H13/7

Shear Wall Test Data Summary

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ABSTRACT

Ten tests were performed to provide additional data concerning the scalability of the response of small-scale concrete structures to the response of conventional concrete structures. Experimental modal analyses techniques were employed to obtain the dynamic properties (mode shapes, resonant frequencies) of the structures subjected to low-level random excitations. After modal testing, the structures were subjected to either simulated seismic or static testing until failure. Stiffnesses measured during simulated seismic testing, in the past, have been inferred from resonant frequency measurements. During these seismic tests, strain gages were mounted on several of the structures; therefore, a direct measurement of stiffness could be obtained during the dynamic tests. Cracking could be detected by sudden jumps in the strain readings.

1 INTRODUCTION

Previous work that has been performed at Los Alamos National Laboratory (LANL) as part of the Seismic Category I Structures Program for the U.S. Nuclear Regulatory Commission (USNRC) Office of Nuclear Regulatory Research has consistently measured stiffnesses less than mechanics-of-materials theory would predict for scale models of low-aspect-ratio shear wall structures subjected to working loads. In this context, working loads refer to load levels equivalent to those experienced by a structure during an operating basis earthquake, and would produce nominal base shear stresses (NBSS) on the order of 50 to 100 psi.

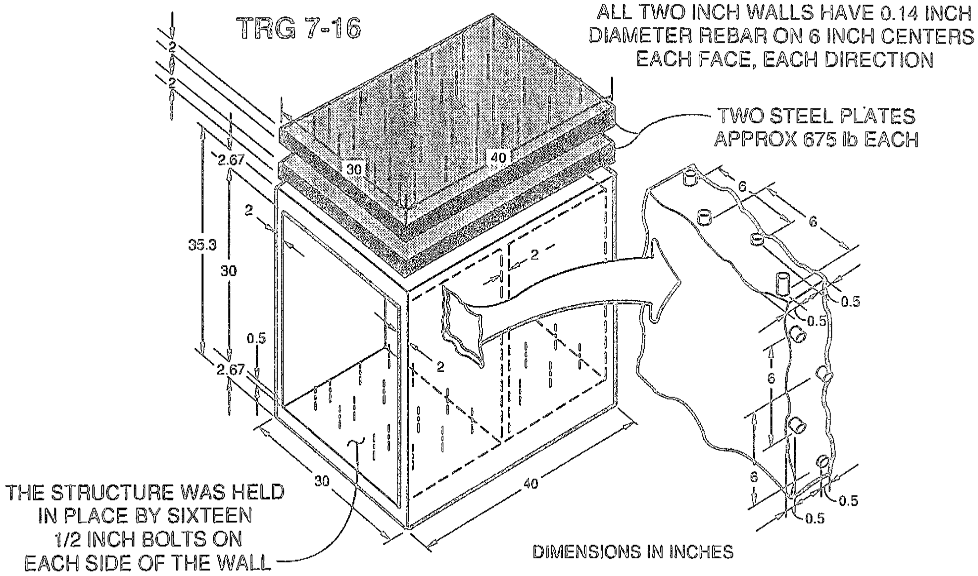
All prior simulated seismic data from this program were obtained by subjecting structures to a series of increasing level seismic excitations. No information was available concerning the response of a virgin structure to a single, high-level seismic pulse. Tests were performed on five structures designated TRG-7 through -11, (Farrar, et al. 1991) that were 1/3-scale models of TRG-4 (Farrar, et al. 1989). In addition, five more structures, TRG-12 through -16, were tested either statically or dynamically (Farrar, et al., 1991). These structures, that are the same size as TRG-7, were used to further establish the scalability of the dynamic response measured on small models to the dynamic response of conventional concrete structures.

2 SELECTION OF MODEL GEOMETRIES AND TEST SEQUENCE

This program has made extensive use of small scale microconcrete models to predict the seismic response of nuclear power plant structures. These models have yielded controversial results, that is, reduced stiffness. There was a need to verify the scalability of the results obtained from these models to the response of conventional concrete structures. The test described in

Farrar, et al. 1989 was a conventional concrete structure that, when tested using experimental modal analysis techniques and when tested in a static, cyclic manner, exhibited a pre-cracking stiffness that agreed almost exactly with theory. It was decided to accomplish the final study on cumulative damage effects and scalability using 1/3-scale models of TRG-4 made with both 3/8-inch aggregate and microconcrete.

Figure 1 summarizes structure size, type of aggregate used, and the tests performed on each structure. Prior to severe testing experimental modal analyses were performed on each structure. Similar experiments had been performed on TRG-4, hence, the dynamic properties of TRG-4 can be compared with similar properties obtained from these tests.



STRUCTURE	MATERIAL	TESTING
TRG 7 THROUGH 11	3/8 in. AGGREGATE	S.S.*
TRG 12	3/8 in. AGGREGATE	STATIC
TRG 13	3/8 in. AGGREGATE	STATIC, S.S.
TRG 14, 15	MICROCONCRETE	S.S.
TRG 16	MICROCONCRETE	STATIC

*S.S. = SIMULATED SEISMIC

Figure 1. Structure Number, Dimensions, Material and Test Method

From TRG-12,-13, and -16 tests the scalability of static response between microconcrete and 3/8-inch aggregate structures of the same size can be addressed and results from the 1/3-scale models can be compared with similar results from the contentional concrete prototypes.

Tests on TRG-7 through 11, and -13 through -15 provided data on cumulative damage effects as well as data concerning the scalability of seismic response between microconcrete structures and 3/8-inch aggregate structures of the same size. TRG-13 was tested both statically (without introducing damage) and then seismically, a direct comparison can be made between the static response and dynamic response of a structure at similar stress levels.

3 MODEL CONSTRUCTION AND MATERIAL PROPERTIES

The primary concern in construction of these models was to build ten structures that were sound, that is, no major cracking from the curing process, and that were as identical as possible.

All ten structures were formed with Plexiglas so that the surfaces could be visually monitored during the concrete placement and compaction. No defects were noticed on the surface of the models after the compaction was completed. However, shrinkage cracks were noticed in the end walls of all the structures after the forms were removed. The shrinkage cracking was much more pronounced in the microconcrete structures. All models were left in their forms for a 28 day curing period. Exposed surfaces were kept moist and covered with a tarp.

4 EXPERIMENTAL MODAL ANALYSES

In this context experimental modal analysis refers to the procedure whereby a measured excitation (random, sine or impact force) is applied to a structure and the structure's response (acceleration, velocity or displacement), is measured at discrete locations that are representative of the structure's motion. Both the excitation and the response time histories are transformed into the frequency domain so that modal parameters (resonant frequencies, mode shapes, modal damping) can be determined by curve fitting the measured frequency domain data to a Laplace domain representation of the equations of motion (Ewins, 1984). These tests were performed to demonstrate that the dynamic properties of these structures can be accurately predicted at very low excitation levels by finite element analysis. Also, because similar tests were performed on TRG-4, results from these tests can be used to examine the scalability of dynamic properties.

Test conditions that were used with TRG-4 were duplicated or, when appropriate, scaled to make the experimental modal analyses as identical as possible. TRG-7 through -16 were supported with four air bearings under their base to simulate free-boundary conditions. Free-boundary conditions were chosen because they can be most easily and accurately obtained during experiments; hence, these test results are best for comparison with finite element analyses.

5 SELECTION OF INPUT SIGNAL, TIME-SCALE AND AMPLITUDE LEVELS FOR THE SIMULATED SEISMIC TESTS

Because the mass has been scaled geometrically (that is, mass is scaled by the length scale cubed), the structures used in these tests will be Case 1 models of the TRG-4 structures. Using the scale factors described in Dove and Bennett (1986), the behavior of these new test structures can be predicted from the static and modal test results obtained from the TRG-4 structure.

A matrix of simulated seismic tests was constructed that brackets the load level necessary to produce first cracking in the test structures. This matrix is shown in Table 1. The virgin condition tests on each of the seven structures are Test 1, 5, 8, and 10. Note that TRG-11 was initially subjected to a load equal to its ultimate load as calculated by ACI 349-85 in test 10.

TABLE 1
SIMULATED SEISMIC EXCITATIONS TEST MATRIX

Model No.	Seismic Test Sequence			
TRG-8,-13,-14,-15	1*	2	3	4
TRG-9		5	6	7
TRG-10			8	9
TRG-11				10
Excitation level (g's)**	1.25	2.5	3.75	5.0
Percent of ACI 349-85 Ultimate Strength	25%	50%	75%	100%

* Refers to the sequence that models will be tested in.
** These levels assume as amplification factor of 1.7, hence a 5.0g base isolation will produce a top slab acceleration of 8.5g.

Comparison of the measured results from Tests 1, 5, 8, and 10 should demonstrate the difference in response of virgin structures to seismic events of different magnitudes. Comparison of results from Tests 2 and 5; or 3, 6, and 8; or 4, 7, 9, and 10 should demonstrate cumulative damage effects.

6 SIMULATED SEISMIC TESTING AND RESULTS

6.1 Instrumentation and Test Setup

The data taken during this sequence of tests consisted of accelerations and strain measurements. Twenty channels of acceleration data were taken. Redundant measurements permitted checks on slippage of the model relative to the base, slippage of the top plate relative to the model, and on torsional response of the top slab.

The tests reported in Farrar, et al. (1989) showed that the stiffness values determined from relative displacement readings during static tests agreed well with stiffness values determined by mechanics-of-materials beam theory analysis accounting for shear deformation. This method of displacement measurement is independent of base-slip and rigid-body motion. Therefore, a similar measurement method was sought for dynamic tests. The method used for the static tests could not be used for the dynamic tests because the digital displacement transducers do not have adequate frequency response. Also, the response of the mounting hardware would invalidate any readings obtained. The displacement transducers and their hardware were replaced with a series of strain gages between the two points for which relative displacement was needed.

It may be shown that the change in resistance of a strain gage is proportional to the relative displacement of two ends of the gage. Thus, in actual use, the gage measures the average strain over the gage length independent of the strain gradient within the gage length. By mounting gages end-to-end between two points and connecting them in series, a long gage-length strain gage is obtained whose signal length may be converted to relative displacement.

A 1.5-inch thick aluminum plate was bolted to the shake-table. The plate was required by the shake-table operators to stiffen the table and prevent warping that might occur when the test structures were bolted down. TRG-7 and -13 were placed on the aluminum plate and were used as practice models. On TRG-8 and subsequent test structures a layer of plaster-of-Paris was placed between the base of the structure and the plate to provide an even bearing surface that would conform to the base of the structure. Tests on TRG-7 had shown that the bottom and top surfaces of the structure were out-of-plane to the point that cracking could be introduced by tightening the studs through the base or the bolts through the top slab.

6.2 Test Results (Accelerometer Data)

Summaries of the simulated seismic tests performed on TRG-8 through -11 and TRG-13 through -15 are provided in Farrar, et al. (1991).

6.3 Test Results (Strain Gage Data)

Stiffness values can also be determined from the strain gage test data. With the instrumentation used during these tests, total deformation was determined from the average of four separate displacement readings. During a dynamic test, cracking can be identified by a sudden shift in the strain-time history that results from a relief of strain within the instrumented region when cracking occurs outside this region.

6.4 Comparison of Strain Gage Data to Accelerometer Data

Until the structures were cracked by loads that resulted from the applied base excitations, no stiffness reduction was detected by the strain gages. The stiffness results obtained from the strain gage data agree with the stiffness results obtained during static, cyclic testing on TRG-12,-13 and -16 as well as stiffness results obtained during static, cyclic testing of TRG-4. Stiffness reductions that are determined from accelerometer data are greater than those determined from the strain gage data. This discrepancy occurs because the fundamental mode of the structure does not correspond to the fixedbase fundamental mode determined by finite-element analyses.

7 STATIC TESTING AND RESULTS

7.1 Instrumentation and Test Setup

The static tests on TRG-12, -13, and -16 were intended to duplicate the static tests performed on TRG-4.

An instrumentation frame was assembled around the structures independent of the base plate. Twenty displacement transducers were placed on the structures and on the instrumentation frame. Ten gages were mounted on the model itself, providing relative displacement readings that were independent of any rigid-body rotation and translation. Overall structural deformations, including rigid-body motion, were monitored with the remaining ten gages.

In addition to the displacement transducers used to measure displacements during the tests on TRG-12 and -16, long gage length (120 mm) strain gages were mounted end-to-end on both sides of the shear wall at locations that correspond to relative displacement gages. The gages were wired in series so that each group of gages, either along the diagonal or vertical, would act as one continuous gage over their entire combined lengths. Similar strain gages were mounted on TRG-8, -9,-10, -14, and -15 during simulated seismic tests so that relative displacements could be measured directly during the dynamic tests.

7.2 Test Results (Displacement Transducers)

TRG-13 exhibited repeatable linear response during all the load cycles that it experienced. This structure was not taken to failure because it was subsequently to be used for simulated seismic tests. Stiffness and hysteric energy losses for TRG-12, -13 and -16 were calculated from the internal relative displacement gages and from the strain gages in an identical manner as on TRG-4.

Both TRG-12 and -16 structures exhibited total stiffnesses that agreed well with theory prior to cracking. Again, the bending displacements were difficult to measure and accurate assessment of this component of stiffness proved difficult. The initial cracking induced by the applies load (as opposed to cracking that existed prior to testing that results from shrinkage during the curing process) on TRG-12 occurred between 12,000 and 13,400 lb. When the differences between the tensile strength of these structures and TRG-4 structure are accounted for, the first cracking loads measured on TRG-16 accurately predicts the first cracking load measured on TRG-4.

7.3 Test Results (Strain Gages)

The deformations determined from the strain gage readings are compared to the deformations measured with the displacement transducers. The strain gages provided a more accurate estimate of the hysteretic energy loss and viscous damping ratios determined from these data agree with the pre-cracking viscous damping ratios measured during simulated seismic tests and during experimental modal analyses.

8 SUMMARY AND CONCLUSIONS

These tests were to provide additional data concerning the scalability of the seismic response of small-scale concrete structures to the seismic response of conventional concrete structures. Experimental modal analyses results show that when the structures were subjected to low-level random excitations the dynamic properties (mode shapes, resonant frequencies) of the prototype (TRG-4) are accurately predicted by both 3/8-inch aggregate and the microconcrete models. All models were 1/3-scale. The distortion of the normal forces that result from geometric scaling (Dove and Bennett, 1986) appears to have no adverse effect on the similitude of the dynamic properties as identified by these methods.

There was no appreciable difference between the stiffness measured with strain gages and the stiffness measured with displacement transducers during the static tests. Both measurement methods show that the structures respond with a stiffness accurately predicted by mechanics-of-materials theory until cracking is induced from the externally applied load.

Stiffnesses measured during dynamic test have in the past been inferred from resonant frequency measurements. Damage caused by transportation, stresses introduced by bolting the structures to the shake-table, and response of other modes associated with shake-table and connections to it have yielded excessively low initial stiffness measurements on structures tested in the early part of this program (TRG-3 and before) (Farrar and Bennett, 1989). With the strain gages mounted on the TRG-8 through -10, -14 and -15 a direct measurement of stiffness could be obtained during the dynamic tests. Cracking could be detected by sudden jumps in the strain readings. Strain gage stiffness data from the dynamic tests agree with the static stiffness data up to initial cracking.

The strain gage data obtained during these tests showed that, prior to base excitation levels that produced cracking in the end walls, the structures responded with repeatable theoretical stiffness values implying elastic response and no cumulative damage effects. After cracking, the response of the shear wall structures appears to be a function of the peak load level experienced by the structure during its lifetime.

The two areas where scalability has not been demonstrated are during simulated seismic excitation because no such reliable data has been obtained on a conventional concrete prototype and during post-cracking static cyclic response because of dissimilar post-yield properties of the reinforcement steel (rebar).

Viscous damping ratios of the structures, prior to cracking, as determined from either static or dynamic test data are in the neighborhood of 1% of critical. These values are considerably lower than the 4% OBE level specified in Regulatory Guide 1.61 (U.S. NRC, 1973). The Regulatory Guide specifies system damping values that would take into account factors such as construction joints that increase damping. Previous damping values (3-5%) that have been reported as part of this program were determined from accelerometer data and represent the entire shake table-test specimen system and not the wall element.

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