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Trends in Large-scale Testing of Reactor Structures

Thomas E. Blejwas

Sandia National Laboratories, Albuquerque, New Mexico, USA
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ABSTRACT

Large-scale tests of reactor structures have been conducted at Sandia National Laboratories since the late 1970's. This paper describes a number of different large-scale impact tests, pressurization tests of models of containment structures, and thermal-pressure tests of models of reactor pressure vessels. During the presentation at the conference, video clips of some of the latest tests will be shown. The advantages of large-scale testing are evident, but cost, in particular limits its use. As computer models have grown in size, such as number of degrees of freedom, the advent of computer graphics has made possible very realistic representation of results – results that may not accurately represent reality. A necessary condition to avoiding this pitfall is the validation of the analytical methods and underlying physical representations. Ironically, the immensely larger computer models sometimes increase the need for large-scale testing, because the modeling is applied to increasing more complex structural systems and/or more complex physical phenomena. Unfortunately, the cost of large-scale tests is a disadvantage that will likely severely limit similar testing in the future. International collaborations may provide the best mechanism for funding future programs with large-scale tests.

KEY WORDS: large-scale, testing, reactor structures, impact, containment, reactor pressure vessel, severe accidents, failure, international collaborations.

INTRODUCTION

The watershed study WASH-1400 [1] identified the small but real potential for accidents beyond design basis, but the accident at the Three Mile Island nuclear power plant in 1979 was the key event that precipitated a need to understand the probabilities and potential consequences of severe accidents. In the area of structural technology, researchers and analysts were challenged to apply models and software to the nonlinear behavior of structures up to, and including, failure. For the cylindrically and spherically shaped structures used around the reactors, i.e., the reactor pressure vessel and the containment building or structure, experimental data to validate the structural-thermal models did not exist. Similarly, data on impacts on concrete structures were limited and inadequate to validate analyses for conditions up to penetration of the structure or other failure. Although laboratory-scale tests are good for providing properties of the materials in the structures and for developing some constitutive relationships, the complex three-dimensional interactions of composite structures and/or complex thermal and mechanical forces require physical models at a large scale. Large-scale tests of reactor structures have been conducted at Sandia National Laboratories since the late 1970's.

REVIEW OF LARGE-SCALE TESTING

From the late 1970's through the present, Sandia National Laboratories (SNL) has performed large-scale tests of reactor structures, often with partial or complete support of the U.S. Nuclear Regulatory Commission (NRC) and/or Japanese organizations, including the Nuclear Power Engineering Corporation (NUPEC). Although the many tests have helped researchers develop a physical understanding of nonlinear structural and thermal response to failure, a primary motivation for most of the tests was to validate models and analytical methods for predicting future structural response under severe accident conditions. The many tests include, but are not limited to, the following. In particular, the author has not attempted to include tests on fuel-shipping and fuel-storage casks, which are extensive in their own right.

Tornado-Missile and Turbine Blade Impact Tests

Tornado-missile and turbine blade impact tests [2,3] were planned before the accident at Three Mile Island. They were designed to help evaluate whether certain design-basis events (failure of a turbine blade or tornado-driven missiles) could initiate an accident beyond design basis. The answer to that question for these particular initiating events can now often be stated as "no," with a high degree of confidence gained from direct comparison to the tests and/or analyses using methods validated by the data from the tests. Both of these sets of tests were sponsored by the Electric Power Research Institute (EPRI) and conducted at SNL.

Pressurization to Failure of Reactor-Containment Models

A series of tests of models of reactor containment to failure through static internal pressurization have been conducted at Sandia National Laboratories over the past 20 years [4,5]. The tests were designed to help understand the margin between design pressure and failure pressure for different categories of containment structures. The following large-scale models were tested to failure:

1) 1/8-scale model of a free-standing steel containment (typical of PWR ice-condenser steam-suppression systems) (test sponsored by the U.S. NRC);
2) 1/6-scale model of a reinforced-concrete containment (typical of a large, dry PWR containment) (test sponsored by the U.S. NRC);
3) 1/10-scale model (with ¼-scaling of the shell thickness) of a steel BWR, Mark II containment (work sponsored by NUPEC and the U.S. NRC); and
4) 1/4-scale model of a pre-stressed concrete containment (modeled after Japanese PWR containments) (jointly sponsored by the NUPEC and the U.S. NRC).

Knowledge of ultimate capability is necessary to predict the response and potential consequences to a severe accident. From its inception, the containment programs have included pre- and post-test analyses, including so-called "round-robins" involving dozens of international organizations. The results of these "round-robins" have often shown considerable differences of results between analyses and/or the experiments as the structural behavior becomes nonlinear and approaches failure, thus emphasizing the need for these experiments for validation purposes.

Impact of F4 Jet Aircraft

An F4 jet aircraft was impacted into a concrete block to determine the time-dependent impulsive loads from such an event [6]. The reinforced-concrete block weighed almost 25 times the weight of the F4 and was supported on air bearings so the impulse could be determined with minimal deformation of the concrete wall. The results generally validated the so-called "Riera approach" [7]. This approach has since been used with higher confidence for certain analyses of aircraft impacting structures. On the other hand, the test results have sometimes been represented in the press as demonstrating the robustness of nuclear power plant structures. Because the test was designed to measure the force-time history against an impenetrable block, such uses are clearly incorrect and are strongly discouraged. The test was funded by the Muto Institute of Structural Mechanics and performed at SNL.

Impact of Aircraft Engine Missiles

Full-scale tests were used as a part of a study of the impact of aircraft engines onto reinforced concrete structures [8,9]. Unlike the F4 tests, the aircraft engine tests used impact targets representative of wall sections of nuclear power plant structures. GE-J79 engines, which are installed in many F4 aircraft, were used in the tests. The full-scale test followed an extensive series of small- and intermediate-scale tests. The results provided the basis for empirical predictions of the damageability of reinforced concrete panels [9]. Perhaps more importantly, the data are available for code validations. For example, the author has personal knowledge of the use of this data for the validation at Sandia National Laboratories of finite-element methods and codes for predicting the complex behavior of concrete structures to dynamic, crushing loads. Without these or similar experiments, the potential penetration of reactor structures by aircraft-engine missiles could not be predicted with any real confidence. Like the F4 test, the aircraft-engine missile impacts were funded by the Muto Institute of Structural Mechanics and performed at SNL.

Lower Head Failure Experiments

Two series of 1- to 4.85-scale models of the lower head of reactor pressure vessels were tested to failure using pressure with increasing temperature. One of the motivations for the experiments was that state-of-the-art finite-element methods were indicating that the pressure vessel at Three Mile Island would have failed during the accident, when, in fact, it did not. In the first series [10], the temperature differential through the thickness of the vessel was only about 25 deg. K. The U.S. NRC funded this first series of experiments. Although several important observations were made during the first series of eight experiments, the significance of stress re-distribution due to large through-wall temperature differences had not been addressed. In the second series of four experiments, the temperature differential through the shell thickness was increased to 200-400 deg. K. Although the detailed results of these experiments have not been made publicly available at this time, analysts from the sponsoring countries of the Office of Economic Cooperation and Development (OECD) are finding the results very useful and are developing models that, at first comparison, compare well with the experiments.

Impact of Fluid Tanks on Concrete Wall Panels

As a part of a program sponsored by the U.S. NRC to investigate the vulnerability of nuclear power plants to terrorist attacks using aircraft, complex finite-element methods and codes are being utilized. One area of uncertainty is the transfer of kinetic energy between the aircraft fuel and the impacted structure and the resulting structural response. A series of large-scale tests that may validate the analytical methods are being conducted at Sandia National Laboratories. Large tanks filled with water are accelerated and impacted onto reinforced-concrete wall panels. At the time of the writing of this paper, the tests are not complete, but the author hopes to include a short discussion of the results at the conference.

ADVANTAGES AND DISADVANTAGES OF LARGE-SCALE TESTS

The advantages of testing of large-scale models are clear. At large scale, the geometric and material complexities of the subject structures can generally be more accurately represented. The three-dimensional nature of loading conditions can be depicted in scale models (subject to scaling laws). Often, the materials used in large-scale models can be the same or nearly the same as those in the subject structures. For example a #8 rebar may be well represented by a #4 rebar in a ½-scale model. At the largest scales, fabrication techniques, such as welding, can be reasonably represented in the scale model. Instrumentation on large-scale tests can often be as extensive as the program budget will allow, because space is generally not a limiting factor.

The greatest disadvantage of large-scale testing is cost. Because of cost, some large-scale test programs will never be undertaken. Other programs will be limited to a small number of tests that inadequately cover the parameter space of interest. Next, the conduct of large-scale tests often requires large amounts of space and unique or unusual facilities and, hence, may be limited to a small number of locations in the world. For example, all of the impact tests described above were conducted using sled-track facilities at Sandia National Laboratories. Large objects, such as an F4 aircraft can be accelerated to speeds of 180 m/sec or greater and impacted into stationary targets. Such a facility is truly unique. Finally, consistent scaling is not always possible, because of scaling laws or the availability of construction materials and/or fabrication processes at the scales of interest. This disadvantage can often be reduced by focusing the large-scale tests on the validation of methods or codes, rather than on creating a scaled test of the subject structure.

COMPUTER MODELS AND LARGE-SCALE TESTS

As the speed of processors and memory-storage capacity of computers has grown in the last few decades, the size of some computer models of reactor structures has correspondingly grown. For example, computer models used in recent research at Sandia National Laboratories on high-speed parallel-processor machines include several tens of millions of degrees of freedom. Also, computer graphics representing the calculated response of the structures have become increasingly realistic in appearance, so that computer-generated videos can be made to appear almost as actual motion pictures of the analyzed event. Unfortunately, this movie-like appearance can make analyses that are poor representations of reality look real. To help avoid this pitfall, validation of the analytical methods/techniques and the underlying physical relationships is critical. Although load-frame and other bench-scale tests may be adequate for validating behavior of pieces or components of structures for design analyses, modeling complex behavior to failure can often only be accomplished with confidence using large-scale testing. Ironically, the immensely larger computer models sometimes increase, not decrease, the need for large-scale testing, because the modeling is applied to increasing more complex structural systems and/or more complex physical phenomena. The experience at SNL described above is evidence of this need. The sponsors of these tests programs are to be congratulated for their vision on the need for large-scale testing for validation of complex structures/phenomena. In the author's experience, the increased need for validation is too often overlooked in program planning.

FUTURE RESEARCH NEEDS

Each of the tests conducted at SNL was motivated by the need to understand the structural loadings and resultant responses during potential scenarios of severe accidents, including those initiated by possible terrorist attacks. The sponsoring agencies believed that only tests at a large scale would provide the necessary insights and/or model validation. The results of the tests form the basis for analyses that can be input into probabilistic risk/safety assessments for evaluating hypothesized new threats and/or evaluating changes to reactor structures. But the author believes that future potential issues for U.S. light-water reactors (LWRs) are unlikely to justify the expenditures of the large resources needed for large-scale testing. Although new LWR designs have been certified but not yet built in the U.S. and even newer designs are under development, the new designs are intended to be more inherently safe and, hence, safety issues of a magnitude to justify large-scale tests are unlikely. One possible exception to this is the continuing need to understand the potential effects of hypothesized terrorist attacks. Since, by their very nature, terrorists attempt to surprise their targets, it is unlikely that their threat space can be bounded with confidence. New attacks will likely lead to an expanded set of scenarios.

As the U.S. Department of Energy leads an international initiative towards a new generation of nuclear power plants, the so-called Generation IV Nuclear Energy Systems Initiative [11], the accident scenarios for the new reactors will be significantly different. Although the safety bases for these new systems are not defined or, in some cases, well understood, some needs are evident. Materials for some reactor systems will be different from those in LWRs because of corrosive reactor coolants and, in some cases, because of significantly higher operating temperatures of 1000 deg. C or greater. The structural behavior of these different materials may present a significant challenge. The significantly higher operating temperatures of some of the Generation IV concepts will require attention to thermal loads, while pressure loads in many of the concepts are expected to be lower. Whether these factors will lead to large-scale testing is unclear, but Sandia's experience with high temperatures in pressure vessels suggests that the need for such tests is more than negligible.

The trend in the U.S. is for greater and greater scrutiny of program budgets. Generally, dividing program budgets among many small projects and many participants avoids challenges from reviewing individuals or agencies. The large amount of money required to conduct large-scale tests does just the opposite—it attracts attention and scrutiny. Therefore, the case for programs of large-scale tests must have greater justification than ever. International collaborations are perhaps the most likely mechanism for funding future large-scale tests, because of the reduced expenditure for each of the participating countries. At Sandia National Laboratories, we will complete our ongoing tests and attempt to maintain our capability to conduct large-scale tests, so that, when such tests are needed in the future, we will be willing and able.

CONCLUSIONS

Testing at large scales is often essential to the understanding of complex structural behavior and the validation of analytical methods and codes, especially for nonlinear response to failure. The advent of computer models with immensely large numbers of degrees of freedom and the realistic representation of results using computer graphics present the pitfall of realistic-looking results that do not well represent reality. The need for large-scale tests for validation may now be more important than ever, because the structures being modeled and/or the phenomena being represented are more complex. Unfortunately, the cost of large-scale tests and economic-political situations in the U.S. will likely severely limit large-scale testing programs in the future. International collaborations may provide the best mechanism for funding future programs with large-scale tests. Organizations like Sandia National Laboratories must try to maintain capability for future testing needs that will arise.

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