THE STRUCTURAL INTEGRITY OF REACTORS

by Charles A. Anderson and Joel G. Bennett

During the TMI accident, the last line of defense against a major release of radioactive fission products was the reactor containment building. This barrier functioned as designed and survived a 2-bar pressure spike from a sudden hydrogen burn inside the building. But how large a pressure spike was possible before the containment would have failed, releasing radioactive material? Was there, in fact, a margin of safety beyond the approximately 4-bar design limit?

These questions emphasize the fact that while much attention is being focused on the role of the reactor core during a nuclear

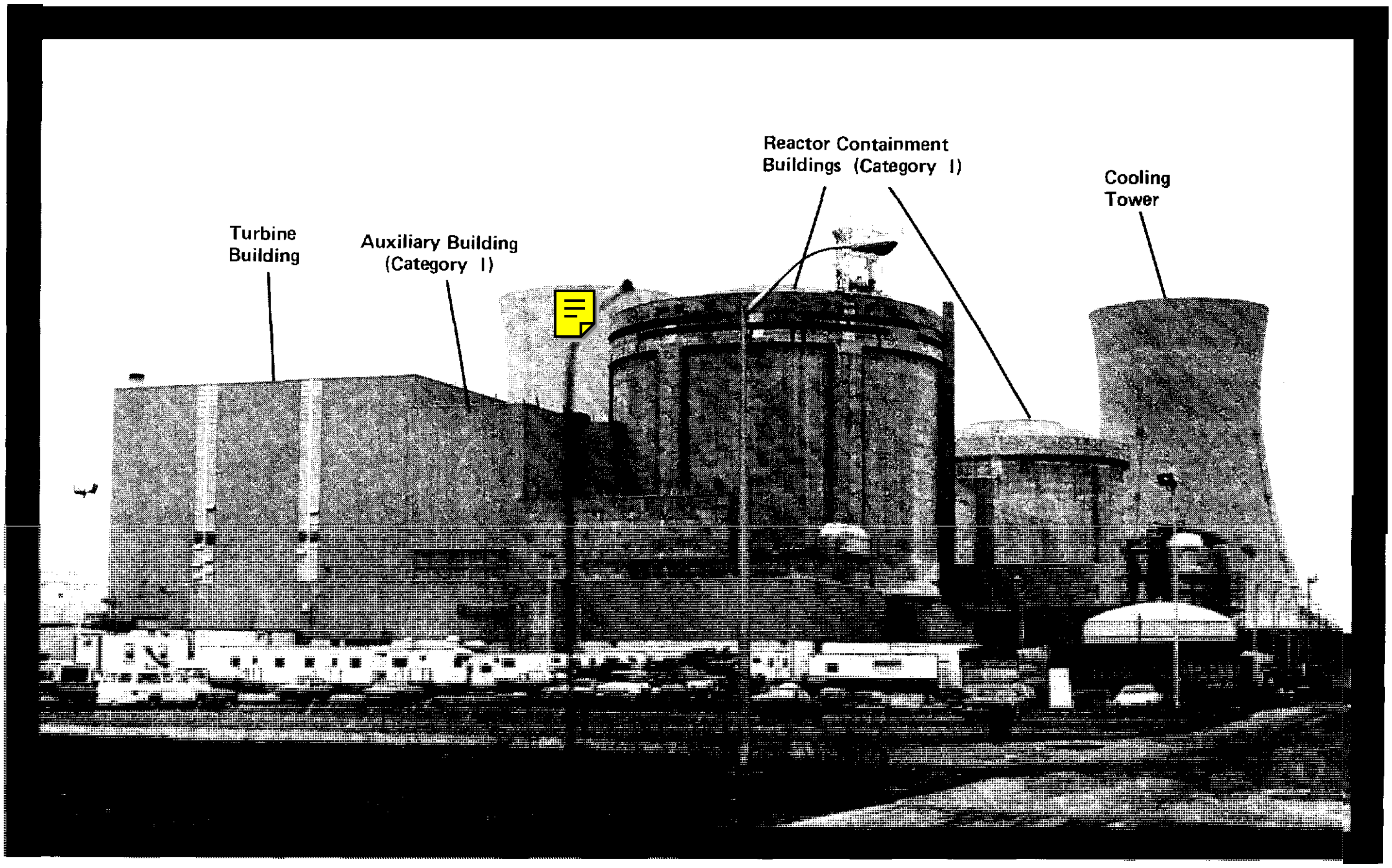


Fig. 1. Building categories at Three Mile Island Nuclear Generating Station. Category I buildings are vital to the prevention of the release of radioactive material during an accident or a natural disaster such as an earthquake. Except for the reactor containment building, these structures are usually box-shaped, are made with reinforced concrete, and include steel columns and beams where deemed necessary. The turbine building and the cooling tower are examples of buildings that are not Category I.

accident, there are structural components in the power plant that must be relied on to protect the public against the consequences of such an accident. Moreover, these structures must also provide protection of sensitive plant equipment during natural disasters such as earthquakes and tornados. As a result, the proper design of these structures must take into account a wide variety of loads and failure modes.

SAFE DESIGN. Any structure that can initiate an accident sequence if it fails or that must remain functional during an accident to prevent release of radioactive material is called a Category I structure. In a typical nuclear power plant (Fig. 1) the building housing the reactor core and the control building are both Category 1. Auxiliary and equipment buildings are considered Category I if they include vital equipment such as backup diesel generators, safety valves, the spent-fuel pit, or fuel handling and radioactive waste facilities. A turbine building is usually not a Category I structure, although its potential impact on adjacent Category I structures must be considered.

Safe design of Category I structures is the responsibility of an architect-engineer under contract to the electrical power utility. Crucial to his work are design-basis loads. Certain of these, such as earthquake and tornado-born missile loadings, are site specific, while others, such as pipe-break loadings, are plant specific. The architect-engineer sizes the plant structural members both to withstand various combinations of these design-basis loads and to transmit only acceptable loads to sensitive plant equipment.

The Nuclear Regulatory Commission insures proper design by requiring the architect-engineer to adhere meticulously to certain design-procedure rules. These include the Commission’s regulatory guides and Standard Review Plan, as well as the pressure vessel and piping codes of the American Society of Mechanical Engineers (ASME), and the construction codes of the American Concrete Institute. Also, certain of the Category I structures critical to the safety of the nuclear plant are tested before the plant is permitted to operate. Thus, the containment building is subject to a static internal pressurization of 15 per cent over the design-basis pressure.

MARGIN TO FAILURE. The design of Category I structures is inherently conservative since it is based on, among other things, restricting loads to the linear elastic region of material behavior. Thus, a typical structure stressed by design-basis loads will behave elastically and return to its original configuration upon unloading (Fig. 2). It is well known, however, that there is a large additional capacity beyond elastic behavior for resisting applied loads. This capacity can be used to ameliorate the consequences of accidents that load the structure beyond the expected design-basis loads. Design procedures using this reserve capacity are allowed in Europe, but not, at present, in the United States.

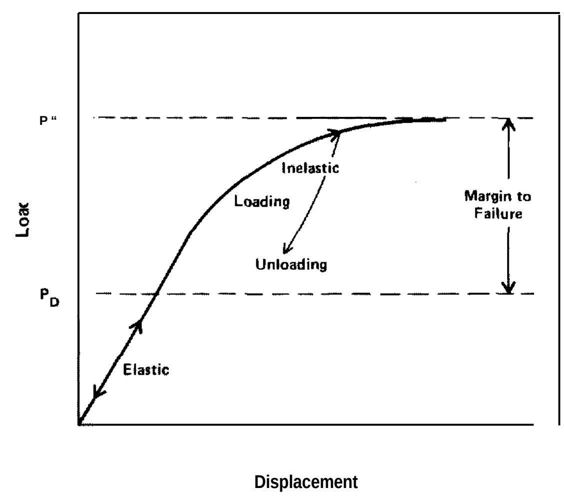


Fig. 2. Representative load-displacement relationship for Category I structural elements. In the elastic region the element will unload by returning to its original shape. However, in the inelastic region loading is large enough to cause a permanent net displacement such as in buckling or crushing. The design-basis load, P_D, is in the linear region while the ultimate load before failure, P_u, includes the reserve capacity due to inelastic deformation. The quantity $P_u - P_D$ is proportional to the margin to failure defined in the text.

A useful measure of this reserve is the margin to failure, defined as

$$\frac{P_U}{P_D} - 1$$

The variable P_D is the design-basis load and P_u is the ultimate load on the structure before failure, including the inelastic reserve capacity.

Why is it important to assess the margin to failure? The Diablo Canyon nuclear power plant, sited in an earthquake-prone area, is one example. A fault was found near the plant after it had already been constructed, so the potential seismic loads are greater than those for which the plant was designed. Knowledge of the structural margin to failure under earthquake loadings would greatly help now in relicensing the plant under revised seismic criteria. Also, knowledge of the ultimate load capacity for the Three Mile Island reactor containment building would have done much to allay the concern about the possible rupture of that containment by a hydrogen explosion.

But there are difficulties in determining the margin to failure. The behavior of Category I structures near P_u is strongly nonlinear and is often characterized by cracking and crushing of concrete, yielding of metals, buckling of metal shells, and slippage at support points. Thus a realistic treatment of this behavior will necessarily involve mathematically sophisticated analyses using computers followed by careful experimental verifications.

Los Alamos Program

Los Alamos and Sandia National Laboratories, under the sponsorship of the Nuclear Regulatory Commission, are carrying out a research program to develop methods that determine ultimate load capacities. The Los Alamos program is studying the failure of two types of Category I structural systems: concrete box-type structures where heavy shear walls provide resistance to earthquake ground motion, and steel containment vessels which could fail by buckling. Specific program tasks are 1) to develop analytical or numerical models for the behavior of these structures near ultimate load, 2) to verify these models with experiments on scaled structural systems, and 3) to propose amendments to code rules or the Nuclear Regulatory Commission's licensing requirements. Participants in the program include Laboratory contractors (e.g., the Earthquake Engineering Research Center at Berkeley, where we plan to carry out seismic testing) and an advisory committee of persons from universities and relevant industries to help plan the program and review the results.

BUCKLING OF STEEL CYLINDERS. As an example of how the Los Alamos program is working, the recent study of the buckling of thin-walled steel cylinders with large penetrations will be outlined.

Figure 3 shows the large concrete and steel containment building used for certain light-water reactors. The building is the last line of defense in the event of an accidental break in the reactor pressure vessel or its associated coolant system. One example of a penetration is shown: the entry for personnel and equipment which, during normal operation of the reactor, would be closed and sealed. Other sealed penetrations exist for pipes and cables. The ice condenser (an ice-tilled device included to condense steam during an accident) is shown as an example of a large mass of equipment attached to the steel containment shell.

Buckling of the inner steel vessel in this structure may occur during several types of accidents. For example, if a coolant pipe, carrying water at about 150 bars, suffers a large break inside the building, a high-pressure jet will be directed against the steel cylinder.

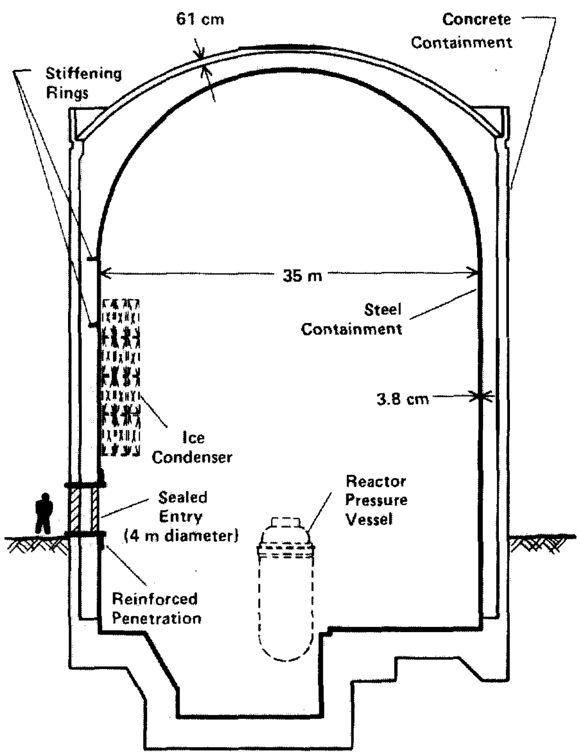
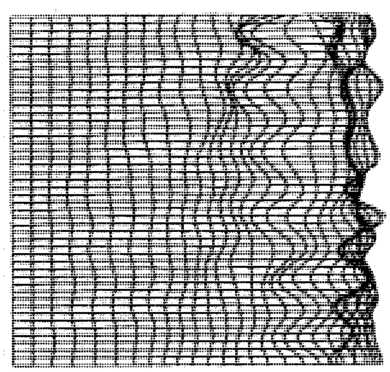


Fig. 3. One type of steel and concrete containment for the main reactor building. A large reinforced penetration for personnel and equipment access is shown; other smaller penetrations would be included for pipes and cables. The heavy ice condenser attached to the wall is an example of a source of asymmetrical loading that could lead to buckling during an accident. The reactor pressure vessel and its associated coolant system constitute another containment barrier within the containment building.

Or during an earthquake the large masses attached to the cylinder and the shifting of the structure relative to the large pipes penetrating the vessel will result in buckling stresses. Also, during a steam explosion, the ice condenser may create sharp temperature and pressure gradients that result in asymmetrical loading of the shell. If buckling occurs, radioactive material can be released in at least two ways: through any punctures that result from the impact of the displaced shell against adjacent structures and through any broken seals around penetrations.

(a)



(b)

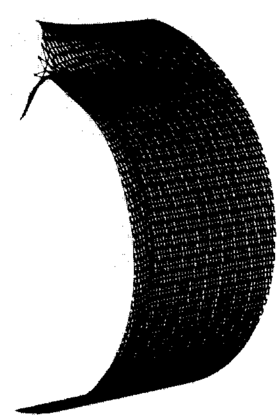


Fig. 4. Two examples of the computer-generated buckled shapes of steel cylinders. Part (a) is a side view of an unpenetrated cylinder and shows the wave pattern typical of a buckling failure. In part (b), the computer has rotated a section of a penetrated cylinder to reveal the buckling that occurs close to the hole at the top left edge of the mesh.

The entry for personnel and equipment constitutes the largest penetration (about 4 meters in diameter) of the containment shell. An important question is how this penetration affects the buckling stability of the shell. The ASME code rules specify the amount of reinforcing needed around the penetration to keep it from affecting the ultimate load capability when failure is by plastic flow of steel. Such material flow is the type of failure normally encountered in thick-walled steel boilers and pressure vessels and is, thus, the type of failure originally dealt with in the code. However, reactor containment vessels are thin walled and subject to buckling. Will the same code rules specifying the amount of reinforcement work for both failure types?

COMPUTER ANALYSIS. Los Alamos engineers first performed an analytical study of this problem using a three-dimensional, finite-element buckling code. This computer code calculates in model structures the stresses caused by external loads and can show how the stresses are affected by changes in geometry. Thus, a long, narrow, perfectly straight column under axial loading (a compressive force on both ends of the column) has a certain load-carrying capacity determined by the material's capability to withstand stress. If, however, the column is slightly bowed, the ultimate load-carrying capacity is reduced dramatically.

To analyze this type of problem, the model structure is divided into a large number of cells, equations of elastic equilibrium are formulated numerically for each cell, and the equations are solved by the code for the given loads. The equations include both a linear term representing small elastic deflections and a nonlinear term representing the effect of large deflections on the stresses in the structure. It is through this last term that the buckling behavior is incorporated into the analysis and the margin to failure determined.

The analytical study of containment vessels attempted to identify the buckled shapes at failure of unpenetrated, penetrated, and penetrated-reinforced cylinders when subjected to axial loading. The calculations also simulated the imperfections in both geometry and end loading that naturally occur in steel cylinders; that is, a typical fabricated cylinder will not be perfectly round and will not have a perfectly constant height for the end loading to bear down upon. Examples of computer-generated buckled shapes are shown in Fig. 4.

The analysis showed that the penetration significantly lowered the ultimate buckling load. Also, while imperfections in roundness had only a small influence on this load, the buckling capacity of the cylinder was very sensitive to height imperfections and, therefore, the distribution of the applied end load. Finally, the calculations showed that reinforcing the penetration according to the ASME code would raise the buckling load, but not to the value for the unpenetrated cylinder.

SCALED EXPERIMENTS. A comprehensive series of experiments was carried out to verify the analytical results. Steel cylinders simulating containment shells were fabricated to one-sixtieth actual size. A number of these cylinders were left unpenetrated; others were fabricated with a scaled penetration and then reinforced to various amounts according to the ASME code rules; none were stiffened by rings as is normal for containment vessels. The cylinders were checked for roundness, end parallelism, variation in wall thickness, and other fabrication imperfections, and then were instrumented with strain gages. Measured imperfections were similar in scaled magnitude to those measured in actual reactor containment shells. After careful shimming between the cylinder and testing machine to help approach uniform end loading, the cylinder was loaded to failure. Figure 5 shows one of the penetrated and reinforced cylinders after testing.

These experiments clearly showed that fabrication imperfections dominated the buckling failure of steel cylinders. For example, unpenetrated cylinders buckled at a load considerably lower than the value predicted for perfect cylinders. Cylinders with penetrations but no reinforcement failed at essentially the same load as unpenetrated cylinders; that is, the effect of the hole was apparently too small to cause buckling before the shell failed from imperfections. Imperfections are, thus, felt to be the main reason for the considerable scatter in the data for the steel cylinders shown in Fig. 6 (dots). For comparison, data (triangles) are also plotted from a study of a reusable Mylar shell. Because of the high quality of the Mylar cylinder, these data show little scatter as the buckling load increases with reinforcement. In both cases, the amount of reinforcement is expressed as a percentage of that recommended in the ASME code for reinforced penetrations.

Since the computer analysis indicated the ultimate buckling load to be highly sensitive to the distribution of the applied end load, the data were examined with this idea in mind. Strain gage records from the experiments were used to determine a parameter, A, measuring the degree of asymmetrical loading with respect to the position of the hole. When the load at which the first buckling occurs is plotted versus this parameter, the expected correlation becomes apparent (Fig. 7). If A is greater than 1, the hole is overloaded with respect to the average load on the cylinder, and this leads to the predicted lower buckling loads. When A is less than 1, the opposite effect occurs.

The data, viewed in this light, supported the analytical conclusion that reinforcing the penetration in the manner prescribed by the ASME code would increase the buckling toad, but not back to the unpenetrated value. More importantly. this description of the buckling study reveals the importance of the interplay of analysis and experiment in revealing key parameters and their effect on the ultimate failure load. As it turns out, a part of the ASME code accounts for fabrication imperfections in a manner that agrees with the results of the buckling tests; it is this part of the code that insures a margin to failure for the buckling of steel containment vessels when the normal imperfections of these vessels dominate the failure.

Experiments are now underway to investigate the buckling behavior of ring-stiffened scale models of reactor containment shells for loadings that could occur under accident conditions. These experiments will be used to benchmark the computer codes being proposed to predict the ultimate load-carrying capacity of containment shells. Other experiments will investigate the behavior of reinforced concrete shear walls at ultimate load. Information from all these experiments will be used by the Nuclear Regulatory Commission to help establish the margin to failure for Category I structures subjected to severe accident loads. ■

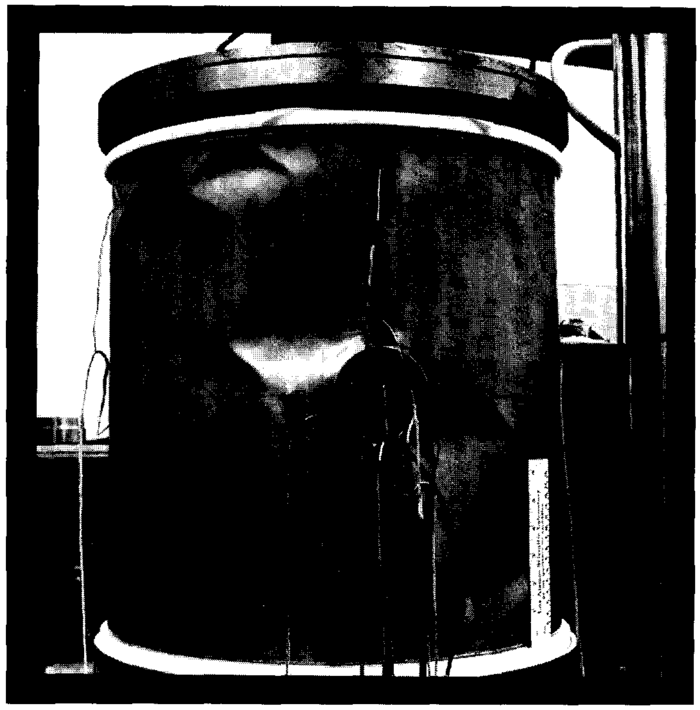


Fig. 5. One of the steel cylinders used in the simulated tests of containment shell buckling. The central hole is a scaled representation of the penetration for personnel and equipment access. In this case, the penetration has been reinforced inside the cylinder to 33 per cent of that recommended by the ASME code. Considerable buckling is evident around the hole. The small wired devices attached to the cylinder on both sides and above the hole are strain gages. Other gages are attached on the sides and back of the cylinder and at the same positions inside.

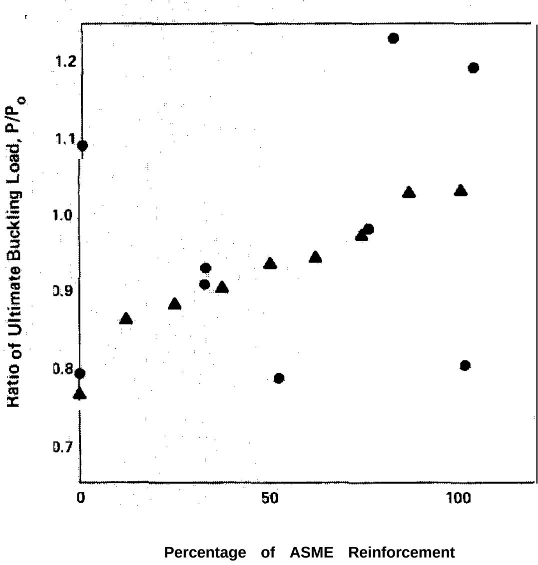


Fig. 6. The dependence of buckling load on the amount of reinforcement (expressed as a percentage of that recommended by the ASME code). The load ratio used here, P/P., is the ratio of the ultimate buckling load for a penetrated-reinforced cylinder (P) to that for an unpenetrated cylinder (P_o). Thus, a value of one for P/P_o means the penetrated-reinforced cylinder was as strong as the unpenetrated cylinder. The triangles are from a buckling study of a reusable, high-quality cylinder and thus show little scatter as increased reinforcement raises the buckling load back to the value for the unpenetrated cylinder. The large scatter in the Los Alamos steel cylinder data (dots) is felt to be due largely to the variation of fabrication imperfections from cylinder to cylinder.

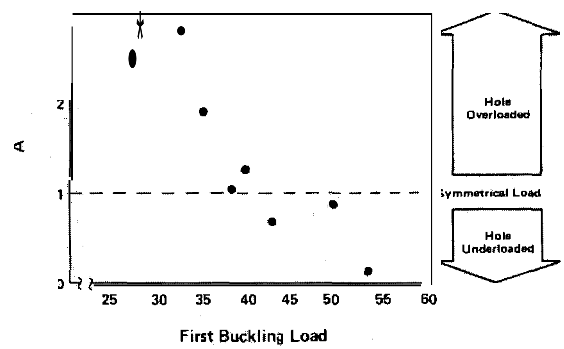


Fig. 7. The effect of asymmetrical loading on the magnitude of the buckling load. The parameter A *is a measure of the degree of asymmetrical loading with respect to the position of the hole. When* A *is greater than 1, the hole was overloaded with respect to the average load on the cylinder and buckling occurred at lower loads. When* A is less *than 1, the hole was underloaded and buckling occurred at higher loads. The correlation shown here demonstrates that load asymmetry resulting from height imperfections accounts for much of the experimental scatter in steel cylinder buckling loads.*

Further Reading

J. G. Bennett, R. C. Dove, and T. A. Butler, "An Investigation of Buckling of Steel Cylinders with Circular Cutouts Reinforced in Accordance with ASME Rules," Los Alamos National Laboratory report LA-8853-MS (June 1981).

E. Endebrock, R. Dove, and C. A. Anderson, "Margins to Failure-Category I Structures Program: Background and Experimental Program Plan," Los Alamos National Laboratory report LA-9030-MS (October 1981).