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PSEUDODYNAMIC TESTING METHOD USING THE NEWMARK IMPLICIT INTEGRATION METHOD

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SUMMARY

The authors have developed the pseudodynamic testing method using the unconditionally stable Newmark implicit integration method. This paper presents the pseudodynamic testing procedure, the control techniques of actuator for the metod and the verification test results on a two story braced steel frame and a RC shear wall. Particularly, we wish to emphasize that it is possible to estimate a sufficiently accurate stiffness matrix experimentally, which can be applied to numerical culculation in the pseudodynamic test.

INTRODUCTION

For pseudodynamic testing method, an explicit integration method such as central difference method (CDM) is employed so that the equation of motion of a structure can be solved without iterations and a stiffness matrix, which are difficult to treat experimentally (Ref.1). However, because of conditionally stable nature of the explicit integration method, the application of the pseudodynamic test is limited only to small structure with a few degrees of freedom. Partcularly, in substructuring techniques, Since large natural frequeny is caused by increaes of the degrees of freedom or revival of rotatory degrees of freedom, it is made more difficult to employ the explicit method.

The authors thought much of unconditionally stable nature of the Newmark implicit integration method, and have studied to apply the Newmark method to the pseudodynamic test. The points for practical application of the method are; 1) to calculate the displacement responses without iterations; 2) to estimate stiffness matrix experimentally. In this paper, we wish to present the pseudodynamic algorithm and to propose a procedure and control techniques of actuator, which parmit us to estimate a stiffness matrix with sufficient accuracy. Verification test results performed on a two story braced steel frame and a RC shear wall are demonstrated.

PSEUDO DYNAMIC TESTING PROCEDURE

The Psudodynamic algorithm is shown in Fig. 1. The algorithm repeats the following procedure; 1) determine loading paths to estimate stiffness matrix; 2) check the size of the loading path; 3) the loading paths is imposed on the test structure and culculate the stiffness matrix; 4) calculate the displacement response; and 5) the displacement is impose on the test structure again. The Newmark implicit integration method by Clough's expression (Ref.2) is employed so that the displacement responses can be calcurated without iterations. As shown in Fig. 2, the loading paths are selected as many as the degrees of freedom, and the stiffness matrix can be calculated by the relation between the load increment and the displacement increment measured at each loading path. The stiffness estimated is, strictly speaking, a tangent modulus in a small displacement interval. The loading path should be determined in consideration of the following conditions in order to ensure the accuracy of the stiffness matrix ; 1) there is no reversal of load during each loading path; 2) the final displacement mode caused by the loading paths is as nearly as possible the displacement response at the next time step; 3) the size of each loading path is sufficiently larger than mesurement accuracies of displacement. The size is adequate from ten times to twenty times the resolution of displacement transducer.

As shown in Fig. 3, the stiffness matrix is revised when the change of stiffness exceeds a specified allowable error or the direction of velocity reponse change. At that time, the displacement response and unbalanced force (the difference between measured force and calculated one) are calculated. The unbalanced force is added to the external force in the next time step.

TECHNIQUES OF ACTUATOR CONTROL

Usually, actuator is controlled by feed back of actuator displacement or structure displacement (designate as displacement control) in pseudodynamic test. However the displacement control makes the variation of load larger in proportion to the stiffness of the structure, and so it is difficult to performe the pseudodynamic test on the structure with large stiffness. As shown in Fig. 4, the variation of load (K/Rd) is decided by the relation between resolution of displacement transducer (Rd) and stiffness (K).

The variation can be reduced by using feed back control by means of actuator load (designate as force control). Furthermore, considering the change of stiffness in a test, for example reduction of stiffness with failure or revival of the stiffness with unloading, the displacement control and the force control should be selected according to the stiffness at each loading step (Fig. 4). This selection can be judged by comparing the stiffness with ratio of resolution (RL/Rd) of displacement transaducer and load cell. If the stifness is greater than the ratio, the force control is selected otherwise the displacement control is selected. To apply this control technique to the pseudodynamic test, it is necessary to impose displacement responses by the force control. Such a position control of the displacement can be performed by calculating the force corresponding to the target displacement by means of the stiffness matrix and by outputting the force to the actuator as a command value. However, in this pseudodynamic testing method, to ensure the measurement accuracy of stiffness matrix is important, and it is unnecessary to control for displacement responses accurately as long as the stiffness does not change rapidly. Fig. 5 shows the system block diagram. In this system, feedback selector which feedback signal can be switched, is devised.

VERIFICATION TESTS

Outline of Test on Braced Steel Frame The pseudodynamic testing method was applied to a two story braced steel frame as shown in Fig 6. Each actuator was set at the floor level of each story, and the displacement was measured at the center point of the transverse beam at the middle of the structure. In this test, minimum displacement increment imposed to estimate stiffness matrix was 0.05mm, which coresponded to ten times resolution of displacement, and all actuators were controlled by the structure displacement. The N-S component of the El Centro earthquake(1940) record was used as the input acceleration. The maximum acceleration was normlized to 50 gal and 300 gal. For comparison purposes, an additional test by the CDM was conducted for the 50 gal input. Viscous damping was assumed to be proportional to the initial stiffness and a 1.0% damping ratio for the first natural period was introduced. Time interval for the numerical integration is 0.01 sec.

Test Results Fig. 7(a) compares the displacement time histories of the pseudodynamic tests with analysis at 50 gal input. In this test, the structure behaved elastically. The response analysis was conducted by linear acceleration method using the stiffness matrix measured by static loading test. As shown in the figures, the correlation between both of the tests and the analysis was good ,and so the appropriateness of the pseudodynamic testing method could be verified. Fig. 7(b) shows the time histories of measured stiffness (diagonal element of the stiffness matrix). Although the stiffness varies about 2.0 tf/mm at the first story and 1.0 tf/mm at the second story, the average of each stiffness was good agreement with the stiffness measured by static loading test.

Fig. 7(c) shows the displacement time histories of the test and inelastic analysis at 300 gal input. In this analysis, hysteretic rule was assumed as the bi-linear type model, and using linear acceleration method. In this case also, the test results and analytical one conform well with each other. Fig. 7(d) shows the stiffness time history for the first story. Inelastic behavior of the structure such as reduction of stiffness caused by yielding of brace or revival of stiffness with unloading, is well expressed.

Outline of Test on RC Shear Wall The pseudodynamic testing method was applied to a two story RC shear wall illustrated in Fig. 8. The purpose of the test is to verify feasibility for the pseudodynamic test by means of the force control. This structure is difficult to performe the test by displacement control because the initial stiffness of first story is so high as 210 tf/mm (the variation of load reach 6.0tf, using displacement control). The N-S component of the El Centro earthquake (1940) record was used as the input acceleration. The maximum acceleration were normalized to 50 gal, 100 gal and 300 gal, and the tests were conducted for the respective acceleration in turn. Viscous damping was to be proportional the initial stiffness and a 5.0% damping ratio for the first natural period was introduced. The time interval for the numerical integration is 0.01 sec.

Test Results Fig. 9(a) shows the displacement time histories of the test and elastic analysis by linear acceleration method (using the stiffness matrix obtained from the static loading test) at 50 gal input. The test results are smaller displacement response than the analysis, because the load-displacement relation had hysteretic loops (a little cracks occurred on the wall of first story shear force and bending moment). But the periodic characteristics of the test were qualitatively similar to the analysis.

Fig. 9(b)～(d) shows the test results at 100 gal and 300 gal input. In these tests, inelastic behaviors of the structure are remarkable, so inelastic analyses was made to compare with the test results by using the hysteretic model which was assumed origin oriented type model for Q-γ reration and degrading tri-linear type model (by Nomura) for M-ϕ relation. The test results were good agreement with analysis at 100 gal input. At 300 gal input test, although the displacement of each story tended to drift into the negative direction, the periodic characteristics of displacement responses were similar to analysis qualitatively. The reason for the displacement drift seems to be affected by residual displacement after the 100 gal input test.

CONCLUSIONS

This paper presented a pseudodynamic testing method using the Newmark implicit integration method. The verification tests were also performed on a two story braced steel frame and a RC shear wall. Major results and conclusions follow; 1) On the steel frame, both of the elastic test and inelastic one were good agreement with analysis. Furthermore, the elastic test results were conformed with test results by CDM; 2) The test on a RC shear wall with large stiffness was performed by force control. In this case, the test results were not always agreed with analyses, quantitatively owing to influence of residual displacement or the difference between the actual behavior of the structure and the analytical model. However the periodic characteristics conformed qualitatively; 3) The Stiffness matrix can be estimated experimentally with sufficient accuracy by selecting the loading paths; 4) Force control is effective means to apply the test to the structure with large stiffness.

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2. Clough, R.W., "Analysis of Structural Vaibrations and Dynamic Response," Japan-U.S.A Seminor on Matrix Method of Structural Analysis and Design, August, 1969, Tokyo, Japan

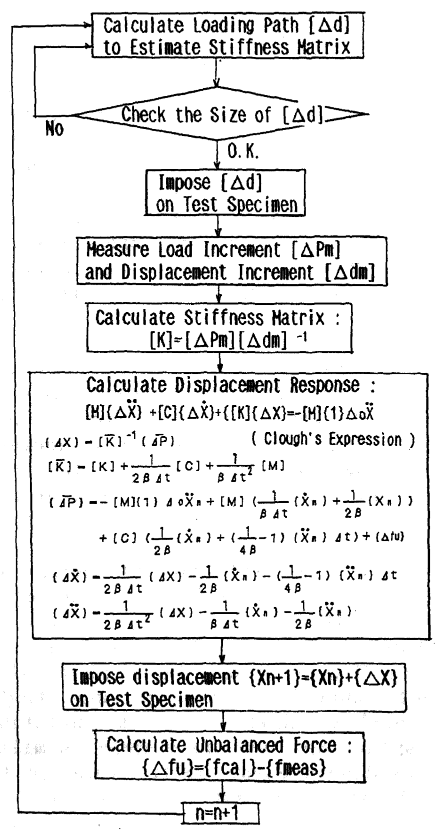


Fig.1 Pseudodynamic Algorithm

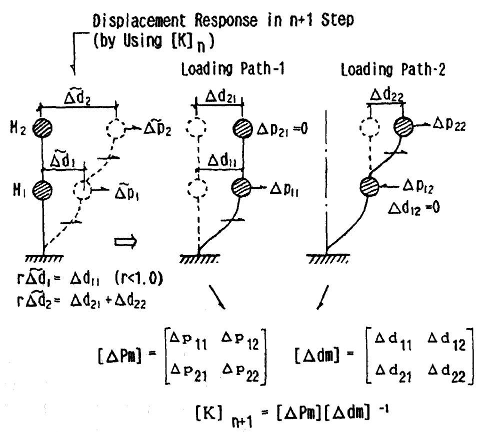


Fig.2 Loading Path to Estimate Stiffness Matrix

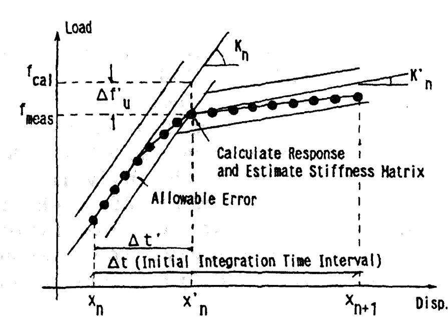


Fig.3 Monitor of Stiffness

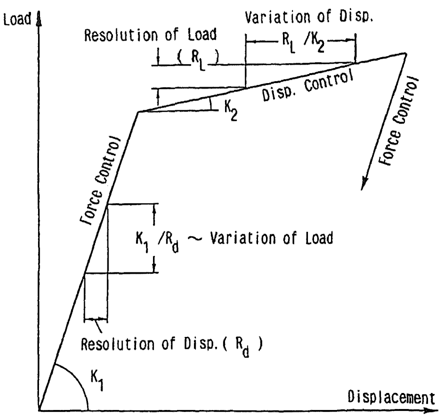


Fig.4 Control Technique of Actuator

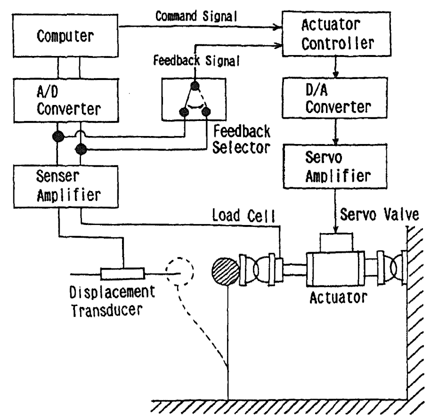


Fig.5 Pseudodynamic Test System

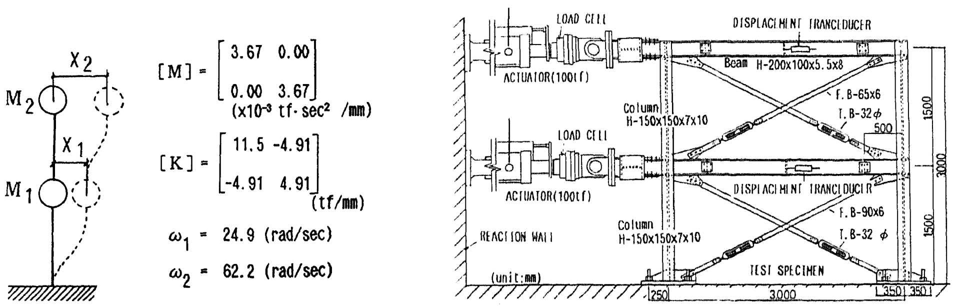
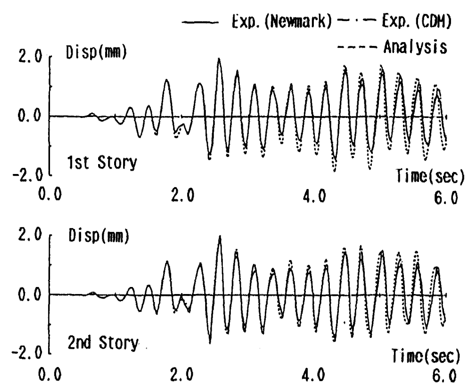
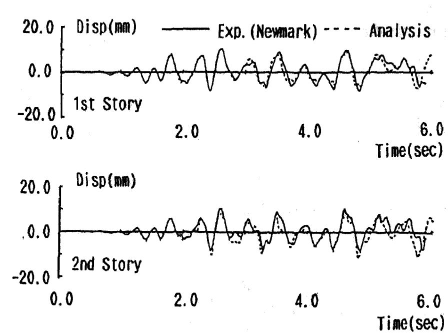


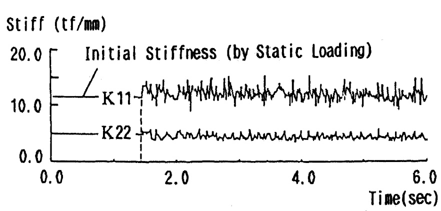
Fig.6 Test Setup of Braced Steel Frame



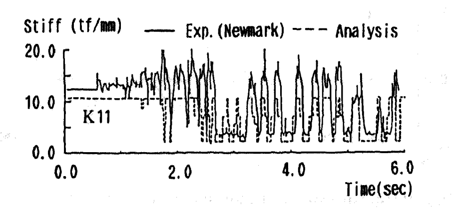
(a) Displacement Time History at 50gal Input



(c) Displacement Time History at 300gal Input



(b) Stiffness Time History at 50gal Input



(d) Stiffness Time History at 300gal Input

Fig.7 Pseudodynamic Test Results on Braced Steel Frame

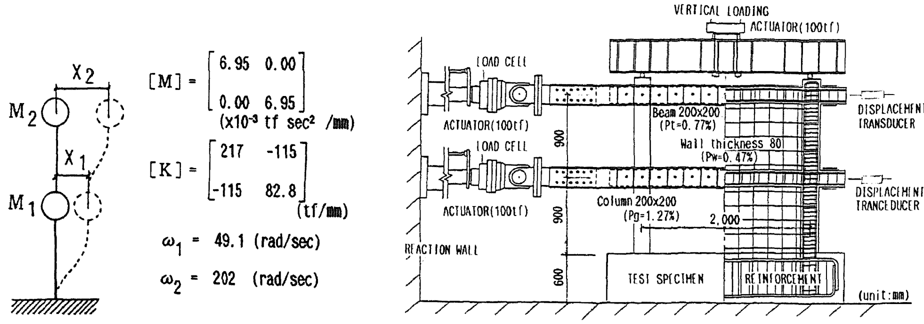
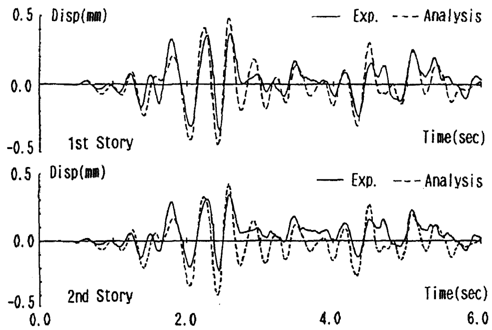
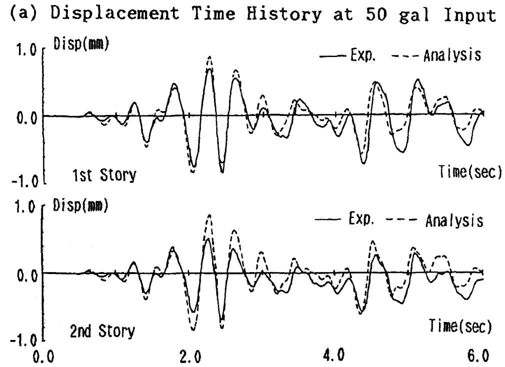


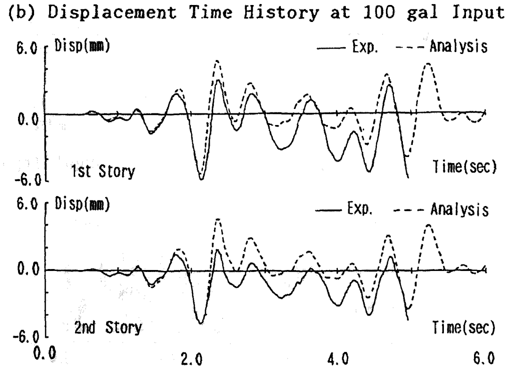
Fig.8 Test Setup of RC Shear Wall



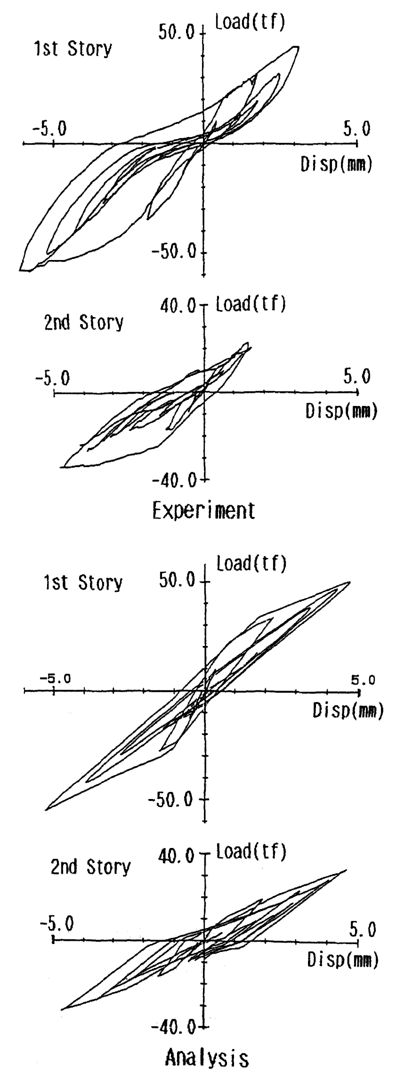
(a) Displacement Time History at 50 gal Input



(b) Displacement Time History at 100 gal Input



(c) Displacement Time History at 300 gal Input



(d) Force-Displacement Relationships at 300gal Input

Fig.9 Pseudodynamic Test Results on RC Shear Wall