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Session Report
SUMMARY REPORT: SPECIAL THEME SESSION (SI) ON EXPERIMENTAL METHODS FOR STRUCTURES (Part 2: SCALE EFFECTS IN MODELING STRUCTURES)

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SUMMARY

This is a summary report of Part 2 of the Special Theme Session: SI, entitled "Experimental Methods for Structures," and, in this session, "Scale Effects in Modeling Structures" were highlighted. This paper describes the outline of the state-of-the-art report and technical papers presented in this session and summarizes the discussions and closing remarks.

OPENING REMARKS

At the beginning of this session, one of the chairpersons, Professor Wakabayashi, provided an opening address and stated the objectives and scope of this session. A summary of his remarks follows.

Summary of Opening Remarks The Special Theme Sessions have been organized for highlighting subjects that are deemed very important for the future advancement of earthquake engineering. This session is the second half of the Special Theme Session: SI (Experimental Methods for Structures), and entitled "Scale Effects in Modeling Structures." The variety of experiments related to earthquake engineering studies has increased in recent years. Thanks to the advancement of experimental hardware, it is not difficult to conduct structural tests on a very large scale, and tests under dynamic loading conditions have become popular. Having utilized many advanced experimental techniques, the time has come to evaluate these techniques and to compare results obtained from different individual techniques. This session is intended to provide a forum to discuss this subject in depth. In particular, the focus of this session will be on scale effects in modeling structures, and, because of the nature of earthquake loading, on loading-rate effects. One state-of-the-art report and eight technical papers, all dealing closely with this focus of the session, are scheduled to be presented, and after those presentations, time will be available for open discussion. We would like all of you attending this session to join the discussion.

STATE-OF-THE-ART REPORT

Professor Krawinkler presented the state-of-the-art report of this session. His report consisted of three parts. The first part dealt with effects of scaling on stress-strain properties of steel and concrete; the second part with effects of scaling on the response of models of steel and reinforced concrete structures and elements; and the last part with a subjective evaluation of scale effects in different test methods. Among various types of scale effects, the presentation focused on the effects of scaling size and time (strain (loading) rate). A summary of the report follows.

Scale Effects on Stress-Strain Properties of Structural Steel The strain-rate effect on the stress-strain properties of structural steel can be summarized as follows: (1) the modulus of elasticity remains unchanged; (2) the yield stress increases as the strain-rate is increased; (3) the tensile strength also increases with an increase of the strain-rate, but this increase is smaller than the increase in yield stress; (4) the fracture strain is not affected significantly; and (5) the effect is generally less significant in the cyclic loading condition than in the monotonic loading condition. With respect to the size effect on the stress-strain properties, a reduction in the specimen size leads to an increase in the strength properties.

Scale Effects on Stress-Strain Properties of Concrete and Microconcrete When the strain-rate is increased, both the stiffness and compressive strength increase, and this increase is more significant in microconcrete than in prototype concrete. Generally speaking, the strain-rate effect is greater in concrete than in steel. The size affects the flexural tensile strength most significantly because of the high strain gradient in small scale specimens.

Scale Effects on Response of Models of Steel Structures and Elements Among various problems associated with the fabrication of the model, welding is most critical. The heat-affected zone is much larger in a small-scale model than in the full size model and will be subjected to higher temperatures. Further, the large surface area to volume ratio of the section in a small scale model results in more rapid cooling, causing much larger residual stresses in the model. The shape, distribution, and size of initial imperfections in the weldment cannot be reproduced in a scaled model, either. Thus, crack initiation and propagation cannot be simulated. The loading-rate effect on the behavior of steel elements can be estimated from the strain-rate effect on the stress-strain properties of the material used. Generally, the loading-rate effects are more significant in composite structural elements than in bare steel elements, because concrete is more rate-dependent than steel.

Scale Effects on the Response of Models of Reinforced Concrete Structures and Elements Two of the critical problems encountering in a small scale model are shrinkage and bond. Because of the larger surface area to volume ratio, a small scale model is more susceptible to shrinkage cracks, and, therefore, maximum care should be taken to avoid such shrinkage cracks before the test. With respect to the bond similitude, the type of model reinforcement has the largest effect on bond characteristics, and cold-rolled wire reinforcement is found to be most suitable. Crack patterns can be simulated in reduced size specimens, but, with a reduction in size, the number of cracks decreases. This decrease in the number of cracks is significant even if the scale ratio is only 1/2. The strain hardening of the reinforcement plays an important role in the simulation of crack propagation. The peak resistance of reinforced concrete structures and elements increases with an increase of the loading-rate, and the material strain-rate effect may be useful in evaluating this increase in strength. Strength deterioration is more significant for a lower loading-rate and creates a problem when static test results are used to predict the dynamic response of structural elements.

Evaluation of Scale Effects in Different Test Methods Three test methods, quasi-static testing, pseudo dynamic testing, and reduced scale model testing, were compared, and the results of the respective methods were evaluated. Quasi-static testing with a predetermined loading history is most useful for acquisition of fundamental data for design purposes. It should be remembered that slow testing results in a decrease in strength and an increase in deterioration, although these changes in properties normally provide conservative design recommendations. Pseudo dynamic tests in which loading is applied a slow rate will overestimate the ductility demands and underestimate the ductility capacities. If a reduced model is used for dynamic loading tests, the loading-rate effect is normally less significant, but the size effect should not be overlooked. If the global behavior is of major concern in the investigation, the reduced scale model testing is effective, but when local behavior, such as the load-resistance characteristics of a beam-to-column joint, are to be examined, a reduced scale model cannot guarantee reliable results.

SUMMARY OF TECHNICAL PRESENTATIONS

Pseudo Dynamic Test Applied to Full Scale Steel Structure (by Yamanouchi) An overview of the pseudo dynamic tests performed on a full-scale six-story steel frame structure with concentric-K bracing was presented, and load-deformation responses and failure mechanisms were displayed. It was demonstrated that a local failure could trigger large damage of the structure and such behavior can be examined most effectively by using a large scale structural model.

Shaking Table Test Applied to 1/3 Scale Steel Structure (by Bertero) Results of a series of shaking table tests performed on a 1/3-scale steel structure with K bracing were presented. It was stressed that every effort should be made to fabricate a reliable reduced scale model, including the simulation of the material and geometrical properties of individual structural elements and that, in some cases, fabricating such a reduced scale model is more costly than fabricating the prototype. Using a carefully fabricated model, global behavior can be reproduced satisfactorily, unless a local behavior controls the global one. The model used in these tests could predict accurately the natural periods, damping coefficients, and vibrational modes of the prototype. Even with such careful modeling, local behavior is sometimes difficult to reproduce; for example, the brace fracture occurred in the fifth story in the model, while the third story brace fractured in the prototype. Advantages of the dual framing system were demonstrated, and the effectiveness of frictional damping devices in increasing the seismic resistance of the model structure was illustrated.

Shaking Table Test of 1/7 Scale Reinforced Concrete Structures (by Abe) Earthquake response behavior of a 1/7-scale reinforced concrete structure was presented. Two model structures were fabricated; one was tested on a shaking table under a uniaxial (one horizontal component) condition, while the other was tested under a biaxial (two horizontal components) condition. The difference in failure mode between the two tests was demonstrated. It was noted that fabrication of a 1/7-scale reinforced concrete structural model was extremely time consuming.

Shaking Table Test of 1/5 Scale Reinforced Concrete Structures (by Mollick) Two 1/5-scale models of one-bay by one-bay reinforced concrete structures were tested using a shaking table. In one test, the excitation was applied in one of the principal directions, while in the other test, it was applied in a diagonal direction of the structure. Substantial contribution of the floor slab to the beam flexural resistance was stated.

Quasi-Static and Dynamic Loading Tests of Slender RC Columns (by Iwai) Reinforced concrete columns having either a square or a rectangular cross section were tested under a monotonically increasing axial force. In these tests, the amount and angle of the eccentricity, the slenderness, and the loading-rate were chosen as the major parameters. The ultimate strength of the columns tested decreased significantly because of the P-delta effect. When the loading-rate was increased, the ultimate strength increased; in some tests, this increase was as much as 15 percent of the ultimate strength. Analysis in which the loading-rate effect was taken into account in terms of the strain-rate effect on the material stress-strain properties was also performed, and the effectiveness of the analysis was demonstrated.

Shaking Table Test of 1/5 Scale 3 Story Masonry Buildings (by Modena) Two different types of 3-story masonry structures were tested using a shaking table. A variety of input ground motions were applied to the structures, and linear and nonlinear responses of the structures as well as their failure mechanisms were investigated.

Shaking Table Test of 1/2 Scale Steel Frames Infilled With Brick Walls (by Elnashai) Results of a series of shaking table tests applied to 1/2-scale steel frames infilled with brick walls were presented. Effects of the infilled bricks on the frame resistance, performance of the brick walls in out-of-plane loading, and ductilities of the cracked panels were examined based on the results.

Shaking Table Test of Small Scale Adobe Houses (by Krawinkler) Using 1/5-scale adobe bricks, a total of six adobe house models were tested using a shaking table. It was reported that significant improvement of the seismic performance of adobe houses can be achieved by introducing bond beams and anchored roof beams. The strain-rate effect was found approximately in the same order between concrete and adobe materials. The reduction in size affected significantly the material properties of adobe mainly because of the increase in the surface area to volume ratio. It was emphasized that reducing the scale in porous materials such as masonry and adobe most likely leads to drastic changes in the material properties of brick-mortar assemblies.

DISCUSSION

Following the eight technical presentations, the chairpersons asked for comments and questions from the floor. A summary of the discussion follows.

General Comments (by Jurukovski) Although all of the presentations in this session dealt only with building structures and elements, scale effects may be more crucial for other types of structures such as bridges and dams.

Question on Pitching Effects in Shaking Table Studies (by Jurukovski) In many shaking table studies, it was reported that pitching of the table cannot be neglected. In Professor Bertero's study, was the pitching effect included in the analysis?

Comments on Pitching Effects in Shaking Table Study (by Bertero) The pitching effect cannot be ignored. In the Berkeley shaking table, the acceleration caused by pitching can be as much as 0.5 to 0.6 g with a weight of 120 kip on the table. In the analysis conducted after the tests, the pitching effect was indeed included.

Question of Loading Sequence in Shaking Table Study (by Elnashai) In the shaking table study of adobe house models, multiple levels of excitation, with a larger excitation in each successive test run, were applied to each model. With such a sequence of loading, the structural characteristics may have changed due to the previous test runs. Is there any comment about this possible change in structural characteristics and eventually in a failure pattern?

Comments of Loading Sequence in Shaking Table Study (by Krawinkler) We always deal with a limited number of test structures and want to maximize the information that could be obtained from the tests. What type of loading program we should select is the issue to be determined in view of the purposes of the study.

Question on Evaluating Damping in Nonlinear Range in Shaking Table Study (by Elnashai) How can we measure realistic values of damping in the nonlinear range?

Comments on Evaluating Damping in Nonlinear Range (by Krawinkler) If the damping in question means the equivalent viscous damping, it does not seem to be a critical issue. It is because the equivalent viscous damping is after all not a good measure of damage, particularly for distributed mass systems such as the discussed adobe houses, where equivalent viscous damping cannot be estimated reliably by any means.

Comments on Evaluating Damping in Shaking Table Study (by Bertero) Equivalent viscous damping in a nonlinear range is very difficult to properly estimate from shaking table tests applied to a reduced scale model, because, in such a model, crack patterns as well as tensile strengths of the materials can be significantly different from those in the prototype. In addition, the table actuators absorb some energy which may not be negligible in most occasions.

Question of Values of Pseudo Dynamic Test (by Calvi) Shaking table tests are usually more expensive and more difficult than pseudo dynamic tests. Further, the strain-rate effect is said to be not so significant. Then, what can we learn from shaking table tests that cannot be learned from pseudo dynamic tests?

Comments on Values of Shaking Table Test (by Krawinkler) Some of the previous correlation studies in which shaking table and pseudo dynamic test results were compared exhibited considerable differences in response between the two tests. It seems that the pseudo dynamic test method is a technique yet under development, and when the validity of this method is fully confirmed, the shaking table test may be more and more replaced by the pseudo dynamic test. However, we should not overlook the fact that the lumped-mass assumption is employed in the pseudo dynamic test. As long as the structure under study can be represented reasonably by a lumped mass system, the results obtained from the pseudo dynamic test should be meaningful, but if the mass is distributed over the entire structure, the lumped-mass assumption cannot guarantee reliable results.

Comments on Reliability of Pseudo Dynamic Test (by Hanson) In the pseudo dynamic tests of a full-scale 7-story reinforced concrete structure, the structure was simplified to a single degree of freedom system. The full-scale 6-story steel structure was treated as a 6 degree-of-freedom system with high mathematical damping for the highest three modes, and these tests produced reliable results. With the present hardware and software available for large scale testing, it is difficult to utilize the pseudo dynamic test method to structural models having many degrees-of-freedom.

Further Comments on Reliability of Pseudo Dynamic Test (by Thewalt) Contrary to Professor Hanson's comment, the pseudo dynamic test method is believed to have been sufficiently developed to ensure reliable results. Because of the significant effect of experimental errors on the pseudo dynamic responses, it is important to validate the pseudo dynamic test system employed and to agree on data necessary to demonstrate that each test was successfully performed.

Comments on Differences in Quasi-Static and Dynamic Loading Tests (by Abrams) In a recent comparison of quasi-static testing of a large-scale 2-story masonry building and dynamic testing of a quarter-scale model of the same structural configuration, a number of differences were observed and are summarized in Paper P1B-16. One observation in the large-scale test was that cracks continued to propagate when the lateral deflection was held constant. This observation indicated that the cracking was rate-dependent and perhaps that the shaking table test would reveal a slightly different form of response.

CLOSING REMARKS

After about 40 minutes of discussions, one of the chairpersons, Professor Hanson, addressed concluding remarks. A summary of his remarks follows.

1. Our common perception with respect to the loading-rate effect can be summarized as follows: (1) the loading-rate (under earthquake loading conditions) indeed affects the restoring force behavior of structures and elements but that the influence is in a range of at most 15 to 20 percent; and (2) considering other uncertainties involved in our analysis as well as design procedures, such as uncertainties associated with the type and intensity of the ground motion, the loading-rate effect can be considered secondary.

2. Size effects vary from one material to another. The effects are less significant in steel and most crucial in masonry and adobe materials. Particularly, the tensile force properties (including cracking and crack propagation) of these materials are affected a great deal by their size.

3. Viscous damping properties may also be subject to scaling, but the hysteretic damping overwhelms the viscous damping in nonlinear responses in most of the structures and elements used. Possible change in viscous damping properties by scaling does not seem to be crucial.

4. The reduced scale model testing is most effective when we wish to simulate global behavior of the prototype. We should not rely too much on this testing if the purpose of the study is to examine local behavior such as connections details and bonding.

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