SMALL SCALE MODELS OF CONCRETE STRUCTURES SUBJECTED TO DYNAMIC LOADS

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SYNOPSIS

The use of small scale models to predict the behavior of reinforced concrete structures has become increasingly important in recent years because of the complexity of many modern structures and the need to understand their behavior in the inelastic range. A well known example is the prestressed concrete pressure vessel for nuclear applications, where the only feasible method for investigating the effects of severe loading combinations is with scaled models. This paper presents the state-of-the-art in the field of models of concrete structures in dynamic loading applications. The major problems met in dynamic modeling include (a) materials that meet similitude conditions, (b) proper simulation of mass, (c) loading methods, and (d) strain measurements in the reinforcing and model concrete. These topics are discussed here, along with selected applications of both true dynamic and pseudo-static modeling. It is concluded that small scale structural models are highly useful for studying certain types of dynamic response, both elastic and inelastic.

INTRODUCTION

Small scale models have been used for many decades by structural engineers. Until about two decades ago, however, their use was mainly confined to static, elastic behavior of structures. Recent use of ultimate strength theories in both reinforced concrete and steel design, and the development of increasingly complex structures, have forced the structural engineering profession to dwell much deeper into both inelastic and dynamic response. Since full scale testing is limited because of expense, the use of small scale models offers an excellent potential to help fill the current gaps in our understanding of inelastic behavior. Considerable work on statically loaded models of concrete structures has been undertaken in various laboratories around the world, but research and design using dynamic models has been rather limited because of the many problems involved and the sophisticated loading equipment required.

In this paper the term "small scale" means models with a geometric scale factor of 1/6 or smaller. At this scale the problem of size effects in the model concrete may be present, even with static models. Furthermore, properties of materials under dynamic loading are different than under static loading. Thus two difficult problems may appear in modeling the dynamic response characteristics of prototype concrete - overall size effects, and strain rate effects. These problems are addressed later in this paper.

Structural models have two distinct but supportive types of applications. The research model is used to help verify the adequacy of analytical approaches and to increase the understanding of complex behavior needed to formulate new and better mathematical models. The research model normally does not have to meet detailed similitude requirements of a particular prototype; instead it

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must exhibit the full range of behavior modes associated with a particular class of structures. Once the analytical model is sufficiently well refined to predict the dynamic behavior of the research model, then it can be used with reasonable confidence for predicting response of specific prototypes. Physical research models are often of medium scale, say about 1/3, and are many times designed to predict the behavior of structural components rather than a complete structure.

Design models are associated with a particular prototype. They are further characterized by tending to be more complete replicas of an entire structural system, which automatically leads to a smaller scale in nearly all applications. They are usually built to the specifications of a preliminary analytical design for the prototype structure.

Many types of structures and associated loading histories are candidates for structural modeling, including:

1. Tall building systems subjected to earthquakes or high wind forces.
2. Suspension bridges, cable suspended roof systems, and other geometrically complex systems that must be studied for aerodynamic response.
3. Nuclear power plant containments and other crucial structures subjected to seismic loadings.
4. Highway bridges carrying high seismic force levels.
5. Above-ground and buried structures subjected to blast loadings.
6. Dams subjected to earthquakes.

It is not possible to fully discuss all modeling problems associated with these many different types of structures. The selective coverage given here should be supplemented by readings from the references (1-6 cover basic modeling theory).

Both dynamic and pseudo-static models have application in research and design. In true dynamic modeling for earthquake effects, the structure is subjected to a simulated earthquake acceleration history by a shaking table or similar facility. Most existing shaking tables have rather modest horizontal force capabilities. An additional serious problem that may arise in using a shaking table is the large overturning effect that may be produced by the heavy masses that may be needed to generate the appropriate inertia forces. To overcome these problems, slowly applied reversing loads (called pseudo-static) are often used to load both small and medium scale models. In pseudo-static testing the reversing loads can be very carefully controlled, but a basic problem remains in relating the slow-speed cyclic loading response to rapid dynamic response. A very important advantage of pseudo-static loading as compared with dynamic loading is that in the former approach, it is possible to easily follow the sequence of cracking, damage levels, etc. during each load reversal. A dynamic test that is completed in seconds may well extend over several days when converted to a pseudo-static loading. The ideal approach is a combination of the two, using pseudo-static modeling to investigate the full range of behavior under well-defined load conditions, and supplementing the pseudo-static models with true dynamic models to assess potential differences between the two.

SIMILITUDE REQUIREMENTS

Similitude requirements for dynamic structural models are well known (Refs. 1-6). They are normally derived from Buckingham's Pi Theorem. A typical dynamic response problem can be expressed in three fundamental measures (force F or mass M, length L, and time t). Thus three fundamental scale factors may be selected and the remaining scale factors become dependent functions of these three. Rocha (6) presents similitude requirements for two modifications of the general case: (a) with a preset distortion factor on the accelerations, and (b) with a preset distortion factor on the forces. Several approaches to dynamic modeling similitude are summarized in Ref. 5.

Identical materials in model and prototype are preferred in dynamic modeling for rather obvious reasons (post-elastic behavior, time-dependent behavior, equal Poisson's ratio in both), but such choice of model materials does force the time scale to be a fixed function of the length scale. If a distorted time scale for loading must be used (small models require rather high frequency loading rates), then the model material modulus and density must be chosen along with the length scale to satisfy the following relation:

$$\sqrt{\frac{E_p}{\rho_p}} \cdot \frac{t_p}{\ell_p} = \sqrt{\frac{E_m}{\rho_m}} \cdot \frac{t_m}{\ell_m}$$

where E, ρ, t, and ℓ are elastic modulus, density, time, and length parameter for prototype and model respectively.

or

$$\frac{t_m}{t_p} = \sqrt{\frac{E_p \cdot \rho_m}{E_m \cdot \rho_p}} \cdot \frac{\ell_m}{\ell_p}$$

Furthermore, if self weight stresses are to be accounted for, there is an additional requirement that

$$\rho_m = \frac{\ell_p}{\ell_m} \cdot \frac{E_m}{E_p} \cdot \rho_p$$

Often the latter cannot be satisfied, and additional masses must be placed on the model in such a fashion that they do not stiffen it.

DYNAMIC PROPERTIES OF MATERIALS

It is generally found that the strength properties of any material increases with increasing strain rate. Clough and Bertero (7) and others have studied the effect of strain rate on the behavior of typical reinforced concrete sections carrying moment, shear, and axial load. These medium scale experiments were run at displacement rates of both 0.1 in/sec and 10 in/sec. Results indicate that both the cracking strengths and initial steel yielding strengths were increased about 20% as the displacement rate was increased by a factor of 100, but that ultimate strengths and failure modes were not significantly affected. Pseudo-static testing is thus an acceptable alternate to true dynamic modeling when the loading applied is extreme, that is, induced deformations are far beyond the yield deformation. It must be noted that these conclusions are based on rather large models, and that additional verification work with small-scale model materials is needed. The strain-rate effects must not be confused with size effects. The work of Chowdhury (11) shows that model materials with no significant size effects can be developed for modeling severe reversing load effects in frames, and the authors are optimisitic that strain-rate effects in small scale models made with proper materials will be no different than those found by Clough and Bertero.

LOADING TECHNIQUES AND INSTRUMENTATION

Once the model is established as to its geometry, based on the various considerations cited above, then proper loading must be applied and measurements taken to assess its response. Invariance in gravitational forces causes a distortion in dead load scaling which becomes significant in massive structures. Hence to alleviate it the density of the system is artifically augmented with additional dead loads (8). Dynamic loading, particularly in reference to seismic model testing, consists of applying suitable motions to the foundation of the model during the preassigned time interval. Techniques have been developed in recent years on both small and medium scales to achieve the desired forcing function. One example (9) includes an electro-mechanical shaker with a frequency response from 5 to 5000 Hz. By means of a random noise generator, electric band pass filters, and a time switch, it is possible to generate a simulated earthquake acceleration to a suitable scale. The accelerations are transferred to the model structure through the rigid connection between shaker and foundation. Another form of loading involves use of a shaking table (7) that may also have vertical acceleration capabilities.

Pseudo-static loading systems are much simpler and normally use hydraulic and/or mechanical loading devices. Control of a number of loading devices becomes critical when the structure is being loaded to near-collapse stages. It may be necessary to use displacement control rather than load control to achieve the high ductility factors often encountered in severe reversing loads.

Measurement of strain in the reinforcement becomes a rather severe problem if the scale becomes too small. Substantial experience does exist, however, with application of electrical resistance strain gages to reinforcing wires on the order of 1/10 in. (2.5 mm) diameter. Commercially available urethane protective coatings have given excellent results in terms of sealing the gage installation from moisture and protecting it from the concrete placement operation. Elaborate and bulky waterproofing techniques used on gages in full scale structures simply cannot be used in small scale models because they produce too much displacement of model concrete.

EXAMPLES

Four examples of pseudo-static and dynamic modeling studies are cited here to help portray the range of applicability of these techniques to reinforce concrete structures.

Sabnis and White (10) tested two reduced size prototype portal frames and eighteen 1/5 scale models of these prototypes under pseudo-static reversing loads. Reinforcement details in the models, which had cross section dimensions 1 in. by 2 in. (25 x 50 mm), were provided as in actual prototypes. Models agreed very well with the prototypes and it was concluded that repeated gravity loads at 95% of the ultimate capacity (measured in a single monotonic loading) did not affect the load capacity of the frame, but that fully reversing loads of about 75-80% of the single cycle lateral load capacity led to reductions in frame strength.

Chowdhury (11) extended the above work and tested three story, two-bay 1/10 scale model reinforced concrete frames under combined constant gravity loading and steadily increasing pseudo-static reversing lateral loads up to failure. Considerable work was done prior to the frame tests on perfecting materials that would enable nearly exact duplication of reversing load effects on typical joint specimens tested at a full-scale by Hanson and Conner. Reference 12 gives full details on the model concrete and on the special heat treatment needed for the model reinforcing, as well as many comparisons of model and prototype response. Once the proper materials were achieved, the small scale models faithfully duplicated all aspects of behavior, including cracking as a function of load cycling, steel stresses, displacements, and moment-rotation characteristics over the critically loaded portions of the joint.

Williams and Godden (13) used a shaking table to dynamically load 1/30 scale models of a long curved highway bridge. The small models were designed to closely approximate the behavior of similar prototypes that collapsed during the 1971 San Fernando earthquake in California. Expansion joints, expansion joint retainer systems, and column ductility were all modeled, and the models were loaded with both horizontal and vertical components of motion to determine both overall response and failure modes. Experimental studies of this type give substantial new insight into major design questions that are extremely difficult, if not impossible, to resolve analytically.

Otani and Sozen (14) also used an earthquake simulator to load two types of 1/6 scale three-story frames. Scaled acceleration histories were applied from two input earthquakes. The models were designed in accordance with normal design assumptions and did not represent any particular prototype. The model structures withstood rather intense base motions without collapse; this was attributed to design methods that prevented diagonal shear and anchorage failures.

CONCLUSIONS

It may be concluded that dynamic structural modeling can be a versatile and valuable tool for both research and design. In other fields, such as fluid mechanics and aerospace structures, dynamic models have been used with wide success; however, in civil engineering applications, the full potential has not been reached. This has been due in the past to lack of suitable testing facilities, lack of understanding of model material properties, and perhaps a hesitancy on the part of many structural engineers about the general validity of small scale models. Small scale models made of appropriate materials can be loaded either in a dynamic or pseudo-dynamic fashion to give important behavioral information about full scale structures subjected to severe seismic actions.

BIBLIOGRAPHY

1. Sabnis, G.M., White, R.N., and Mirza, S.M., "Structural Modeling and Experimental Techniques". To be published by Prentice-Hall, Inc., Englewood, New Jersey, 1977, approximately 600 pages.

2. Baker, W.E., Westine, P.S. and Dodge, F.T., "Similarity Methods in Engineering Dynamics," Hayden Book Company, Inc., Rochelle Park, New Jersey, 1973, 396 pp.

3. Young, D.F., "Basic Principles and Concepts of Model Analysis," Journal of Experimental Mechanics, July 1971, pp. 325-336.

4. Murphy, G., "Similitude in Engineering," Ronald Press Co., New York, 1950.

5. Zia, P., White, R.N., and Van Horn, D.A., "Principles of Model Analysis," Proceedings of Symposium on Structural Models, SP - 24, American Concrete

Institute, Detroit, 1970, pp. 19-40.

6. Zienkiewicz, O.C. and Holister, G.S., "Stress Analysis," Chapter 16 - Structural Model Techniques, by M. Rocha, Wiley, New York, 1965.

7. Clough, R.W. and Bertero, V.V., "Laboratory Model Testing for Earthquake Loading," Proceedings of ASCE/EMD Specialty Conference on Dynamic Response of Structures, UCLA, March 1976. (Also see Report No. 72-9, 73-4 and 75-19 of the Earthquake Engineering Research Center, University of California, Berkeley, 1972-1975).

8. Fumagelli, E., "Statical and Geomechanical Models," Springer Verlag Publishing Co., New York, 1973, 182 pp.

9. Borges, J.F. and Pareira, J., "Dynamic Model Studies for Designing Concrete Structures," Proceedings of Symposium on Structural Models, SP-24, American Concrete Institute, Detroit, 1970, pp 251-264.

10. Sabnis, G.M. and White, R.N., "Behavior of Reinforced Concrete Frames Under Cyclic Loads Using Small Scale Models," Journal of ACI, September 1969, pp. 703-715.

11. Chowdhury, A.H., "Inelastic Behavior of Small Scale Reinforced Concrete Beam-Column Joints Under Severe Reversing Loads," Ph.D. Thesis, Cornell University, 1972.

12. Chowdhury, A.H. and White, R.N., "Inelastic Behavior of Small Scale Reinforced Concrete Beam-Column Joints Under Severe Reversing Loads," Report No. 342, Department of Structural Engineering, Cornell University, October 1971.

13. Williams, D. and Godden, W.G., "Seismic Behavior of High Curved Overcrossings," Proceedings of the U.S. National Conference on Earthquake Engineering - 1975, Ann Arbor, Michigan, June 1975.

14. Otani, S. and Sozen, M.A., "Behavior of Multistory Reinforced Concrete Frames During Earthquakes," Civil Engineering Studies, Structural Research Series, No. 392, University of Illinois, November 1972.