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Development of accurate pseudodynamic test method for R/C structures

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ABSTRACT:Pseudodynamic(PSD) test is one of useful techniques to obtain the response behavior of structures subjected to earthquakes. However, this test method has some problems from the point of accuracy. For example, 1)loading is applied statically as well as stepwise, 2)experimental errors in the loading system have a bad influence on the response behavior. In order to overcome such problems and to establish a more accurate PSD test than the usual one, a new PSD test method based on an actual restoring force under earthquakes was developed.

1 INTRODUCTION

An on-line computer-controlled experimental procedure, so-called pseudodynamic(PSD) test, has been recently developed combining the simplicity of static testing with the realism of shaking table tests. The merit of this test method is that response behavior is proceeded step by step directly using the measured restoring force from the test specimen. In this way, the more reliable results can be obtained than in the ordinary response analysis because simplified restoring force models are not used in the PSD test. During the PSD test, the specimen behaves as if it is subjected to an actual earthquake although time is largely lengthened as compared with the real earthquake. An advantage over the shaking table tests is that response behavior and the failure mode of the specimen can be observed in detail. Moreover, the PSD test does not need such a large scale testing equipment or measuring devices as the shaking table test, and it can be applied to almost all kinds of structures regardless of their scales. However, the PSD test has some following problems from the point of accuracy;1)the load is applied to the specimen discontinuously as well as statically, unlike in real earthquakes, 2)cumulative errors during the test influence the response behavior. Therefore, the accuracy of the results should be evaluated. As for the errors in the PSD test, various studies have been carried out intending to make them smaller, and algorithms to control the loading has been developed. However, very few studies have been conducted on the effect of static and discontinuous loading on the test results. The objectives of this study are to investigate the accuracy of the PSD test comparing with the shaking table tests using R/C and steel members, and to develop a more accurate PSD test than the usual one.

2 OUTLINE OF EXPERIMENT

In order to evaluate the accuracy of the response behavior obtained from the PSD test, the PSD tests and the shaking table tests were carried out. Two kinds of materials(steel and R/C) were used for the test specimens to investigate the influence of the material characteristics on the response behavior.

2.1 Test specimens

The R/C specimens, of which cross section is 10x15 cm and height is 60 cm, were used for the both tests, as shown in Fig.1. The amounts of the reinforcements were determined to represent actual R/C bridge piers. Figure 2 shows the H-shaped steel specimen, of which height is 180 cm.

2.2 Shaking table test

Using the R/C and the steel specimens, shaking table tests were carried out. 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 earthquake waves used in the tests were made from El Centro 1940 N-S and Taft 1952

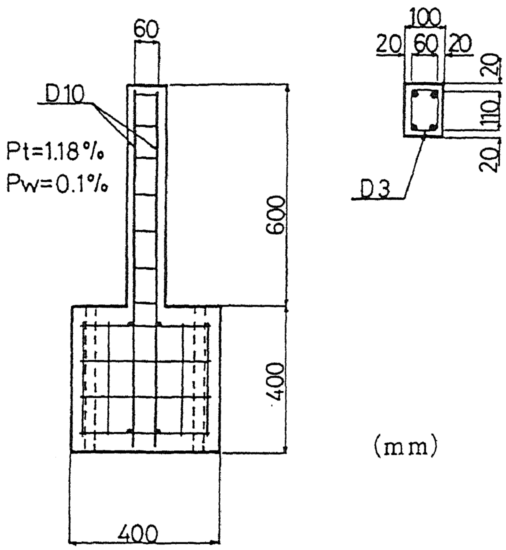

Fig. 1 R/C test specimen

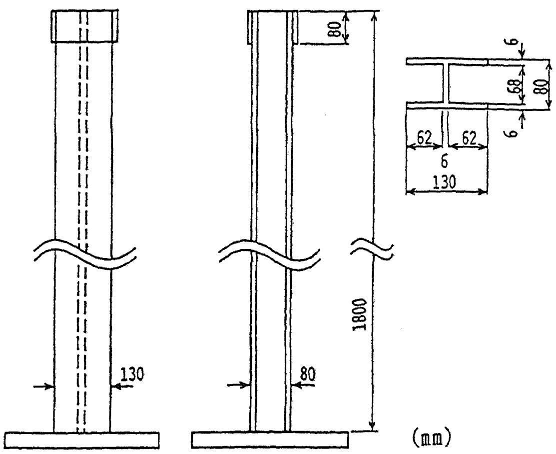

Fig. 2 Steel test specimen

N-S by shortening the time to 1/4 and magnifying the acceleration. The compound sine waves, of which periods are similar to the natural period of the specimens at various damaged conditions, were also used to make clear the fundamental vibrating characteristics. Table 1 shows the variables of the shaking table tests for the R/C specimens.

2.3 PSD test

In an ordinary PSD test, the calculated displacement at one step is sent from the computer to the actuator until the displacement of the specimen reaches the calculated value by the computer. It was judged

Table 1 Variables of shaking table test for R/C members

Specimen	Test method	Input acceleration	Max acceleration	Time scale
D-EL	ST	EL-Centro	1816 gal	1/4
P-EL	PT	N-S		
D-TA	ST	Taft	1656 gal	1/4
P-TA	PT	N-S		
D-SIN	ST		925 gal	—
P-SIN	PT	sin wave		

ST:Shaking table test
PT:Psendodynamic test

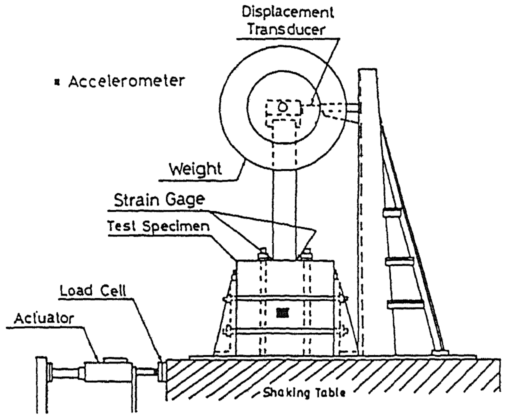

Fig. 3 Test set up for shaking table test

whether the measured displacement by the displacement transducer attached to the specimen reached the calculated one or not. The algorithm to control the displacement, shown in Fig. 4, is as follows;

1. The small amount of the displacement(ΔY) applied to the specimen in one time is indicated as follows;

$$\Delta Y = \alpha \cdot (Y - Y') \qquad (1)$$

where Y:the final required displacement at one step, Y':the measured displacement, α:a coefficient(=0.6).

2. If the measured displacement does not reach Y after the procedure 1, the displacement is applied stepwise by the magnitude corresponding to the minimum electric voltage the computer can output. The loading is stopped if the measured displacement is within the allowable error(ε).

In the PSD test, such a systematic error that the measured restoring force is always a little smaller than the correct one because the measured displacement is always between Y and Y-ε. This error is called the undershooting error, and it has been pointed out that the effect of such an error becomes

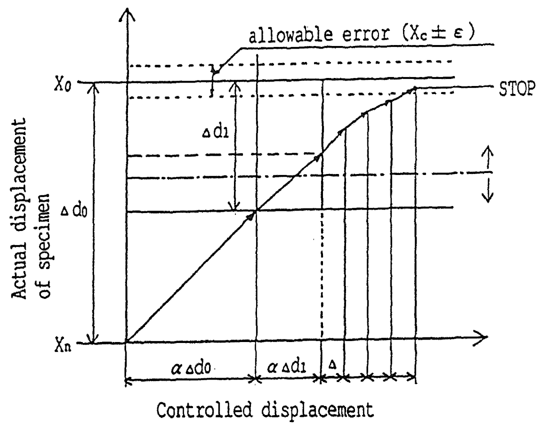

Fig.4 Controlling of displacement in PSD test

larger when the rigidity of the specimen is high. It is very important to minimize the undershooting error in the PSD test. In this study, the undershooting error was made as small as possible by setting the allowable error to a half of the displacement which corresponds to the minimum output voltage of the computer.

The earthquake waves measured at the footing of the specimen from the shaking table tests were used for the PSD tests. Since the hysteretic damping is dominant, the viscous damping coefficient was assumed to be 0% in the PSD tests. The same mass used in the shaking table tests was installed at the top of the specimens, and the load was applied at the central axis of the mass.

3 COMPARISON OF SHAKING TABLE TESTS WITH PSD TESTS

3.1 Response behavior of steel members

Figure 5 shows the response behavior of the steel members obtained from the PSD test and the shaking table test. There is a good agreement between the both tests. In the case of using steel members, the PSD test carried out in this study can give almost the same response behavior as the shaking table test.

3.2 Response behavior of R/C members

Figure 6 shows the time histories of the displacement obtained from the shaking table tests and the PSD tests. There is generally a difference of the response behavior between the both tests. The displacements obtained from the PSD tests tend to shift to one direction, and the difference of the displacements between the both tests becomes larger with time and the magnitude of the plastic displacement. This phenomenon is more severe under the compound sine wave, as shown in Fig.6(c). The PSD test is useful method to some extent to simulate the response behavior under earthquakes. However, the ordinary PSD test can not always show the correct response behavior depending on the materials used.

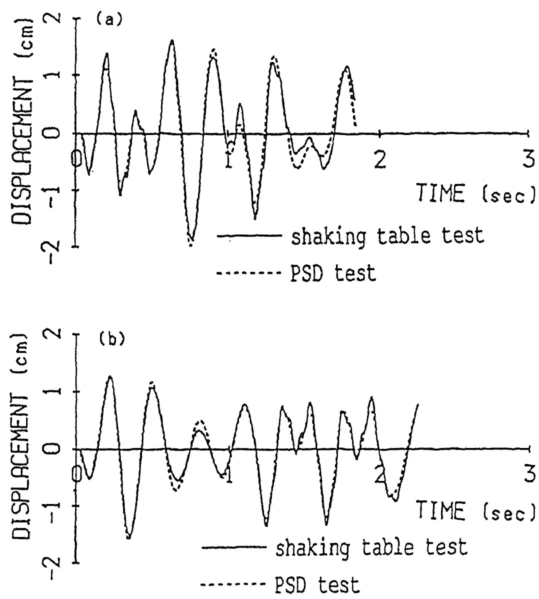

Fig.5 Comparison of shaking table test with PSD test using steel member

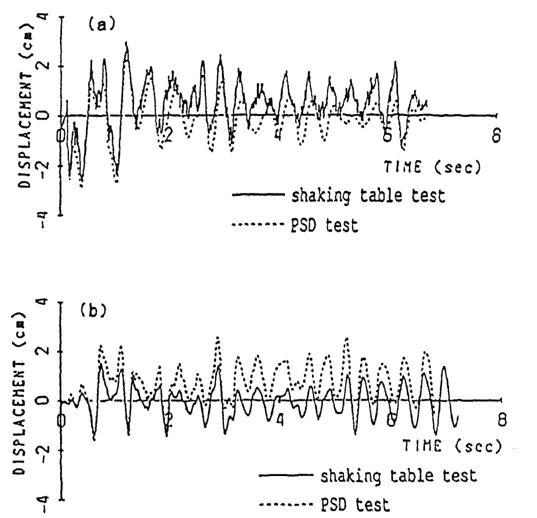

Fig.6(1) Comparison of shaking table test with PSD test using R/C member

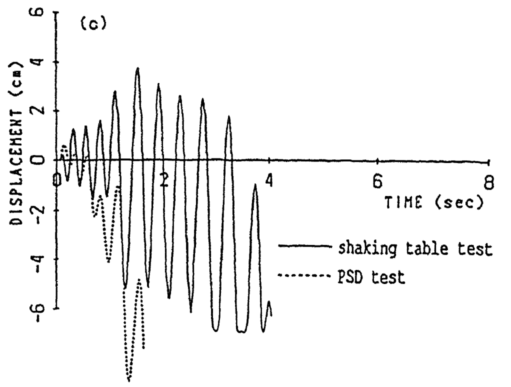

Fig. 6(2) Comparison of shaking table test with PSD test using R/C member

4 INFLUENCE OF STATIC AND DISCONTINUOUS LOADING ON RESPONSE BEHAVIOR OF R/C MEMBER

The reason for the results shown in Fig. 6 is attributed to relaxation of R/C members. The restoring force of R/C members keeping a certain displacement is gradually reduced due to relaxation. Since the PSD test proceeds in a stepwise manner under a step by step integration procedure, it is impossible to carry out the PSD test without stopping the loading. This is the main difference from the shaking table tests. Therefore, the influence of such relaxation on the response behavior should be investigated.

In order to make clear the above problem, the following two tests were carried out. The first one is to make clear the effect of time length to stop the loading on the restoring force of R/C members. In this test, the specimen shown in Fig. 2 was used, and the restoring force was measured every one or two minutes after the displacement reached the required displacement. The results are shown in Fig. 7. There is little difference between both restoring forces. However, the relation between the displacement and the restoring force, which was monitored in real time by using a X-Y recorder, showed that the restoring force decreased at the moment when the loading was stopped. Stopping the loading to measure the data may have a big influence on the change of the restoring force. Therefore, the influence of continuous and discontinuous loading on the restoring force was investigated. In the continuous loading test, the actuator was always controlled to keep 5 mm/sec of the displacement rate using the programmed displacement history. In the discontinuous loading, the load was applied in a step wise manner using the same displacement history as used in the continuous loading test. This loading condition is similar to the PSD test. In these tests, the specimens shown in

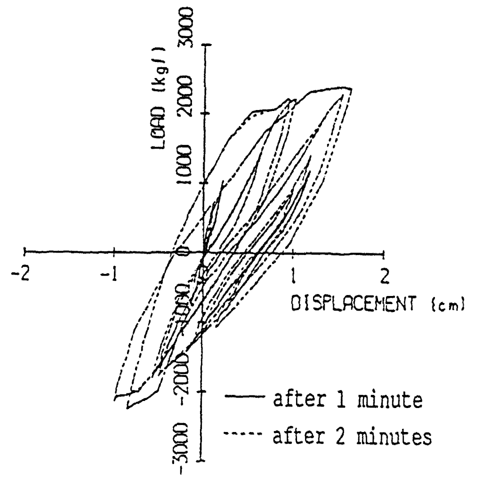

Fig. 7 Influence of time to stop loading on restoring force

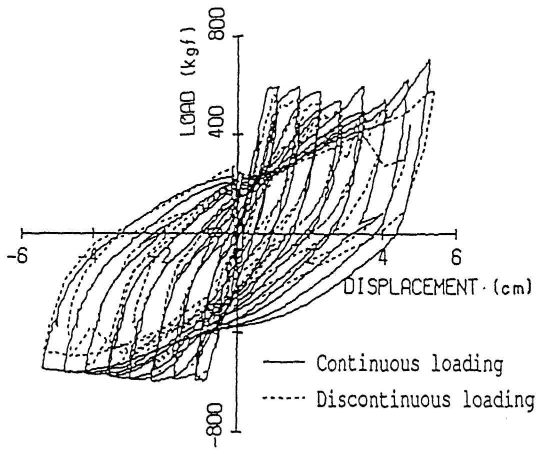

Fig. 8 Restoring force under continuous loading and discontinuous loading

Fig. 2 were used. The comparison of the test results is shown in Fig. 8. The restoring force under discontinuous loading, that is stepwise loading, is a little smaller than that under continuous loading. This phenomenon is more remarkable on condition that the displacement is larger than the yield displacement and the load proceeds on the skeleton curve. This fact indicates that the same phenomenon as above should occur in the PSD test. That is, a larger displacement than the correct one is sent from the computer because the reduced restoring force is measured and the displacement is calculated based on this reduced restoring force. As a result, the displacement tends to shift to one direction because a larger displacement is always calculated. This phenomenon is more remarkable in the plastic range.

5 DEVELOPMENT OF NEW PSD TEST

There are mainly three factors which produce the error in the PSD test. The first one, as described above, is the decrease of restoring force due to stopping the loading. The second one is the undershooting error, and the third one is strain rate effect under dynamic loading. In order to establish an accurate PSD test method, three above factors must be taken into account in the PSD system.

5.1 Modification of measured restoring force

Considering the decrease of the restoring force due to relaxation, the procedure to modify the measured restoring force was applied to the PSD system. The first step of the procedure is to add ΔF_1, which is the amount of the decrease of the restoring force, to the measured restoring force when the loading is applied in a plastic range over the maximum displacement previously experienced, and the second step is to calculate the required displacement for the next step using the modified restoring force. The corrected force(ΔF_1) was assumed to be 10 % of the load carrying capacity of the member based on the test result in this study. The measured restoring force is not modified in unloading stage while the amount of the force, that is (measured displacement/maximum experienced displacement)x10% of the member strength, is added to the measured restoring force in reloading stage.

5.2 Modification of undershooting error

In order to modify the undershooting error, the following force is added to the measured restoring force;

$$\Delta F_2 = \Delta \varepsilon * k \quad (2)$$

in which, ΔF_2:the amount of the corrected force due to the undershooting error, $\Delta\varepsilon$:the difference between the measured and the required displacement, k:the stiffness at the measured displacement.

5.3 Strain rate effect

Increase of the yield point of the main reinforcing bars due to strain rate effect was considered in the measured restoring force. The corrected restoring force including the above all factors is shown in Fig. 9.

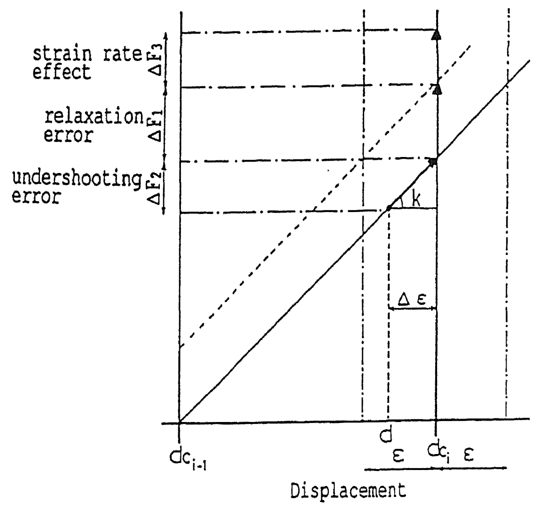

Fig. 9 Schematic figure of modified PSD test

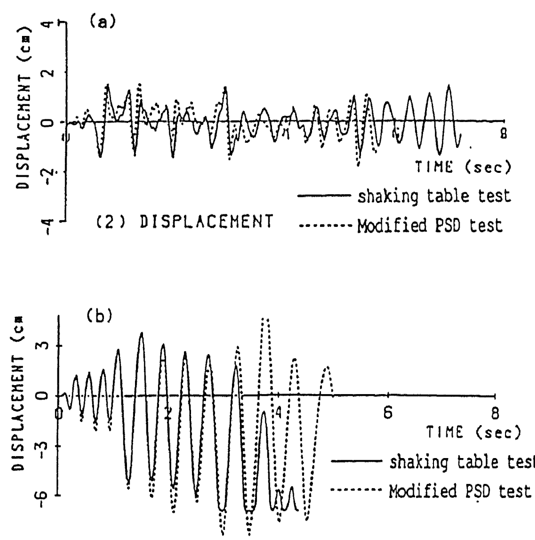

Fig. 10 Accuracy of modified PSD test

6. ACCURACY OF NEWLY PROPOSED PSD TEST METHOD

The result of the modified PSD test is shown in Fig. 10. The input waves are the same as used in Fig. 6(b) and (c) previously. According to Fig. 10, the response behavior obtained from the modified PSD tests agrees generally well with that obtained from the shaking table tests even if the displacement shifts to one direction. This fact means that it is able to obtain a real response behavior of R/C structures subjected to an earthquake using the developed PSD test. The new PSD test in which the influence of the relaxation, the undershooting error and the strain rate effect were incorporated could be newly established. This test method is clearly more accurate than the ordinary one, and can be applied to any R/C structures instead of the shaking table tests.

7 CONCLUSIONS

It is concluded that;

1. The PSD test is a useful method to simulate earthquake response behavior of structures. However, the usefulness of the ordinary PSD test is often limited. In the case of R/C members, the correct response behavior can not be obtained due to cumulative errors introduced by relaxation, undershooting, and strain rate effect.
2. A new PSD test in which the influence of the relaxation, the undershooting error and the strain rate effect are incorporated could be newly established. This test method is clearly more accurate than the ordinary one, and can be applied to any R/C structures instead of the shaking table tests.

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