video recording system. This confirms that the newly developed system is not influenced by the frequent pauses in loading required by the recording procedure. As for concrete members, the experimental results might be influenced by creep effects occurring during pauses in loading. However, since displacement control is a fundamental process of PD testing, creep deformation is not expected during these loading pauses. It was confirmed that the VTR was able to record the shape of the specimen at the intended times and intervals and that loading was able to maintain the status quo during recording.

The simulated dynamic response of the column is visualized by playing back the tape; the playing time was found to be nearly equal to the intended value. The time taken to complete the experiment for an original duration of eight seconds of earthquake motion was 429 seconds with the VTR system while it was 182 seconds in the case of no VTR recording. The ratio of time is thus 2.4 to 1. Since the VTR is switched 40 times for earthquake acceleration data lasting eight seconds, the time taken to record one shot was approximately 11 seconds. In this case, when the tape is played at ordinary speed, there are five pictures per second, and the monitor displays an almost smooth visualization of the specimen's dynamic response.

5. VISUAL SIMULATION OF DYNAMIC RESPONSE OF REINFORCED CONCRETE COLUMNS

5.1 Specimens and experimental method

The characteristics of each reinforced concrete (RC) column specimen used in these visual simulations are summarized in Table 1. Figure 6 gives details of one specimen and its loading conditions [5],[6]. The specimens are RC columns standing on footings. In order to prevent early shear failure, hoop reinforcement, the amount of which is equal to 104%-109% of the necessary values of JSCE's Specification based on allowable stress design method of 1980 edition [7], was arranged having the spacing of less than one half of the effective depth (d/2) for each specimen. As indicated in Table 1, the specimens were divided into four categories by their mechanical properties, such as ratio of longitudinal reinforcement, the shear span-effective depth ratio (a/d), and the axial compressive strength. Two specimens of each category were made, one for static testing and the other for PD testing; that is, for the visual simulation

Table 1 - Characteristics of specimens

Specimen	Longitudinal reinforcement			Hoop reinforcement			Shear span - effective depth ratio	Axial compressive strength (MPa)
Type*1	Size*2	Amount (cm^2)	Ratio (%)	Designation (size)	Space (cm)	Ratio*3 (%)		
PS−1 PD−1	D13	25.34	2.82	D6	7.0	0.30 (106)	2.78	0.98
PS−2 PD−2	D13	25.34	2.82	D6	13.0	0.16 (109)	4.63	0.98
PS−3 PD−3	D10	11.41	1.27	D3	2.5	0.19 (104)	2.78	0.98
PS−4 PD−4	D13	25.34	2.82	D6	4.5	0.47 (107)	2.78	4.71

*1 : PS:Static test、PD:Pseudo-dynamic test
*2 : Size is expressed in terms of JIS ; D means " Deformed " and the number is the nominal diameter
*3 : Values in ( ) show the ratio of actual hoop reinforcement to the value given in JSCE's Specifications , 1980 edition.

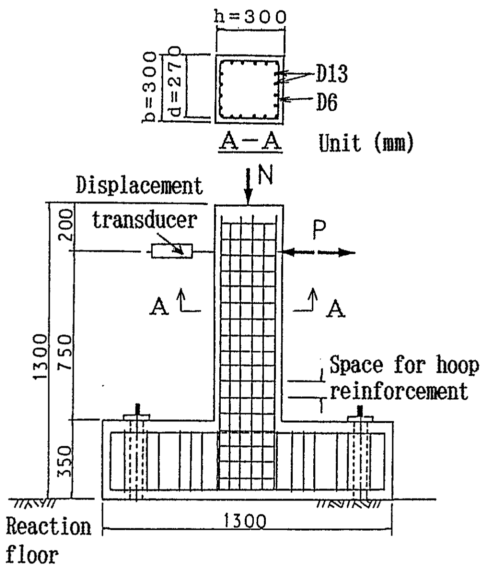


Fig.6 - Details of specimen and loading conditions (PS-1,PD-1)

of dynamic response. The static and PD test loads were applied using two actuators, as shown in Fig.6. One actuator applies a constant axial compressive force at the top of the column, while the other applies a horizontal force or displacement. Table 2 shows the mechanical properties of the materials used in the specimens.

Table 3 gives calculated values and experimental results for the static test. A fiber model, in which the cross section is replaced by many fiber elements, was adopted to carry out this calculation. Figure 7 shows the stress-strain curves of the concrete and reinforcement used in the calculation. A pattern of static reversed cyclic loading was as follows : After applying the axial force, a horizontal force was introduced in one complete cycle of the calculated yield load P_y. Then, the displacement control method was used such as one cycle of $2\delta_y$ displacement (δ_y is horizontal displacement under the yield load), one cycle of

Table 2 - Mechanical properties of materials

<table>
<tr><th colspan="6">Reinforcement</th></tr>
<tr><th>Size*1</th><th>Type</th><th colspan="2">Yield strength (MPa)</th><th>Tensile strength (MPa)</th><th>Application</th></tr>
<tr><td>D13</td><td>SD30</td><td colspan="2">357</td><td>519</td><td>Longi. reinf. of No.1, 2, 4</td></tr>
<tr><td>D10</td><td>SD30</td><td colspan="2">355</td><td>514</td><td>Longi. reinf. of No.3</td></tr>
<tr><td>D6</td><td>SD35</td><td colspan="2">416</td><td>539</td><td>Hoop reinf. of No.1, 2, 4</td></tr>
<tr><td>D3</td><td>SD30</td><td colspan="2">303</td><td>396</td><td>Hoop reinf. of No.3</td></tr>
<tr><th colspan="6">Concrete (MPa)</th></tr>
<tr><th colspan="3">Compressive strength</th><th colspan="2">Tensile strength</th><th>Young's modulus</th></tr>
<tr><td colspan="3">26.5</td><td colspan="2">2.26</td><td>0.24×10^5</td></tr>
</table>

*1 : Size is expressed in terms of JIS ; D means " Deformed " and the number is the nominal diameter
Longi. : Longitudinal   reinf : reinforcement

Table 3 - Calculated values and results of static tests

<table>
<tr><th rowspan="2">Specimen</th><th colspan="3">Calculated values (kN)</th><th colspan="3">Experimental results</th></tr>
<tr><th>Cracking load P_{cr}</th><th>Yield*1 load P_y</th><th>Maximum load P_u</th><th>Yield displacement (cm)</th><th>Maximum load (kN)</th><th>Displacement at maximum load (δ_y)</th></tr>
<tr><td>PS-1</td><td rowspan="2">26.5</td><td rowspan="2">136.0</td><td rowspan="2">173.0</td><td>0.46</td><td>170.0</td><td>3</td></tr>
<tr><td>PD-1</td><td colspan="3">—</td></tr>
<tr><td>PS-2</td><td rowspan="2">15.7</td><td rowspan="2">78.5</td><td rowspan="2">99.1</td><td>0.92</td><td>96.1</td><td>2</td></tr>
<tr><td>PD-2</td><td colspan="3">—</td></tr>
<tr><td>PS-3</td><td rowspan="2">24.5</td><td rowspan="2">73.6</td><td rowspan="2">94.1</td><td>0.25</td><td>91.2</td><td>3</td></tr>
<tr><td>PD-3</td><td colspan="3">—</td></tr>
<tr><td>PS-4</td><td rowspan="2">52.0</td><td rowspan="2">179.0</td><td rowspan="2">206.0</td><td>0.50</td><td>214.0</td><td>2</td></tr>
<tr><td>PD-4</td><td colspan="3">—</td></tr>
</table>

*1 :P_y is the load at which the tensile strain in the outside longitudinal reinforcement reaches its yield value.

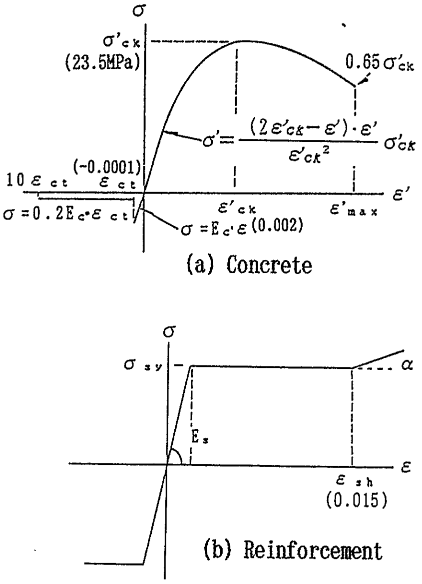


Fig. 7 - Stress-strain curves of materials

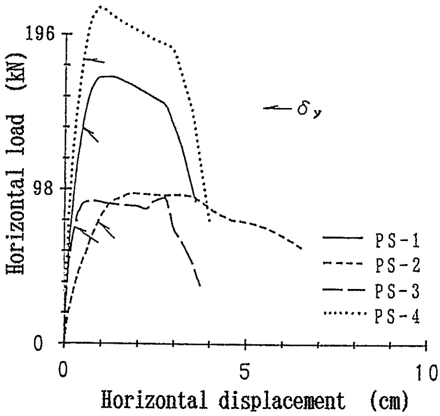


Fig. 8 - Envelope curves on positive side

$3\delta_y$ and so forth until the specimen failed. Figure 8 shows the envelope curves on the positive side derived from the load-displacement curves. The maximum load-bearing capacity was seen under $2\text{-}3\delta_y$ loading in each specimen. The reason for this is the existence of longitudinal bars in the web portion. The maximum load-bearing capacity and failure mode of specimens differed greatly due to differences in the mechanical properties of the specimens. In the case of specimens PS-1 and PS-4, the diagonal cracks extended after $2\delta_y$ loading, and eventually a shear failure occurred in specimen PS-1 and bending failure with the buckling of the longitudinal reinforcement in specimen PS-4. In the case of specimens PS-2 and PS-3, bending failure occurred due to the growth of cracks at the bottom of the columns. As for specimen PS-2, evident deterioration was seen in the concrete over a wide area of the column bottom.

The initial data used in the PD test are shown in Table 4. The adopted damping ratio was 0.05 to reflect ordinary RC members. The vibration mode was assumed to have one degree of freedom. In order to carry out PD testing at the large acceleration response of the El-Centro wave, the natural period of specimens PD-1 to PD-4 was assumed to be 0.5 seconds and the virtual lumped mass for each specimen was 187 tons, 54 tons, 186 tons, and 227 tons, respectively. In this case, the value of magnification in the acceleration response spectrum was about 2.5. Here, the virtual lumped mass was a value calculated using the secant modulus at the yield loads of each load-displacement curve obtained in the static tests. The limit state modification factor (ν_4) shown in Table 4 is stipulated in Chapter 9 of the JSCE's 1986 Standard Specifications of Concrete [8]. ν_4 is a reduction factor for earthquake forces according to the serviceability of the structure after the earthquake. In the Specification, serviceability after an earthquake was classified into four levels of damage according to the maximum response displacement in such a way that a $1\delta_y$ displacement corresponds to sound condition, a $2\delta_y$ displacement corresponds to light damage, a $3\delta_y$ displacement corresponds to medium damage, and a $4\delta_y$ displacement corresponds to significant damage. The maximum acceleration applied to the specimen was adjusted so as to correspond to the significant damage ($4\delta_y$) level and

Table 4 - Data used in pseudo-dynamic tests

Specimen		PD-1	PD-2	PD-3	PD-4
Earthquake wave		El Centro 1940(NS) 0.02～16.0(sec.) Δt=0.02 sec.			
Damping ratio	h	0.05			
Natural period	T(sec)	0.5			
Secant stiffness at the yield load	Ko(MN/m)	29.6	8.5	29.4	35.9
Virtual lumped mass	M(ton)	187	54	186	227
Level of damage	Limit state modification factor ν_4	Maximum acceleration of earthquake wave (m/s^2)			
$4\delta_y$* level	0.4	0.91	1.82	0.49	0.99
Failure level	———	1.82	3.63	0.99	1.98

* δ_y : Yeild displacement

failure level, as shown in Table 4. Here, the failure level is defined such that it is an acceleration two times greater than the significant damage level; it results in severe failure. Loading up to the failure level was carried out after $4\delta_y$ level loading was finished for each specimen.

The equation of motion for the spring-mass system was solved numerically by the central difference method with Δt as the integration time interval. The feed-back control system as shown in Fig.2, with the allowable error in displacement set to 0.04mm, was adopted during loading using the actuator.

The recording system was operated such that a VTR was set to record a still picture for 0.2 seconds for every 0.1 seconds of the earthquake acceleration record used in the PD test. Thus, the total recording time was 32 seconds, corresponding to twice the elapsed time of the earthquake record. This 0.1-second recording interval was selected since it suited the natural period of the specimen, which was assumed to be 0.5 seconds, and the picture was played back at double speed to generate a dynamic response lasting 16 seconds. This resulted in smooth motion since there were 10 pictures per second.

5.2 Experimental results of PD test and visual simulation

Figures 9 and 10 show the relationship between response displacement and time as obtained from PD tests at the failure loading level. The frequency characteristics of the response displacement are almost identical except for specimen PD-1, in which the diagonal cracks extended. Photos 2-5 show the damaged features of columns at the times shown in Figures 9 and 10. These are still pictures taken from the monitor using a video printer, and the numbers in the photographs represent the time (in seconds) into the El-Centro (NS) earthquake wave. Hence, it was thought that the minimum crack width which could be seen in the photographs was larger than that on monitor screen. As these photographs show, the crushing of concrete at the bottom of the specimen PD-4 column had already occurred by 2.0 seconds. Within 4.5 seconds, the diagonal cracks in specimen PD-1 had already greatly extended and crushing of the concrete at the bottom of the specimen PD-2 column had already occurred. Up to 16 seconds, which was the end of the loading, failure mode of each specimen was not the same as in the static test. The damaged features indicate that not only the amount but also the spacing and diameter of hoop reinforcement at the bottom of a column are a matter of significance as regards ductility improvement. For example, the ductility of a column under severe earthquake acceleration may be improved if the spacing of the hoop reinforcement at the bottom is reduced below d/4 accord-

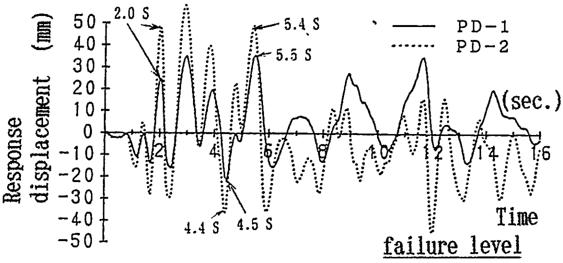


Fig. 9 - Curves of response displacement against time (a)

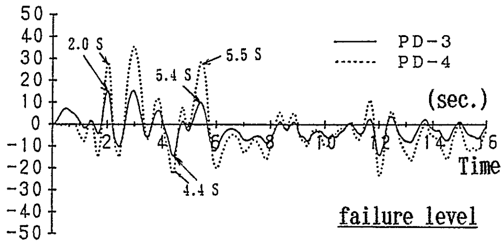


Fig. 10 - Curves of response displacement against time (b)

Table 5 - Experimental results of pseudo-dynamic tests

Specimen	Maximum response displacement (Failure level)		Maximum*1 restoring force $4\delta_y$ level P (kN)	Maximum shear strength P/bd (MPa)
	Time of occurr. (sec.)	Displacement (mm)		
PD−1	5.48	35.58	182.4	2.25
PD−2	2.92	58.22	109.8	1.35
PD−3	2.96	15.47	98.1	1.17
PD−4	2.98	35.69	218.7	2.70

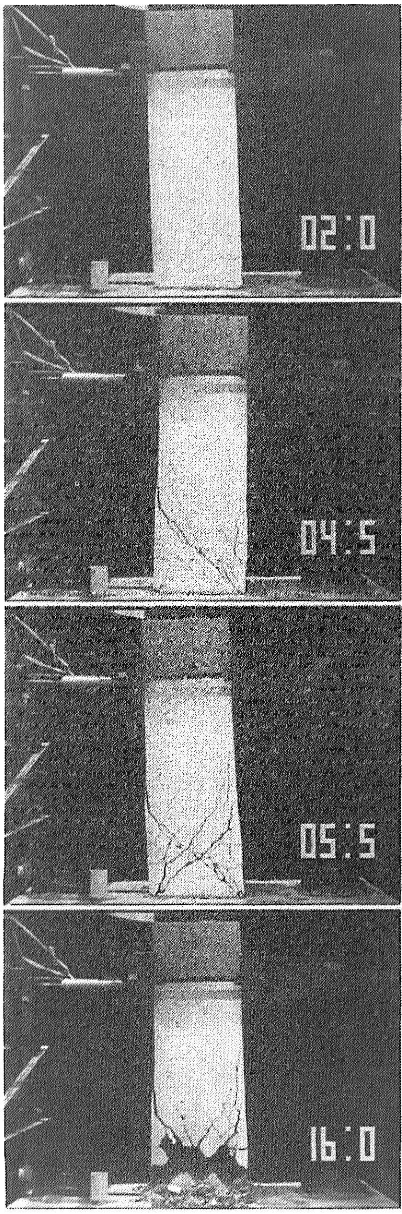
*1: Maximum restoring force occurs under $4\delta_y$ loading. The values were obtained from the $P-\delta$ curves recorded on an X-Y recorder.

occurr. : occurrence

ing to the 1986 Specification. It should be noted that the maximum acceleration applied to each specimen was adjusted to correspond to its mechanical properties, as shown in Table 4. Hence, the maximum force applied to specimens in the PD test depended on the specimen. Table 5 shows the experimental results of the PD tests.

The dynamic response of a column during an earthquake can be visualized on any time scale simply by changing the playback speed of the tape. The dynamic response at the failure level was visualized on the monitor in one half of the actual time speed, and this led to the following observations: In the case of specimens PD-1, PD-3, and PD-4 in which a/d is 2.78, the displacement at the top of the column was merely due to the rotation at the bottom of the column and not by deformation of the column itself. In the case of specimen PD-1, which suffered shear failure, it was observed that the column moved horizontally without rotating at the bottom due to diagonal cracks in the concrete. When the tape was played back at a speed coincident with the length of the earthquake acceleration record, the dynamic response appeared realistic. Naturally, the simulated dynamic response can also be watched slowly in order to clarify the crack pattern and so on in detail.

Also, it should be noted that the column displacements seen in these pictures are displacements relative to the ground; that is, the observer is moving with the ground during the earthquake. Hence, the displacement of columns and the opening and closing of cracks can be seen clearly because the footings are fixed to the ground. If a system in which the video camera moves according to the calculated displacement of the ground is set up, the dynamic response of the column will include the ground's displacement on the screen, just as in the case of a shaking table test. However, the displacement and crack pattern seen on the monitor may not be clear, because the column itself moves with the footing. In other words, the observer would see the response of the column from the viewpoint of an absolute coordinate system in this case.



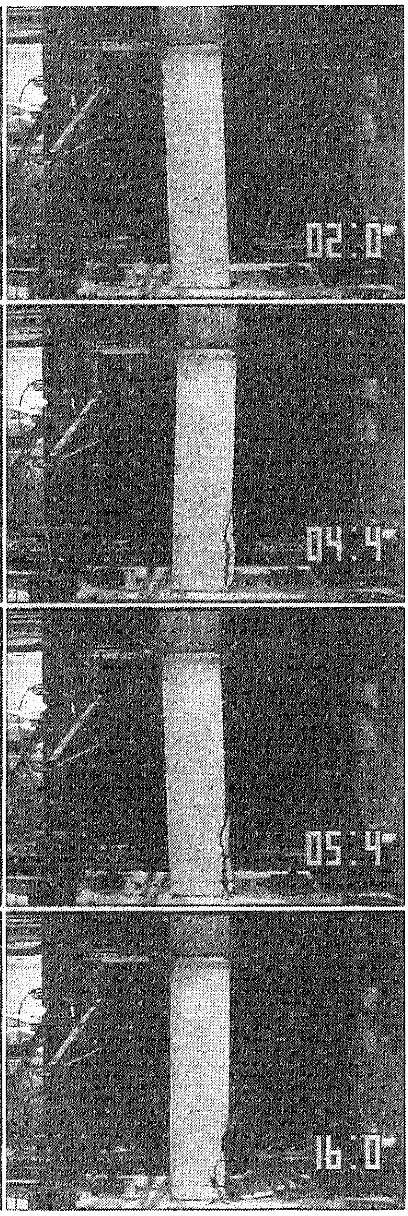


Photo.2 - (PD-1)

Photo.3 - (PD-2)

Photo.2 , Photo.3 - Features of deterioration at various times

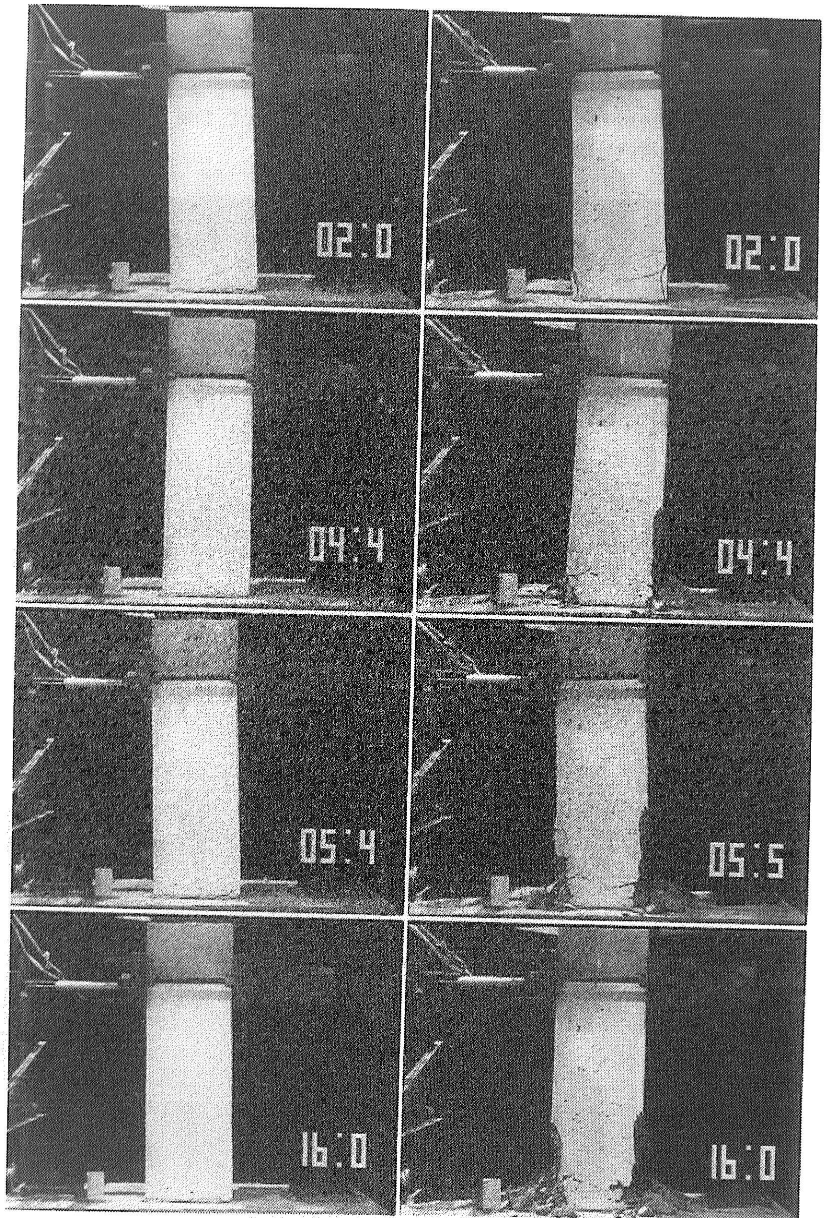


Photo.4 - (PD-3)

Photo.5 - (PD-4)

Photo.4 , Photo.5 - Features of deterioration at various times

It has been indicated in many investigations [9] that the response behavior obtained from a PD testing does not coincide exactly with that of a shaking table test due to differences in the loading speed. However, it is recognized that any difference plays a minimal role in the main issues of response behavior. On the other hand, if a shaking table test were carried out using the same RC column specimens as in the PD testing to obtain pictures of the dynamic response, many difficulties would have to be confronted, such as the capacity of the shaking table, the need for a very heavy mass which does not influence the gravitational force on the structural system, and the placement of the video camera to obtain relative displacements. Considering these difficulties, the PD loading test combined with this recording system appears to be a very useful method of visualizing the dynamic response of RC structures. Furthermore, if the loading speed of the PD testing can be greatly increased, this system will become more coincident with the actual dynamic response during an earthquake.

6. CONCLUSION

The results of this study lead to the following conclusions:

(1) A successful PD loading system connected to a computer-controlled VTR was developed. It is able to record images of a specimen at any time during the earthquake acceleration record. To achieve this, a still picture of the specimen's response behavior is recorded for a short time at each time step, with the timing of the recording corresponding to the elapsed time of the earthquake acceleration record.

(2) The continuous dynamic response of the specimen under earthquake conditions can be seen on the monitor by playing the tape containing the sequential still pictures.

(3) Given the present capabilities of VTRs, the best recording time for these still pictures was set at 0.2 seconds. In the case of an RC specimen with a natural period of 0.5 seconds, a series of play-back pictures with a rate of 10 pictures per second offered a smooth play-back of the dynamic response on the monitor.

(4) The peculiar behavior and differences in dynamic response among RC columns of four different types were clearly demonstrated by playing the tape.

(5) An investigation of the influence of mechanical properties such as the diameter and spacing of hoop reinforcement at the bottom of the column by using this simulation system was found to be extremely effective in helping to improve the ductility of reinforced concrete structures during severe earthquakes.

(6) The hardware of the recording system, its reliability, and the quality of the image will be improved greatly in future. Eventually, it is hoped this system will find application in investigations of many different types.

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