EVALUATION OF ON-LINE COMPUTER CONTROL METHODS FOR SEISMIC PERFORMANCE TESTING

P. B. Shing (I), S. A. Mahin (II), and S. N. Dermitzakis (I)
Presenting Author: S. A. Mahin

SUMMARY

The seismic performance of structures that are too large, massive, or strong to be tested with available shaking tables can be efficiently studied by pseudodynamic testing. The pseudodynamic method, which utilizes a numerical algorithm in the on-line computer control of a test specimen, can realistically simulate the inelastic seismic response of a structural model. In spite of certain limitations, results of recent studies at Berkeley verify the practicality and reliability of the method.

INTRODUCTION

Shaking table testing is one of the most realistic experimental methods for studying the inelastic seismic performance of structural systems. Nevertheless, the weight and size of a structure which can be tested are significantly limited by the capacity of a table. Installing a new shaking table facility or increasing the capacity of an existing one is very costly. For this reason, on-line computer control (pseudodynamic) methods have been developed [1], which have the economy and versatility of conventional quasi-static testing, but achieve the realism of shaking table tests. In pseudodynamic testing, the seismic response of a structure is numerically evaluated by a computer, based on the direct experimental feedback of structural restoring forces, and is quasi-statically imposed on the structure through hydraulic actuators. This method has been successfully applied to tests of various structures by Japanese researchers [2]. As part of the U.S. - Japan Cooperative Earthquake Research Program, extensive analytical and experimental studies have been carried out at Berkeley to develop this method and to assess its capabilities and limitations. Some of the major findings are summarized in this paper.

THEORETICAL BACKGROUND

Numerical Formulation. The equations of motion of a discretized structural system can be expressed in terms of a family of second-order differential equations, which can be numerically solved by a direct step-by-step integration method for any arbitrary external excitations. This is a well-established numerical procedure in structural dynamics; and the mass, damping, and stiffness matrices of a discretized system can be formulated by the finite element method [3]. In pseudodynamic testing, the dynamic behavior of a structure is experimentally simulated by using the same numerical approach. However, instead of obtaining the stiffness matrix by finite element formulation, the restoring forces developed by structural deformations are directly measured from the test specimen during an experiment. Because of this, the inelastic dynamic response of a structure can be accurately simulated in a laboratory without the uncertainties associated with idealized inelastic mechanical properties of the structure.

Considering the dynamic response of a multiple-degree-of-freedom structure to an excitation of duration T, which is subdivided into N equal intervals Δt, i.e., $\Delta t = T/N$, we can write the equations of motion at time $(i+1)\Delta t$ as

$$\underline{m}\ \underline{a}_{i+1} + \underline{c}\ \underline{v}_{i+1} + \underline{k}\ \underline{d}_{i+1} = \underline{f}_{i+1} \tag{1}$$

where $\underline{m}$, $\underline{c}$, and $\underline{k}$ are the mass, damping, and stiffness matrices of the structure; $\underline{a}_{i+1}$, $\underline{v}_{i+1}$, and $\underline{d}_{i+1}$ are the acceleration, velocity, and displacement vectors at $(i+1)\Delta t$; and $\underline{f}_{i+1}$ is the external force excitation vector. To solve the equations of motion during a pseudodynamic test, we can use an explicit

(I) Junior Specialist, Univ. of California, Berkeley, CA, USA
(II) Assoc. Prof. of Civil Engineering, Univ. of California, Berkeley, CA, USA

form of the Newmark integration method [4], which assumes that

$$\underline{v}_{i+1} = \underline{v}_i + \frac{\Delta t}{2}(\underline{a}_i + \underline{a}_{i+1}) \tag{2}$$

$$\underline{d}_{i+1} = \underline{d}_i + \Delta t\, \underline{v}_i + \frac{\Delta t^2}{2}\underline{a}_i \tag{3}$$

By substituting $\underline{v}_{i+1}$ in Eq. (1) with Eq. (2), we can solve for $\underline{a}_{i+1}$ in terms of $\underline{v}_i$, $\underline{a}_i$, and $\underline{k}\,\underline{d}_{i+1}$. Since the product $\underline{k}\cdot\underline{d}_i$ can be measured as the restoring-force vector $\underline{r}_i$ in every step of a test, the displacement response $\underline{d}_{i+1}$ can be readily computed and imposed on a test structure. However, the mass matrix $\underline{m}$ and viscous damping $\underline{c}$ have to be analytically modeled.

Structural Idealizations. During a pseudodynamic test, we have to idealize the test structure as a discrete-parameter system, of which the mass is concentrated at a limited number of degrees of freedom. In doing that, a lumped-mass matrix is usually constructed for the structure. This is exactly analogous to the discretization and static condensation procedures carried out in most dynamic analyses [3], in which the higher mode effects of a structure are neglected. The adequacy of a discrete-parameter model depends on the actual mass distribution of a structure as well as on the characteristics of excitations. In general, discrete-parameter idealizations are adequate for load carrying structures which have most of their masses located at the selected degrees of freedom [5], such as for building systems having heavy floor slabs.

Structural damping is most conveniently modeled by a viscous damping mechanism. However, other forms of energy-dissipation exist in real systems, such as Coulomb damping due to friction and hysteretic damping caused by inelastic material behavior. Both Coulomb and hysteretic damping mechanisms are automatically taken into account in pseudodynamic testing by using the actual restoring-force feedback in numerical computations; whereas, viscous damping coefficients have to be analytically specified. The damping property of an elastic structure can be easily measured by vibration tests. Based on these measurements, appropriate viscous damping coefficients can be selected for pseudodynamic testing. The damping characteristic can usually be realistically included in pseudodynamic testing since energy dissipation is eventually dominated by hysteretic damping during inelastic response. Furthermore, due to strain-rate effects, the inelastic behavior of a structure tested pseudodynamically may be different from that in an actual seismic response. However, the difference is usually insignificant for steel structures which generally have fundamental frequencies less than 10 Hz [5].

Numerical Stability and Accuracy. The stability and accuracy of numerical integration are major considerations in the selection of integration time interval Δt. The Newmark explicit method is stable (i.e., solution will not grow without bound for any arbitrary initial conditions) when $\omega_M \Delta t \leqslant 2$, where ω_M is the highest angular frequency of a structure. Frequency distortion is usually observed in a numerical result. However, it is negligible when $\omega \Delta t$ is small (< 0.5) [5]. Although these properties are based on linear elastic systems, they are still valid for nonlinear systems by the fact that a nonlinear system can always be considered as piecewise linear. In addition, the Δt selected should be sufficiently small so that the nonlinear behavior of a system can be accurately traced by the discretized displacement increments. Otherwise, the stability and accuracy of an algorithm can be impaired [5].

EXPERIMENTAL ERROR PROPAGATION

Sources of Experimental Errors. In addition to the previously discussed problems, errors may also be introduced into pseudodynamic testing by experimental apparatus or improper instrumentation techniques. For example, the numerically computed displacements may not be exactly imposed on a test structure due to instability or lack of sensitivity of actuator-controller systems, miscalibrations of displacement transducers, or resolution errors in analog-to-digital (A/D) conversions of displacement control signals. The restoring forces measured from a test structure may be in error due to electrical noise or friction in actuator connections. Since the pseudodynamic response at any time depends on

experimental feedback from all previous steps and there may be hundreds or thousands of time steps in a single test, the experimental errors will have a significant cumulative effect. Because of this, test results may be rendered unreliable even though the errors introduced at any step might be small.

Error Propagation Effects. The error-propagation phenomenon in pseudodynamic testing can be mathematically modeled [6]. It can be shown that numerical results will be more accurate if the computed displacements are used instead of the measured ones in step-by-step computations. Even if this is done, displacement control errors are still introduced into the numerical computations through the resulting force feedback errors. Force feedback errors can have significant effects on experimental results depending on whether the errors are random or systematic in nature. Systematic errors, which often result from poor performance of experimental equipment or improper instrumentation techniques, can induce a significant cumulative error growth due to resonance-like effects. The cumulative growth of systematic errors within a fixed computational time span cannot be effectively reduced by decreasing Δt. Random errors may result from electrical noise or other less well-defined sources. Their effects are less severe and can be mitigated by reducing Δt. In both cases, the larger $\omega \Delta t$ is, the faster will be the rate of cumulative error growth with respect to the number of integration steps. Therefore, the higher modes of a multiple-degree-of-freedom system will be more sensitive to experimental errors than the lower modes. To illustrate this fact, analytical simulations were performed with a two-degree-of-freedom system shown in Fig. 1a. The exact response of the system to the El Centro ground motion was dominated by its fundamental frequency (see Fig. 1b). Random and systematic errors were then introduced into the computations by round-off and truncation, respectively, in the A/D conversions of displacement control signals. In both cases, the resulting cumulative errors were dominated by the second mode frequency (see Figs. 1c and 1d). In the case of systematic errors, the spurious second mode effect grew very rapidly. To assess error tolerance limits for a test, methods for establishing cumulative error bounds have been derived [6].

Error Correction Methods. Due to the error-propagation effects, experimental errors should always be eliminated or reduced to insignifcant levels in any test. This may not be always possible, especially in systems which have many degrees of freedom. In such systems, even small errors can propagate very rapidly in the higher modes. Under that circumstance, frequency-proportional numerical damping can be used to suppress the spurious higher mode effects. This numerical damping property can be introduced into the Newmark explicit algorithm by the following modification of the equilibrium equation (Eq. (1)):

$$\underline{m}\, a_{i+1} + \left[(1+\alpha)\, \underline{k} + \frac{\rho}{\Delta t^2}\, \underline{m}\right] \underline{d}_{i+1} = \underline{f}_{i+1} + \left[\alpha\, \underline{k} + \frac{\rho}{\Delta t^2}\, \underline{m}\right] \underline{d}_i \tag{4}$$

where α and ρ are parameters which control the damping characteristics (see Fig. 2). This method is applicable to inelastic systems. For example, a two-story shear building with inelastic inter-story force-deformation relations was numerically simulated. The results in Fig. 3 show that the spurious higher mode effect introduced by experimental errors was efficiently removed by numerical damping. A method based on conservation of energy has also been developed to compensate for the energy changes caused by systematic errors. Detailed discussions of these methods can be found in Reference 6.

VERIFICATION TESTS

A series of pseudodynamic tests were performed with simple one- and two-degree-of-freedom systems fabricated from steel columns. Tests involving 2000 time steps can be performed in less than 30 min. The results of these tests show good correlations with analytical predictions. Fig. 4a shows the pseudodynamic response of a two-degree-of-freedom system subjected to the El Centro 1940 (NS) earthquake excitation with 0.5g peak acceleration. The system had the configuration shown in Fig. 1a. It consisted of a 96 in. long, W6×20 steel cantilever column which carried two concentrated masses (m_1 and m_2 are 0.0054 and 0.0083 kip in/sec^2, respectively) at equal distances along its length. Significant yielding was developed at the fixed base of the column during the test. The results of this test

correlated well with an analytical simulation using inelastic beam elements, as shown in Fig. 4b. In addition, a tubular steel x-braced frame specimen previously tested on a shaking table [7] was repaired and tested pseudodynamically [8]. The correlations between the two experimental results are briefly discussed here.

Description of Tubular Frame Tests. The tubular frame specimen was a 5/48 scale planar model of a representative offshore platform constructed in Southern California. The shaking table test specimen was subjected to three levels of excitation based on the 1952 Taft (S69E) record. These corresponded to strength level (0.28g), ductility level (0.58g), and maximum credible (1.228g) events. The recorded motions of the table in these tests were used as the input for the pseudodynamic tests. Since 99% of the mass was concentrated at the top of the frame as service loads, the specimen could be considered as a single-degree-of-freedom system. A 1.5% viscous damping ratio, which was measured from the shaking table tests, was numerically specifed in the pseudodynamic tests. The pseudodynamic test setup is shown in Fig. 5.

Test Results. Due to the flexibilities of the specimen's base support and of the table itself, the frame stiffness measured on the table was 31% lower than that in the pseudodynamic tests. Because of this, the frame responses in the low level events were very different in the two experiments. However, the pseudodynamic response of the frame closely matched the analytical result in the elastic range, as shown in Fig. 6a, except that it had a slightly higher damping effect due to local nonlinearities. Excellent correlations were obtained for the inelastic responses as well. Furthermore, the inelastic seismic behaviors and the failure modes of the specimens in the two experiments were very similar. In the maximum credible event, the pseudodynamically tested frame had a deteriorated stiffness nearly identical to that of the shaking table specimen. Consequently, the two experimental results were almost identical during that event (see Fig. 6b). These results verify the reliability of the pseudodynamic method.

SUBSTRUCTURING METHODS

Based on the analytical formulation of the pseudodynamic method, it is possible to apply substructuring techniques to experimental testing, whereby part of a structure is tested pseudodynamically and the rest of it is modeled analytically. Computer software has been developed to incorporate a mathematically modeled system into a test specimen; and a mixed implicit-explicit integration method [9] is adopted to solve the resulting equations of motion. This program is capable of modeling three-dimensional structural systems. Additional efforts are currently devoted to improve the computational scheme and to expand modeling capabilities. By the substructuring methods, subassemblages of complete structural systems or equipment mounted in structures can be tested pseudodynamically, and the effects of soil-structure interaction can be analytically modeled and included in the testing as well.

CONCLUSIONS

The studies presented here indicate that the pseudodynamic method is a powerful and versatile experimental technique. However, as with all testing and analytical methods, users must have a clear understanding of its limitations and the factors which might influence its accuracy. To avoid severe experimental errors, particular attentions should be directed to the selection of appropriate test equipment and to instrumentation techniques. The accuracy of test results also depends on the mechanical properties of a structure and the numerical techniques used. In spite of that, it is possible to develop relatively error resistant systems using the methods discussed in this paper. In the future, the substructuring concepts should greatly expand the applicability of the method and permit testing of many types of structures not previously tested.

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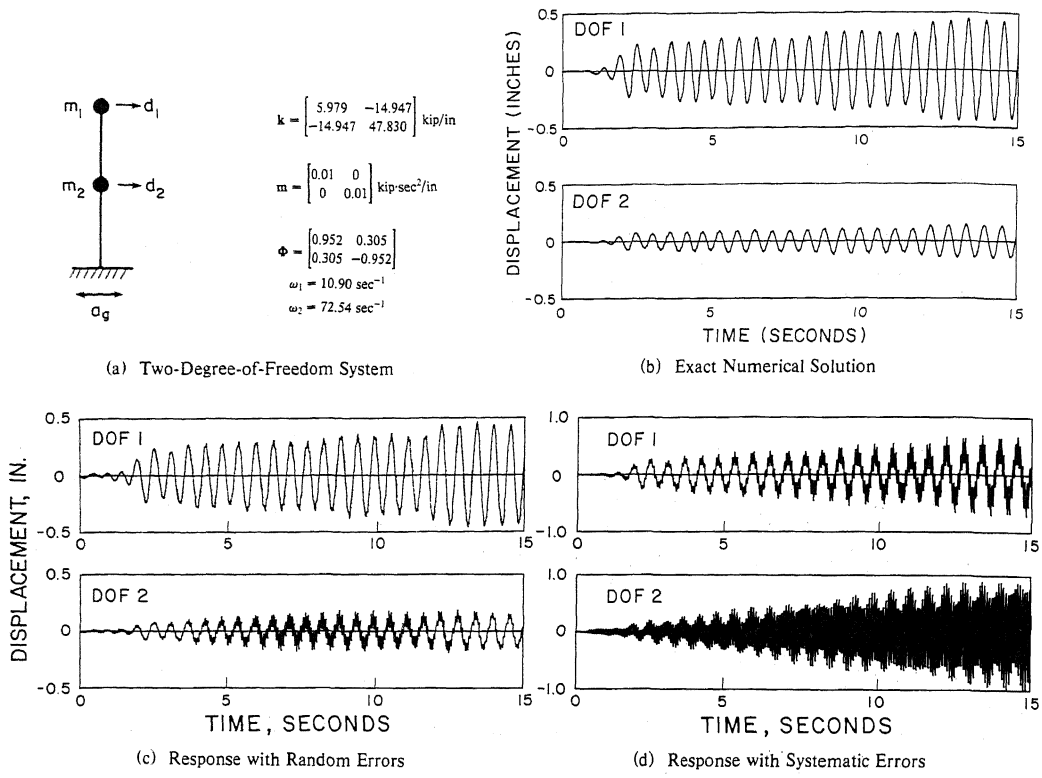


(a) Two-Degree-of-Freedom System

(b) Exact Numerical Solution

(c) Response with Random Errors

(d) Response with Systematic Errors

Fig. 1 Simulation of Experimental Error Effects using Newmark Explicit Method (Δt = 0.02 sec; a_g = 1940 El Centro (NS) with 0.02g Peak Acc.)

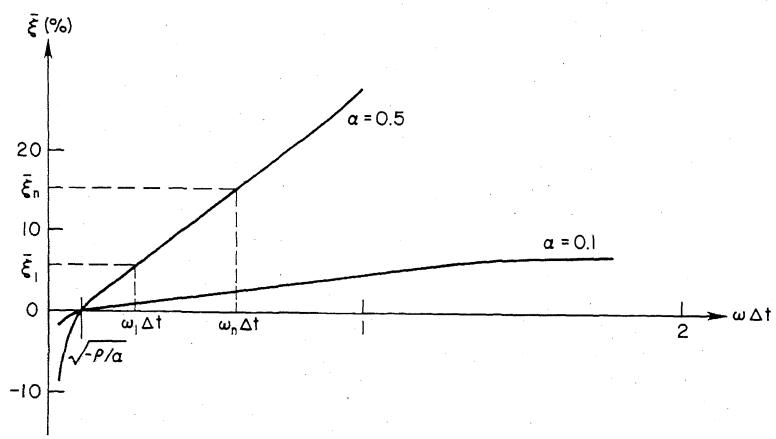
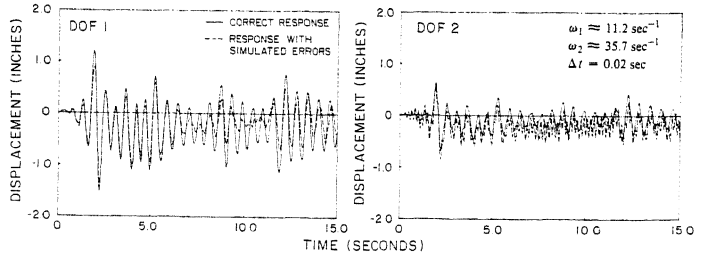
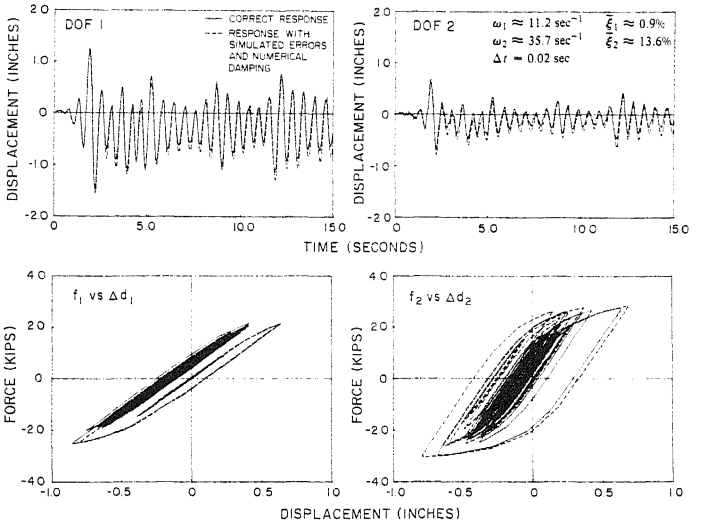


Fig. 2 Numerical Damping for the Modified Newmark Method

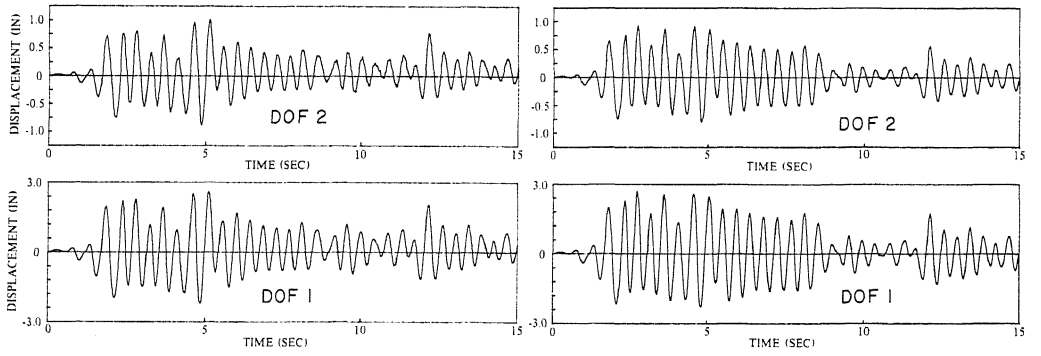


(a) Newmark Explicit Method
($\alpha = 0, \rho = 0$)



(b) Modified Newmark Method
($\alpha = 0.4, \rho = -0.016$)

Fig. 3 Removal of Experimental Errors by Numerical Damping for a Simulated Two-Degree-of-Freedom Inelastic Shear Building (1940 El Centro (NS) with 0.18g Peak Acc.)



(a) Pseudodynamic Test Results

(b) Analytical Results

Fig. 4 Comparison of Pseudodynamic Test Results with Analytical Simulation for a Two-Degree-of-Freedom Inelastic System (1940 El Centro (NS) with 0.5g Peak Acc.)

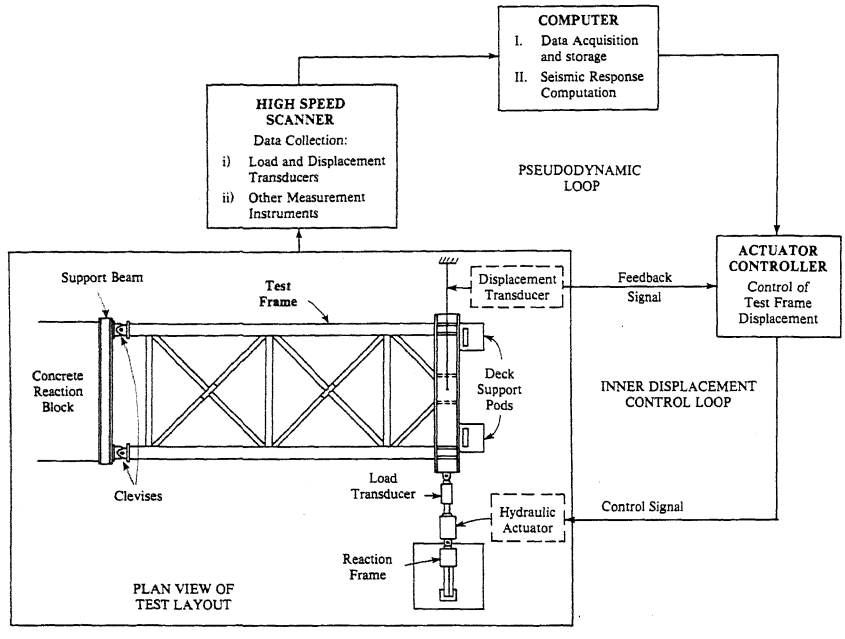
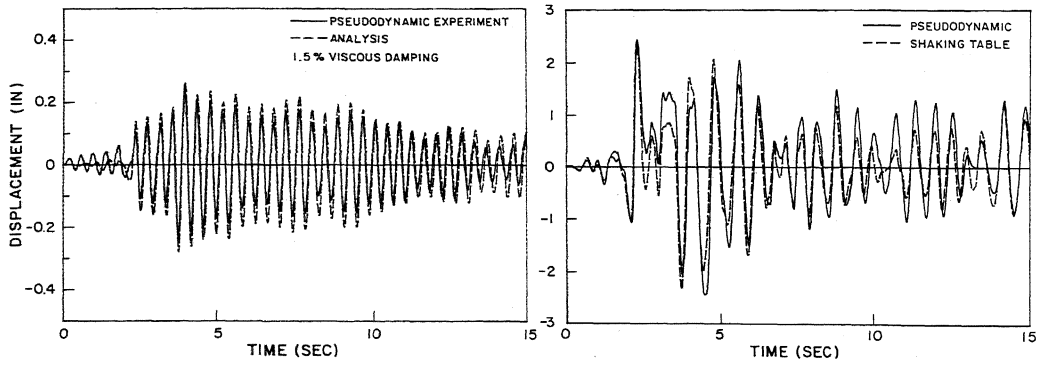


Fig. 5 Pseudodynamic Test Setup for a Tubular Steel Frame



(a) Elastic Response at 0.069g Taft

(b) Inelastic Response at 1.228g Taft

Fig. 6 Comparison of Pseudodynamic Test Results with Analytical and Shaking Table Test Results for a Tubular Steel Frame (1952 Taft S69E)