IDENTIFICATION OF THE ENERGY ABSORPTION CHARACTERISTICS OF AN EARTHQUAKE RESISTANT STRUCTURE: IDENTIFICATION OF PARAMETERS FROM SHAKING TABLE EXPERIMENTS

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Conference on
Dynamic Response of Structures
U.C.L.A. 1976

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. NSF/RA-760772	2.	3. Recipient's Accession No. PB 290460

4. Title and Subtitle
Identification of the Energy Absorption Characteristics of an Earthquake Resistant Structure, Identification of Parameters From Shaking Table Experiments (Proceedings, Conference on *

5. 1976

6.

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8. Performing Organization Rept. No.

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University of California at Berkeley
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10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)
(G)

12. Sponsoring Organization Name and Address
Applied Science and Research Applications (ASRA)
National Science Foundation
1800 G Street, N.W.
Washington, DC 20550

13. Type of Report & Period Covered

14.

15. Supplementary Notes
* Dynamic Response of Structures, University of California at Los Angeles, 1976

16. Abstract (Limit: 200 words)
An alternate procedure is presented for adjusting parameters, a procedure based on well known principles of optimization theory. In this procedure the parameters to be modified can be systematically adjusted using measured response data until, based on a predefined criterion, the best possible correlation is achieved between the predicted and measured response. The theoretical aspects of this procedure coupled with the selection of the mathematical model is known as system identification. This paper describes system identification in the context of a set of experiments conducted on the shaking table at the Earthquake Engineering Research Center at the University of California at Berkeley. The primary objective of this testing program is to illustrate the viability of system identification as a research tool in earthquake engineering.

17. Document Analysis a. Descriptors

Earthquake resistant structures	Energy absorption	Dynamic structural analysis
Seismic waves	Earthquakes	Mathematical models

b. Identifiers/Open-Ended Terms
Shaking table experiments

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
NTIS		16
	20. Security Class (This Page)	22. Price PCA02 MFA01

(See ANSI–Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4–77) (Formerly NTIS–35) Department of Commerce

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INTRODUCTION

One of the major research efforts in earthquake engineering is directed toward trying to understand the way in which structures absorb energy during earthquakes. One avenue of this research is laboratory experimentation in which structural models are subjected to simulated earthquake excitation. One of the objectives for such tests is the verification of a mathematical model to ensure that it is capable of adequately predicting the inelastic behavior of the structure. The basis on which the adequacy is judged is a comparison of the response measured during an experiment to the response predicted by the mathematical model, when the same excitation is used for each. A problem arises when the comparison is not satisfactory. It then becomes necessary to alter the mathematical model. In a mathematical sense, a model is nothing more than a set of differential equations with each equation containing a set of parameters. There are, therefore, only two possibilities for this modification - either the parameters in the existing set of equations can be adjusted, or the basic form of the equations can be changed, in which case the parameters must still be adjusted. Changing the form of the equations requires insight into the physics of the problem and can best be accomplished by the engineer reevaluating the physical mechanisms that contribute to the response. Adjusting the parameters, on the other hand, is a quantitative instead of a qualitative process and involves not so much insight as numerical manipulation - or, put another way, trial-and-error. This rather tedious process becomes especially difficult when the model considered is nonlinear.

This paper presents an alternate procedure for adjusting parameters - a procedure based on well known principles of optimization theory. In this procedure the parameters to be modified can be systematically adjusted using measured response data until, based on a predefined criterion, the best possible correlation is achieved between the predicted and the measured response. This means that the best set of parameters has been found for a mathematical model ~~for~~ of this form.

The theoretical aspects of this procedure, which when coupled with the selection of the mathematical model is known as system identification[1]*, are presented in another paper[2] at this conference.

*Numbers in parentheses correspond to references listed at the end of the paper.

Being able to find the best set of parameters is a worthy result. It leads to another result, however, that is perhaps of equal importance - the establishment of a basis on which the basic form of the equations can be judged. This result arises from the observation that, if the correlation is still not adequate after the best set of parameters has been found, the form of the equations is the only aspect of the model left open to change. The present paper describes system identification in the context of a set of experiments conducted on the shaking table at the Earthquake Engineering Research Center at the University of California at Berkeley.

TESTS

The primary objective of this testing program is to illustrate the viability of system identification as a research tool in earthquake engineering; gaining insight into inelastic structural behavior is of only secondary interest. Hence a relatively simple energy absorbing structure, shown in Figure 1, was selected for testing. It has one set of mild steel wide flange columns, fixed to the shaking table and pinned at the top to a rigid horizontal diaphragm, and another set of columns pinned at both the top and bottom, used merely to support the other end of the diaphragm. To ensure that the global response would be sufficiently inelastic, the cantilever columns were oriented to bend about their weak axes, and a 4000 pound concrete block was attached to the diaphragm.

The instrumentation requirements for the experiments were modest since only the global response was considered. Accelerograms and potentiometers were attached to both the diaphragm and to the table - the potentiometers measuring displacements relative to a fixed reference frame outside of the shaking table. With this positioning of transducers, it is possible to find relative frame accelerations and displacements as well as the table acceleration. Details on the data acquisition system and other aspects of the testing facility have been discussed by Rea and Penzien[3].

Three sets of tests on three identical sets of columns were performed on the shaking table. They were designed to reveal the influence on the parameters of a variety of testing conditions. The first set of columns was subjected to a version of the El Centro 1940 earthquake scaled so that it was severe enough to force the structure well into its inelastic region. The test was repeated twice on the same columns in order to determine the effect of loading history on the parameters. The other two sets of tests were similar to the first - the second using the El Centro record at a different intensity and the third using a Taft, 1952 record. The purpose of these tests was to determine the effect of the intensity and of the shape of the motion on the parameters.

After each set of columns was installed in the structure, but before the dynamic tests were started, traditional pull-back and free-vibration tests were performed. From these preliminary tests, the linear structural parameters were estimated.

SYSTEM IDENTIFICATION

The first and by far most important step in system identification is the selection of the form of mathematical model. It must represent the best *a priori* knowledge the engineer has about the structure. In our case, because the structure is particularly simple and because only its global behavior is of concern, we are able to use a very straight forward mathematical model. It is given by a single nonlinear differential equation and a pair of auxilliary algebraic equations which define Ramberg-Osgood type hysteretic behavior:

$$M\ddot{x} + C\dot{x} + P = -M\ddot{x}_g; \quad \dot{x}(o) = x(o) = 0 \qquad (1)$$

$$x = \frac{P}{K}\left(1 + A\left|\frac{P}{K}\right|^{R-1}\right) \quad \text{for skeletal curves} \qquad (2)$$

$$x = x_{re} + \frac{P-P_{re}}{K}\left(1 + A\left|\frac{P-P_{re}}{2K}\right|^{R-1}\right) \quad \text{for branch curves} \qquad (3)$$

where

$\ddot{x}_g$ is the ground (table) acceleration,
x is the relative displacement,
M is the mass,
C is the viscous damping coefficient,
K is the linearized stiffness at the origin,
A and R (with K) are the Ramberg-Osgood parameters, and
(P_{re}, x_{re}) is the coordinate of the most recent reversal of the hysteretic loop.

In this model, the parameters C, K, A, and R, designated by the vector $\bar{\beta}$, are left open to modification. The parameter M is assumed to be known (not necessarily a good assumption) and is therefore not adjusted during the identification process.

The second step in system identification is the selection of an objective criterion on which the "goodness of fit" between the response predicted by the model and the response measured during the test can be evaluated, when both the model and the structure are subjected to the same excitation. The traditional method of comparison, in which the predicted response found by using a trial set of parameters is plotted with the measured response, is inappropriate for use on a computer since it requires a subjective judgement of the goodness of fit. The criterion used here is an integral squared error function in which errors in both accelerations and displacements are considered. The error function, as it is called, is a function of both the time interval, T, over which the two responses are compared and of the current set of parameters, $\bar{\beta}$:

$$J(\bar{\beta},T) = \int_0^T \left[(\ddot{x}(\bar{\beta},t) - \ddot{y}(t))^2 + (x(\bar{\beta},t) - y(t))^2\right]dt \qquad (4)$$

where $x(\bar{\beta},t)$ describes the motion produced by the mathematical model using the parameter set $\bar{\beta}$
and $y(t)$ describes the motion of the test structure.

With an error function such as this, each set of parameters will, in general, give a different value for the error. Therefore, if two sets of parameters are likely candidates for selection, this function can be used to make an objective judgement about which set is better.

The third step in system identification is the parameter adjustment algorithm. It is rather complex and will not be given here. Conceptually, it is based on an interpretation of the error function as describing a surface imbedded in five-dimensional space: four parameter dimensions plus the error. A Gauss-Newton descent method and a cubic interpolation function are used to systematically search the surface, as it were, until the minimum is found. The resulting set of minimizing parameters, when inserted into the differential equations, give the best prediction of the measured response over the interval T. This final mathematical model is then, by definition, the best model of this form.

Before using actual test data in the algorithm, simulated data was used to check out the numerical aspects of the program. The simulated data was generated by assigning what we thought were realistic values to the parameters and then integrating the differential equation over the time interval of the earthquake. The parameter adjustment process was started by choosing a time interval - only a small fraction of the duration was required as it turned out - and an initial set of parameters which was some distance from the assigned values. Several of these preliminary numerical experiments were performed, and in each case the algorithm converged to the correct values in a very few iterations.

RESULTS AND DISCUSSION

The first test data to be used in the identification algorithm were from an initial test in an El Centro series. The measured table acceleration from this test is shown in Figure 2. To gain some idea of the nature of the inelastic response, pseudo hysteretic loops were plotted. The global inelastic force used for these loops was approximated by multiplying the effective mass by the absolute acceleration at the top of the columns. As it turned out this was not a bad approximation since the viscous damping was light.

To start the parameter adjustment algorithm, recall that it is necessary to specify the time interval, T, and an initial estimate of the parameters, $\bar{\beta}$. It is well known that in order to identify nonlinear parameters, T must be large enough to include some inelastic response. However it is not so well known how small T can be and still have the algorithm converge. Our experience with simulated data lead us to the conclusion that only the first few excursions into the inelastic region were required. For the El Centro motion, which has some very intense motion early in the record, only four seconds of data were used.

The initial estimate of the parameters, given in Table 1, represent the best information available before the adjustment algorithm was used. The values for C and K were calculated from the preliminary tests: C from the decay of the low-amplitude free vibration test, and K from the pull-back test. The pseudo hysteretic loops were used to estimate the other two Ramberg-Osgood parameters A and R, and to verify K.

The value of the error function using this initial set of parameters was 11506. In 42 iterations the algorithm converged to the minimum error of 420.

The final set of parameters which define this point are given in Table 1. The values for C, A, and R are quite different from their initial estimates, but this only serves to illustrate that a good initial estimate is not absolutely necessary. The better the original estimate is, of course, the faster the algorithm will converge.

After the minimizing set of parameters has been found, the mathematical model has been improved as much as possible. How good is this "best model"? To find out, the differential equation must be integrated, using the minimizing set of parameters, over the entire duration of the El Centro accelerogram; and the resulting acceleration and displacement plotted with their measured counterparts. Figure 3 shows the results of this comparison. The correlation is surprisingly good, especially for the acceleration. The reason that the permanent set in the displacement was not picked up by the model may be seen in Figure 4 which shows the pseudo hysteretic loops from the measured data and the predicted loops from the Ramberg-Osgood equations. The measured data indicate that the behavior of the structure during the first major excursion into the inelastic region is fundamentally different from the behavior during all subsequent excursions. This type of behavior, which is normal for tests on virgin steel, simply cannot be accommodated with the mathematical model used here. The best that the identification algorithm can do is to fit an average model through the first four seconds of data.

This comparison of measured and predicted data shows that the mathematical model is good but still open to improvement. It also gives an indication of how the model might be improved. An improved model might have two phases: the first using parameters identified from the first major inelastic excursion, and the second using parameters from the subsequent loops. It is not possible to identify parameters in this way with our present algorithm. To obtain a second set of parameters, note that the lower limit in the error function as well as the initial conditions will no longer be zero. Modifications to give the program this added versatility are planned for the near future.

It is interesting to observe that the minimizing set of parameters from the El Centro accelerogram also works very well when used with the Taft record, even though the earthquakes are quite dissimilar as may be seen from the table acceleration shown in Figure 2. The comparison of the predicted response using this combination of parameters and table motion to the measured response is given in Figure 5. One reason for this exceptionally good fit may be seen in Figure 6 showing the measured and predicted hysteretic loops. The Taft motion does not produce nearly as much inelastic response as the El Centro motion does.

CONCLUSIONS

In the introduction we claim that the parameters in a mathematical model could be systematically adjusted until, using a predefined criterion, the best possible correlation is achieved between the predicted response and the measured response. Using data from an actual test on a simple structure, we demonstrate that the process does in fact work. It is probably too early to judge the usefulness of this type of process for more complicated structures. Progress is being made, however, at Berkeley as well as at other institutions in the development of models and corresponding identification algorithms for other structural problems. Our current research, for example, includes a nonlinear model for a single degree-of-freedom reinforced concrete structure, and a linear model for a three story steel frame. It appears most likely that system identification, with the attention it is now receiving, will soon prove to be a valuable and time saving tool in earthquake engineering research.

REFERENCES

1. Bekey, George A., "System Identification - An Introduction and a Survey," Simulation, Vol. 5, No. 4, pp. 151-166, October 1970.

2. McNiven, Hugh D. and Matzen, Vernon C., "Identification of the Energy Absorbing Characteristics of an Earthquake Resistant Structure: Description of the Identification Method," ASCE-EMD Specialty Conference on the Dynamic Response of Structures: Instrumentation, Testing Methods and System Identification, University of California at Los Angeles, March 30-31, 1976.

3. Rea, D. and Penzien, J., "Dynamic Response of a 20 ft x 20 ft Shaking Table," Proceedings of the Fifth World Conference on Earthquake Engineering, Rome, Italy, 1973.

TABLE 1. Initial and Final Parameters

Parameter	Initial Estimate	Final Value
C(lb - sec/in)	1.	7.8806
K(lb/in)	2500.	2367.0
A	0.1	0.46581×10^{-8}
R	10.	31.654

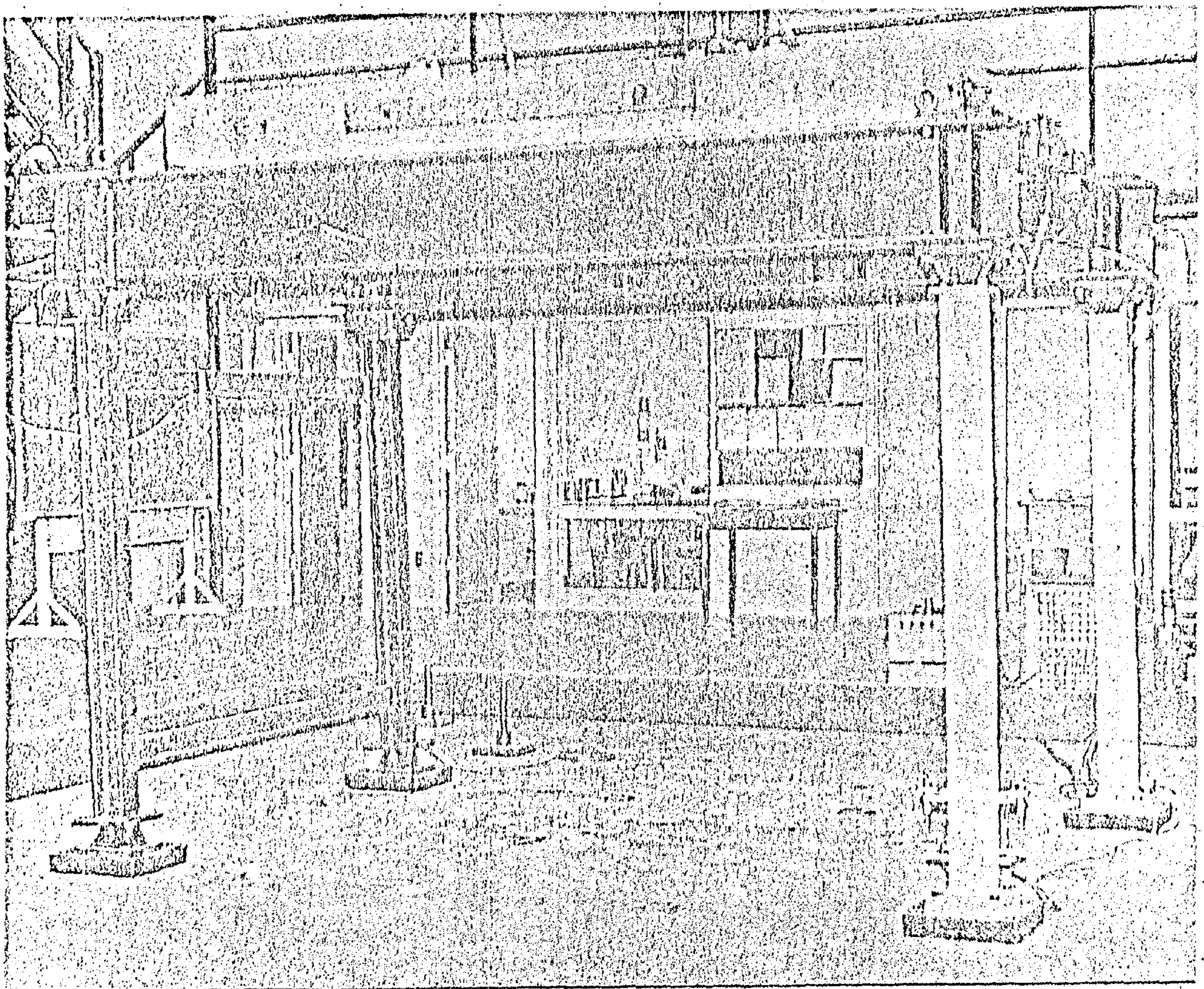

Figure 1. Structure on shaking table after El Centro test

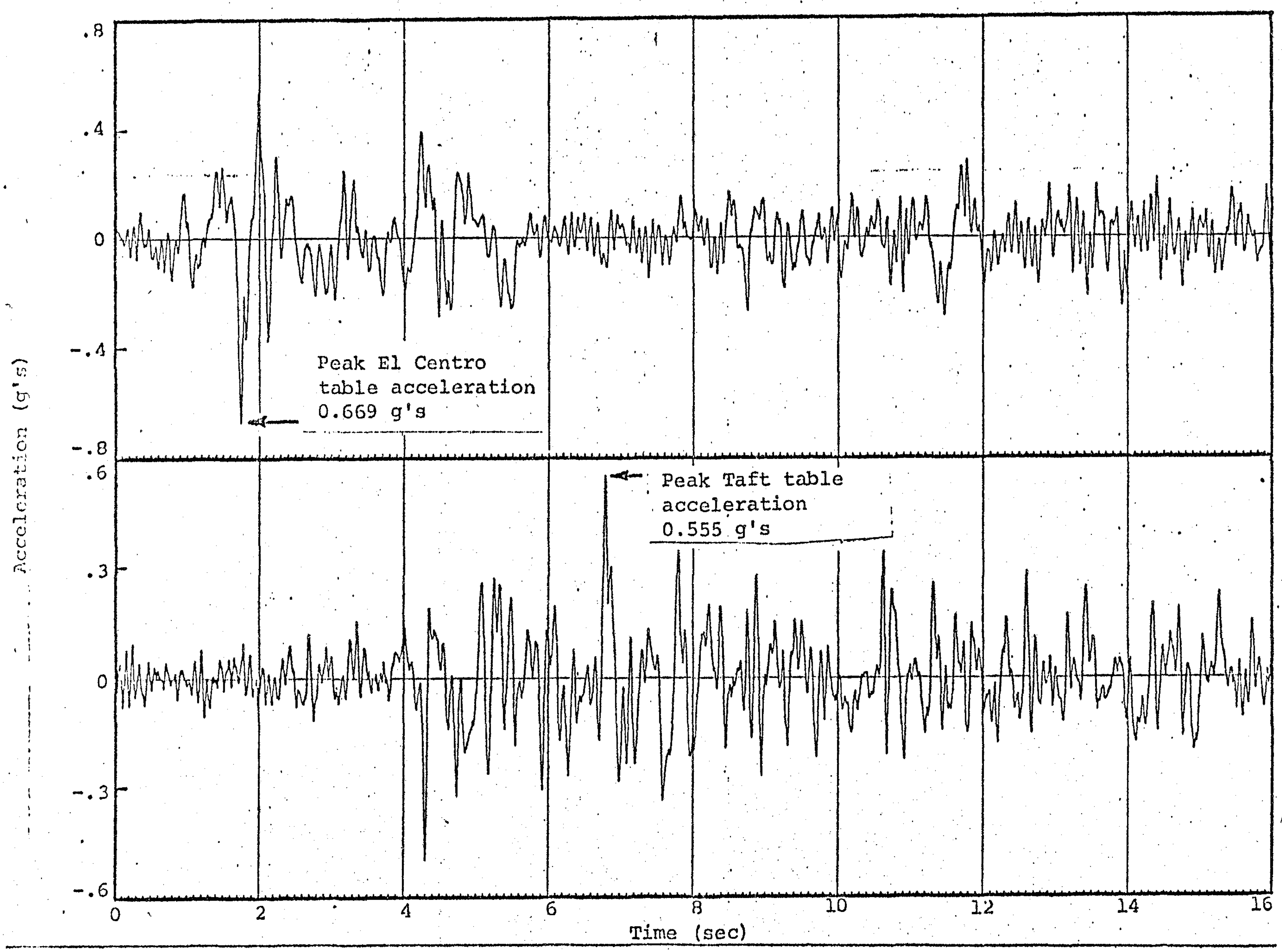

Figure 2. Measured table acceleration from El Centro 1940 (top) and Taft 1952 (bottom)

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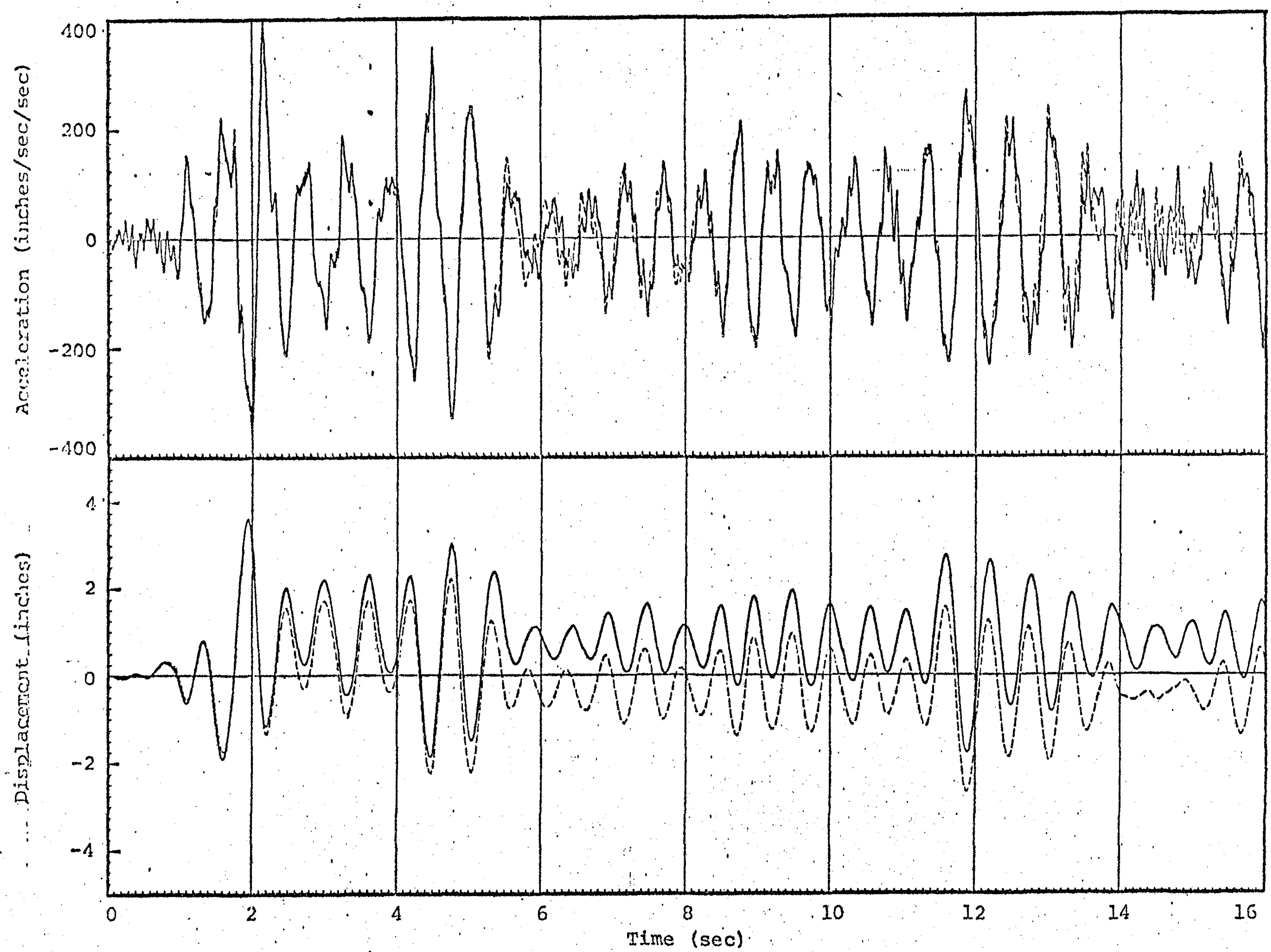

Figure 3. Comparison of measured (solid) and predicted (dashed) time histories from El Centro 1940

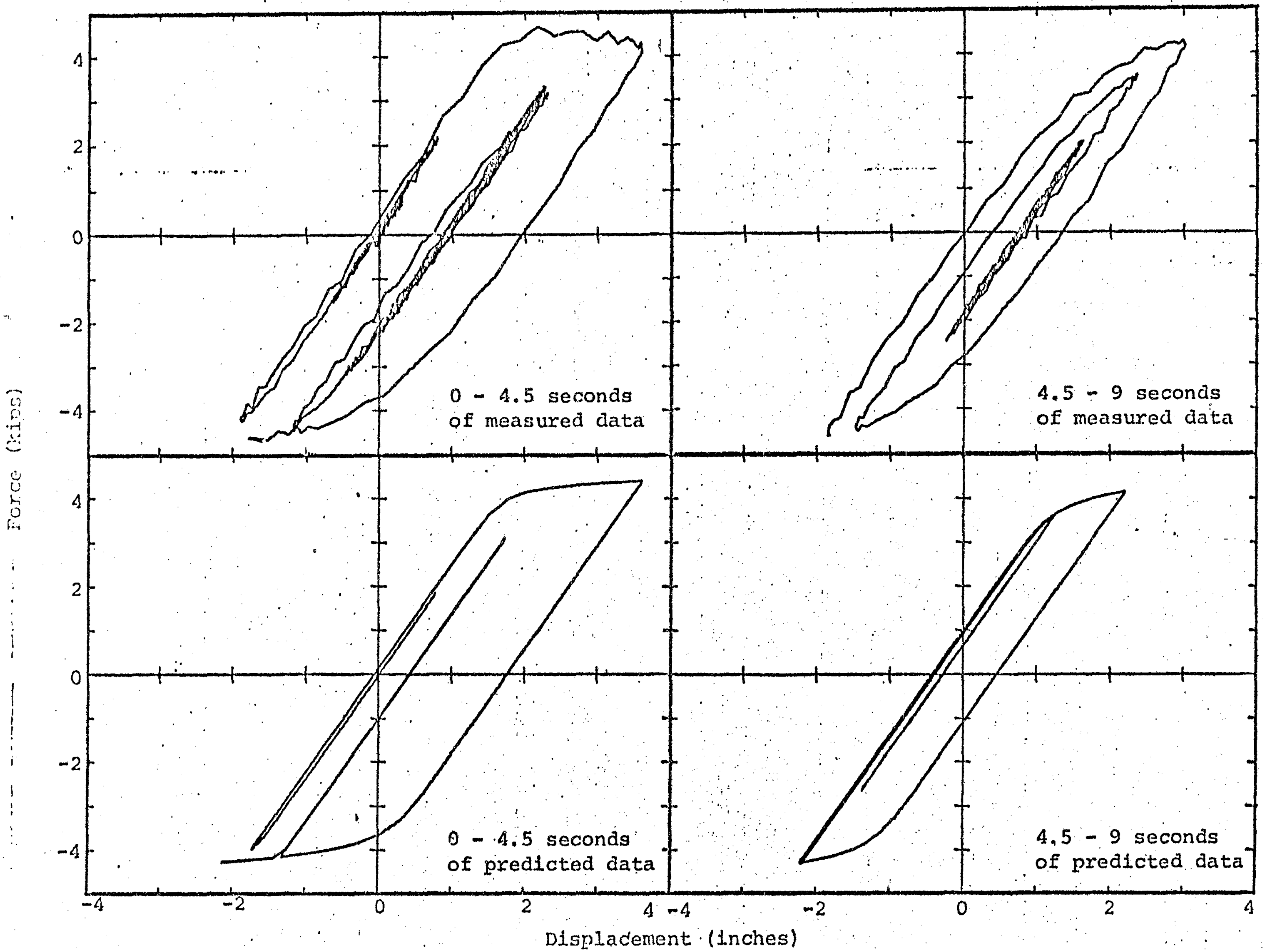

Figure 4. Comparison of measured (top) and predicted (bottom) hysteretic loops from El Centro 1940

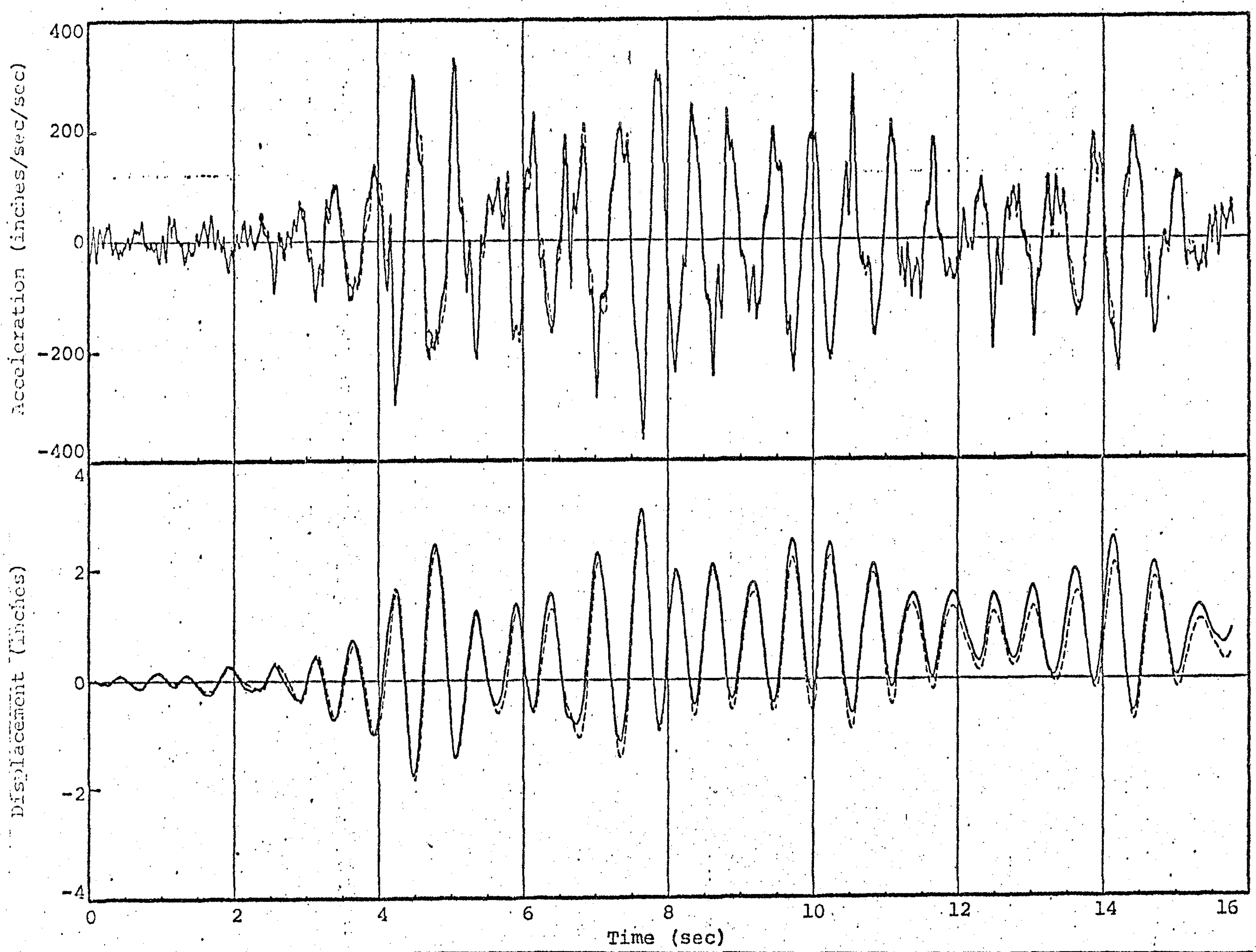

Figure 5. Comparison of measured (solid) and predicted (dashed - using parameters found from El Centro test) time histories from Taft 1952

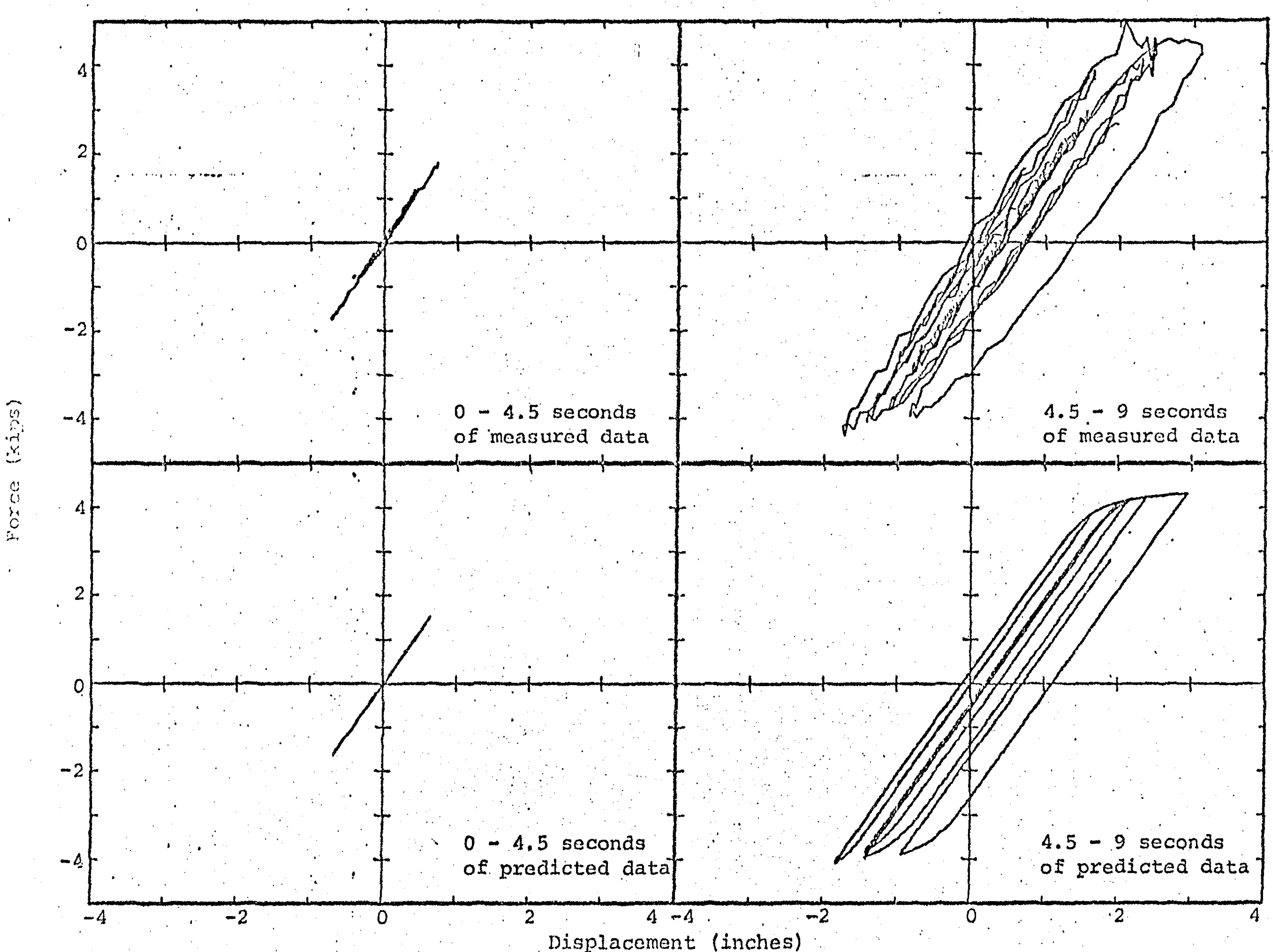

Figure 6. Comparison of measured (top) and predicted (bottom - using parameters found from El Centro test) hysteretic loops from Taft 1952