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EFFECTIVE FORCE SEISMIC SIMULATION FOR THE EARTHQUAKE ENGINEERING LABORATORY

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ABSTRACT

Effective Force Testing (EFT) is a method which enables real-time earthquake simulation studies of large-scale test structures. Other testing methods have limitations including specimen size, power requirements, or the control algorithm to achieve real-time response. Because the effective force testing method is based on a force control algorithm, the control signal is known a priori. It does not change with the response of the structure as in the case of deformation control algorithms. Research has been conducted on a single-degree-of-freedom system at the University of Minnesota to investigate the potential and limitations of the Effective Force Testing Method.

KEYWORDS

Effective force testing, earthquake simulation, test methods, dynamics, lumped mass systems, control requirements

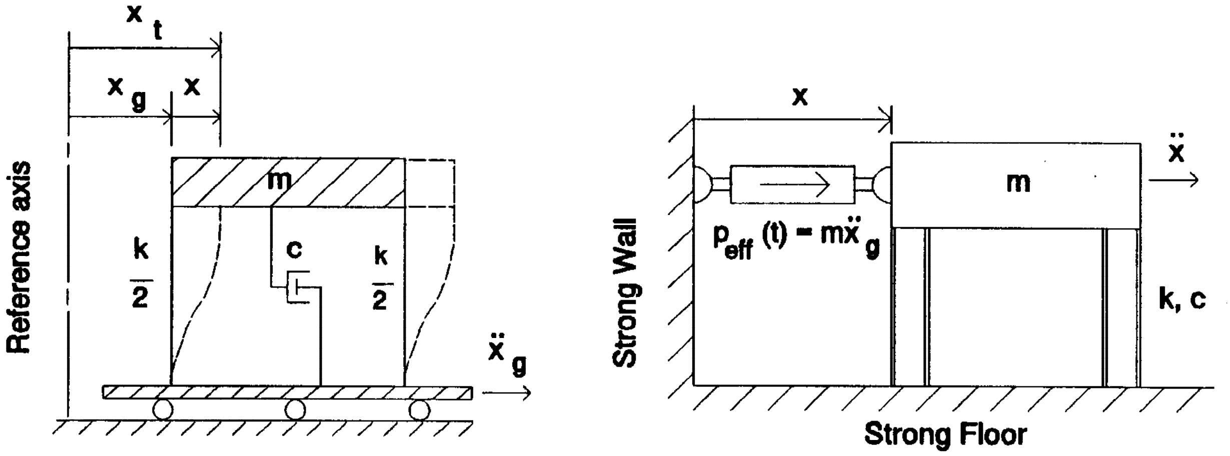
INTRODUCTION

There are three primary types of test methods to investigate the performance of structural systems in seismic regions. They are earthquake simulation studies on a "shake table," quasi-static cyclic studies of components, and pseudo-dynamic test methods. Each of these methods has advantages and disadvantages. For example for the case of "shake table" studies, test structures may be subjected to actual earthquake acceleration records to investigate dynamic effects; however, the size of the structure is limited by the capacity of the shake table. Typically, the test structure is reduced to less than 1/5-scale of the prototype. In most cases only overall flexural behavior can be investigated. It is difficult to investigate particular reinforcement details, bond, shear, and anchorage, because these phenomena do not scale well. Quasi-static cyclic studies of components offer the advantage of investigating actual details. However, effects associated with the dynamic nature of earthquakes are not captured in these tests. In addition, the demands imposed on the elements may not simulate those imposed in an actual earthquake. Pseudo-dynamic tests enable testing of large structures (details, bond, shear, anchorage), and the loading history is intended to simulate that which would be imposed on a structure in an actual earthquake. The dynamic effects, however, are still difficult to simulate with the pseudo-dynamic test method. It is difficult to conduct real-time tests because a displacement control algorithm is used. The deformation history to be imposed is not known a priori. For this test method, the imposed displacements depend on the response of the structure; they are a function of the structural stiffness which changes throughout the loading history.

The effective force testing method proposed in this paper is based on a force-controlled algorithm. Through a transformation of coordinates, the response of a system to a given ground motion may be replicated by applying an effective force $(m\ddot{x}_g)$ to the mass of the system (Fig. 1). Figure 1a shows a single-degree-of-freedom (SDOF) system subjected to a base motion, $\ddot{x}_g$. The following equation of motion may be obtained for this system:

$$m\ddot{x}_t + c\dot{x} + kx = 0, \qquad (1)$$

where m is the mass of the system, c is the viscous damping coefficient, and k is the system stiffness. Subscript t refers to motion relative to a fixed reference frame. Motions of the mass relative to the ground are nonsubscripted.



(a) Support Motion of SDOF System (b) Effective Force Testing

Fig. 1 Development of Effective Force Testing (EFT) Method

The absolute displacement of the system mass comprises the displacement of the mass with respect to the ground and the ground displacement,

$$x_t = x + x_g. \qquad (2)$$

The coordinate transformation of the accelerations results in

$$\ddot{x}_t = \ddot{x} + \ddot{x}_g. \qquad (3)$$

Combining Eqns. (1) and (3) yields

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{x}_g = P_{eff}(t). \qquad (4)$$

For a SDOF, the mass multiplied by the ground acceleration is equivalent to an "effective force," $P_{eff}(t)$, applied to the mass as shown.

The proposed technique uses the same setup as pseudo-dynamic and quasi-static testing as shown in Fig. 1b. The test structure is fixed to the ground and all motions due to the effective force are measured relative to the ground. Because the mass of a structure is typically known or can be estimated with good accuracy, the effective force to be applied to the structure is just a function of the earthquake ground acceleration record to be used. Consequently, the force-control loading history $(m\ddot{x}_g)$ is known a priori for any earthquake acceleration record.

EXPERIMENTAL INVESTIGATION OF "EFT METHOD"

To investigate the feasibility of this method of testing, including power and control algorithm requirements, a SDOF system was constructed in the laboratory at the University of Minnesota. The system, shown in Fig. 2, comprised a cart which carried a mass of 17,500 lbs (7,940 kg), and a No. 9 150 ksi (1,034 MPa) rod which served as a spring. The rod was initially tensioned to 15 kips (66.7 kN) to insure that the rod would remain in tension through the loading history to prevent buckling of the rod. An "effective force" was applied to the system using a hydraulic actuator applied to the lumped mass (cart). In the course of the investigation, the actuator servovalves were varied to investigate the effect of different flow capacities on the response. Two systems were used: (1) 77 kip (343 kN) actuator with a 15 gpm (0.946 l/s) servovalve; and (2) 77 (343 kN) kip actuator with a 30 gpm (1.89 l/s) servovalve.

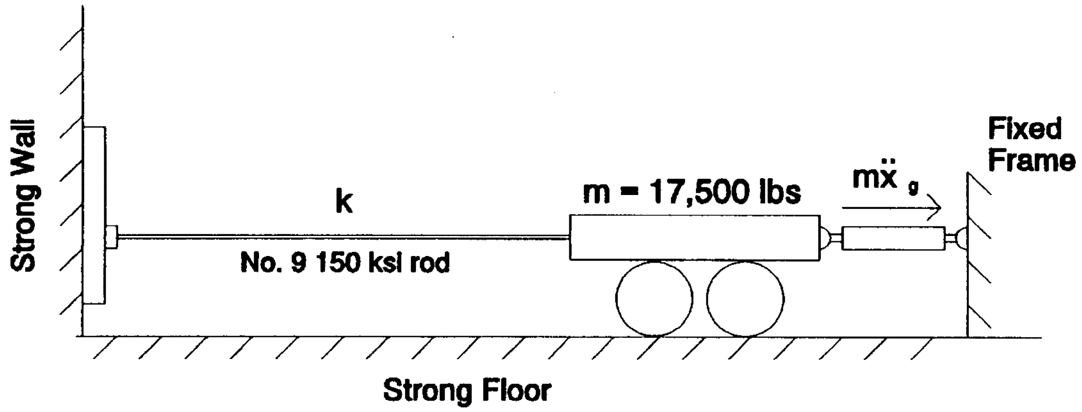


Fig. 2 Test Setup of SDOF Model

The servohydraulic system was controlled by an MTS 468 Test Processor. A Micro Segment Generator within the MTS 468 was used to input earthquake motions to the actuator. The feasibility of the EFT method can be investigated by comparing the input force function versus the force output measured from the actuator load cell (Fig. 3). This figure shows the input function superimposed on the output forces measured by the 77 kip (343 kN) actuators using 15 gpm (0.946 l/s) or 30 gpm (1.89 l/s) servovalves. The similarity of the force measured in the actuators relative to the input function demonstrates the potential of the EFT method. It is evident in the figure, however, that the 30 gpm (1.89 l/s) system was better able to follow the input signal.

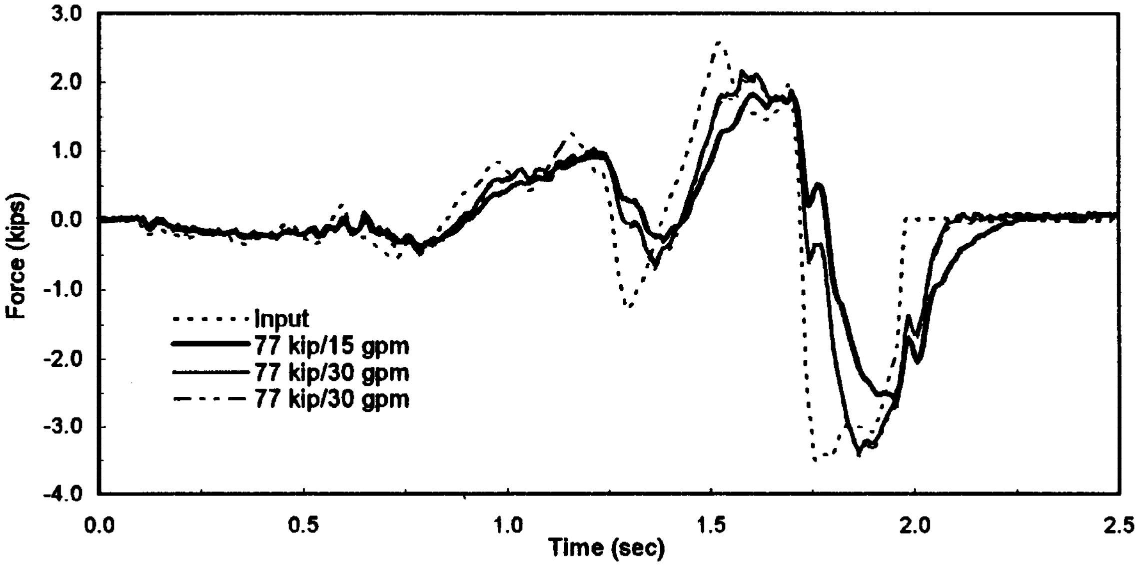


Fig. 3 Input Force Function versus Applied Load

Design equations have been developed to predict the performance of a given servohydraulic system (Clark, 1983). The force capacity of an actuator (F) as a function of velocity (V) may be written as:

$$F(V) = (\text{sign } V) F_{\max} \left(1 - \frac{1}{\alpha^2} \frac{V^2}{V_{\max}^2}\right)$$

where F_{max} is the maximum actuator force with full effective supply pressure drop across the actuator, and α is the servovalve spool opening (1.0 equals 100 percent open). V_{max}, the maximum velocity with full effective pressure drop across the servovalve, may be calculated as:

$$V_{\max} = \frac{k}{A}\sqrt{\frac{p_s}{p_d}}$$

where k is the servovalve flow rating, A is the actuator piston area, p_s is the hydraulic supply pressure, and p_d is the servovalve pressure drop rating. Using these equations, force-velocity curves may be developed to illustrate the theoretical limitations of a given servohydraulic system.

Figure 4 presents force-velocity curves for the two servohydraulic systems tested, as well as the actuator force-velocity requirements for simulating the input force function used (accounting for the pretension of 15 kips [66.7 kN]). The velocity required of the actuator in applying the input force function to the SDOF system was determined using a piecewise linear analysis of the loading function. Approximately 1.75 seconds into the loading function, the power requirements extend beyond the capabilities of the 77 kip (343 kN) actuator with a 15 gpm (0.946 l/s) servovalve. The power requirements stay within the capabilities of the 77 kip (343 kN) actuator with a 30 gpm (1.89 l/s) servovalve throughout the entire loading function.

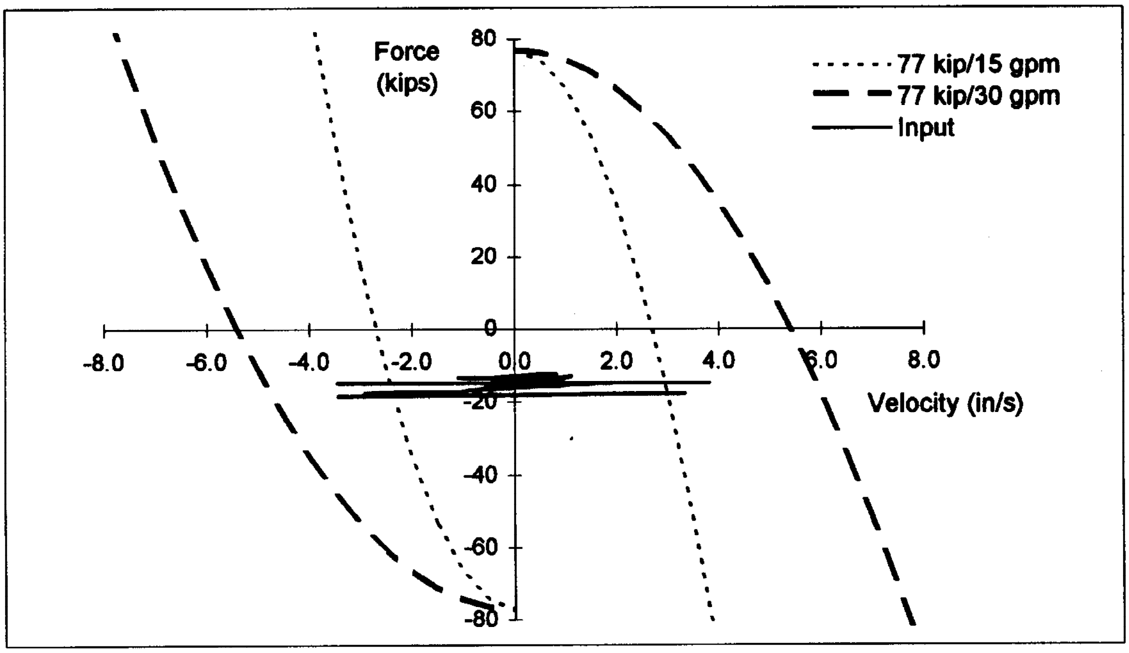


Fig. 4 Prediction of Servohydraulic System Performance

To better investigate the potential of the EFT method, it is useful to compare the response spectra of the input motion relative to that of the applied load. As for earthquake simulation studies, it is not as important for the motion to be exactly replicated as long as the response spectra is replicated in the range of frequencies that are of importance to the model. Figure 5 shows the displacement response spectra obtained from the ground acceleration records associated with the input and measured effective forces ($m\ddot{x}_g$). The better performance of the 77 kip /30gpm (343kN/1.89 l/s) system is more pronounced in this figure.

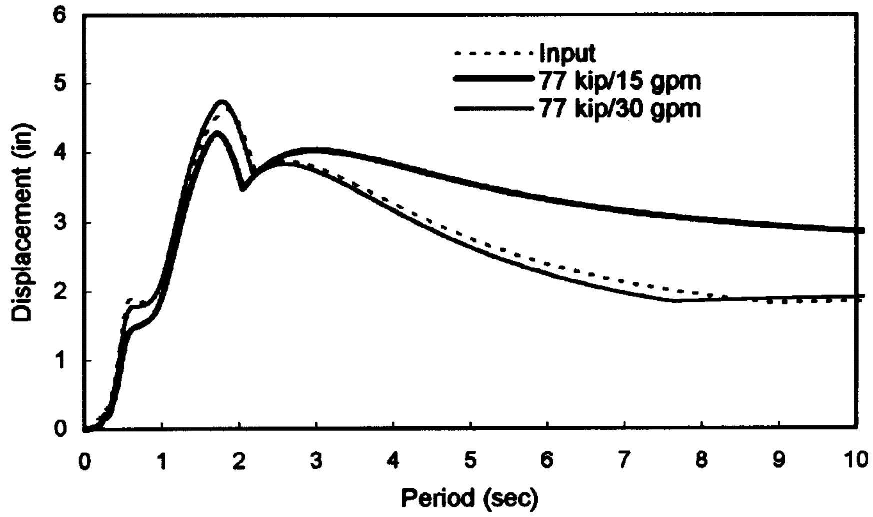


Fig. 5 Displacement Response Spectra

Another important feature of an earthquake simulation test is that the motion be repeatable. Referring back to Fig. 3, there are two curves shown for the 77 kip (343 kN) actuator with the 30 gpm (1.89 l/s) servovalve. These two measured force histories were conducted at different times and their responses lie virtually on top of each other, demonstrating the repeatability of the EFT "ground acceleration." It is especially important for situations in which the response of a number of details/structures are to be compared, that the input ground motion be replicated.

In addition, to comparing the response spectra, it is possible to analytically model the SDOF system with the applied effective force and compare the response with the measured results. To this end, accelerometers and LVDTs were used to measure the acceleration and displacement of the cart with respect to a fixed reference frame. From the known values of the system mass (17,500 lbs [7,940 kg]) and stiffness (69.6 kip/in 122 [kN/cm]), the natural frequency was calculated as 6.24 Hz. System damping was determined to be 3.3%. Figure 6 shows the analytically predicted displacement response of the cart calculated using the system parameters and the measured effective force superimposed on the actual displacement response of the cart measured relative to the laboratory floor. The similarity between the two displacement responses demonstrates experimentally the theory behind the EFT method.

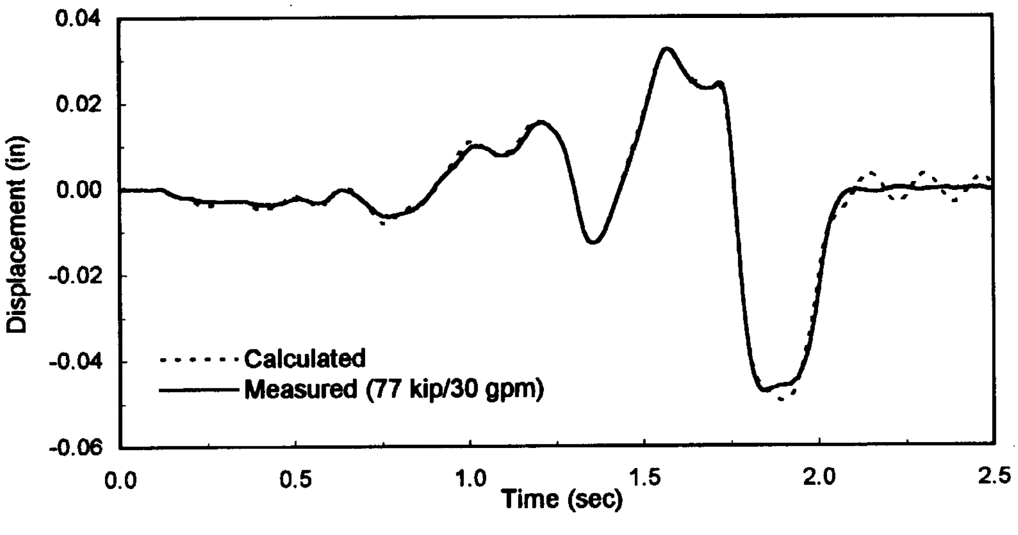


Fig. 6 Displacement Response (77 kip actuator/30 gpm servovalve)

COMPARISON OF "EFT METHOD" TO "SHAKE TABLE METHOD"

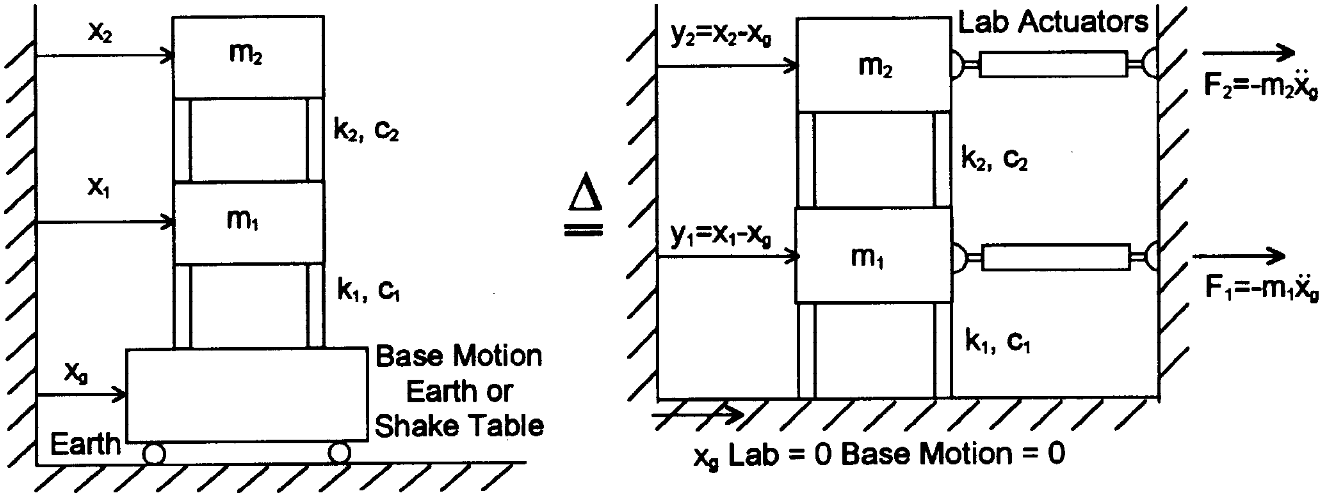
There is an interesting mechanical duality between shake table testing and effective force testing. In shake table testing, the input of the earthquake motion (acceleration, velocity, and displacement) is known, and the base excitation force that must be applied is unknown depending on the response of the structure. In effective force testing, the input of the earthquake effective applied force is known for a given earthquake, and the velocity of the mass due to that force is unknown depending on the response of the structure.

It can be shown that for low damping ratios (on the order of 1 to 5 percent for civil engineering structures) that at resonance the power input from the earthquake is the same for the two testing techniques. This makes sense from a physical principle point of view. For equal structural deformation response, the energy input to the structure would be expected to be the same for the two testing techniques.

The potential for laboratory energy and power savings for EFT is the lack of the need to move the table part of the earthquake simulator. A rough rule of thumb is the table mass is equal to the maximum specimen size for a particular earthquake simulator design. For the example studied in this paper this would mean that the hydraulic power requirements for the shaking table would be approximately twice that required for the same specimen tested by EFT. However, although the actuator force requirements are much lower, the actuator strokes required are higher. Also, there are significant problems to be solved to achieve high accuracy dynamic load control.

FUTURE POSSIBLE ENHANCEMENTS TO "EFT METHOD"

The effective force technique is easily extended to multiple degrees of freedom (Fig. 7). For a multiple-degree-of-freedom (MDOF) system, with lumped masses such as a shear-beam type system, the effective force applied to each level (lumped mass) is equal to the mass of each level multiplied by the ground acceleration. <u>All</u> the applied effective forces are completely known before the test begins.



Prototype Structure

Laboratory Structure

Fig. 7 Application of EFT to MDOF Systems

The systems discussed in this paper are linear, but this is not necessary for the technique to test correctly. Nonlinear stiffnesses and damping mechanisms would be tested accurately by applying the a priori effective force. The only criteria needed is for the structure to be of a lumped mass nature, which is a common earthquake engineering assumption for many practical structures.

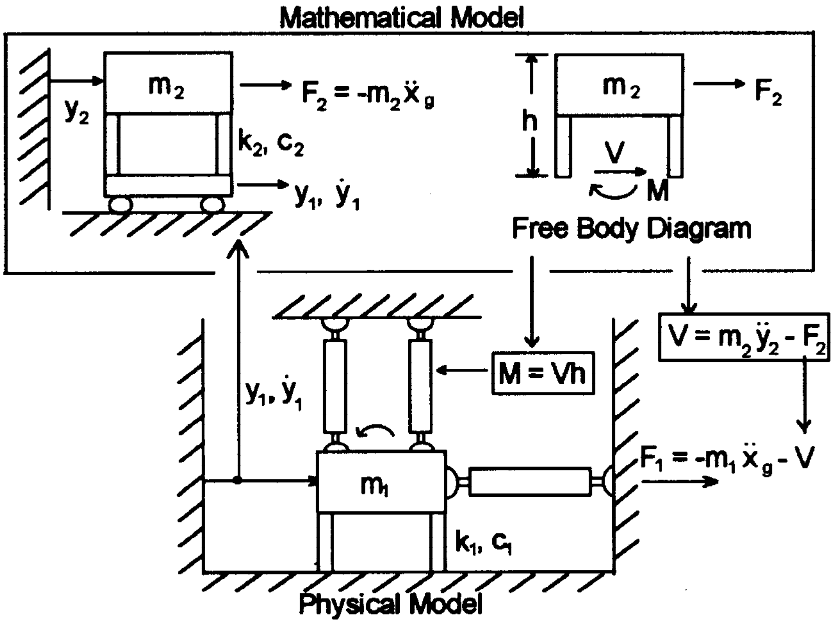


Fig. 8 Application of EFT to Substructuring

It is also straightforward (Fig. 8) to model parts of a structure under test on the digital computer and use the effective force test technique for applying the correct loads to a larger physically scaled part of the structure of interest. To do this correctly, it would be necessary to communicate in real time the position and velocity of the physical lumped mass under test to the computer model remainder of the structure, and also necessary to modify the effective applied force with the correct calculated shear from the computer modeled part of the total structure.

A new and current area of interest is the evaluation of active structural control systems for reducing earthquake structural damage. Effective force testing can be used to evaluate these systems. The only change required from shake table testing is that if accelerometer feedback transducers are used in the system, then the laboratory EFT test must modify the laboratory sensed acceleration by the earthquake acceleration before use in the system under evaluation. If strain gages or load cells are used as the feedback transducers no modifications are necessary.

CONCLUSIONS

Effective force testing is a new earthquake simulation technique which is complementary to existing methods. The feasibility of the technique has been demonstrated using a SDOF model, and application of the technique to the testing of other systems, including MDOF and substructures, has been presented. Although there are inherent disadvantages as with the existing methods, use of the EFT method will offer the advantages of economical real-time testing of large scale models and proper modeling of the damping and strain rate effects.

REFERENCES

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