

Comparison of Pre-Test Analyses with the Sizewell-B 1:10 Scale Prestressed Concrete Containment Test

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ABSTRACT

This paper describes pretest analyses of a one-tenth scale model of the "Sizewell-B" prestressed concrete containment building. The work was performed by ANATECH Research Corp. under contract with Sandia National Laboratories (SNL). Hydraulic testing of the model was conducted in the United Kingdom by the Central Electricity Generating Board (CEGB). In order to further their understanding of containment behavior, the USNRC, through an agreement with the United Kingdom Atomic Energy Authority (UKAEA), also participated in the test program with SNL serving as their technical agent.

The analyses that were conducted included two global axisymmetric models with "bonded" and "unbonded" analytical treatment of meridional tendons, a 3D quarter model of the structure, an axisymmetric representation of the equipment hatch region, and local plane stress and $r-\theta$ models of a buttress. Results of these analyses are described and compared with the results of the test. A global hoop failure at midheight of the cylinder and a shear/bending type failure at the base of the cylinder wall were both found to have roughly equal probability of occurrence; however, the shear failure mode had higher uncertainty associated with it. Consequently, significant effort was dedicated to improving the modeling capability for concrete shear behavior. This work is also described briefly.

ACKNOWLEDGMENT

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1 INTRODUCTION & OVERVIEW OF TEST RESULTS

The principal objectives of the work were to use blind pretest analyses to critically evaluate analytical methods for predicting global structural response, to gain insight into the potential structural failure modes of a prestressed concrete containment, and to make recommendations for instrumentation of the model. A variety of potential failure modes and locations were listed at the outset of this work; the analyses were chosen to investigate, rank, and possibly add to that list. Information about the test and more detailed information about the analyses performed is reported by Dameron, et al, 1990. The geometry of the model is shown in Figure 1.

The model was tested with four loading cycles to 1.15 x design pressure and one ultimate pressure test in July, 1989. Design pressure of the model was 0.345 MPa (50 psig). The model behavior was observed to be primarily

elastic during the low pressure tests, except that the basemat uplift response was somewhat larger at the end of the fourth low pressure test than after the first, indicating the occurrence of inelastic damage to the basemat or wall-base region or both. During the high pressure test, a maximum pressure of 0.834 MPa (121 psig) (including the hydrostatic head of the filled bladder) was reached at the model base (2.4 x design pressure). At this point, the test was discontinued due to excessive basemat bending, which was manifested by large basemat uplift, corresponding tilting of the model, and spalling of concrete off the underside of the base. Although the model has not been sectioned, a sketch has been made of a section of the final condition of the basemat based on observed surface cracking and spalling and information obtained from coring. This is shown in Figure 2. The figure shows the large basemat uplift that occurred and illustrates the internal cracking that is believed to have occurred.

The observed and measured behavior during the ultimate pressure test can be summarized as follows: basemat uplift was the largest displacement response component (30 mm not including tilting of the model at 0.774 MPa, 112 psig). The maximum radial displacement was 13.5 mm at the midheight. The hoop and meridional tendons appear to have performed satisfactorily, except that the test measurements show evidence of significant friction and lack of slippage, particularly after concrete cracking or in areas of shear and bending. Bonded tendon behavior is observed particularly in the 8 mm tendons, the smaller of the two tendon sizes. This result is shown in Figure 3 in which the tendon strain measurements indicate higher strains, the further a gage is located from the tendon anchorage. A tendon behaving in frictionless fashion would not exhibit these strain gradients. This is a critical result since the pre-test analyses consisted of both a frictionless tendon model and a bonded tendon model, and the bonded tendon model matched the experiment better for basemat uplift response than did the frictionless tendon model. No meridional tendon yielding was observed in the gages. However, no tendon strain measurements were available in the wall-base juncture region, and it is postulated that, because of bonding, local tendon yielding may have occurred there. Small amounts of barrel hoop rebar yielding began to occur by the end of the test. More variation exists in the rebar strains than tendon strains because of local behavior. The areas with failure potential evidenced by the rebar strain transducers are the basemat bottom rebars at R=800 mm (maximum measured rebar strain of 1.2%), the inner meridional bars at the wall base, and the hoop reinforcement adjacent to the concrete thickness transitions of the equipment hatch (maximum measured rebar strain of over 2%). Upon post test inspection, model failure may have been associated with basemat spallation and the related loss of bond in basemat bottom rebars as illustrated in the sketch of Figure 2.

2 DESCRIPTION AND RESULTS OF ANALYSES

The Sizewell B model did not have a steel liner. Instead, a rubber bladder was used to maintain a leak-tight boundary for the applied hydrostatic pressure. Thus, the primary objective of the analyses was to predict the behavior of the concrete, reinforcement, and prestressing tendons. The concrete analysis methodology that was used was developed over the course of a six-year program funded by the Electric Power Research Institute (EPRI). The concrete constitutive model has its roots in early work by Rashid, 1968. Early in the EPRI program, the smeared cracking methodology was incorporated into a user subroutine UMAT for use with ABAQUS, a general purpose finite element program described by Hibbitt, 1984. Results using this model have been compared and calibrated to many experiments.

Small displacement theory was used throughout the analyses, i.e., no geometric nonlinearities were included. The number of iteration cycles (in this case a minimum of three) performed at each load increment to handle

material nonlinearities are preset by the user. The number of cycles is set based on experience in performing containment analyses with similar geometries. Selecting this parameter is important as a means of conserving computation time. It should be noted that in concrete analysis, failure to meet the ABAQUS force convergence criteria does not necessarily imply an inaccurate solution. Large force residuals are attributed to the fact that in cracked elements the stresses are discontinuous as are the nodal point forces which are computed from the element stresses.

The concrete constitutive model uses tensile cracking (Dunham, et al, 1985) and modified Drucker-Prager compressive yield surface. The concrete model also accounts for post-cracking shear retention, which for the 1:10 scale model was found to be quite important. This is especially true in the local region of the base of the cylinder where large shear transfer occurs coupled with major cracking. Tension stiffening, which is included in some concrete models, seems to be of lesser importance for concrete containment analysis. Because of the importance of shear-friction modeling, an additional feature was added to the constitutive model, namely, a rough-crack model. This aspect of the model allows compression to develop across an open crack due to crack surface roughness, which in turn adds more stress to rebar that crosses a crack. The shear friction model development was based on work by White, 1972, and others.

In the first axisymmetric model, called the bonded tendon analysis, all rebar and tendons were modeled with ABAQUS rebar subelements. With this feature the rebar or tendon stiffness is essentially that of a truss superimposed at the element stiffness level onto that of the parent concrete element. The rebars do not carry shear through dowel action or as individual beams since they have the properties of a truss element.

In the second axisymmetric model, called the unbonded tendon analysis, it was recognized that greased tendons will not, in general, have strain compatibility with the surrounding concrete. Therefore "unbonded" meridional tendons were introduced which replaced the rebar subelements corresponding to these tendons. Hoop tendon strain compatibility is required in axisymmetric analyses, so hoop tendons were modeled as before. The meridional tendon subelements were replaced with external beam elements, tied to the concrete grid with rigid links. The links allow the nodes on the tendons to move tangentially with respect to the concrete.

No account was taken for tendon friction other than for simple angular friction and lock-off losses through the ABAQUS "Initial Stress" procedure. In addition to the bonded and unbonded tendon axisymmetric grids, a 3D quarter model was analyzed to investigate the effects of orthogonally placed tendons in the dome and the interaction of the free-field shell with buttresses. Two dimensional grids were also developed to study stress/strain concentrations near the equipment hatch and near buttresses.

Based on the unbonded tendon analysis results, the failure mode with the lowest uncertainty was predicted to be exceedance of tendon ductility at the barrel mid-height at 2.58 x design pressure, or 0.889 MPa (129 psig). Based on the bonded tendon analysis and shear response modeling using the "rough crack" UMAT model, a shear/bending failure mode at the base of the cylinder wall was predicted. The pressure level was actually lower than given above (between 0.76 and 0.86 MPa - 110 to 125 psig). However, because the tendons were assumed to behave more as "greased" than as bonded, greater uncertainty was associated with this failure mode. Thus, it was given as the second most likely failure mode in the predictions. This type of failure is exemplified by large basemat uplift and shear dislocation of the wall-base.

3. COMPARISONS OF ANALYSIS VS. EXPERIMENT

In general, the bonded-tendon pretest analysis shows good agreement with the measured results. Both approaches show good agreement with global barrel response, as shown in Figure 4, but the bonded-tendon analysis shows much

better agreement with basemat response, as shown in Figure 5. Good comparisons can also be made with tendon and rebar strain gages as shown in Figures 6 and 7 for a cylinder mid-height hoop tendon and for rebar in the base of the wall, a region of large shear and bending. The local equipment hatch and local buttress analyses also appear to have predicted important local effects such as local cracking and elevated rebar strain. The bonded tendon assumption appears to be justified by the friction evidenced in the gage measurements, especially after the concrete was significantly damaged. The reason for the large difference between basemat response in the bonded and unbonded tendon analysis stems from the early occurrence of a plastic hinge at the base of the wall in the bonded tendon analysis model. This is due to the tendon's local participation in the meridional bending moment, thereby sustaining local yielding and loss of stiffness. Once this loss of stiffness occurs at the wall-base, the already yielded basemat becomes free to bend upwards significantly. Proper prediction of this plastic hinge appears to be critical to accurate calculation of the basemat response. This underscores the need for accurate concrete constitutive modeling of cracking, post-cracking shear retention, and compressive plasticity.

4 CONCLUSIONS

The analytical method consisting of global axisymmetric analysis using the ABAQUS code and ANATECH's UMAT concrete constitutive model appears to be adequate for the prediction of global response including barrel and basemat deformation and tendon and rebar strains. Thus, the method is adequate for prediction of failure modes other than those associated with local effects. The exercise has validated several key modeling assumptions such as axisymmetric modeling of orthogonal rebar layouts and the modeling of post-cracking tension and shear behavior in the concrete. The bonded versus unbonded tendon solution differences point out an area of uncertainty in prestressed concrete containment modeling, but the true solution is bounded by the perfectly bonded and the perfectly unbonded solutions. Further, the barrel response prediction is largely unaffected by this modeling assumption. Axisymmetric modeling results in unsatisfactory prediction of local and 3D effects such as rebar debonding, very localized concrete spallation, response near penetrations and dome response due to the non-axisymmetry of the buttresses and the orthogonality of the tendon layout. Calculation of these local effects can be accomplished with local or 3D models, but this is at considerable labor and computational expense.

REFERENCES

- Dameron, R.A., Rashid, Y.R., Sullaway, M.F. (1990). Pretest Predictions of a 1:10 Scale Model Test of the Sizewell-B Containment Building. ANATECH Report to Sandia National Laboratories, Albuquerque, NM, NUREG/CR-5671.
- Rashid, Y.R. (1968). Ultimate Strength Analysis of Prestressed Concrete Pressure Vessels. Nuclear Engineering and Design, Vol. 7, pp. 334-344.
- Hibbitt, H.D. (1984). ABAQUS-EPGEN-A General Purpose Finite Element Code With Emphasis on Nonlinear Applications. Nuclear Engineering and Design, Vol. 77, pp. 271-298.
- Dunham, R.S., Rashid, Y.R., Tang, Y.K. (1985). Recent Results on the Evaluation of the Overpressure Response of Concrete and Steel Containments. Nuclear Engineering and Design, Vol. 90, pp. 193-208.
- White, R.N., Holley, M.J., Jr. (1972). Experimental Studies of Membrane Shear Transfer. Proceedings of the American Society of Civil Engineers, August, 1972.

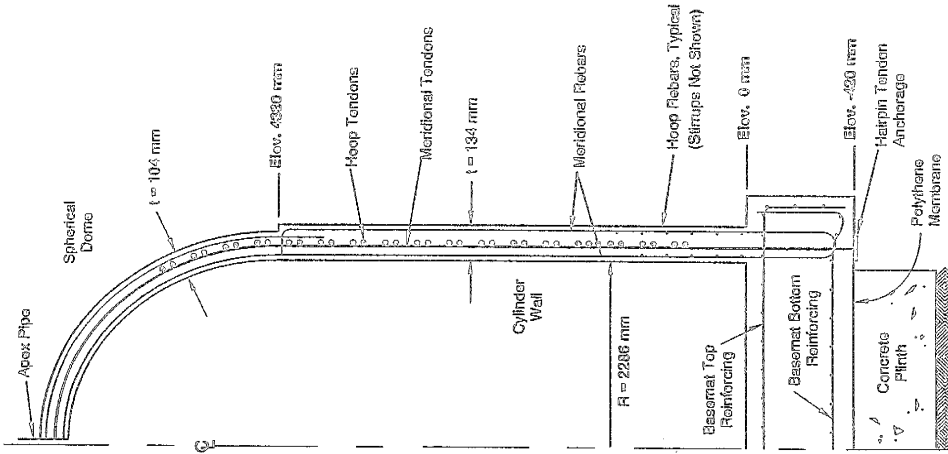


Figure 1. Schematic of 1:10 Scale Model Geometry (Drawing Not to Scale)

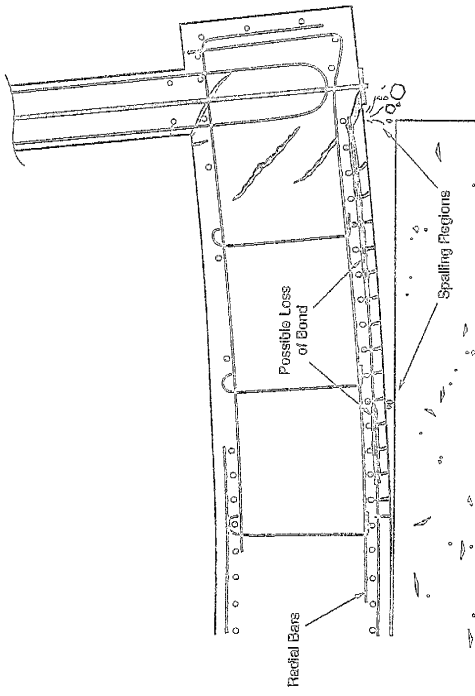


Figure 2. Section View of Post-Test Condition of 1:10 Scale Model (Drawing Not to Scale)

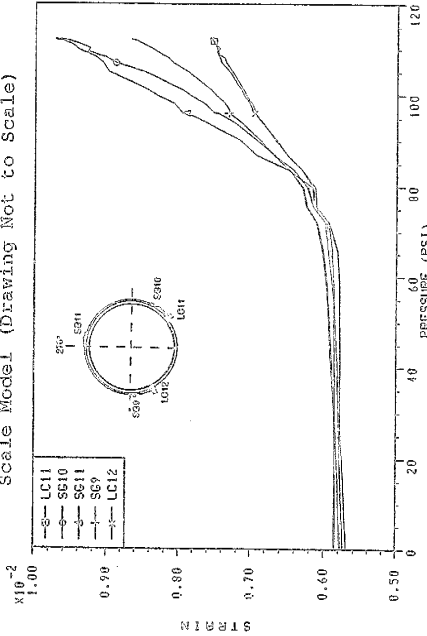


Figure 3. Hoop Tendon Gage Measurements for an 8 mm Tendon Near the Cylinder Mid-Height

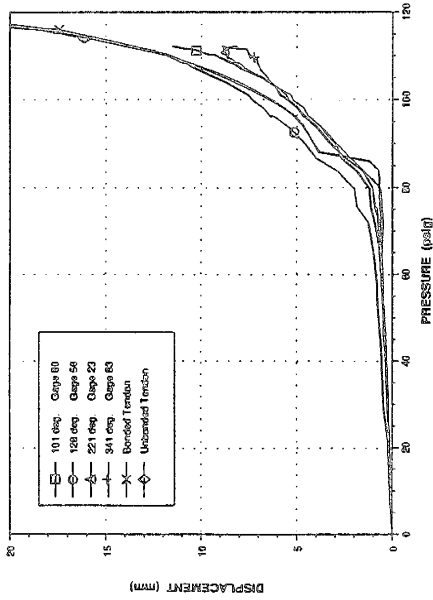


Figure 4. Comparison of Pretest Analyses vs. Experiment for Radial Displacements at Cylinder Midheight

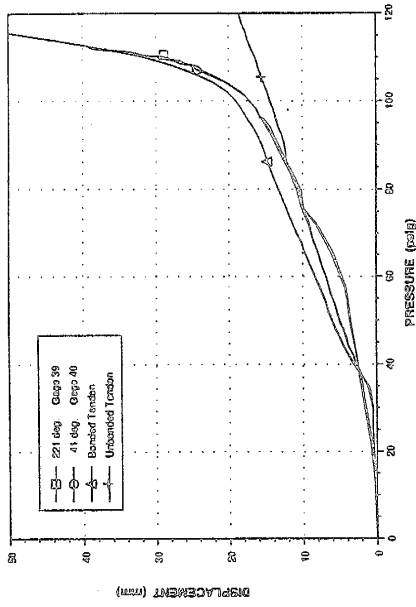


Figure 5. Comparison of Pretest Analyses vs. Experiment for Basement Uplift Displacement

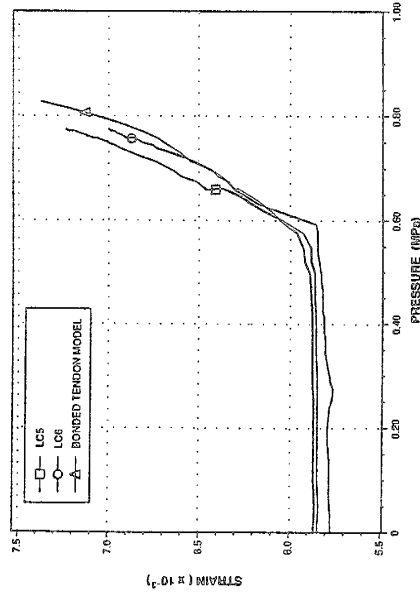


Figure 6. Comparison of Pretest Analyses vs. Experiment for Hoop Tendon Strain Near Cylinder Midheight

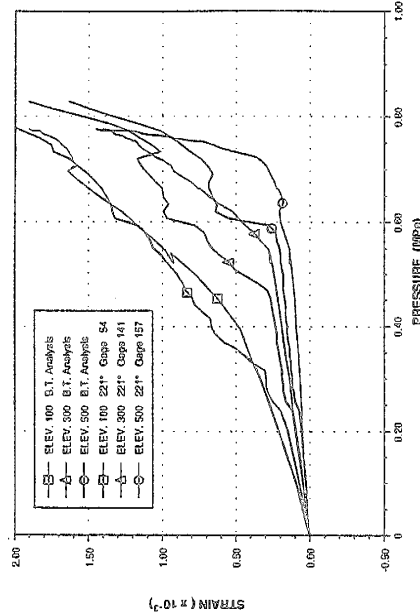


Figure 7. Comparison of Pretest Analyses vs. Experiment for Meridional Rebar Strains, Inside Surface, Base of Wall, Measured From Top of Basement