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HYBRID ANALYSIS TECHNIQUES FOR SEISMIC PERFORMANCE TESTING

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SUMMARY

Reliable prediction of inelastic structural performance during a severe seismic event is an extremely difficult task, due to the complex nonlinear behavior exhibited by members and connectors. Therefore, experimental testing remains the most reliable means of assessing seismic performance and devising improved design and analysis methods. An on-line computer controlled experimental procedure has been developed which appears to combine the simplicity of quasi-static testing with the realism of shaking table tests. The method has been under investigation for more than ten years now, and this paper will examine recent research and extensions to the applicability of the pseudodynamic test method.

INTRODUCTION

The inelastic behavior of structures is generally quite sensitive to the imposed histories of displacement. Therefore, the nature of a testing technique has a significant effect on the observed data. Quasistatic tests are simple to perform, but due to the preselection of force or displacement histories, it is difficult to relate specimen response to expected seismic performance. Shake table tests provide realistic assessment of the specimen's response to an earthquake, but such tests limit the size, mass and strength of the specimens to be tested. Furthermore, most available shaking tables can only excite the specimen in one lateral direction and on some tables also in the vertical direction. A new technique, called on-line or pseudodynamic testing has recently been proposed (Ref. 9) as a means for overcoming many of these difficulties.

A coordinated series of investigations has been performed to evaluate the pseudodynamic technique as part of the U.S. - Japan Cooperative Earthquake Research Program. These studies were performed in Japan at the Building Research Institute in Tsukuba, and in the U.S. at both the University of California at Berkeley and the University of Michigan, Ann Arbor. These feasibility studies yielded theoretical and practical information useful for test implementation (Refs. 1,3,5,11,12). Several summary papers have been published (Refs. 9,10,13) which discuss progress in a variety of areas related to pseudodynamic testing. In this paper, recent developments at Berkeley will be presented, together with possible new application areas that may now be feasible due to recent breakthroughs.

BASIS OF THE PSEUDODYNAMIC METHOD

The pseudodynamic method is a an integrated experimental-analytical procedure. It is similar to standard step by step dynamic analysis procedures in that the controlling software consideres the response to be discretized into a series of time steps. The pseudodynamic algorithm can be described as: calculate the displacement state at the next time step using a suitable numerical integration technique, move the specimen into the new configuration, measure the restoring forces, solve the equations of motion for the time step to get the acceleration and velocity of the specimen. These operations are then repeated for each step of the input earthquake. The governing equation of motion in this case is :

$$\mathbf{M}\mathbf{a}_i + \mathbf{C}\mathbf{v}_i + \mathbf{r}_i = -\mathbf{M}\mathbf{B}\mathbf{a}_g \qquad (1)$$

where **M** and **C** are the mass and damping matrices; $\mathbf{a}_i$ and $\mathbf{v}_i$, are the acceleration and velocity respectively at time step i; $\mathbf{r}_i$ is the measured restoring force; and **B** and $\mathbf{a}_g$ are the ground acceleration transformation matrix and the ground acceleration vector respectively.

In order to perform such a test, the user must specify the inertial and damping properties of the specimen in terms of the mass and damping matrices, as well as the duration of a time step and a time history representing an earthquake record. Since experimental errors can be introduced at each step and propagate throughout a test, the pseudodynamic method has been found to be quite sensitive to errors, but a wide variety of error mitigation techniques have been proposed (Refs. 4,6,7,8).

Previous tests have used planar structures subjected to single components of earthquake excitation in order to be able to correlate the results to those obtainable from existing shaking tables. A recent verification study (Ref. 13) has lifted this restriction, and subjected a three degree of freedom non-planar structure to a fixed base five component earthquake motion. A sample of the correlation between pseudodynamic and shaking table results during a severe earthquake can be see in Fig. 1.

IMPLICIT NUMERICAL INTEGRATION TECHNIQUES

In previous pseudodynamic tests, an explicit numerical integration operator had been used so that displacements could be directly calculated at each step. However, the use of an explicit integration operator results in stability bounds on the time step. In particular, $\omega \Delta t \le 2$ must be satisfied for all natural frequencies (ω) of a structure. This means that the maximum size of the time step is determined by the highest natural frequency of a specimen. For specimens with a large number of degrees of freedom, the small step time determined by the highest modal frequency would aggravate error propagation problems, since error accumulation is related to the total number of time steps in a test. Test duration would also increase as the number of steps increased.

The use of an implicit integration technique can guarantee numerical stability regardless of the step size. Furthermore, there are globally stable techniques with dissipative properties that are suitable for error mitigation (Ref. 2). Implicit techniques have not been used to date in pseudodynamic testing because they require either iteration to converge on the next step displacement, which is intolerable since a real specimen is involved, or knowledge of the tangent stiffness characteristics of the specimen, which has proven extremely difficult to estimate. The initial stiffness matrix of a specimen is difficult enough to measure, the changes to the tangent stiffness matrix as the structure undergoes nonlinear deformation can be expected to be even more difficult to measure accurately.

A new method has been developed (Ref. 13), that allows a fully implicit numerical integration technique to be used without the need for iteration and without any need for estimates of the tangent stiffness matrix. The new algorithm can best be understood by examining the equations of motion together with an implicit integration algorithm proposed by Hilber, Taylor and Hughes (Ref. 2). step.

$$\mathbf{M}\mathbf{a}_{i+1} + \mathbf{C}\mathbf{v}_{i+1} + (1+\alpha)\mathbf{r}_{i+1} - \alpha\mathbf{r}_i = \mathbf{f}_{i+1} \tag{2}$$

$$\mathbf{d}_{i+1} = \mathbf{d}_i + \Delta t\, \mathbf{v}_i + (\tfrac{1}{2} - \beta)\Delta t^2 \mathbf{a}_i + \beta\Delta t^2 \mathbf{a}_{i+1} \tag{3}$$

$$\mathbf{v}_{i+1} = \mathbf{v}_i + (1-\gamma)\Delta t\, \mathbf{a}_i + \gamma\Delta t\, \mathbf{a}_{i+1} \tag{4}$$

where α, β and γ are parameters of the integration method.

The key to the new method is in the realization that as the new displacements are being applied as voltages sent out from the computer, the actual restoring force is available in terms of the voltages measured by the load cells. Although the computer does not explicitly know what restoring force will result from a given displacement, the voltage representing the actual restoring force exists as the displacements are changing. The new method consists of calculating the explicit terms of the new displacement and sending this signal to the actuators, and in addition, summing a portion of the measured restoring force voltage into the desired command signal. The portion of the forces needed becomes apparent when the equations of motion are recast as :

$$\begin{aligned}\mathbf{d}_{i+1} = \mathbf{d}_i + \Delta t\, \mathbf{v}_i + (\tfrac{1}{2} - \beta)\Delta t^2 \mathbf{a}_i - \beta\Delta t^2 \mathbf{B}\mathbf{a}_g + \beta\alpha\Delta t^2 \mathbf{M}^{-1}\mathbf{r}_i \\ - \beta(1+\alpha)\Delta t^2 \mathbf{M}^{-1}\mathbf{r}_{i+1}\end{aligned} \tag{5}$$

The last term of Equation 5 gives the portion of the restoring force signal that must be added to the explicit portion of the displacements to complete the implicit form. Using the calibration constants one can then sum this value into the desired displacement signal. Thus, the computer never knows where the specimen will go in this scheme, it only calculates the explicit portion and imposes it as a command voltage, the implicit component is summed to this voltage in analog form to give the actual displacement which are measured and recorded.

A two degree of freedom specimen, shown in Fig. 2 was constructed to test this technique. The explicit integration method had a critical time step of 0.016 sec., so time steps of 0.01 and 0.02 sec. were used to judge the behavior of the new method. It can be seen that the explicit analytical method goes unstable with a time step of 0.02 (in Fig. 4), while the implicit method gives good results with the same time step (Fig. 5). The period elongation is due to the characteristics of the integration scheme and the very long time step chosen in this test. In a real test, one would select the time step to accurately trace the response, in this test it was chosen primarily to demonstrate stability of the procedure. The small magnitude of the implicit portion of the overall displacement can be seen in Fig. 3.

CONCLUSIONS

The pseudodynamic method has been successfully extended to nonplanar tests with multiple components of excitation. A new fully implicit integration scheme has successfully been implemented and tested. This new method makes it possible to use implicit substructuring techniques and, by rearranging the equations of motion, the new method could be used to run tests under force control, making the testing of extremely stiff structures possible for the first time.

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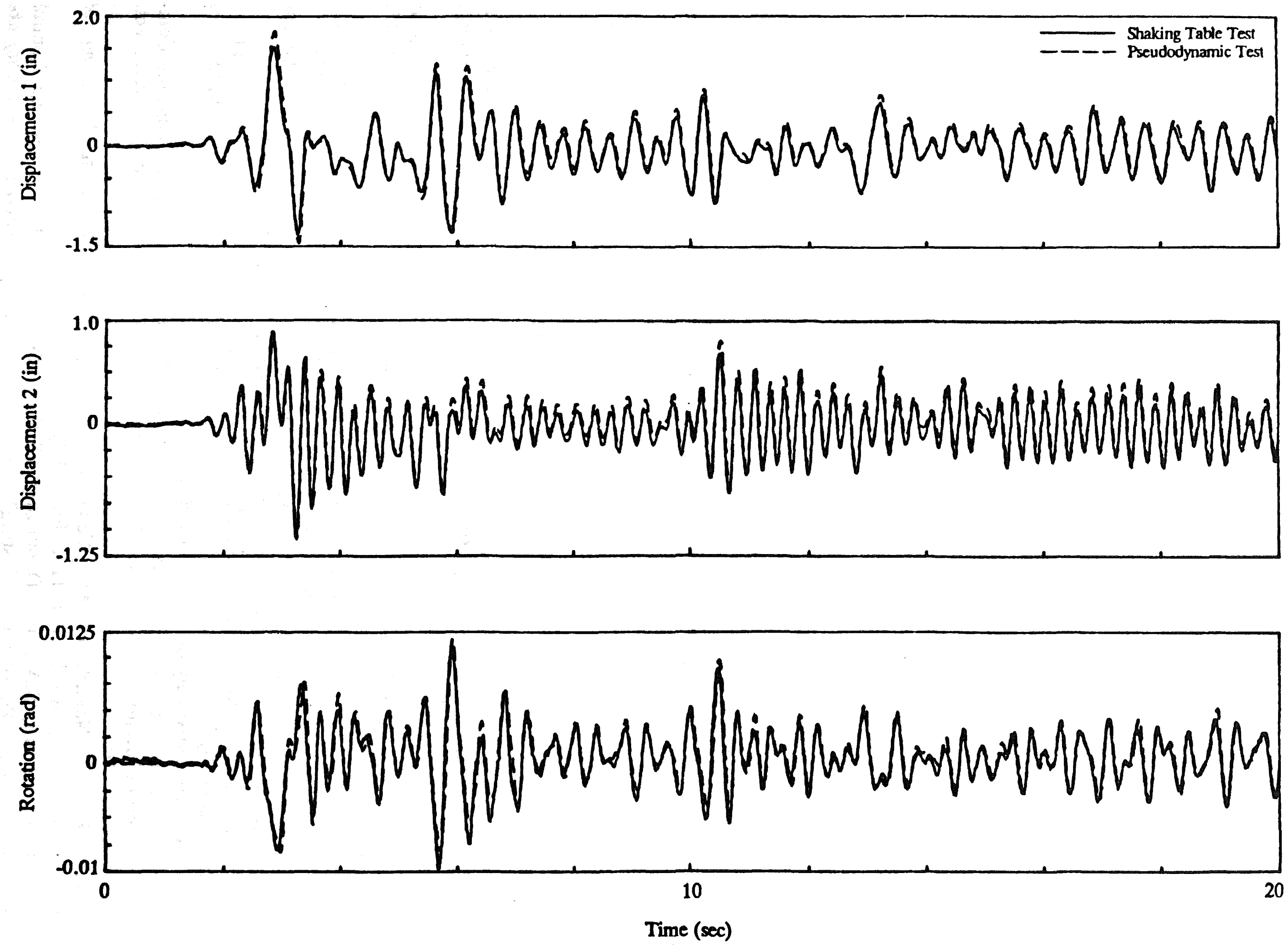
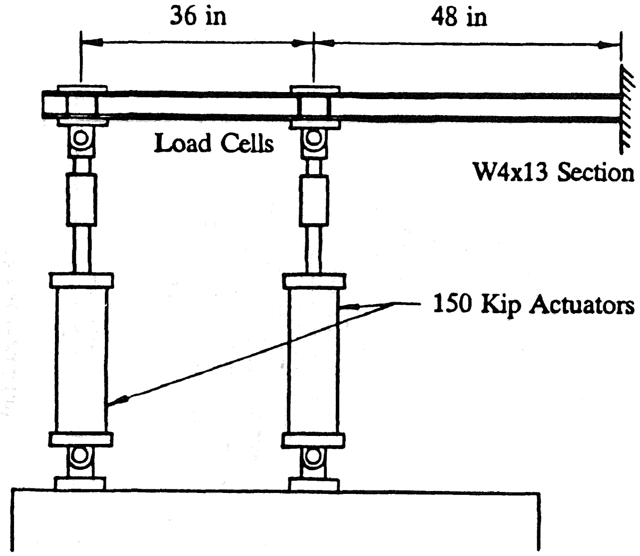
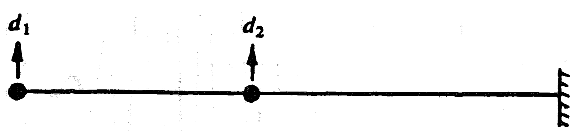


Figure 1 - Displacement Response of Non-Planar Structure



(a) Physical Setup



(b) Analytical Model

Figure 2 - Two Degree of Freedom Setup for Implicit Verification Test

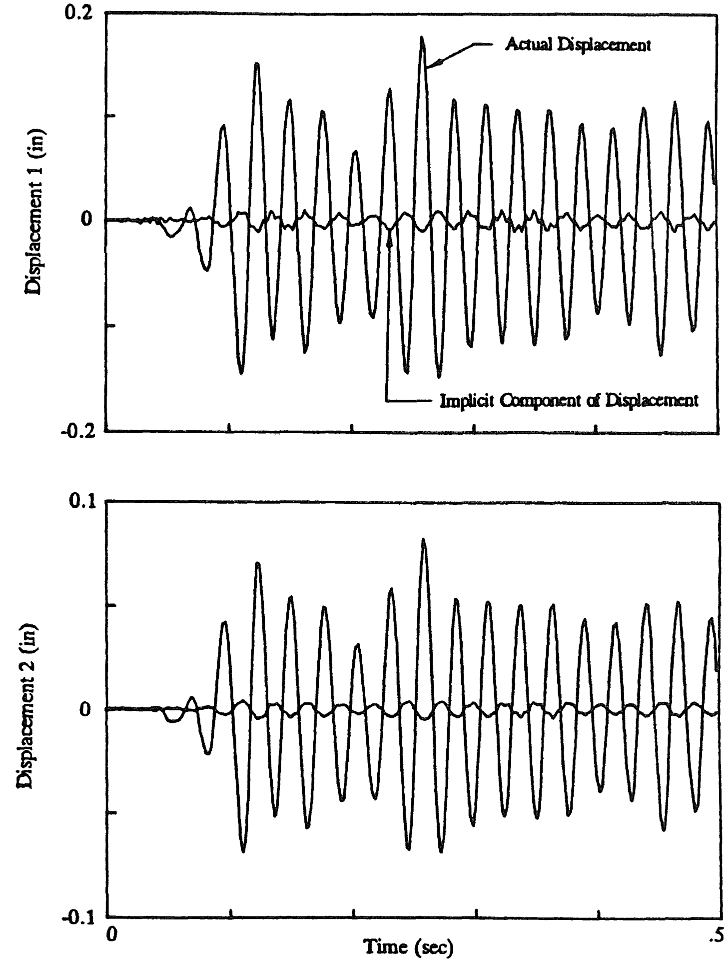


Figure 3 - Implicit Contribution to Displacement

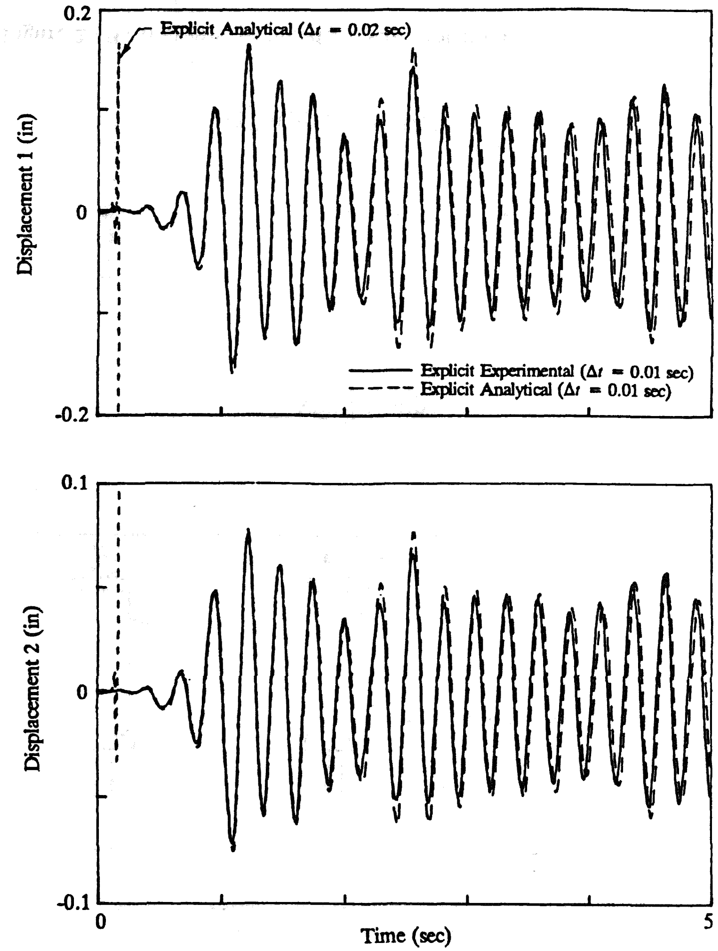


Figure 4 - Displacement Response (Explicit Test)

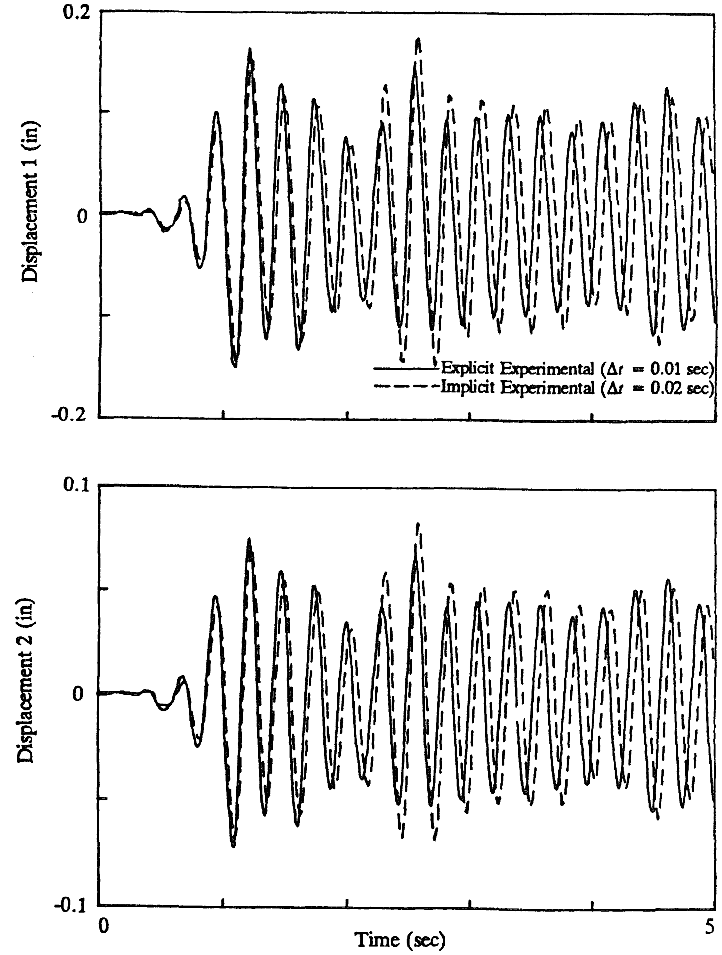


Figure 5 - Displacement Response (Implicit Test)