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INVESTIGATION OF RADIAL SHEAR IN THE WALL-BASE JUNCTURE OF A 1:4 SCALE PRESTRESSED CONCRETE CONTAINMENT VESSEL MODEL[1]

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ABSTRACT

Construction of a prestressed concrete containment vessel (PCCV) model is underway as part of a cooperative containment research program at Sandia National Laboratories. The work is co-sponsored by the Nuclear Power Engineering Corporation (NUPEC) of Japan and US Nuclear Regulatory Commission (NRC). Preliminary analyses of the Sandia 1:4 Scale PCCV Model have determined axisymmetric global behavior and have estimated the potential for failure in several areas, including the wall-base juncture and near penetrations. Though the liner tearing failure mode has been emphasized, the assumption of a liner tearing failure mode is largely based on experience with reinforced concrete containments. For the PCCV, the potential for shear failure at or near the liner tearing pressure may be considerable and requires detailed investigation. This paper examines the behavior of the PCCV in the region most susceptible to a radial shear failure, the wall-basemat juncture region.

Prediction of shear failure in concrete structures is a difficult goal, both experimentally and analytically. As a structure begins to deform under an applied system of forces that produce shear, other deformation modes such as bending and tension/compression begin to influence the response. Analytically, difficulties lie in characterizing the decrease in shear stiffness and shear stress and in predicting the associated transfer of stress to reinforcement as cracks become wider and more extensive. This paper examines existing methods for representing concrete shear response and existing criteria for predicting shear failure, and it discusses application of these methods and criteria to the study of the 1:4 scale PCCV.

BACKGROUND

As part of the NUPEC and NRC sponsored program, Sandia is constructing an instrumented 1:4 scale model of a prestressed concrete containment vessel (PCCV) for pressurized water reactors (PWR), which will be pressure tested up to its ultimate capacity. One of the key program objectives is to develop validated methods to predict the structural performance of containment vessels when subjected to beyond design basis loadings. Analytical prediction of structural performance requires a stepwise, systematic approach that addresses all potential failure modes. The analysis effort includes two and three-dimensional nonlinear finite element analyses of the PCCV test model to evaluate its structural performance under very high internal pressurization. Such analyses have been performed using the nonlinear concrete constitutive model, ANACAP-U, [1] in conjunction with the ABAQUS [2] general purpose finite element code. The analysis effort is being carried out in three phases: (1) Preliminary analysis, (2) Pretest prediction, and (3) Post-test data interpretation and analysis evaluation. The work described in this paper is from the first analysis phase.

The testing of the one-fourth scale PCCV model represents a valuable opportunity to examine the ultimate pressure capacity of a steel-lined prestressed concrete containment model in a manner similar to Sandia's USNRC sponsored 1:6 scale model of a reinforced concrete containment [3]. Pretest predictions and post-test analysis of the 1:6 scale model were carried out by ANATECH as part of the Electric Power Research Institute's (EPRI) participation in Sandia's round-robin analysis program. In that effort, a concrete analysis methodology and liner tearing criteria developed under EPRI's sponsorship were utilized to obtain reasonably close predictions of the failure pressure and failure modes of the 1:6 scale model.

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DISCLAIMER

The analysis methodology used in the present work is similar to that employed in the analysis of the 1:6 scale model. However, the 1:4 scale PCCV model introduces new elements into the analysis due to the prestressed design. Prestressed containments may be more prone to failure in a structural rupture mode rather than a leakage mode as in reinforced containments for three main reasons:

(1) In prestressed containments concrete cracking occurs at high pressure when the tendons are approaching yield. Thus the leakage mode and rupture mode are not as well separated in prestressed as they are in reinforced containments. This may make both leakage and rupture probable failure modes.

(2) There is generally a much narrower pressure range in prestressed containments over which most of the significant deformations occur because of the lower ultimate ductility of tendons compared to rebar. This could lead to burst failure under high loading rates.

(3) Prestressed containments rely on the concrete's residual compression induced by the prestress to carry the pressure load. This compression enhances the concrete's shear capability, but once the compression is lost at very high pressure, there may be a higher possibility of a sudden shear failure.

The Sizewell B test of a 1:10 Scale PCCV in England and associated analyses emphasized investigation of structural failure modes [4], but since that test was loaded with a water-filled rubber bladder, the leakage mode could not occur. The issues stated above make the 1:4 Scale PCCV model particularly interesting for purposes of addressing competing structural and liner tearing failure modes. In the current work, prediction of ultimate capacity and gross structural failure modes such as radial shear failure are, therefore, of equal importance to the prediction of liner tearing failure.

GLOBAL AXISYMMETRIC MODEL

Some details of the 1:4 scale test structure are shown in Figure 1. The general objectives of the preliminary phase of the pre-test analysis were to predict global behavior and to form a preliminary list of possible failure modes. Prior to starting the analysis, a list of potential failure mechanisms and vulnerable regions and components of the structure were developed. Then a detailed plan was developed for systematically eliminating or investigating each of the failure mechanisms and vulnerable components. Many of the structural failure mechanisms can be addressed with 2D axisymmetric analysis.

Based on experience from prior global analyses of containments, the computational grid shown in Figure 2 was developed. Grid refinement was provided at the shear transition regions in the basemat, at the base of the wall and at the springline. The mesh size was selected after a brief study of mesh size sensitivity. The concrete was modeled with 8-node quadrilaterals (ABAQUS CAX8R) with reduced (2x2) Gaussian integration. This grid used an unbonded meridional tendon configuration. The meridional tendons were represented with truss elements and attached to the concrete with friction tie elements. Friction was specified between the trusses and the concrete which was calibrated to develop friction losses that agreed with the friction losses assumed in the design. At just above a 45° dome angle, the trusses were replaced with a shell layer to the apex. This shell layer was given an area equivalent to the tendon area and a Poisson's Ratio of zero to avoid any in-plane/out-of-plane stress-strain interaction. This modeling approach is reasonable because above 45°, the tendons are all meridional (no hoop). While the meridional tendons in this mesh can slide relative to the concrete, the hoop tendons cannot due to the limitations of 2D axisymmetry. The model plane was assumed to be the 135° azimuth, which is reasonably far from penetrations. Meridional tendons and some basemat rebars intersect this model plane at ± 45°. Choosing the model plane on this basis has been found to simplify and increase the reliability of axisymmetric modeling of rectilinear reinforcement patterns. The liner is constructed of quadratic shell elements, and 3 node quadratic beam elements are used for the liner anchors.

The Finite Element program used for the analyses was ABAQUS [2] in conjunction with the concrete and steel material models in ANACAP-U [1]. Constitutive modeling attributes of ANACAP-U are described later in this paper.

SHEAR BEHAVIOR IN THE PCCV

The PCCV preliminary analyses have shown some elevated shear stresses at various locations in the model. Since round-robin pre-test prediction analyses are currently in progress by other organizations, the shear behavior of only the wall-base juncture location is discussed here.

At the wall-base juncture the basemat discontinuity completely restrains the wall. Circumferential cracks in the wall, either at the corner or a few inches up, are calculated to form under the combined effect of bending and tension. These cracks could extend either across the wall or extend into the basemat as illustrated in Figure 3. In the first case, the crack will run into the compressive zone at the outer surface. In the second case the crack will run into the basemat in an area of smaller compression. In both cases enough flexural deformation and shear strain exists to warrant further investigation of shear failure potential.

ANALYTICAL REPRESENTATION OF SHEAR BEHAVIOR

Shear response of concrete has been found to follow three stages of deformation:

i. the concrete resists the deformation with no assistance from the reinforcement or the aggregate; as soon as cracks begin to develop at some angle (between 0 and 45° depending on location) to the direction of the applied shear force, the structural shear stiffness drops suddenly.

ii. frictional resistance increases with further deformations as aggregate interlock begins to mobilize; during this stage the cracks grow wider.

iii. the structure reaches its maximum resistance and begins to soften and eventually fail in a mixed mode of shear sliding, crushing and rebar yielding under combined tension and dowel action; the latter mechanisms are due to the dilation of the cracks which forces rebars into direct tension and bending beyond their yield limit.

These deformation states vary considerably over the failure "plane", but tests to measure shear behavior are generally expressed only in terms of average shear stress across a section vs. average shear strain. Experimentalists have developed shear behavior material models from such tests. However, to apply such models in a continuum analysis approach where the models have to be applied locally (at an integration point) requires consideration of fundamental mechanics, and use of damage parameters calibrated to match experimental results. This is the approach used in the current modeling.

The finite element program used for all analysis was ABAQUS in conjunction with ANACAP-U, which is called by ABAQUS. ANACAP-U uses a smeared crack approach [5] to simulate the effects of concrete cracking, crushing, and post-cracking shear behavior. Experimentation and research in the late 70's and early 80's has supported the representation of post-cracking shear behavior with a simple relationship of shear modulus degradation to crack opening strain. This is the relationship that is represented in the standard shear retention model in ANACAP-U.

The standard shear retention model reduces the incremental shear modulus across an open crack according to the Al-Mahaidi formula [6]

$$G = 0.4G_0\,(\varepsilon_{frac}/\varepsilon), \tag{1}$$

where $G=G(\varepsilon)$ is the <u>incremental</u> shear modulus across an open crack, G_0 is the uncracked shear modulus, ε_{frac} is the cracking strain ($\sim10^{-4}$), and ε is the normal strain across a crack. While this model has predicted response of many laboratory tests and actual structures, in situations with high local shear stresses, the basic shear retention model has the limitation that shear stress can be "locked-in" even after the shear modulus attenuates nearly to zero. Thus, the standard model predicts shear force capacity well, but may under-predict the deformation behavior after ultimate shear capacity is reached.

Recently, a model has been implemented that addresses predictions of deformation behavior <u>after</u> shear force capacity is reached. This model has been called the shear shedding model, and its additional parameters are described briefly below.

In the standard and shear shedding model, cracks form in the principal strain directions so there is no shear across a crack when the crack first opens. However, as the loading continues, even if it is monotonic and "proportional", there is a tendency for shear stress to build up across an open crack. The ANACAP-U constitutive model uses an incremental formulation to update the stress, which for shear takes the form

$$\tau_{n+1}=\tau_n + G(\varepsilon)\,\Delta\gamma, \tag{2}$$

where $\Delta\gamma$ is the incremental shear strain across an open crack in a load increment from "n" to "n+1". The new shear shedding model reduces this build-up and begins shedding the shear stress when deformations in crack zones become large by modifying Eq. (2) in the following empirical manner

$$\tau_{n+1}=\tau_n e^{-(\Delta\varepsilon/\varepsilon_{ss})}+G(\varepsilon)\,\Delta\gamma, \tag{3}$$

where $\Delta\varepsilon$ is the incremental normal (tensile) strain across an open crack and ε_{ss} is a shear-shedding degradation parameter. There is no change in the incremental shear modulus over that of the standard model. A second parameter that is included in the shear shedding model, ε_{beg}, represents the normal (tensile) strain at which Eq. (3) is activated. The ε_{beg} parameter has almost no effect until 0.001 is exceeded. Increasing ε_{ss} has no effect on the maximum shear stress, but it reduces the rate of shear shedding. ε_{ss}=0.003 and ε_{beg}=0.0002, have been found to produce results that are in agreement with some shear test data and these have been used in the preliminary PCCV analyses in which shear shedding was activated. The authors are currently conducting a more extensive set of comparisons with tests to calibrate the shear shedding model, and comparisons to some shear failure tests are planned prior to finalizing the PCCV analysis.

PRELIMINARY RESULTS & PREDICTIONS

Global axisymmetric analysis has been conducted based on the 1:4 Scale PCCV model material properties known to date, but these analyses are still preliminary. The analysis has predicted the overall response behavior and has provided a list of possible failure modes and their associated pressures. These failure modes include liner tearing at various locations and shear failure at the wall-base juncture. Many of these modes are possible within a narrow range of failure pressures. To complete the overall prediction analysis and select which mode will occur first, each competing failure mode is being characterized as accurately as possible. Results pertaining to the wall-base shear failure mode study are summarized below.

The model shows primarily linear behavior up to about 1.5 x design pressure (P_d = 0.39 MPa), but then hoop prestress is overcome in the cylinder and hoop cracking occurs. At pressures larger than 2 x P_d the response is highly nonlinear, including cracking of concrete, and yielding of rebars, liner, and tendons. Meridional tendon strain and liner vertical strain histories are shown in Figures 4 and 5. These plots show rapid strain increases after 0.98 MPa (2.5 P_d). This is the pressure at which the hoop reinforcement in the cylinder begins to yield, so the cylinder begins more rapid expansion. The maximum principal strains in the wall-base region are shown at 1.38 MPa (3.5 P_d) in Figure 6. These contours show the growth of a large shear crack at an angle through the base of the wall and additional cracks in the basemat under the wall. The plots also show concrete crushing on the outer side of the wall and liner yielding on the inner side of the wall.

Explicit shear failure prediction is made by observing when large shear distortions of the entire wall base section exceed prescribed criteria. However, establishing the criteria is as difficult as predicting the deformation response. On the response side of the question, the prediction is believed to be improved by moving from the standard shear retention model to the shear shedding model which now predicts shear distortion to be somewhat larger. On the capacity side of the question, criteria can be based on forces or average stresses within the section or based on deformations. Most design methods are based on forces or stresses, but criteria more compatible to use with detailed finite element continuum analyses are those that are deformation-based. Both kinds of criteria are being applied to the pretest prediction analyses. The most promising stress-based criteria the authors have found for the PCCV is the Modified Compression Field Theory developed by Collins & Mitchell [7].

This theory is a refined version of a strut and tie model which provides a rational basis for calculating compression strut angles of less than 45 degrees, and, with the "modified" theory, the local resistance of concrete in tension between cracks and the effect of aggregate interlock is considered. The difficulty with applying force or stress-based theories to the PCCV is that the shear force is indeterminate, i.e., it is a function of the pressure, the relative hoop stiffness of the cylinder to the basemat, and the flexural stiffness of the cylinder wall. Because of these factors, the shear at the section does not necessarily monotonically increase with pressure.

Far less is found in the literature for deformation based criteria. For the PCCV failure prediction the authors have chosen a criteria based on strain in the shear reinforcement of 10% (which is still approximate at this point in the research program). Failure in the shear reinforcement at the wall-base juncture is judged to lead to shear failure of the section. Based on this criteria, shear failure is predicted to occur at between a pressure of 1.57 MPa (4.0 P_d) and 1.64 MPa (4.2 P_d).

In order to further quantify the shear conditions in the wall-base juncture region, Figure 7 plots peak shear vs. pressure from the analysis and from a Modified Compression Field Theory Assessment. Using the Modified Compression Field Theory, the section is adequate (but with a decreasing margin at high pressure) to carry the section shear demand that exists in the analysis up through 4.0 P_d. A more detailed investigation of the conditions (stress, strain, etc.) under which shear failure will occur is scheduled in the Pretest Analysis Phase of the project.

CONCLUSIONS

A study of the wall-base shear behavior of the 1:4 Scale PCCV, as a preliminary analysis, has been completed. All analyses showed extensive spalling on the outer edge of the containment wall and major cracking associated with shear and flexure. The standard shear retention model nor the shear shedding model predicted a radial shear failure of the wall at less than 1.57 MPa (4.0 P_d). At this pressure however, the new shear shedding model predicted large shear deformations with local strains in excess of 10% across part of the section, while the standard shear retention model predicted maximum strains of only 4%. The total shear force at a section cut through the wall-base was observed to reach a relatively constant upper bound at pressures larger than 0.98 MPa (2.5 P_d). This shows that significant shear cracks will probably form at this pressure and that the concrete contribution to the total shear is small. Liner tear at a penetration may still precede a structural shear failure at the wall-base, but if the 4.0 P_d pressure is reached, the analyses described herein predict that failure of shear reinforcement and subsequent failure of the wall-base section will be imminent.

Analyses are in-progress to refine these predictions of failure location and failure pressure.

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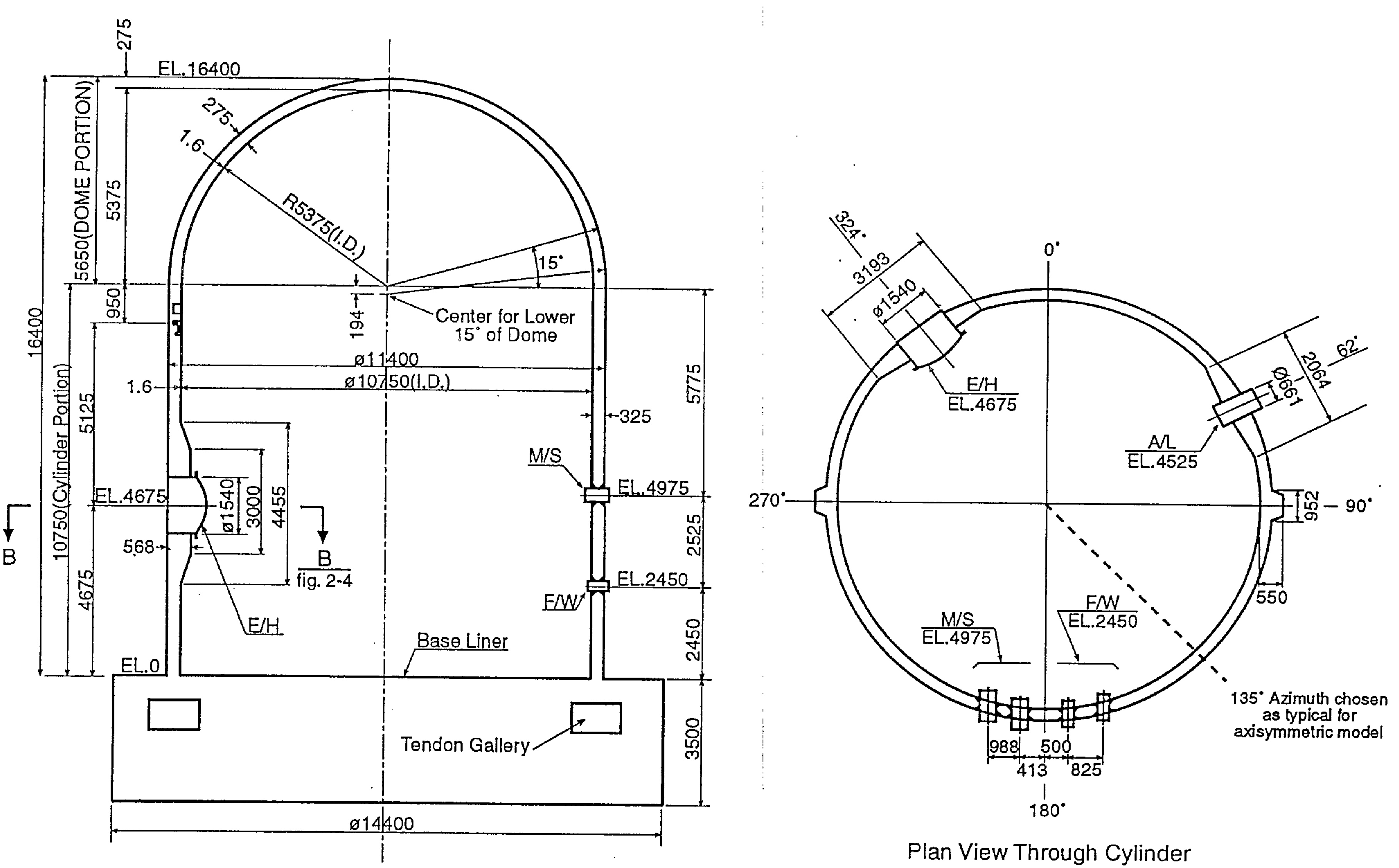

Figure 1. 1:4 Scale PCCV Model Geometry (Dimensions in mm)

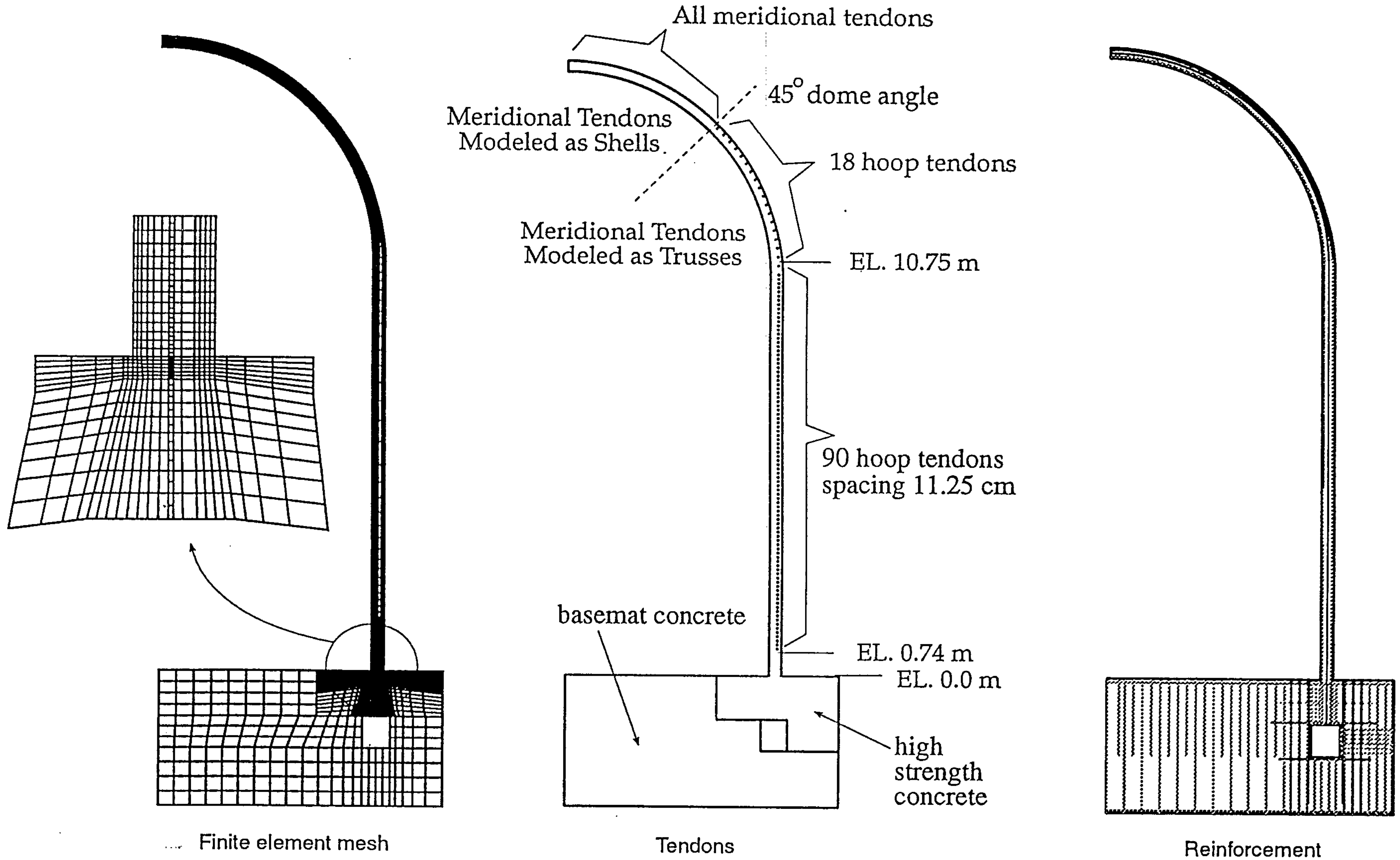

Figure 2. Axisymmetric Model, Tendons, and Reinforcement Used for Wall-Basemat Study

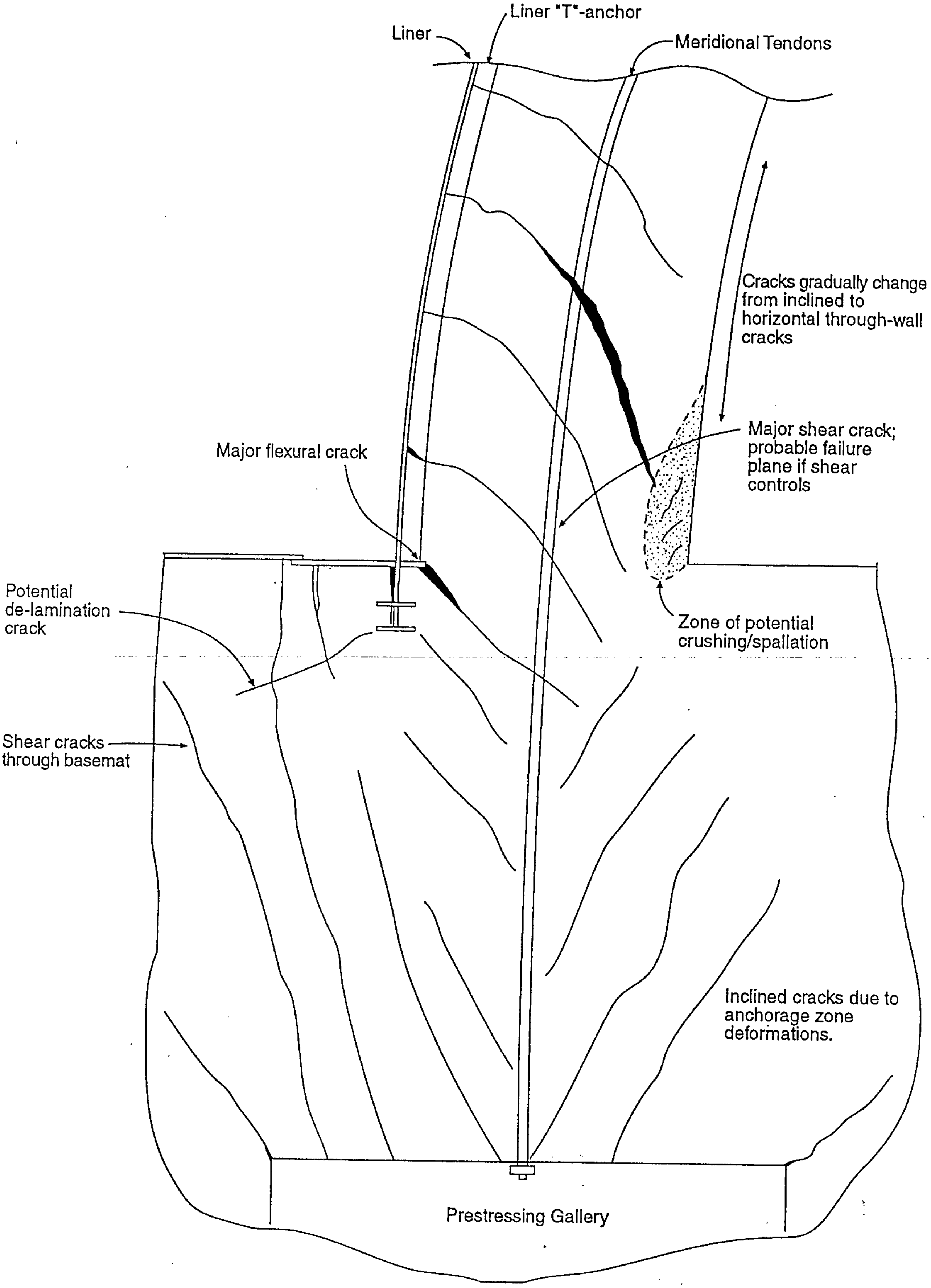

Figure 3. Deformed Shape and Crack Patterns of Wall-Base Juncture Region

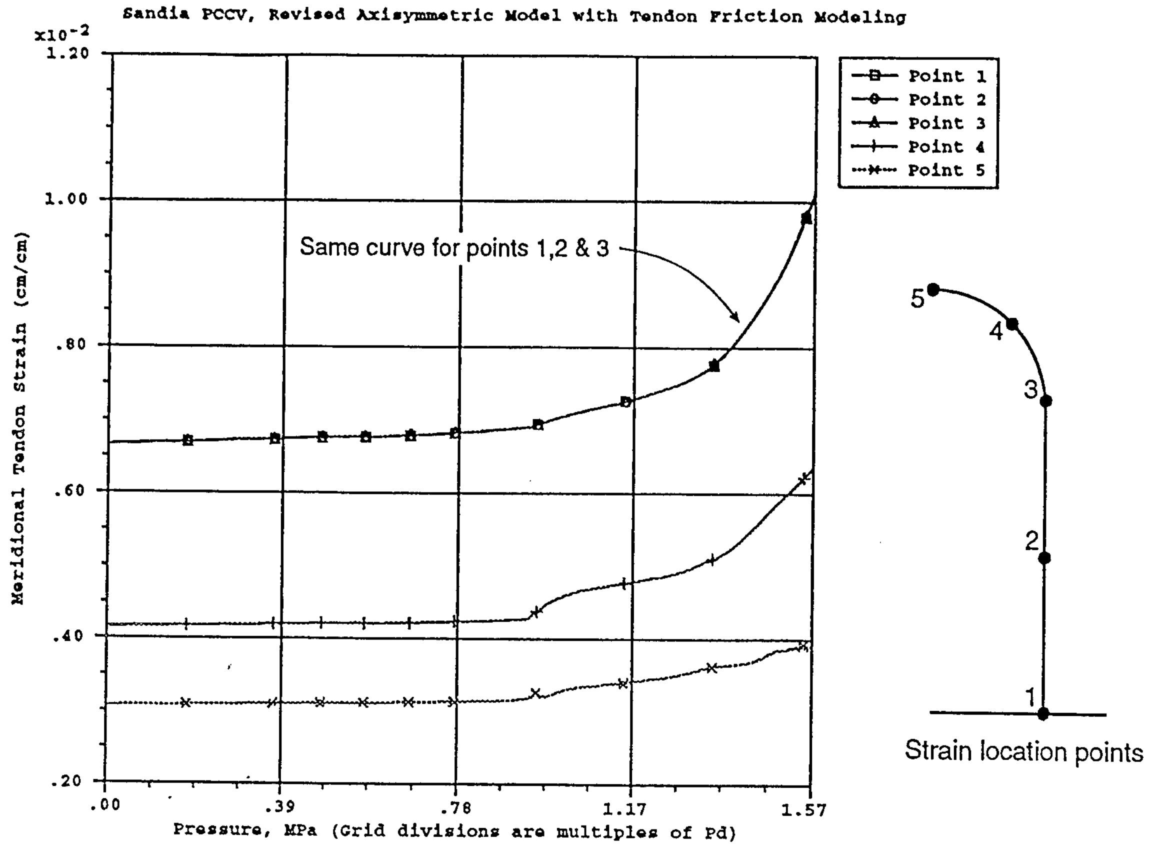

Figure 4. Meridional Tendon Strains in PCCV as a Function of Pressure

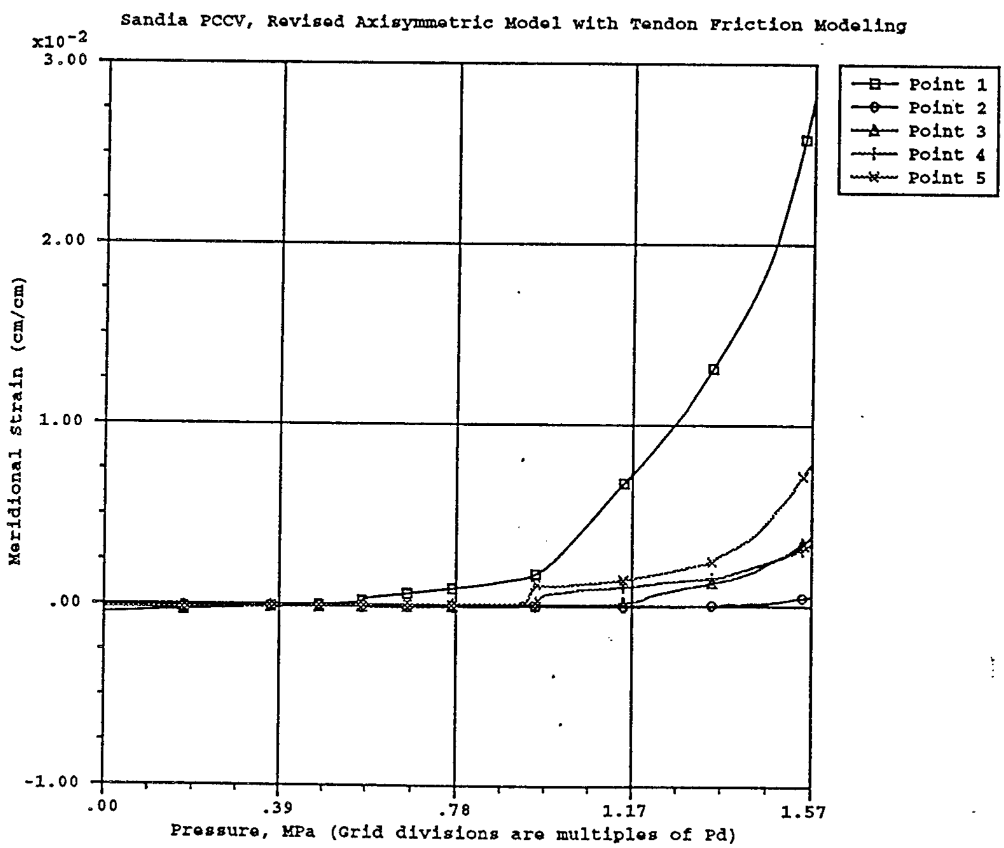

Figure 5. Meridional Strains in Liner as a Function of Pressure

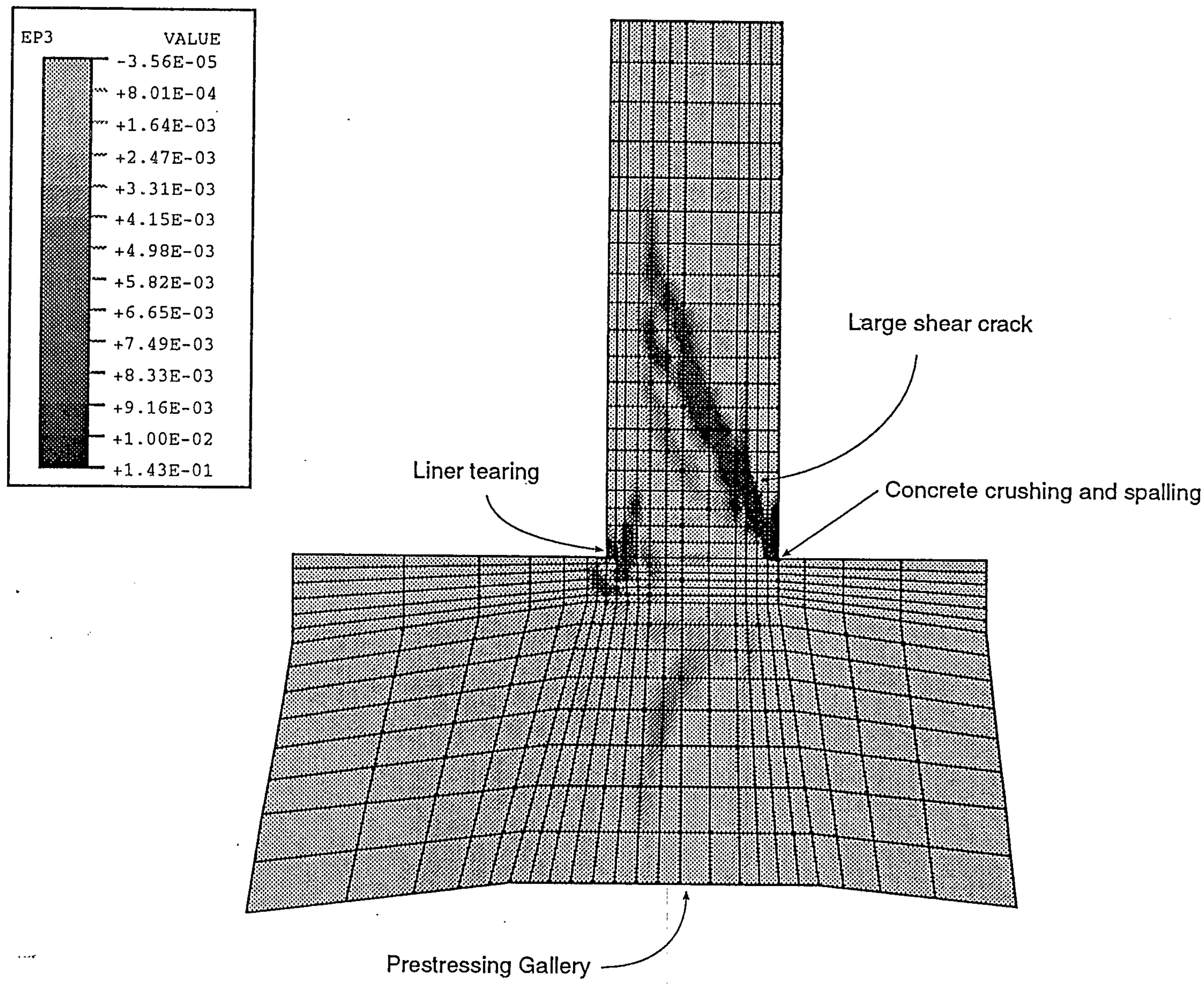

Figure 6. Axisymmetric PCCV Model at Wall-Basemat Region showing Maximum Principal Strains at Pressure of 3.5 x Design Pressure

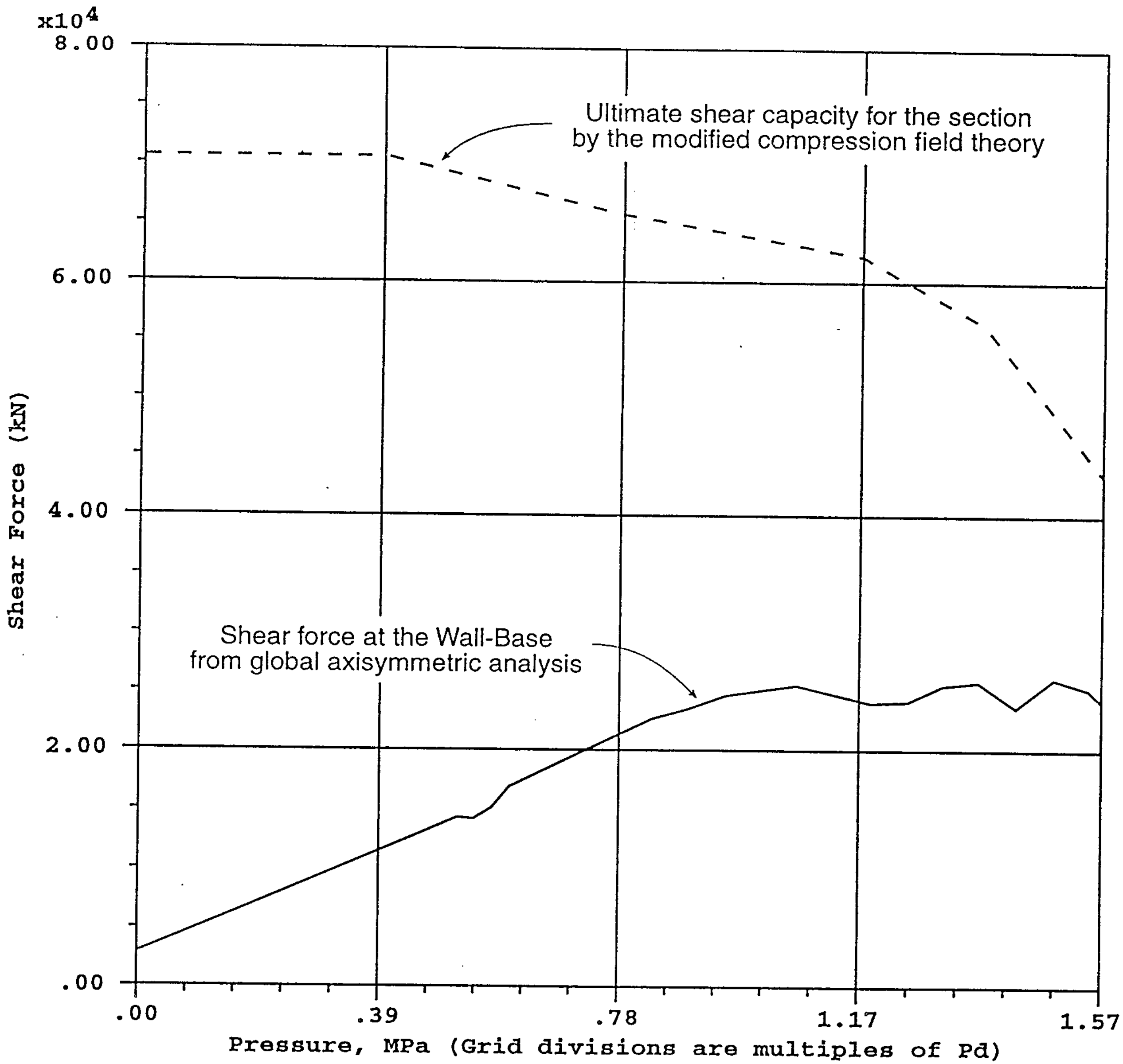

Figure 7. Shear Force at Wall Base of the PCCV as a Function of Pressure Loads

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