State-of-the-art review of concrete containment response to severe overpressurization

Y.R.Rashid & R.S.Dunham
ANATECH International Corporation, La Jolla, Calif., USA
H.T.Tang
Electric Power Research Institute, Palo Alto, Calif., USA

1 INTRODUCTION

Several major containment integrity research programs were started, soon after the Three-Mile Island incident, by the United States Nuclear Regulatory Commission (USNRC), Electric Power Research Institute (EPRI), the Industry Degraded Core Rulemaking (IDCOR) program and others. These programs motivated a large number of publications in conference procedings: SMIRT7 Vol. J (1983), SMIRT8 Vol J (1985); workshops: NUREG/CP-0033, SAND82-1659 (1982), NUREG/CP-0056, SAND84-1514 (1984), NUREG/CP-0076, SAND86-0618 (1986); and journals: NED V82, No. 1 (1984), NED V77, No. 3 (1984). While a vast amount of information is disseminated through these publications regarding the general design characteristics of concrete containments, the EPRI and USNRC/Sandia programs, which began after 1980, are the most relevant to the central problem of containment failure characterization. EPRI's program is aimed at the development of a test-validated methodology for the realistic predictions of the overpressure capacity of reinforced and prestressed concrete containments. The USNRC/Sandia program is aimed at producing scaled-model response data to be used in failure interpretation and the assessment of analytical capabilities. The ultimate use of the results of these programs is to enable the prediction of sequential failure modes of containment structures and the characterization of leakage paths and leak rates as functions of pressure, time and temperature.

The state of the art of concrete containment analysis prior to these programs emphasized the global behavior of concrete containments where design acceptance criteria were the primary objective of the analysis. However, characterization of leakage and other types of failure modes required special material modeling and analysis techniques that were not generally available, which motivated the present activities in containment integrity research. The scope of these research activities is large and encompasses many aspects of containment functions, including structural integrity, penetrations, source term, temperature effects and pressure loading histories (von Riesemann (1985)). All of these areas affect the response of containments to varying degrees; however, total coverage of these areas is outside the scope of this paper. The purpose of the present review is to describe the level of understanding that has been achieved as a result of several years of analytical and experimental research. We shall attempt to do this through examples that depict analytical results as well as experimental data.

2 ANALYSIS REQUIREMENTS

The evolution of containment analysis requirements under continually changing design bases is illustrated in Table 1. Conventional engineering design practice precludes containment failure under design basis loads and presumes structural failure to be a hypothetical state that has no consequence on the operational performance of the structure. The first instance where containment failure was invoked as an event to be contended with was the WASH-1400 reactor safety study, which used the Surry containment as a model. The WASH-1400 assessment of the overpressure capacity of the Surry containment is based on the limit-load assumption (see Table 1) that global yield of the primary reinforcement determines the value of the limit pressure. The basic consequence of this assumption is that at a given pressure, defined within a small uncertainty band, the containment function is suddenly and catastrophically lost. Further, it is implicit in limit-load analysis that the liner remains intact until the back support provided by the reinforcement and the concrete is suddenly lost due to concrete cracking and plastic deformation of the reinforcement. The precise size of the resulting rupture is not important since it is bound to be sufficiently large to vent the containment.

This traditional concept of characterizing containment loss of function as a limit load phenomenon does not provide information regarding containment response to precise loading history scenarios under severe accidents. While limit load assessment of containment structures is a useful component of the design process, it provides little data from which actual failure sequences and leakage characteristics could be determined. Thus, a more appropriate characterization of containment failure was sought, thereby motivating current research programs.

Concrete containment structures, despite their apparent simplicity, are highly inhomogeneous structures and consequently their failure analysis is complex, even under such simple loading as internal pressure. However, as tension structures, they can be greatly simplified for limit load determination. Contrary to popular beliefs, limit loads calculated by hand are no worse than those calculated by highly sophisticated finite element codes. The reason is that both types of analyses rely on the same failure criterion, i.e., global yield of the primary reinforcement. Containment leakage, however, is governed by liner rupture which is controlled by local deformation states produced by highly complex liner-concrete interaction. Calculation of these local strain states requires much greater care, both in material and structural modeling, than is given to the routine application of general purpose finite element codes. Therefore, it became necessary to seek major improvements in containment response and failure analysis methods through analytical development and experimental verification. Both EPRI's and Sandia's programs were designed in response to this need. As a vehicle for accomplishing their goals, EPRI is pursuing an analytical and experimental research program that consists of a large number of full-scale tests of structural segments and sub-structures and extensive analytical investigations of containment global and local behavior. The Sandia program focuses on the behavior of a geometrically scaled model of a reinforced concrete containment, extensively instrumented to produce response and failure data for validation of computer codes.

Sufficient analytical and experimental work has been done to sustain the belief that leakage through localized liner rupture is the earliest mode of failure in concrete containments. This is caused by liner-

concrete interaction at major concrete cracks subjected to both in-plane motion and out-of-plane dislocation motion. Analysis, supported by tests of full scale sub-structures performed within the EPRI program, shows that strain concentration factors of magnitude 10 to 20 can occur in discontinuity regions at the wall-base mat junctures and around large penetrations. Overall verification of this behavior will soon be put to the test in Sandia's 1:6 scale model.

Table 1. Requirements for containment analysis.

Purpose	Measure of Structural Capability	Material Data Requirements	Computational Model Requirements	Experimental Verification Requirements
Design Analysis				
Design Accept.	Stress allowables	Elastic properties; Cracked-section	Conventional (ACI code) design methods	Proof test - containment at reference pressure
Limit Load	Pressure at rebar yield	Yield strength of primary reinforcement; Totally cracked concrete	Hand calculations or simple finite element global models	None
Failure Analysis				
Global Failure	Total burst of structure	Elastic-plastic reinforcement; Elastic-plastic-fracturing constitutive model for concrete with smeared-cracking	Conventional finite element model including reinforcement and liner	Model tests with membranes to prevent leakage
Local Failure	Leakage as function of pressure, time and temperature	Same as global failure models; Discrete-cracking, rebar-concrete and liner-concrete interaction models; Crack opening models & liner rupture model	Detailed fine grid global analysis followed by highly detailed local effects models	Specimens and structural segments of discontinuity regions; Model tests

3 MATERIAL AND COMPUTATIONAL MODELING

The concrete pressure vessel technology program for high temperature gas-cooled reactors in the 1960's was the primary motivation for material and computational modeling in concrete. The constitutive basis adopted for concrete structural analysis in finite element codes is a combination of the smeared-cracking model (Rashid (1968)) with various forms of J_2 plasticity models modified to incorporate some measures of the first and third stress invariants in the loading and failure surfaces (ASCE (1981)). However, because of unique features of concrete structures, case-specific modifications of the general constitutive model are often required. Therefore, some of the more advanced codes (Hibbitt et al. 1982) have the capability for utilizing specialized user-written constitutive models. Because of the special requirements of containment structures to include concrete-steel interaction, the use of this capability is of critical importance to the solution of containment problems.

Another important aspect of concrete finite element analysis that requires specialized treatment is solution convergence. Finite element codes dealing with nonlinear analysis often rely on force-based vector norms as convergence measures. These measures work well for steel structures where the stress field is relatively smooth. However, they do not work well for concrete where the stress field is discontinuous within partially cracked elements and at cracked/uncracked element interfaces. The difficulties arise in the crack-induced large discontinuity in the element strain field in a partially cracked element. This discontinuity cannot be accurately represented by the element shape functions, even in quadratic elements, which results in spreading the cracks over wider areas rather than concentrating them in narrow bands. Some of the subtle numerical characteristics of this problem are element-type and mesh-size dependent and are currently the object of constitutive and numerical research.

4 GLOBAL/LOCAL RESPONSE

The global response of concrete containments can be determined with satisfactory accuracy in a 2D axisymmetric analysis. This has become routine and is familiar to most analysts. The finite element model is constructed in a straightforward manner, and generally consists of continuum elements for concrete, uniaxial elements for the reinforcement and prestressing steel and shell elements for the liner. No special interface elements, such as might be required for the concrete/liner or concrete/rebar interfaces, are employed in this type of global analysis. The concrete constitutive model can be a simple elastic-fracturing or elastic-plastic-fracturing model, depending upon the analysis code used. It should be noted, however, that concrete tensile plasticity is very limited, if it exists at all, in this type of global representation; thus, a simple elastic-fracturing or even elastic-no tension model is usually adequate. However, the steel reinforcement and liner require appropriate elastic-plastic constitutive models that utilize true stress-strain curves in order to calculate the response at high pressure regimes, i.e., near the rupture limits of the reinforcement and liner materials. This is usually not difficult since most general purpose codes have these capabilities.

The value of such a global analysis is twofold. First, it provides an

upper bound for the failure pressure which, by definition, is the pressure associated with the burst failure mode; the failure criterion in this case is the ductility limit of the rebars and the liner rather than the yield stress as is usually used in design limit-load analysis. Second, the analysis identifies regions where localized strains and dislocation deformations occur. This information is then used for local effects analyses to determine local failure modes which are leakage sources. These local effects calculations are far more complex, and they require more detailed geometric and material models capable of simulating the interaction between the liner, concrete and rebars. Liner anchorage, rebar bond and dowel action become important mechanisms that should be properly simulated in the analysis. Because of the complexity of this type of analysis, experimental verification is usually required to provide credibility for the results.

This process of global/local simulation of containment response is illustrated in Figure 1 which shows a prestressed containment deformed shape at some pressure level and the locations of potential liner rupture. The two locations identified in the figure, at the springline and the wall-basemat juncture, are typical of both types of concrete, namely, prestressed and reinforced. These analytical results provided definitive clues for a response mechanism that is of critical importance to the failure scenario of concrete containments. If this mechanism exists and is not a manifestation of the analysis assumptions, then the leak-before-break hypothesis becomes an inherent characteristic of concrete containments. The ultimate verification of this response mechanism is clearly a test of a properly scaled model of a containment structure or, alternatively, a properly engineered test of a local effects simulation of the wall-basemat juncture. This simulation is depicted in Figure 1. It should be pointed out, however, that the test specimen was designed as a flat structure for practical considerations (the cost of a curved specimen would have been prohibitive). This necessitated a reconfiguration of the specimen loading in order to simulate the true containment response in the test. Figure 2 shows the results of this simulation in which the displacement field of the specimen is matched to that of the containment both in shape and in magnitude.

The calculated liner strain profile is depicted in Figure 3 where it is compared with gage measurements showing a maximum strain in excess of 3%. Figure 3 also shows the strain history and the damage in the specimen at the knee where the liner rupture was detected at three locations along the knee line. It is important to note that the far field liner strain in the wall above the knee remained in the elastic range, thus a strain concentration factor of at least 15 is in evidence. This test verification of the local effect mechanism is the first experimental evidence that leakage is the most likely and earliest failure mode of concrete containment structures.

5 LINER CRACK GROWTH BEHAVIOR AND POST-RUPTURE RESPONSE

One of the uncertainties in concrete containment failure scenarios is the stability of the liner rupture once it is initiated. Unstable crack growth could lead to rapid depressurization and major release of fission products to the environment. This type of failure is equivalent to a burst mode and clearly involves greater risk to the public. On the other hand, a stable or controlled crack growth in the liner implies slow leakage with far less serious risk consequences.

It can be argued that, given the evidence of early liner rupture demonstrated above, an unstable crack growth in the liner is highly improbable. This clearly depends on the structure's residual strength at the instant of rupture and the rupture location. For instance, a longitudinal orientation of the crack in the barrel section, which is possible at the root of the boss section of large penetrations, could result in a long crack. The mechanism that could prevent this from happening is the constraining effect of the concrete on the crack through the frictional resistence of the liner/concrete interface. This mechanism, which is mobilized after crack initiation, is of equal importance to the overall failure scenario as the local effects mechanism responsible for crack initiation.

An experimental/analytical verification of the crack constraint mechanism is illustrated in Figure 4 which shows the results of test and analysis of an initially cracked liner plate backed by a 2' reinforced concrete slab subjected to tension normal to the crack line. A crack growth analysis was carried out for the liner plate alone (no concrete backing). By comparing the measured crack opening displacement which reflects the presence of the concrete, with the calculations for the free-standing plate, one sees that the crack is highly confined as evidenced by the strong attenuation of the measured displacement profile as compared to the analysis. In this instance, large differences between the analysis and the measurements indicate better correlation. These results imply that crack growth in the liner is always stable.

6 THREE-DIMENSIONAL RESPONSE

Three-dimensional response in containment structures is dominant at pipe penetrations, equipment hatches and personnel airlocks. These penetrations are generally located near the midplane section where the relatively large radial deformations could cause opening ovalization and eventually leakage through the seal. In addition, because of the highly reinforced embossment around these large penetrations, they behave like rigid inclusions in a relatively flexible wall. This stiffness discontinuity is similar to the other two major discontinuities mentioned above and, therefore, is of equal rupture potential. An analytical prediction of this response requires full 3D modeling, which places significant demands on the modeling and analysis capabilities currently available.

As in the case of the axisymmetric analysis, two-step global/local modeling is also required for 3D response analysis. Figure 5 shows the concrete grid of a global 3D model for a 90° sector of Sandia's 1:6 scale containment model. The elements are 20-node isoparametric bricks. The reinforcement grid is also shown in Figure 5. It should be noted that, unlike 2D analysis, the creation of this model and the preparation of the data is far from routine. Similarly, the 3D constitutive model is significantly more complex computationally than its 2D counterpart. Thus, three-dimensional concrete containment analysis requires great care, experience and appropriate software.

Figure 6 shows the rigid inclusion effect of the large penetrations as evidenced by the dimple appearance in the deformed shape. This creates a local strain concentration in the liner similar to the wall-basemat juncture. This is calculated in a detailed 3D submodel which is also shown in the figure. Results of these calculations will be compared to measurements when the 1:6 scale model test data become available.

References

Transactions of the 7th International Conference on Structural Mechanics in Reactor Technology, Vol. J. 1983. Chicago, Illinois.

Transactions of the 8th International Conference on Structural Mechanics in Reactor Technology, Vol. J. 1985. Brussels, Belgium.

Proceedings of the Workshop on Containment Integrity, Vol. II. 1982. Prepared for the U.S. NRC, NUREG/CP-0033, SAND-82-1659.

Proceedings of the Second Workshop on Containment Integrity. 1984. Prepared for the U.S. NRC, NUREG/CP-0056, SAND-84-1514.

Proceedings of the Third Workshop on Containment Integrity. 1986. Prepared for the U.S. NRC, NUREG/CP-0076, SAND-86-0618.

Nuclear Engineering and Design, Vol. 82, No. 1. 1984.

Nuclear Engineering and Design, Vol. 77, No. 3. 1984.

Von Riesemann, W.A. 1985. Recent Research in Nuclear Containment Structures. SMiRT-8, Division J Principal Lecture. Brussels, Belgium.

Rashid, Y.R. 1968. Ultimate Strength Analysis of Prestressed Concrete Pressure Vessels. N.E.D, V7: 334-344.

ASCE Task Committee on Finite Element Analysis of Reinforced Concrete Structures. 1981. State of the Art Report on Finite Element Analysis of Reinforced Concrete.

Hibbitt, H.D. et al. 1982. ABAQUS-EPGEN Version 4-4, Vol. 1, User's Manual and Vol. 2, Theoretical Manual. EPRI Report NT-2709-CCM.

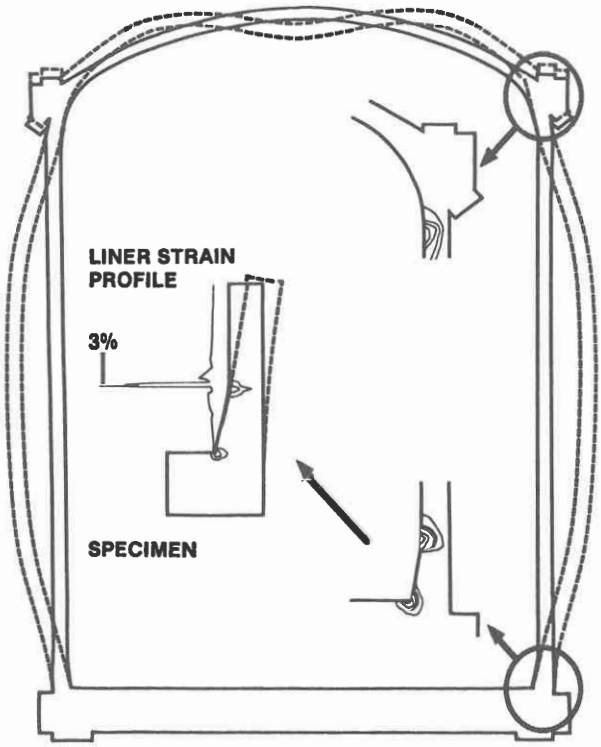


Figure 1. Analytical simulation of global/ local containment behavior specimen

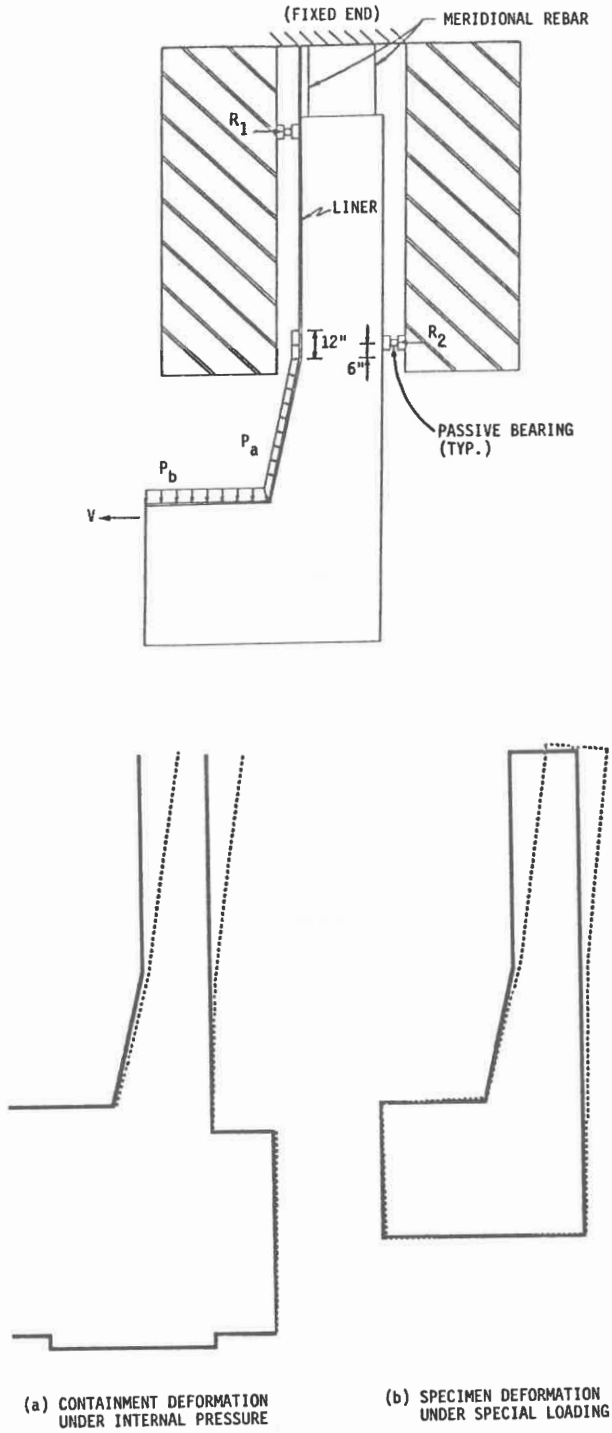
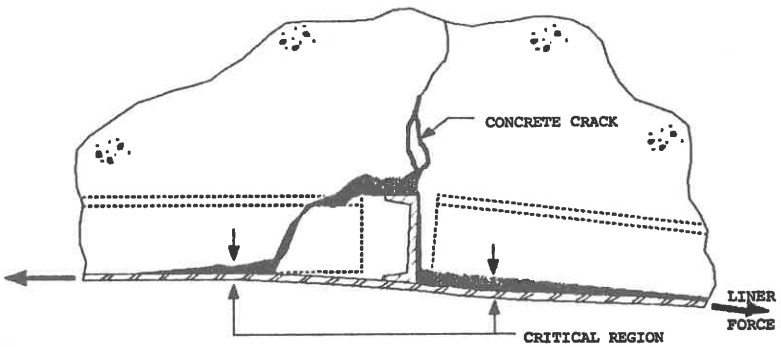
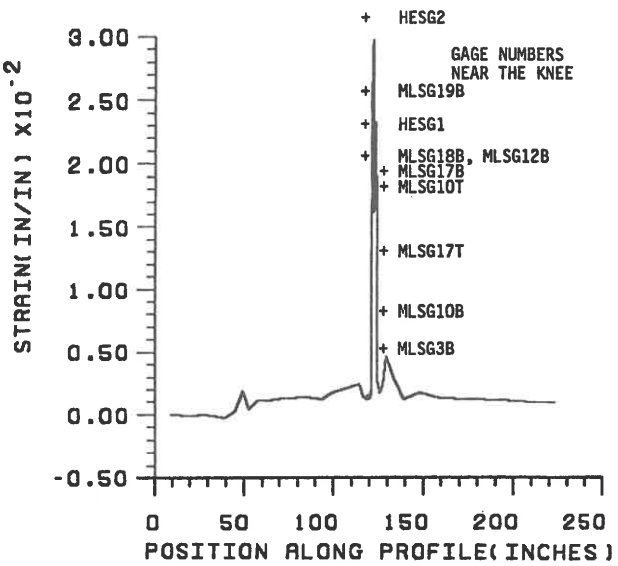


Figure 2. Test simulation of containment local response





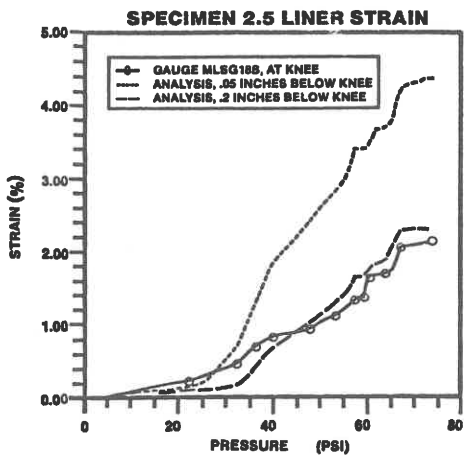


Figure 3. Liner strain concentration at wall-basemat juncture

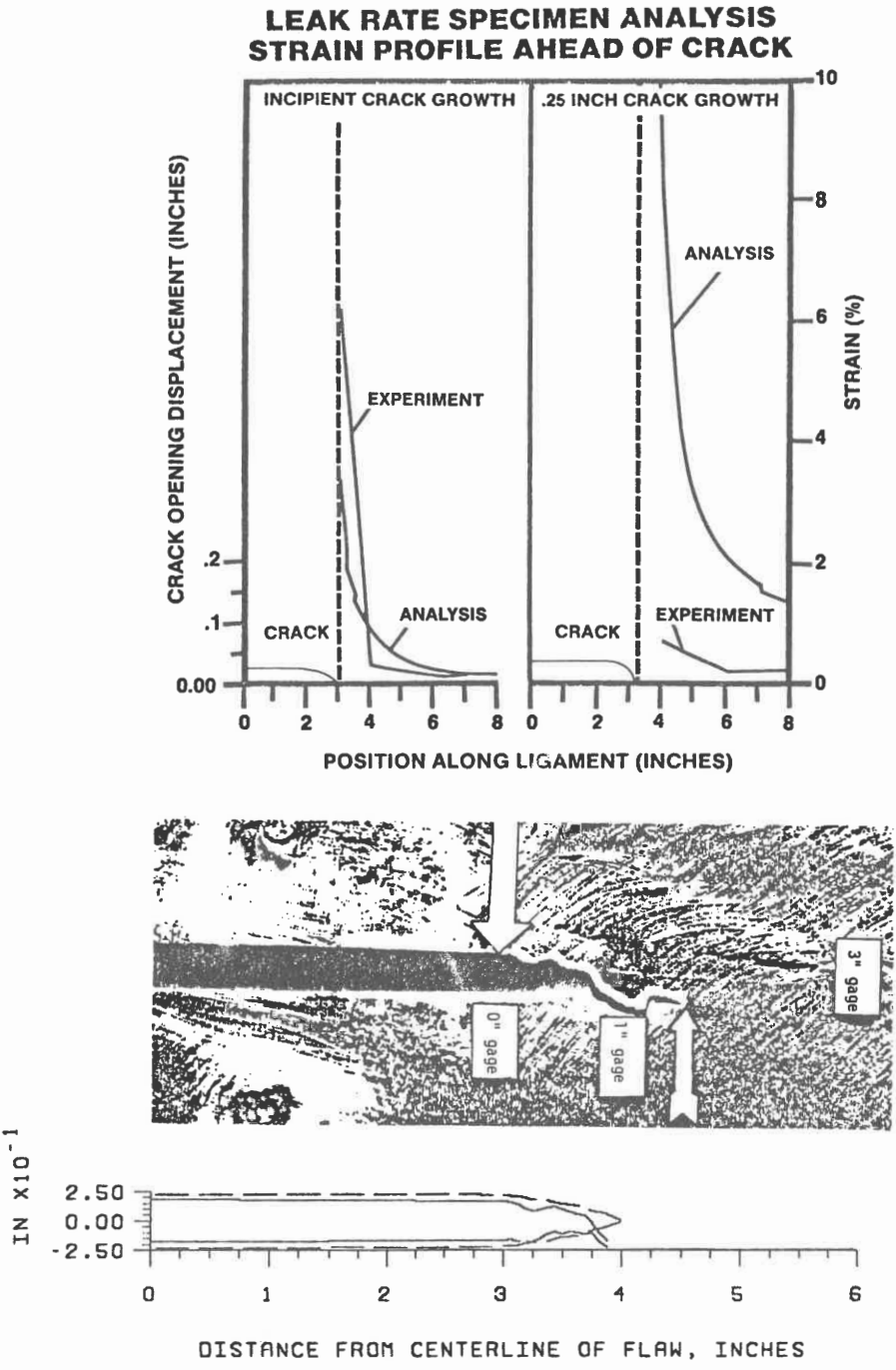


Figure 4. Effects of concrete confinement on liner crack growth

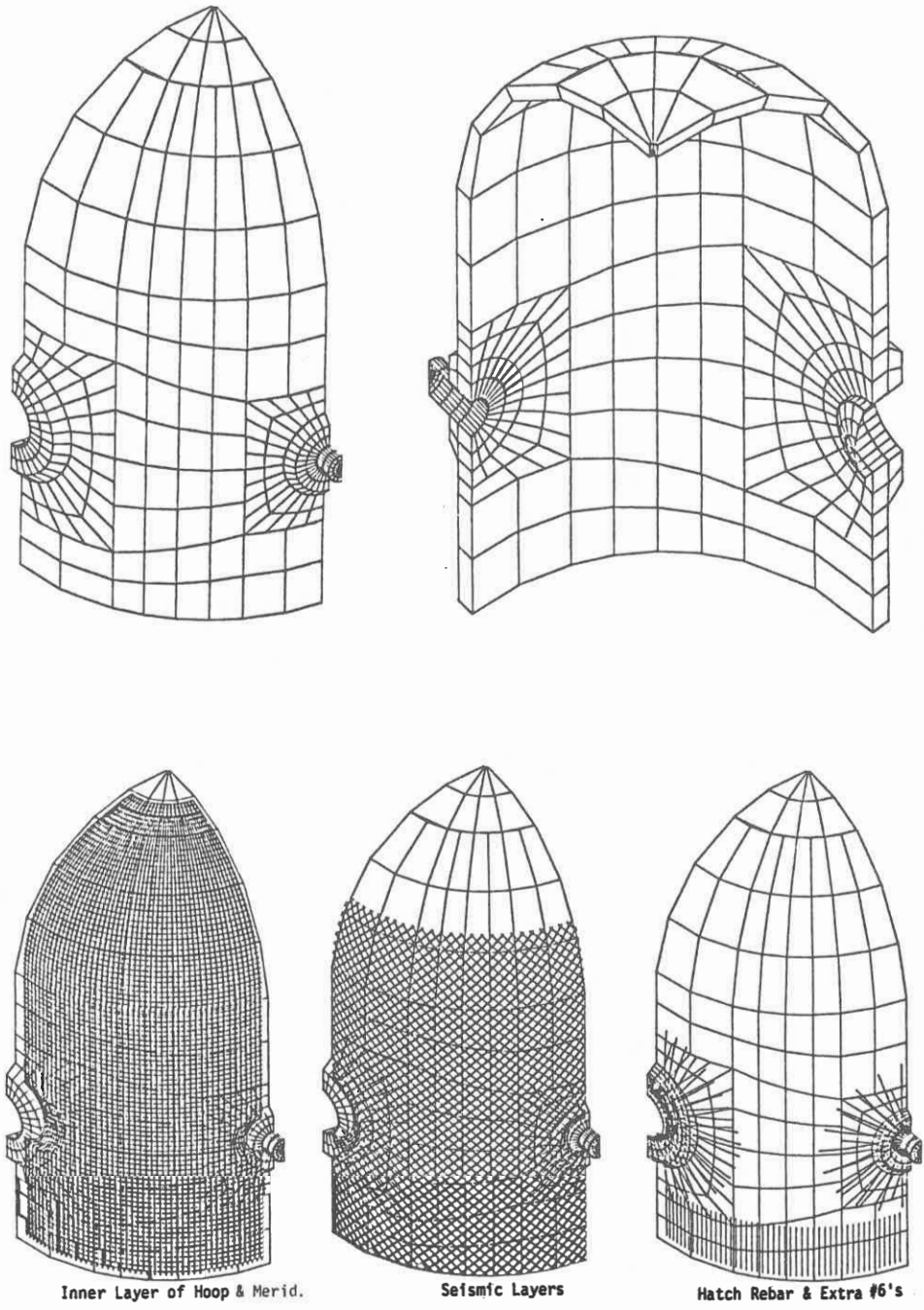


Figure 5. Global 3D grid for Sandia's 1:6 scale model

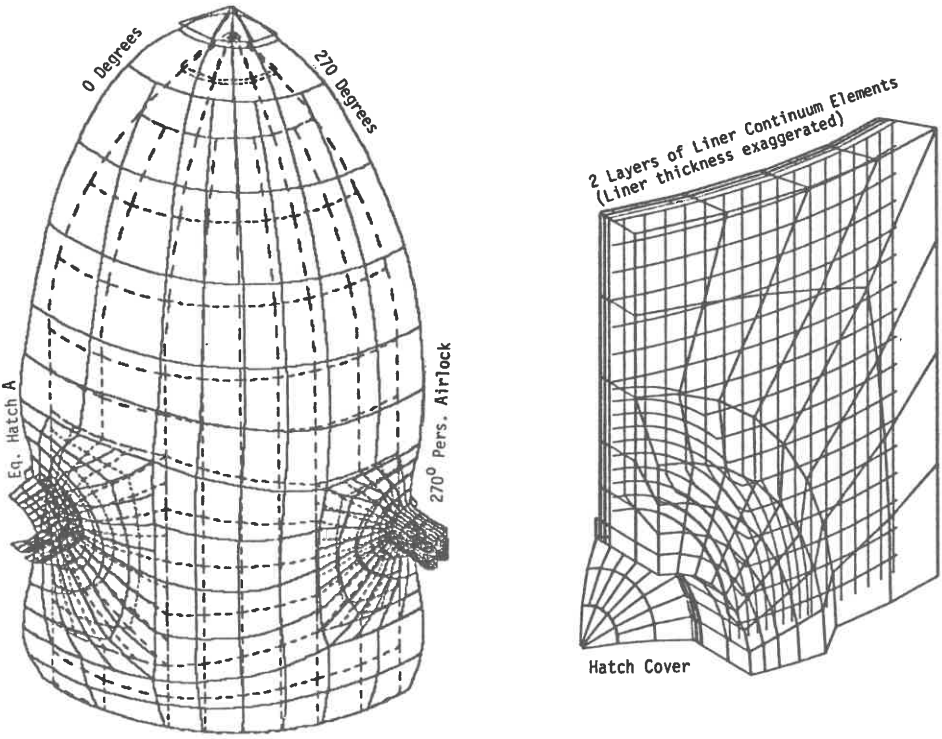


Figure 6. Deformed shape and local effects 3D grid for Sandia's 1:6 scale model