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**LA-UR**-84-1634

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CONF - 8409113 - 1

LA-UR--84-1634

DE84 012451

TITLE: EXPERIMENTAL INVESTIGATION OF REINFORCED-CONCRETE CATEGORY I STRUCTURES AT HIGH LOAD LEVELS

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For Proceedings for Specialty Conference on Structural
Engineering in Nuclear Facilities, Raleigh, NC, Sept. 10-12, 1984,
Structural Mechanics Associates
5160 Birch Street
Newport Beach, CA   92660

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FORM NO 836 R4
ST NO 2629 5/81

# EXPERIMENTAL INVESTIGATION OF REINFORCED-CONCRETE
## CATEGORY I STRUCTURES AT HIGH LOAD LEVELS

Elton G. Endebrock,* Richard C. Dove,** Wade E. Dunwoody*

## Abstract

A US Nuclear Regulatory Commission-funded experimental program
designed to obtain information on the structural behavior of reinforced-
concrete buildings has been underway at the Los Alamos National Labora-
tory since 1980. This information will aid the NRC in evaluating the
seismic capacities of existing Seismic Category I buildings.

Scale models of reinforced-concrete shear walls and buildings were
subjected to static and dynamic tests. Simulated seismic tests were
conducted on model structures constructed to two scales (1/30 and 1/10),
permitting an evaluation of the effect of scale in experimental investi-
gations of reinforced-concrete structures.

Monotonic and cyclic quasistatic tests provide information on
strength, stiffness, strength and stiffness degradation, ductility, and
general load-deflection behavior up to the ultimate load. The dynamic
tests yielded information on natural frequencies, equivalent viscous
damping values, initial stiffness and stiffness degradation, and general
response behavior.

These experimental investigations have indicated that sine-sweep
tests are not suitable for reinforced-concrete structures and that the
initial stiffness of shear wall structures is less than predicted when
assuming an uncracked concrete section.

## Introduction and Background

The Seismic Category I Structures Program currently being carried
out at the Los Alamos National Laboratory is focused on answering

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certain structural questions related to the general issue of whether existing nuclear facilities can continue to operate in light of more demanding criteria than considered in the original design. The Category I structural models being tested are box-like reinforced-concrete configurations representative of sections of auxiliary buildings, fuel-handling buildings, etc., and do not include the reactor containment building. The overall goal of the program is to supply to the Nuclear Regulatory Commission experimental information and a benchmarked procedure to evaluate the sensitivity of the dynamic response of these structures to earthquakes of increased magnitude beyond the design basis earthquake. The main purposes of the experimental program are (1) to provide stiffness and damping values for more demanding loadings on the structures, (2) to obtain general information on how these structures behave in the inelastic range as compared with their elastic behavior, and (3) to provide experimental data for benchmarking inelastic finite element codes.

An extensive survey cover'ng the analytical methods, design methods and construction practices, and the codes and standards used in the design and construction of existing reinforced-concrete Category I structures has been completed. (See Ref. 2). The results of this survey have indicated the types of data that are most necessary to extend analysis and design into higher load regions. In addition, this survey has suggested the kinds of test structures and the experiments that would be most useful in benchmarking analysis and design procedures proposed for considering the problem of loading beyond the initial design. Finally, the survey has helped in selecting the variables that will be included in sensitivity studies.

During FY 82 preliminary experiments were conducted on small, reinforced-concrete isolated shear walls that had been identified in our survey as the most important element in a Category I structure (Fig. 1).

This preliminary experimental program was intended to serve the following purposes:

1. perfect the construction techniques necessary to fabricate the small reinforced-concrete structures;
2. design and evaluate the test equipment and instrumentation necessary to conduct appropriate static and dynamic tests; and

**(a) ONE STORY SHEAR WALL**          **(b) TWO STORY SHEAR WALL**
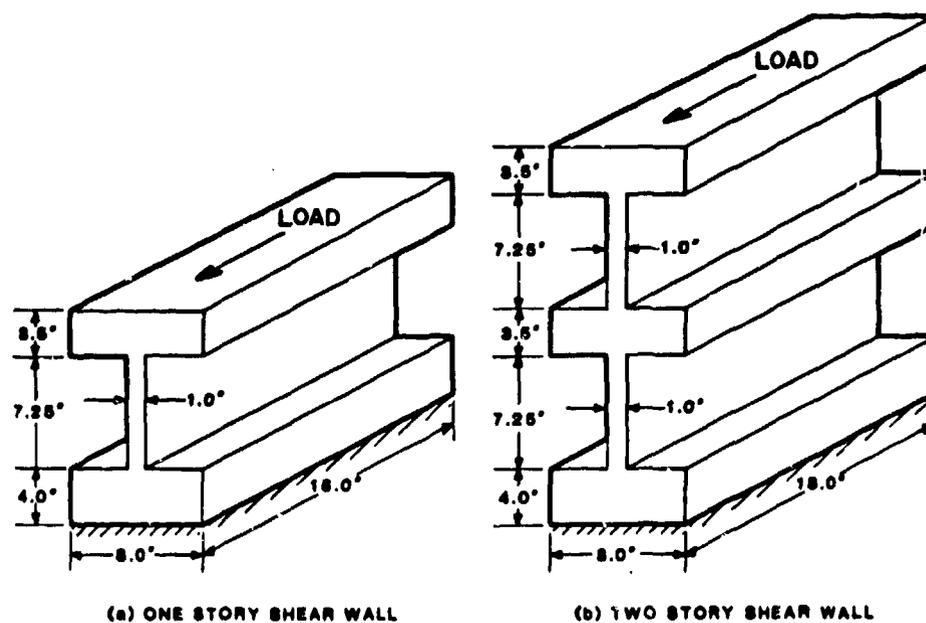
Fig. 1.   Isolated shear wall structures.

3.  conduct and analyze the results of a sufficient number of
    tests to determine the relative merits of static tests, con-
    ventional vibration tests, and simulated seismic tests.

These preliminary experiments, completed in FY 82, are reported on
in detail in Refs. (3) and (4).  The most significant results of these
tests, conducted on 1/30 scale models (where the prototype wall thick-
ness is assumed to be 30 in.), are summarized below.

1.  At high load levels, reinforced-concrete shear walls behave
    in a highly nonlinear and inelastic manner.

2.  The load levels at which these walls crack and fail are in
    reasonable agreement with the values computed using the stan-
    dard design methods as specified in ACI 349.  However, stiff-
    ness of these walls is found to be considerably less than the
    value of stiffness calculated by the usual design methods.

3.  During load cycling, such as would occur during a seismic
    event, reinforced-concrete shear walls exhibit significant
    hysteretic energy loss.  The amount of energy loss per cycle,
    and hence the effective damping, is very dependent upon load
    level.

4.  At higher load levels, the measured acceleration response is considerably less than would be predicted by a linear response spectrum. This latter finding is in agreement with the result predicted by the Newmark-Hall "Nonlinear Design Response Spectrum"(7); and to our knowledge, this is the only experimental verification of this nonlinear approach for the analysis of shear wall type structures.

5.  Standard vibrating test methods (such as sine sweeps, resonance search and dwell, etc.), which are widely used to evaluate damping ratios, modal frequencies, mode shapes, etc. for many structures and machines, were found to be both inadequate and inappropriate when applied to reinforced-concrete shear walls, even at moderate load levels. The reason is that the properties (stiffness and damping) of the reinforced-concrete shear walls change continuously with load cycling, and the load cycle history associated with these conventional vibration tests is in no way representative of the load cycle history associated with seismic responses. As a result of this finding, all of the subsequent dynamics tests carried out as a part of this program used simulated seismic loading. It is important to note, however, that two of the most widely quoted studies of high load tests on reinforced-concrete structures used sinusoidal vibration excitation(1)(5).

Construction of Scale Models of a Prototypical Category I, Diesel Generator Building

All of the structures tested during FY 83 were small-scale models of a prototypical Category I, diesel generator building. The shape and dimensions of the assumed prototype structure are shown in Fig. 2, together with the dimensions of the two scaled versions of this structure. Figure 2 shows a two-story structure; however, several single story versions of the 1/30-scale structure were also constructed and tested.

The 1/30-scale structures were constructed using a microcrete having the following properties:

Fig. 2. Two-story basic structure--model and prototype
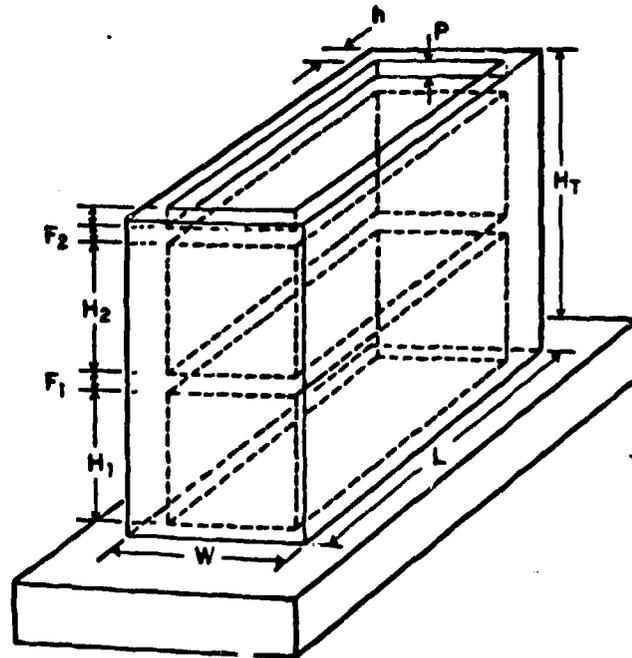
| | h, F$_1$, F$_2$ | W | L | H$_1$ & H$_2$ | P | W$_g$/STORY* (lb) |
|---|---|---|---|---|---|---|
| 1/30 SCALE | 1" | 10" | 18" | 7.25" | 1" | 42 |
| 1/10 SCALE | 3" | 30" | 54" | 21.75" | 3" | 1134 |
| PROTOTYPE | 30" | 25' | 45' | 18'1.5" | 30" | 1,134,000 |

*BASE NOT INCLUDED

Ultimate compressive strength (f$_c$) = 2500-3300 psi
(17,200-22,700 kPa);
Tensile strength (f$_t$) = 300-420 psi (2070-2900 kPa); and
Modulus of Elasticity (E) = 2.3-2.6x10$^6$ psi (15.8-17.9x10$^6$ kPa).

Reinforcement consisted of 1/2-inch (12.7-mm) square mesh hardware cloth at each wall surface. This resulted in 0.28% reinforcement in each direction, on both wall surfaces. The reinforcement properties were:

Yield stress ($\sigma_y$) = 42,7000 psi (0.29x10$^6$ kPa);
Ultimate stress ($\sigma_u$) = 53,100 psi (0.36x10$^6$ kPa);
Modulus (E) = 25.6x10$^6$ psi (176.4x10$^6$ kPa); and
Ultimate elongation ($\Delta_u$) = 4%.

Figure 3 shows a single-story, 1/30-scale structure during con-
struction; the base mat has been cast, the reinforcement has been as-
sembled, and the inside and outside forms (plexiglass) are in place.
The 1/10-scale structures were fabricated using a larger aggregate
microcrete having the following properties:

$f_c'$ = 2850-3500 psi (19,640-24,100 kPa);
$f_t$ = 430 psi (2960 kPa); and
$E$ = 2.6-2.9x10$^6$ psi (17.9-20.0 kPa).

The reinforcement steel, which was obtained from the Portland Cement
Association, had the following properties:

Wire diameter (d) = 0.113 in (2.87 mm);
$\sigma_y$ = 42.4 ksi (0.29x10$^6$ kPa);
$\sigma_u$ = 50.0 ksi (0.34x10$^6$ kPa);
$E$ = 28.5x10$^6$ psi (196x10$^6$ kPa); and
$\Delta_u$ = 13.1%.

This rod was tied in a 1.0-inch (25.4-mm) square mesh to give the same
percentage reinforcement as was used in the 1/30-scale model. Figure 4
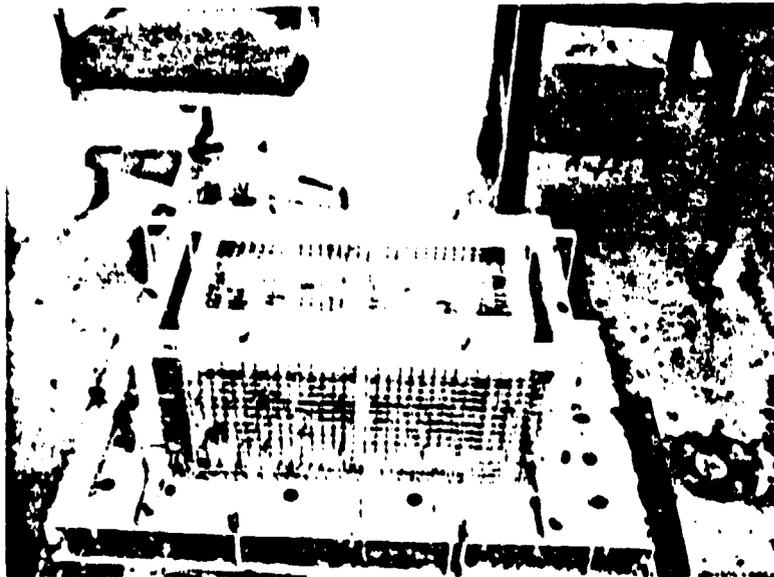


Fig. 3. View of a single-story, 1/30-scale structure under construction.
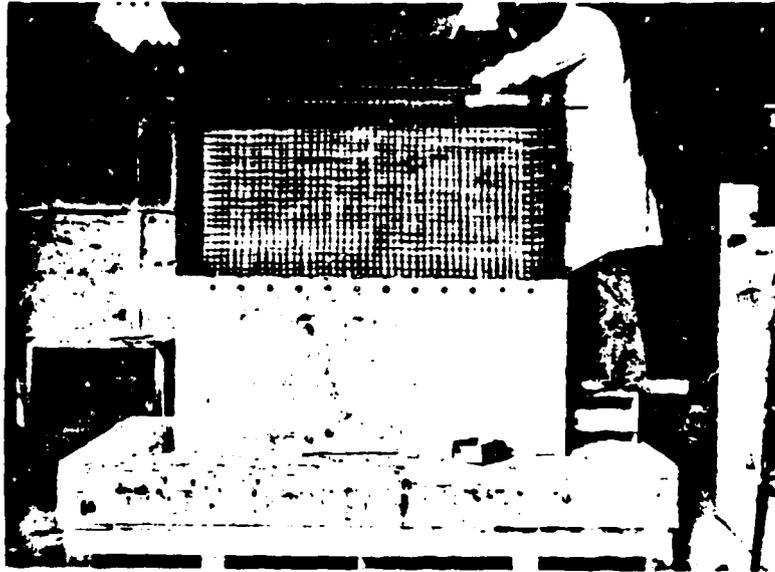
Fig. 4. View of a two-story 1/10 scale structure under construction.

shows a 1/10-scale structure during construction: the base and first
story have been cast and forms striped; the second-story reinforcement
and inside forms are in place.

Static Tests of Single-Story, 1/30-Scale Structures

Four, single-story, 1/30-scale structures were statically tested
to failure under both monotonic and cyclic load conditions. These
tests were conducted using a horizontal, hydraulic testing machine.
Models were tested with the load applied either parallel to the longer
dimension or parallel to the shorter dimension. The load was applied
through a 1-inch-thick steel plate, which was rigidly clamped around
the entire perimeter at the top of the wall. Figure 5 shows a struc-
ture failed by monotonic loading applied parallel to the end walls.

The purpose of these tests was to comparison measured values of
stiffness, cracking load, and ultimate load with the values obtained
by calculation using material properties and geometry. Figure 6 shows
the force vs deformation diagram for structure 3D-2 (shown in Fig. 5),
which was tested monotonically. Table I compares measured and cal-
culated results. These results are typical for all of the tests (both
directions, and with monotonic and cyclic loading), and we conclude
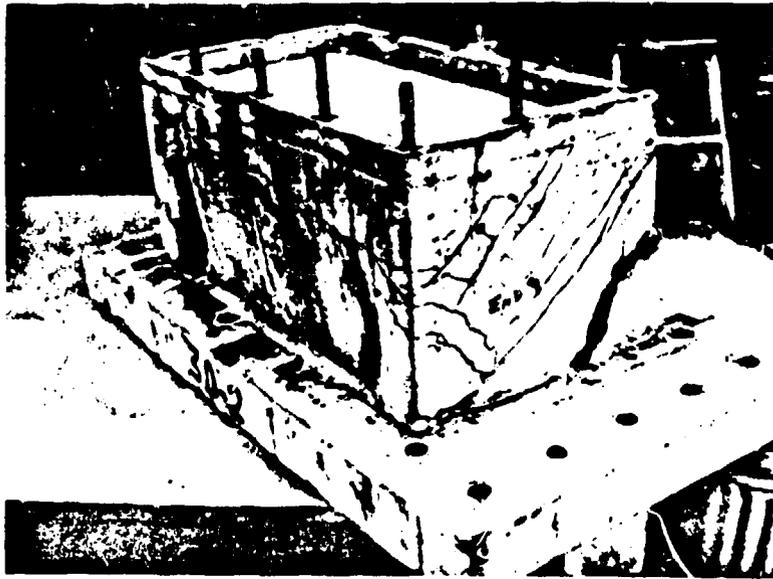
Fig. 5. Structure failed by monotonic load applied parallel to the
end walls.

TABLE I

COMPARISON OF CALCULATED AND MEASURED PROPERTIES

1/30-SCALE MODEL (3D-2)

| Structural Property | Computed Value | Measured Value |
|---|---|---|
| $P_c$ - cracking load; lbs (N) | 5,870 (26,120) | 5,210 (23,180) |
| $P_{ult}$ - ultimate load; lbs (N) | 7,810 (34,750) | 8,940 (39,780) |
| K - stiffness; lb/in. x $10^6$ (N/CM) | 3.18 (5.57) | 0.54 (0.95) |

that the usual computational methods give good prediction for the
cracking and ultimate strengths, but they predict structured stiff-
nesses that are much larger than the measured values. Stiffness is
very important in the dynamic analysis and, hence, this discrepancy
will be discussed further in connection with the simulated seismic
tests.
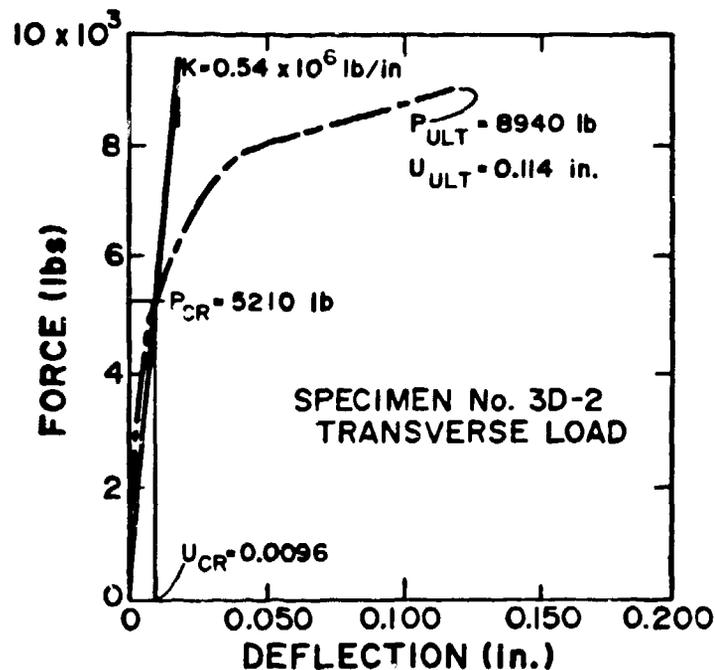
Fig. 6. Force-deformation diagram for structure 3D-2.

## Simulated Seismic Tests of Single-Story, 1/30-Scale Structures

We subjected the single-story, 1/30-scale structures to low-level seismic inputs in order to measure their effective, linear region, resonant or modal frequency ($\omega$). This value ($\omega$) is desired for comparison with the value predicted by the usual calculations using either calculated stiffness or stiffness as measured in static tests.

Figure 7 shows a structure mounted on the shake table at the Los Alamos National Laboratory ready for test. The excitation signal is a properly scaled version of the 1940, El Centro (N-S) acceleration/time signal. The effective modal frequency ($\omega$) is determined by computing the transfer function from the measured input and response accelerations. By repeating this test using different amounts of mass added to the top of the structure, it is possible to eliminate the distributed mass of the structure ($M_0$) from the relationship between modal frequency ($\omega$), total mass ($M_T$), and effective stiffness (K), thus:
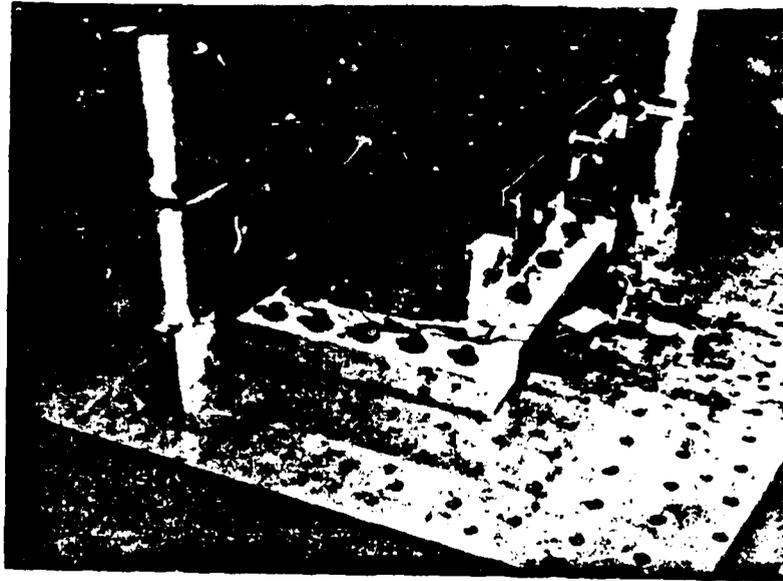
Fig. 7.  A single-story, 1/30-scale structure mounted on shake table at Los Alamos.

$$K = \omega_0^2 \, M_0 = \omega_T^2 \, (M_0 + M_{ADDED})$$

or

$$M_0 = \frac{M_{ADDED}}{\left(\dfrac{\omega_0}{\omega_T}\right)^2 - 1} \qquad ,$$

in which

$\omega_0$ is the measured modal frequency with no added mass;

$\omega_T$ is the measured modal frequency with a given amount of mass added;

and $M_{ADDED}$ is the amount of mass added.

By substituting the second equation back into the first we can compute the structure's stiffness (K) from the data without the necessity of deciding upon the lumped mass equivalent of the structure's distributed mass.  The stiffnesses obtained using the above method together with the values of stiffness obtained from both static tests and calculations based on geometry and material properties are given in Table II.

## TABLE II
## COMPARISON OF MEASURED AND CALCULATED STIFFNESS VALUES
## 1/30-SCALE MODELS

| Method | Stiffness - K<br>lb/in x $10^6$ (N/cm) |
|---|---|
| Simulated seismic | 0.62 (1.09) |
| (two specimens) | 0.71 (1.24) |
| Static test | 0.54 (0.95) |
| (two specimens) | 0.74 (1.30) |
| Calculation | 3.18 (5.57) |

The experimentally determined values of stiffness from static and simulated seismic tests are in good agreement, but the difference between these measured values and the calculated values is very large. This finding is discussed further in the Conclusions section of this paper.

Simulated Seismic Tests of Two-Story, 1/30- and 1/10-Scale Structure

Two, 2-story, 1/30-scale structures were fabricated and tested on the Los Alamos shake table (Fig. 8). Two, 1/10-scale, two-story structures were built at the Los Alamos National Laboratory and transported to Construction Engineering Research Laboratory (CERL) located at Champaign, Illinois. Figure 9 shows a 1/10-scale model mounted on the servohydraulically driven table at CERL.

The models were tested initially with no added mass. These were low-level, or elastic-range tests. Masses were then added to the models to properly simulate the distributed mass of a larger prototype structure. In this condition, the input acceleration level was progressively increased to measure behavior in both the elastic and inelastic regions. In all tests the input signals were properly time-scaled, 1940 El Centro N-S accelerograms.
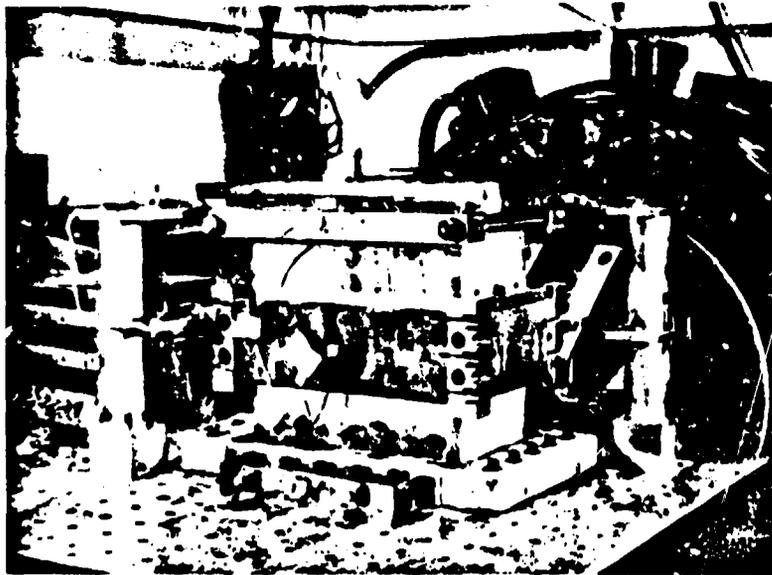
Fig. 8. A two-story, 1/30-scale structure mounted on shake table.
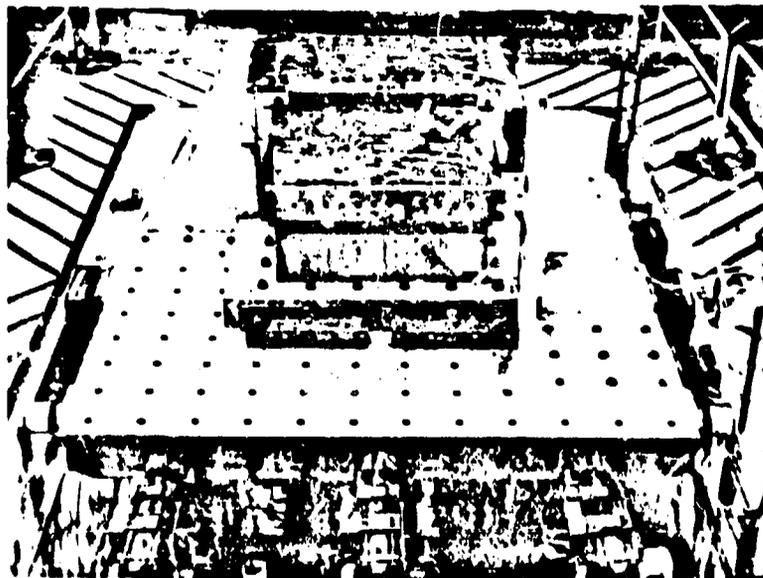


Fig. 9. A 1/10-scale structure mounted on the shake table at CERL.

Comparison of the results obtained from the two scaled structures can be made in either of two ways:

1. The results from the 1/30-scale structure can be used to predict the behavior of the 1/10-scale structure; or

2. The results from the tests on both structures can be used to predict the behavior of the assumed prototype, and these two predictions of prototype behavior can be compared. In the following discussion, both of these methods will be used.

Table III shows the first mode frequencies ($f_1$), as measured and as predicted for the 1/10-scale model from the 1/30-scale test.

We first note that, in the linear region where two different 1/30-scale structures were tested with added mass, there is some variation in measured results. This calls attention to the impossibility of constructing absolutely identical structures, even for structures of the same size (that is, with a scale of unity). The remaining data in Table III compares predicted modal frequencies for the 1/10-scale structure with values measured at progressively higher input levels. We

TABLE III

FIRST MODE FREQUENCIES (Hz)

| | | 1/30-Scale Measured | 1/10-Scale Predicted from 1/30-Scale | CERL #1 Measured |
|---|---|---|---|---|
| 1. | No mass added[1] to model--linear load range | 344 | 115 | 100 |
| 2. | Mass added[2] | | | |
| | 2a. linear load $\ddot{Y}_{pk} \simeq 1g$ | 104, 94[3] | 60, 54 | 54 |
| | 2b. Intermediate load $\ddot{Y}_{pk} \simeq 5g$ | 80 | 46 | 49 |
| | 2c. Nonlinear load $\ddot{Y}_{pk} \simeq 8g$ | 63 | 36 | 41 |
| | 2d. Failure test $\ddot{Y}_{pk} \simeq 12g$ | 57 | 33 | 24 |

Notes: 1. With no mass added the frequency scale is equal to the length scale, that is, $N_f = 3$.
2. With mass added, the frequency scale is equal to the square root of the length scale, that is, $N_f = \sqrt{3}$.
3. Two models tested.

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conclude that the 1/30-scale structure is adequate for predicting the
magnitude and trend (with increasing level of seismic input) of first
mode frequency of the 1/10-scale structure.

When the modal frequencies measured during tests on both the 1/30-
and 1/10-scale structures are used to predict the modal frequencies of
the assumed prototype structure, the results are as shown in Table IV.
Note that models of two different scales (1/30 and 1/10) tested under
two different conditions (no added mass, Case I model; added mass,
Case III model) predict that under low seismic loading (linear region),
the prototype structure can be expected to have a first mode frequency
of between 7.9 and 11.5 Hz.  The authors believe that the scatter in
this prediction is acceptable when viewed with the knowledge that there
will be some scatter in actual first mode frequencies of supposedly
identical structures of the same size.

## TABLE IV
### PREDICTION OF PROTOTYPE MODAL FREQUENCIES

| Model Type | Load Level | Predicted from 1/30-Scale Model | Predicted from 1/10-Scale Model (CERL #1) |
|---|---|---|---|
| Case[1] 1 | Linear $\ddot{Y}_{pk} < 1g$ | 11.5 | 10.0 |
| Case[2] 3 | Linear $\ddot{Y}_{pk} < 1g$ | 8.8, 9.0 | 7.9 |
| Case 3 | Intermediate $\ddot{Y}_{pk} < \approx 5g$ | 6.8 | 7.2 |
| Case 3 | Nonlinear $\ddot{Y}_{pk} < \approx 8g$ | 5.3 | 6.0 |
| Case | Failure $\ddot{Y}_{pk} < \approx 12g$ | 4.8 | 3.5 |

1. For case 1 models, no added mass, frequency is scaled as the length
   scale; hence, model modal frequencies are scaled by factors of 30
   and 10.
2. For case 3 models (that is, models with added mass) 1/30-scale model
   results are scaled by 12.0 and 1/10-scale model results are scaled
   by 6.8.
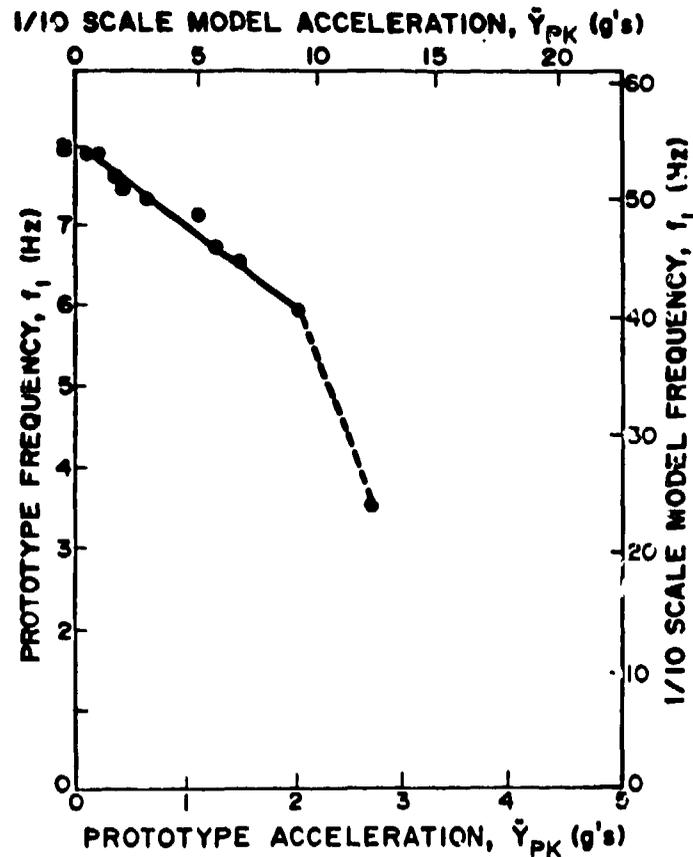
Fig. 10. Variation of first mode frequency vs input acceleration level.

A plot showing the variation of first mode frequency ($f_1$) with input acceleration level ($\ddot{Y}$), Fig. 10, is instructive. In this plot the data from a 1/10-scale structure tested at CERL have been used. Several tests were conducted at peak acceleration levels of 1 g or less, and the first mode frequency was found to remain constant at a value of 54 Hz. This is taken as an indication that the 1/10-scale structure behaves elastically for excitation levels up to $\ddot{Y}_{pk}$ = 1 g. Beyond this excitation level, the structure exhibits progressively decreasing effective stiffness with increasing excitation level. As the excitation level is increased to 10 g's, the first mode frequency decreases to approximately 40 Hz (a decrease of 26%). Even after tests at this level, there is no visible cracking; however, the structure is inelastic, as indicated by the fact that, when retested at a low input level ($\ddot{Y}_{pk}$ < 1g), the first mode frequency does not return to its original value of 54 Hz. Beyond this load level, 10 g's, the modal frequency decreases more rapidly.

These results can be projected to the prototype behavior by using the appropriate frequency and acceleration scale factors (0.147 and 0.216, respectively). This has been done by means of the "prototype" scales shown in Fig. 10. Figure 11 illustrates the crack pattern on one of the lower-story end walls of the model after the test. The orientation of the cracks is consistent with the predominant development of shear stress in the end wall.

How this structure modifies the applied base acceleration ($\ddot{Y}$), and, hence, how the floor-response spectra are modified as the input acceleration level ($\ddot{Y}_{pk}$) is increased, are shown in Fig. 12. This figure has been constructed using data from one of the 1/10-scale model tests, but the measured accelerations and frequencies have been scaled to prototype values (as was done in Fig. 10). The figure was constructed by measuring the response of the second story ($\ddot{X}_2$) for two base excitation levels: $\ddot{Y}_{pk} = 0.35$ g's, and $\ddot{Y}_{pk} = 1.1$ g. A linear response spectra was then computed for each measured response and plotted on Fig. 12. Note that at the 0.35 g input level, where the prototype structure's first modal frequency is 7.6 Hz, the input motion is highly amplified at the second-floor level; as would be expected, the maximum
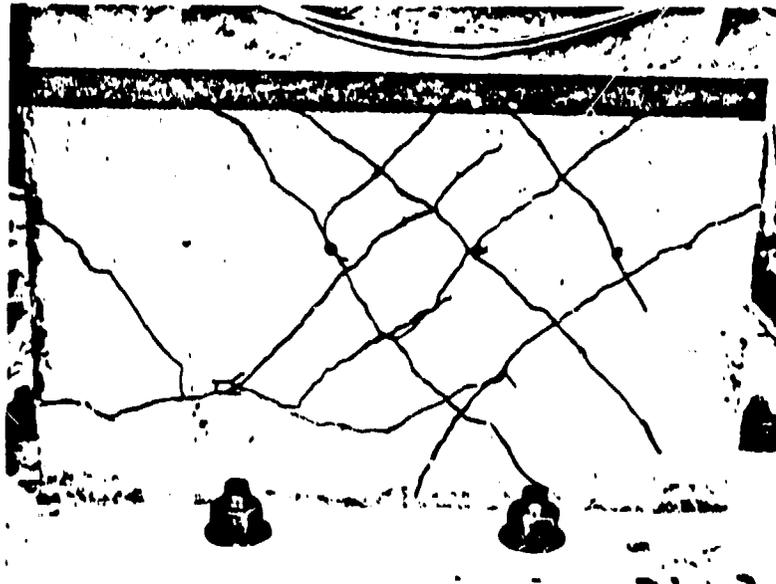


Fig. 11. Crack pattern in lower-story end wall of the 1/10-scale structure.

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**RS-RESPONSE SPECTRA**
**——RS-BASE INPUT**
**-----RS-2nd STORY BASE INPUT (0.35 g's)**
**— —RS-2nd STORY BASE INPUT (1.1 g's)**
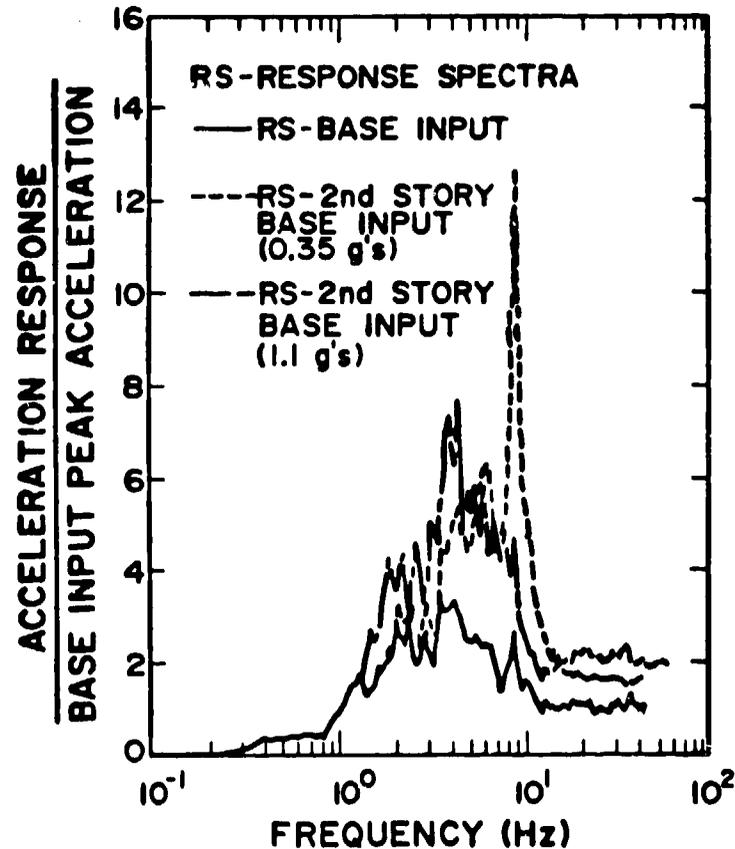
Fig. 12. Floor-response spectra from experimentally determined accelerograms.

amplification occurs in the region of the structure's first mode frequency (7.6 Hz). Because this is a stiff structure (relative to the frequency content of the input, that is, the 1940 N-S El Centro) the second and higher modes produce relatively insignificant amplifications. As the base input level is increased, and the effective first modal frequency is decreased, the frequency region over which amplification occurs is down shifted, and the magnitude of peak amplification is decreased. Note however, that as the first mode frequency is decreased toward the frequency region in which the input signal is maximum, the amplification of the response in this region is increased. If the first mode frequency should be reduced (by the inelastic response associated wih a particular high load level) so as to exactly correspond to one of the frequencies at which the input level reaches a peak, the maximum magnification of response could, of course, be increased.

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How this structure's effective damping is affected by increasing load levels can be investigated by comparison of the actual measured response with response computed using an analytical model for which various amounts of damping are assumed. This phase of the data analysis is currently in progress.

Conclusions

Based on the data presented in this paper, on the data from the isolated shear wall tests (3)(4), and upon recent studies made by other investigators(6)(8), we believe that the actual stiffness of prototypical, Category I structures may be considerably less than the value computed using the usual design procedures. We recognize that, because all of these tests involve small structures (models), the observed smaller values of stiffness could be "structural-size" related. In this regard, shrinkage cracks that would reduce the effective moment of inertia of area (I) of the structure, and that would form more rapidly in small sections then in larger sections, must be considered. This is being investigated further; however, it should be realized that micro-cracking, caused by shrinkage and nonseismic loads applied during the life of a prototype structure, will exist in prototype structures, and that the reduction in stiffness suggested by these tests may still occur; that is, it may only be a matter of time.

We believe that the prototype structures could experience considerable nonlinear and inelastic response without showing visible signs of cracking. When cracking appears, the structure has experienced large nonlinear and inelastic response, and the initial effective structural stiffness has been significantly reduced. The input acceleration level required to produce this condition is, however, very large--that is, 5 x SSE or greater.

The reduction of first mode frequency, which is associated with the reduction in effective stiffness, retunes the structure relative to the input and, as a result, the floor-response spectra are different at different levels of input acceleration (as shown in Fig. 12). How this affects equipment mounted at a given level depends upon its mounted frequency relative to the original structural first mode frequency. In

general, we can say that if equipment is mounted such that its resonance value is less than the original structural frequency, it could be tuned to the structure's resonance during high seismic load response. How load level affects effective damping is not known as yet, but the data is being further analyzed to develop this information.

We believe that the results presented in this report demonstrate the potential value of 1/30- or 1/10-scale-model tests. The 1/30-scale mode's appear to be appropriate to investigate a number of design and test arameters of interest, that is, in sensitivity studies. The relative low cost and convenience of the smaller models allows a larger number of parameters to be investigated. However, for very important parameters or for those that may be judged to be very sensitive to size effects (the attachment of large simulated equipment, for example), larger scales will be appropriate.

## Acknowledgement

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**Key Words**

**to**

**EXPERIMENTAL INVESTIGATION OF REINFORCED CONCRETE
CATEGORY I STRUCTURES AT HIGH LOAD LEVELS**

1. Models

2. Static tests

3. Reinforced concrete

   Shear walls

5. Seismic tests

6. Stiffness

7. Inelastic behavior

8. Crack patterns

9. Shear strength

10. Category I buildings

11. Stiffness degradation

12. Accelerations