An experimental investigation for scalability of the seismic response of microconcrete model nuclear power plant structures

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1 INTRODUCTION

Previous work that has been carried out at the Los Alamos National Laboratory as part of the Seismic Category I Structures Program for the USNRC Office of Nuclear Regulatory Research has consistently measured reductions in the working load stiffness of four or more in scale models of low aspect ratio shear wall structures similar to nuclear power plant diesel generator and auxiliary buildings. In this context working loads refer to load levels equivalent to those experienced by a structure during an operating basis earthquake with peak stress levels as low as 50 psi (0.069 MPa) average base shear stress. Prior to 1985, all models tested in this program were made of microconcrete using wire hail screen for reinforcement. Scalability, Dove et al. (1985) and Endebrock et al. (1984) of these models has been reported in previous SMiRT Conferences along with the results on stiffness reductions, Bennett et al. (1985).

To further verify the findings from the microconcrete models, Los Alamos conducted two additional tests in 1986. The purpose of these tests was to specifically determine if the stiffness reduction found in the microconcrete models carried over to structures made from conventional concrete and reinforcing.

This paper will report the results from these tests including reduced stiffnesses found in the prototype and 1/4 scale model, implications of these test results on the validity of past tests, and implications of these results from these 1986 tests on the seismic behavior of actual Seismic Category I Structures and their attached equipment.

2 PREVIOUS WORK

The static and dynamic testing reported in Dove et al. (1985), Endebrock et al. (1984) and Bennett et al. (1985), was performed on one and two story isolated shear walls (1/30 scale), one and two story idealized diesel generator buildings (1/30, 1/10 scale), and three story idealized auxiliary building (1/14 and 1/42 scale).

The scalability between different size microconcrete low aspect ratio shear wall structures was demonstrated in both the elastic and inelastic range and the results have been scaled to the prototype structure. The reduced stiffness at low load levels was observed in all static and dynamic tests and appears to be independent of geometries tested and the concrete's modulus of elasticity. This last observation is of particular concern in that current design practices by architecture-engineering firms do not account for this reduced stiffness nor does the American Society of Civil Engineers standard for seismic design of nuclear power plants. The question now arises as to whether the reduced stiffness was caused by the microconcrete and if it would be observed in a similar conventional reinforced concrete structure. Also, scaling has only been demonstrated between microconcrete models and again there is some questions as to whether results can be scaled to conventional reinforced structures, particularly when the results concern seismic excitation into the structure's inelastic range.

3 EXPERIMENTAL INVESTIGATION OF MICROCONCRETE EFFECTS ON REDUCED STIFFNESS

It is recognized that, because all of the previous tests involved microconcrete models, the observed smaller values of stiffness could be "structural-size" related. Shrinkage cracks that would reduce the effective moment of inertia (I) of the structure, and that would form more rapidly in small sections than in larger sections, must be considered. However, it should be realized that microcracking, caused by shrinkage and nonseismic loads such as those caused by differential settlement occurring 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.

To investigate the effects of microconcrete on the observed reductions in stiffness, two shear wall elements with flexural boundary elements were constructed. The model shown in Fig. 1 was considered the prototype and was constructed with actual batch plant concrete and No. 3 (10 mm) rebar. The design criteria for this structure is summarized below:

1. maximum predicted bending and shear mode natural frequency $\leq$ 30 Hz,
2. minimum wall thickness = 4 in. (102 mm),
3. height-to-depth ratio of shear wall $\leq$ 1,
4. use actual No. 3 rebar for reinforcing,
5. use standard batch plant concrete,
6. use 0.1 to 1% steel (0.3% each face, each direction ideally),
7. use water blasted construction joints to assure good aggregate interlock.

These structures will be referred to as the TRG structures after the Technical Review Group that established the design criteria.

A second structure, a 1/4 scale model of the structure shown in Fig. 1, but made with microconcrete and wire mesh rebar was also constructed.

It should be noted that the large added mass was placed on the structure to meet the low frequency requirements. However, this mass also put the normal stresses in the range that an actual Category I structure would experience.

Both the model and the prototype were subjected to low level static testing (max. normal tensile stress less than 80 psi (0.55 MPa), and low level modal testing with free-free boundary conditions. The static load-deflection curves for both the model and the prototype are shown in Fig. 2 and modal analysis results are summarized in

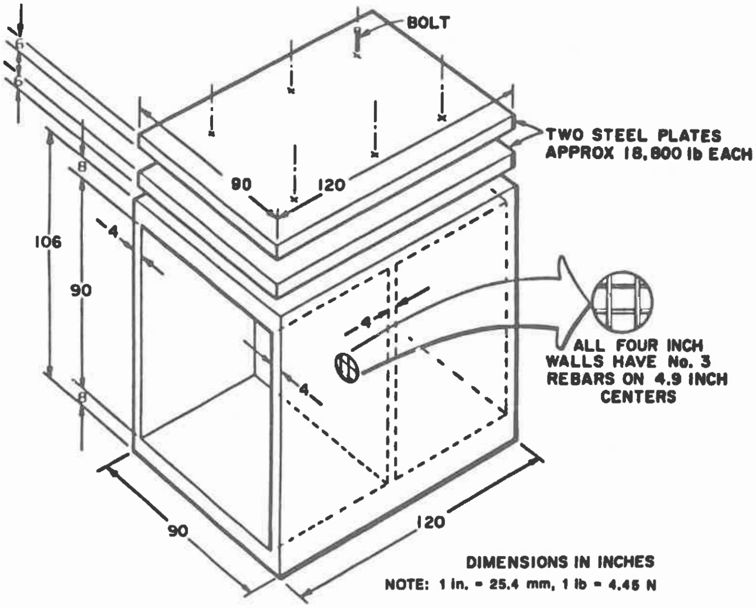

Figure 1. Prototypic TRG test structure and added mass.

Table I. A description of these modal testing techniques can be found in Ewins (1985). These tests were used to characterize the initial stiffness and natural frequency of the structure prior to any damage. Next, both models were seismically tested to failure or, in the case of the prototype, testing machine limits in a manner similar to the previous diesel generator and auxiliary building tests. For the purpose of scaling the seismic input signal (1940 El-Centro N-S) the prototype TRG structure was considered a 1/5 scale model of an actual shear wall. The 1/4 scale model was tested at the Los Alamos shake table facility and the prototype was tested at the Construction Engineering Research Laboratory in Champaign, Illinois. The following results were observed.

1. During low level static testing, the stiffness of the 1/4 scale model and the prototype were found to be within 70-80% of the calculated stiffness values. Also, the dynamic stiffness based upon results from the low level modal testing techniques fell within this same range. These points are plotted on Fig. 3 along with previous results from this program and other investigator's results [Barda et al (1977), Benjamin et al. (1957), Umemura et al. (1976) and Sozen (1984)]. At very low load levels the scalability between microconcrete model and conventional concrete prototype could be demonstrated when differences in concrete modulus were accounted for as shown in Table II.

2. Under working loads induced by simulated seismic excitation, both the prototype and the model showed similar reductions in stiffness as had been observed in the previous testing. These points are also plotted on Fig. 3. The results from the TRG prototype test represent the first actual seismic testing of a low aspect ratio shear wall element. Frequency response functions measured between the base and the top slab during the seismic testing at a 0.5 g acceleration as shown in Fig. 4.

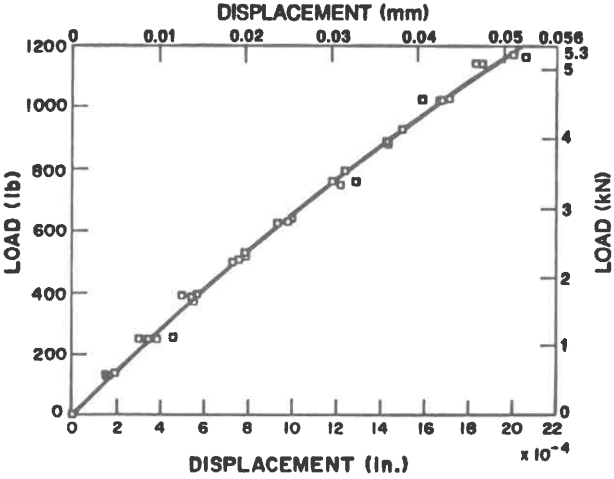

Figure 2A. Static load-deflection curve for 1/4 scale TRG structure, 80 psi (0.55 MPa) maximum normal tensile stress.

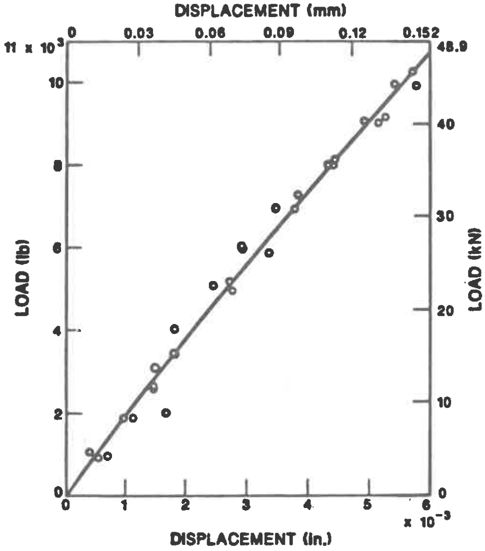

Figure 2B. Static load-deflection curve for prototype TRG structure, 80 psi (0.55 MPa) maximum-normal tensile stress.

TABLE I
FREE-FREE EXPERIMENTAL MODAL ANALYSIS

	1/4 Scale		Prototype	
Mode	Calculated	Measured	Calculated	Measured
Torsion	111.6 Hz	113 Hz	22 Hz	29 Hz
Shear-Bending	303.9 Hz	308 Hz	60 Hz	75 Hz

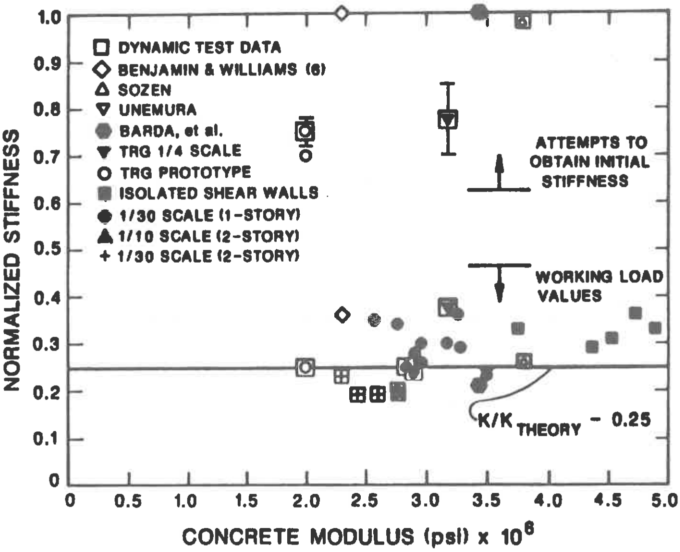

Figure 3. The ratio of statically and dynamically measured stiffness to the theoretical uncracked cross-section stiffness.

TABLE II
LOW LOAD LEVEL SCALABILITY BETWEEN MICROCONCRETE MODEL AND CONVENTIONAL CONCRETE PROTOTYPE

TRG Prototype Properties	Predicted* From 1/4 Scale Results	Measured on Prototype
Static Low Load Level Stiffness	1.86×10^6 psi	1.95×10^6 psi
Free-Free Fundamental Frequency (Torsion)	22.3 Hz	29 Hz

*Corrected for differences in modulus of elasticity between model and prototype.

4 CONCLUSIONS CONCERNING REDUCED STIFFNESS IN LOW ASPECT RATIO SHEAR WALL STRUCTURES

From Fig. 3 it is concluded that at low load levels the computed stiffness value based on an uncracked cross section [Benjamin (1957)] is valid, but at working loads the results are consistent and show the structure responding both statically and dynamically with a reduction in stiffness between 3 and 4. This reduction in stiffness has been observed in different scale models of the same structure (1/30 and 1/10 scale, 1/42 and 1/14 scale and 1/4 and 1 scale) and, based on the TRG results, it cannot be attributed to microconcrete effects. At this point it is believed that the reduction in stiffness is real and there is no apparent reason why it would not be observed in a prototype Category I structures during an actual operating basis earthquake. If the computed values of stiffness were

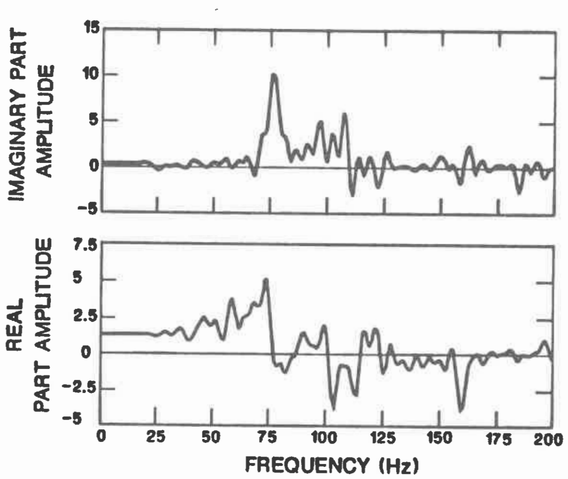

Figure 4A. Frequency response function measured between top and bottom slab of the 1/4 scale TRG structure during a 0.5 g peak acceleration seismic input.

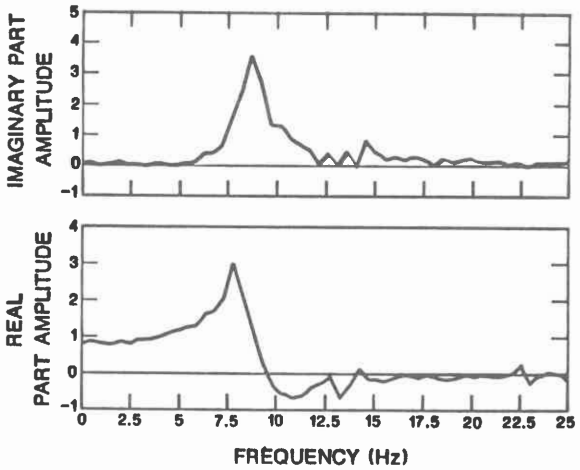

Figure 4B. Frequency response function measured between the top and bottom slab of the prototype TRG structure during a 0.5 g peak acceleration seismic input.

used to predict the modal frequency of the prototype structure, it would be expected that the values would be too large by a factor of $\sqrt{3}$ to $\sqrt{4}$ since modal frequency squared is proportional to stiffness; this error in turn would effect all seismic response calculations.

To illustrate the implications of reduced working load stiffness on equipment attached to a low aspect ratio shear wall structure, Fig. 5 compares a measured floor response spectra for the top slab of the TRG prototype with a computed response spectra for the same location. The measured response spectra was calculated using the test data.

The calculated response spectra used the response determined by subjecting a one-degree-of-freedom lumped mass model to the same base excitation as measured on the TRG prototype (from Fig. 4B it is apparent that the structure was behaving as a 1 DOF system). This analytical model was developed using the computed stiffness based on uncracked cross-sectional properties for the TRG prototype. The analytical model was developed using typical nuclear civil engineering practices by which actual Category I structures have been designed. From Fig. 5 it can be concluded that existing plant equipment and piping in low aspect ratio shear dominated structures may have been designed to improper floor response spectra. Generalization about the response of equipment in existing designs are difficult to make since the response spectra will be a function of the frequency content of the actual seismic event and the natural frequency of the actual structure. The reduced stiffness will in general lower the frequency of the peak response.

At this point several issues concerning the scalability of microconcrete response still remain unresolved. Scalability has only been demonstrated between microconcrete models. Results at working loads from the TRG tests concerning scalability from microconcrete to actual concrete were inconclusive.

Future work will examine the static, cyclic response of six-inch thick structures similar in cross-sectional geometry to the TRG prototype. These models will be designed and constructed in accordance with ACI-349 and typical nuclear industry construction practices. With these models it is hoped that the reduced stiffness can be shown to occur at similar load levels statically as has been observed dynamically.

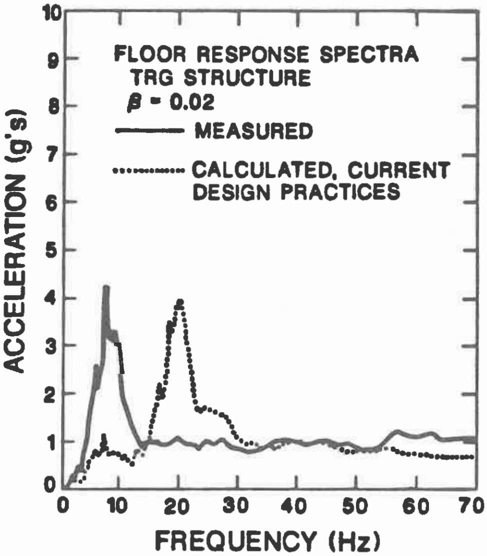

Figure 5. Floor response spectra for the top slab of the TRG structure.

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