DYNAMIC RESPONSE OF REDUCED-SCALE MODELS AND REINFORCED CONCRETE STRUCTURES

D.P. Abrams (I)
S. Tangkijngamvong (II)
Presenting Author: D.P. Abrams

SUMMARY

The study presented in this paper compares response of reduced-scale models and reinforced concrete buildings subjected to strong earthquake motions. General characteristics of member hysteresis relations are correlated for specimens constructed at full scale and at approximately one-twelfth scale. Beam-column assemblages and base-story exterior columns are subjected to slowly applied loading reversals to identify differences in nonlinear behavior attributable to scale. A mathematical model is programmed to compute response of both small and large-scale buildings. A ten-story, three bay frame-wall structure is used as an example for comparison. Different sets of rules defining load-deflection behavior of large and small-scale components are developed based on experiments and used for input to the numerical analysis. Response comparisons are evaluated in light of conclusions deduced from shaking table studies.

INTRODUCTION

Several studies in the past (Ref. 1 through 3) have used reduced-scale models to examine response of reinforced concrete structural systems. This has proven to be less costly than tests using a large-scale structure such as the one done recently in Tsukuba Japan (Ref. 4). This paper discusses the benefits and limitations of using a model structure as small as one-twelfth scale to represent the dynamic properties of a ten-story structure behaving within the nonlinear range of response. Correlations in behavior of large and small-scale components are presented based on tests of beam-column assemblages and base-story column specimens which have been subjected to slowly applied reversals of displacement. Differences in measured load-deflection relationships of these members are examined in terms of the dynamic response of a structure comprised of nonlinear properties of either large or small-scale components.

TESTS OF BEAM-COLUMN ASSEMBLAGES

Stress-strain relations for model reinforcement and model concrete provided a suitable representation of those relations of full-scale materials. Moment-curvature relations for sections in flexure also were

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(I) Assistant Professor, University of Colorado at Boulder, USA

(II) Research Assistant, University of Colorado at Boulder, USA

represented well with a small-scale model. Smooth small-scale wire which was embedded in small-aggregate model concrete, however, was found to be much weaker in bond strength than large-scale deformed bars embedded in normal concrete. Because of this limitation, scaling relations for load-deflection relations were dependent on the component configuration.

Small-scale exterior beam-column assemblages (Ref. 5) responded within linear and nonlinear ranges of response with nearly the same load-deflection relations as that measured for large-scale specimens (Ref. 6). Longitudinal beam reinforcement was anchored sufficiently within the joint for each specimen. Although the large-scale specimens responded with a more uniform distribution of flexural cracks than that observed for the small-scale specimens, overall flexural stiffnesses and strengths were represented well at one-twelfth scale.

Tests of interior beam-column assemblages did not show the good correlations in scale as observed for the exterior joints. For these specimens, local concentrations of bond stress within the joint resulted in local slippage of reinforcement. This phenomenon occurred for both large and small-scale specimens, but to varying extents. Bond was lost completely for the small-scale specimen across the entire width of the column after the first cycle of loading within the nonlinear range. A sharp reduction in stiffness within load reversal regions (Fig. 1) was a result of this slippage. After five large-amplitude cycles, the large scale specimens showed partial bond deterioration and resembled behavior of the small-scale specimens during earlier cycles. Apart from this deviation, the small-scale specimen was able to mimic both the strength and stiffness characteristics of the large-scale specimen.

TESTS OF BASE-STORY COLUMNS

Axial loads were varied with shear forces on column specimens to simulate conditions at the base story for exterior columns. Tests of both large (Ref. 7) and small-scale (Ref. 8) members confirmed the use of a small-scale model to represent moment-curvature relations of a reinforced concrete section. Stiffness characteristics within the elastic range (Fig. 2) were calculated with good correlation using conventional principles of mechanics for specimens of each size. Ultimate strengths were represented well with the model, and were found to be related directly to those of the large-scale specimens by the square of the length scale factor.

Within the inelastic range, the opening and closing of flexural cracks were influenced by the varying axial force. Characterization of nonlinear stiffness properties was difficult using an analytical approach, yet response of specimens at each scale were remarkably similar (Fig. 2). Deflections of each specimen were related by the length scale factor.

SCALING RELATIONS OF CONCRETE BUILDINGS

A computational model was developed to calculate response of structures consisting of components at each scale. The model represented a ten-story building used in previous shaking-table studies at the University of Illinois (Ref. 1-3). Calculations were made for those forms of response measured during an earthquake simulation: accelerations and displacements at each floor level and forces resisted by an internal wall. Computed response was normalized with respect to amplitude and duration according to principles of dynamic similitude for linear systems. Identical response for both large and small-scale structures during early instants of the earthquake (Fig. 3) indicated correct normalization procedures. Differences in response during subsequent periods were attributable to different hysteretic relations for large and small-scale interior and exterior beam-column assemblages. Because the correlation in behavior of large and small-scale base-story columns was good, these elements were considered in the numerical model to behave linearly.

Conclusions made from comparison of response of a reduced-scale model and a concrete structure are noted below.

(a) Apparent natural frequencies of the small-scale structure were less than those of the large-scale structure.

(b) Natural frequencies of both large and small-scale structures decreased with successive cycles of motion, however, the small-scale structure showed more rapid deterioration than did the large-scale structure.

(c) Maximum displacement and acceleration response occurred during the same cycle for both large and small-scale structures. Maximum displacements were very similar for each structure, however, maximum accelerations were consistently larger for the large-scale structure.

(d) Frequency contents of displacement and acceleration response were similar for both large and small-scale structures. Displacement response was dominated by the first mode at each level for both structures. Acceleration response contained frequencies of the base motion at lower levels and modal frequencies at higher levels for both structures.

(e) Amplitudes of lateral force resisted by either the wall or the frames were markedly different for each structure. Sequences and frequencies of wall response (Fig. 3c), however, were similar for large and small-scale structures.

(f) Displaced shapes (Fig. 4) of each structure were nearly the same. This good correlation was observed at all amplitudes of motion as shown in Table 1 where shapes have been expressed in terms of modal participation factors.

(g) Distributions of lateral force resisted by individual lateral-load resisting components varied substantially for large and small-scale structures.

(h) Story shears (Fig. 5) resisted by the combined wall-frame structure were similar for each structure. Correlations in participation of frame and wall in resisting the story shear varied with the story level. Shears resisted by the wall varied substantially for large and small-scale structures above the fifth level, but good agreement in these values could be observed below this level.

CONCLUDING REMARKS

Results of the study have shown that a model as small as one-twelfth scale can be used to capture general characteristics of a reinforced concrete building vibrating within the nonlinear range of response. Overall response of a ten-story structure could be depicted with sufficient accuracy to allow for studies of response of a complete structural system. In some cases, a small-scale physical model could mimic behavior much more accurately than present numerical algorithms for calculating hysteretic response.

When designing a model structure, attention should be given to development of longitudinal reinforcement, particularly for beam reinforcement across the width of a column. Proper simulation of bond characteristics is essential to modeling nonlinear behavior under large reversals of deflection. Forces resisted by individual frames or wall were sensitive to relative differences in stiffnesses of large and small-scale beam-column assemblages and walls. For this reason, care should be taken when examining lateral force distributions of these elements.

ACKNOWLEDGMENTS

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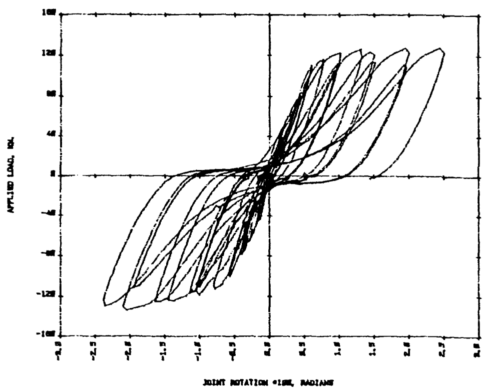
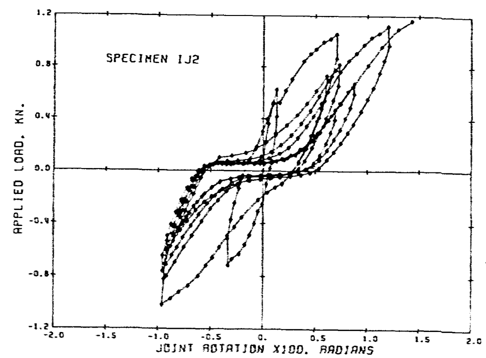
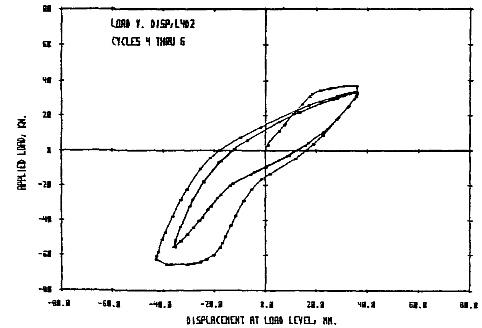


(a) Large Scale

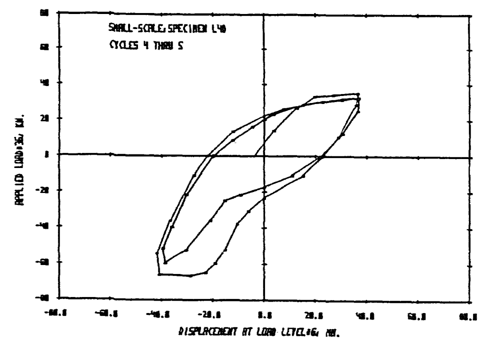


(b) Small Scale

Fig. 1 Measured Load Deflection Relations for Beam-Column Specimens

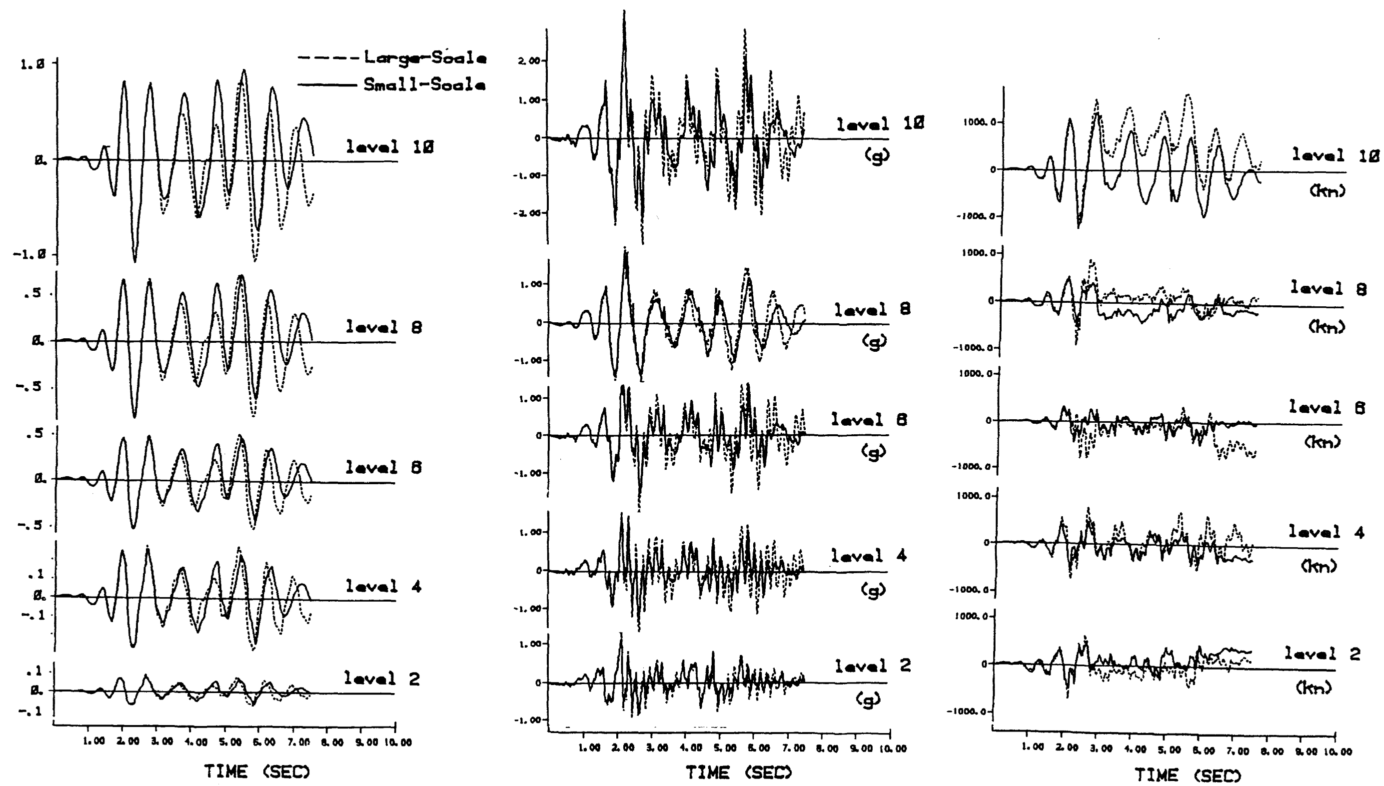


(a) Large Scale



(b) Small Scale

Fig. 2 Measured Load Deflection Relations for Base-Story Column Specimens



(a) Displacements

(b) Accelerations

(c) Forces Resisted
by Interior Wall

Fig. 3 Computed Response of Large and Small-Scale Structures

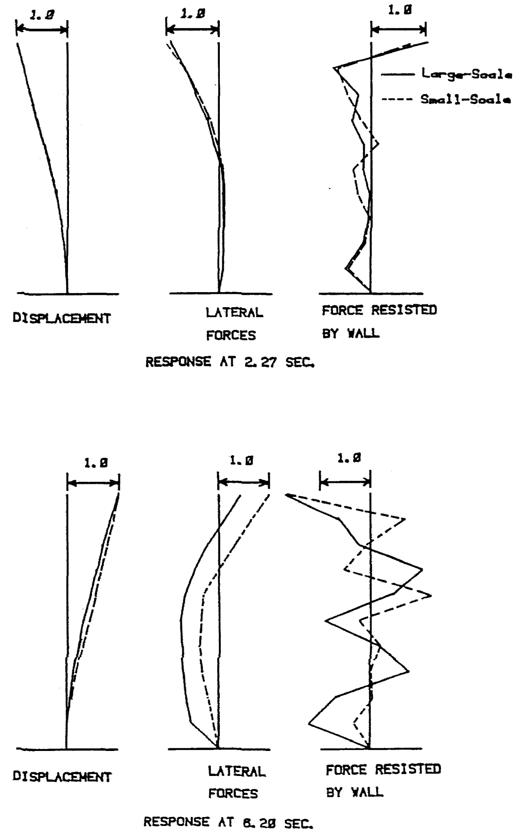
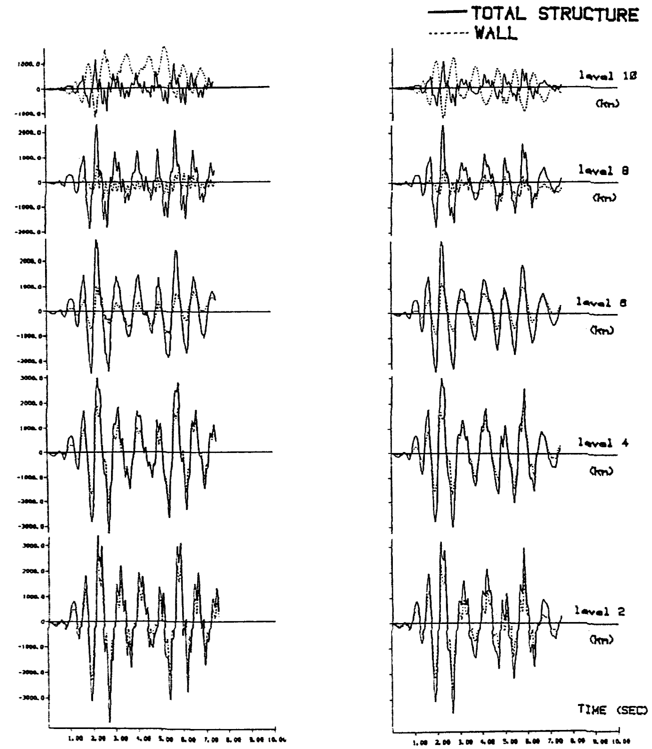


Fig. 4 Distribution of Response along Height of Large and Small-Scale Structures



(a) Large-Scale Structure (b) Small-Scale Structure

Fig. 5 Participation of Wall in Resisting Story Shears of Large and Small-Scale Structures