Posttest Analysis of a 1:4-Scale Prestressed Concrete Containment Vessel Model

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ABSTRACT

The Nuclear Power Engineering Corporation (NUPEC) of Japan and the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research, co-sponsored a Cooperative Containment Research Program at Sandia National Laboratories (SNL) in Albuquerque, New Mexico. As part of the program, a prestressed concrete containment vessel (PCCV) model was subjected to a series of overpressurization tests at SNL beginning in July 2000 and culminating in a functional failure mode or Limit State Test (LST) in September 2000 and a Structural Failure Mode Test (SFMT) in November 2001. The PCCV model, uniformly scaled at 1:4, is representative of the containment structure of an actual Pressurized Water Reactor (PWR) plant (OHI-3) in Japan. The objectives of the pressurization tests were to obtain measurement of the structural response to pressure loading beyond design basis accident in order to validate analytical modeling, to find pressure capacity of the model, and to observe its failure mechanisms.

This paper compares results of pretest analytical studies of the PCCV model to the PCCV high pressure test measurements and describes results of post-test analytical studies. These analyses have been performed by ANATECH Corp. under contract with Sandia National Laboratories. The post-test analysis represents the third phase of a comprehensive PCCV analysis effort. The first phase consisted of preliminary analyses [1] to determine what finite element models would be necessary for the pretest prediction analyses, and the second phase consisted of the pretest prediction analyses [2]. The principal objectives of the post-test analyses were: (1) to provide insights to improve the analytical methods for predicting the structural response and failure modes of a prestressed concrete containment, and (2) to evaluate by analysis any phenomena or failure mode observed during the test that had not been explicitly predicted by analysis. In addition to summarizing comparisons between measured behavior and predicted behavior of the liner, concrete, rebar, and tendons, a variety of failure modes and locations have been investigated. Comparison of pretest and post-LST analysis results to the SFMT data and additional analyses, to provide some insight into the mechanisms leading to the structural failure, are also included in this paper. Observations on the accuracy and adequacy of the pretest prediction analysis, unique lessons learned from the 1:4 Scale PCCV project, such as the modeling and behavior of prestressing and some unique liner seam details, conclude the paper.

SUMMARY OF PRETEST ANALYSIS

The final Pretest Prediction Analysis models [1] consisted of global axisymmetric, semi-global three-dimensional cylinder mid-height (3DCM) model, and local models of the Equipment Hatch (E/H), Personnel Airlock (A/L), and Mainsteam (M/S) penetrations. The local failure predictions were driven by response versus pressure histories calculated by the global axisymmetric and 3DCM models. The axisymmetric model is shown in Figure 1.

The ABAQUS general purpose finite element program [3] and the ANACAP-U concrete and steel constitutive modeling modules [4] were used for the analysis. Tendons and their prestressing were modeled to replicate expected tendon stress-strain behavior and friction effects. Concrete is modeled as a non-linear material throughout the deformation range, with full representation of pressure-dependent compressive plasticity, post-crushing softening, and tensile cracking utilizing the shear-retaining smeared-crack modeling approach. The failure predictions consisted of liner tearing locations, all occurring near the midheight of the cylinder near penetrations and weld seams with “rat-hole” details. The most likely location for the linear tearing failure was predicted to be near the Equipment Hatch (E/H) at the ending point of a vertical T-anchor, near where the liner is attached to the thickened liner insert plate (also a weld seam). The failure pressure was predicted to be 1.27 MPa, which is 3.2 times the design pressure (P_d) of 0.39 MPa.

COMPARISON OF PRETEST ANALYSIS TO THE TEST MEASUREMENTS

During the LST, linear tearing and leakage failure was first detected at a pressure of 2.5 P_d, and a subsequent increase in pressure to 3.3 P_d resulted in very extensive tearing at many strain concentration locations. Ultimately, the leak rate through the tears exceeded the flow capacity of the pressurization system, at which time the test was terminated. In reviewing the PCCV test data, the 55 Standard Output Locations (SOLs) used for the Round Robin prediction exercise held in 1999 [5] proved to be very useful comparison points. Pretest analysis results are compared to test data for radial displacement at cylinder midheight and dome (Figure 2), and vertical displacement at cylinder midheight.

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springline (Figure 3). Analysis results curves were “rezeroed” to the first point of the test data, i.e. the data reading occurring at the start of the test. This shifted the analysis results slightly; but it simplified the comparison of the response to internal pressure and eliminated differences in response to dead load, prestressing and creep and other time-dependent effects. This is justified because most of the PCCV instrumentation was initialized in March, 2000 after dead loads were applied. Soon after, the model was prestressed, and underwent six months of outdoor temperature fluctuations and low-pressure testing prior to the start of the LST (September, 2000). The overall conclusions from the comparisons of the pretest analysis with the LST were as follows:

- Radial displacements in the cylinder wall were well predicted by global axisymmetric analysis, but dome and overall vertical displacements were over-predicted.
- Wall-base juncture behavior, including many rebar and liner strain measurements, were well predicted by the detailed wall-base juncture (axisymmetric) modeling.
- Maximum pressure, 187.9 psig (3.30 P<sub>d</sub>), was closely predicted by analysis, but the failure location was not verified. (Maximum pressure was also limited by the capacity of the pressurization system.) Liner tearing at 2.5 P<sub>d</sub> was not predicted, although this was subsequently attributed to defects in the liner welding. Ultimately, liner tears at many locations occurred, and many of these were identified by analysis.
- The average radial displacement at the midheight of the cylinder of 20mm at maximum pressure, equivalent to an average hoop strain of 0.37%, is within 10% of that predicted by global analysis (21.9 mm or 0.41%) at the same pressure.
- Hoop tendon stress distribution simulated by analysis at start of LST showed fair agreement with measurements, implying that the angular friction and anchor set modeling assumptions at the start of the test were reasonable. Vertical tendon stress distribution at the start of the LST were less consistent with the initial modeling assumptions.
- Hoop tendon stress distributions during high pressure showed poor agreement with pretest analysis. In particular, gages interior from the ends were underpredicted and the anchor forces (gages near the ends) were over-predicted. The cylinder hoop tendon data, in total, shows evidence of the tendons slipping during pressurization, and measurements indicate that the shape of the tendon stress profile completely changes during pressurization.

**POST TEST ANALYSES**

Global Axisymmetric posttest analyses were performed after the LST. Vertical and dome displacement comparisons were significantly improved (e.g., Figure 3 for Vertical Displacement at Springline) by redistributing soil basemat springs according to tributary area, and by improving the dome meridional tendon representation to account for the added stiffness of the overlapping tendons due to the rectilinear “hairpin” layout. Comparisons were also improved by using zero friction for the vertical tendons in the cylinder.

Extensive additional studies were also performed for the posttest 3DCM analysis (shown schematically in Figure 4). In the pretest analyses, the 3DCM model was developed to investigate the non-axisymmetric behavior of the cylinder wall and provide more realistic boundary conditions for the penetration’s submodels. Buttresses above and below the 3DCM model boundaries have vertical beam stiffnesses that are not accounted for in a cylinder slice model. Equivalent spring properties were derived and then applied as radial spring elements. A modeling assumption, found to be at significant variance with observed test behavior, was the representation of friction in the tendon modeling. As shown in Figure 4, the pretest models used tendon friction truss ties oriented at an angle of arctan (0.21) to simulate angular friction. Two important observations were derived from the test about the hoop tendon behavior:

- When pressure overcomes prestress, P = 0.59 MPa, tendon stress distributions change from the classical angular friction design assumption to an approximately uniform distribution; then they stay fairly uniform at most higher pressures. Toward the end of the test, some tendon interior forces slightly exceeded the force at the anchor.
- The apparent strain increases in tendons corresponding to force/strain gage readings are significantly larger (e.g., 0.48% versus 0.35%, for H53 as shown in Figure 5) than the strain that corresponds purely to radial expansion. This can only be attributed to the force redistribution associated with sliding. Thus the position of the tendon relative to the concrete must be allowed to change after initial prestress in order to adequately simulate tendon behavior during overpressurization. (The analytically predicted tendon force distributions are also shown in Figure 5.)

These observations led to changes in tendon friction modeling of the 3DCM model. Because observed tendon friction behavior turned out to be quite complex, new analysis strategies were chosen to bracket tendon behavior:

Model 6. Apply prestress. Then, by using the ABAQUS *MODEL CHANGE capability, fix the tendon nodes at their initially deformed position relative to the concrete. In other words, start from classical design prestress with friction and then effectively bond the tendons.
Model 7. Perform original analysis up to $P = 1.5 \, P_d$ (0.59 MPa), then "MODEL CHANGE" friction elements to non-friction elements (truss ties aligned perpendicular to the tendons). In other words, perfectly unbonded tendons.

Model 9. After prestress, keep the initial friction elements, but add a new set of friction elements in the reverse orientation so that if points on the tendon move relative to concrete in the reverse direction from that of initial prestress, they will experience reverse direction friction.

In general, the tendon friction simulation Models 6, 7, and 9 showed progressively better agreement with test measurements, with Model 9 showing quite good agreement at the anchors and at most points interior to the tendon ends. Based on these and the other observations, the results of Model 9 were used to drive the submodels for E/H and M/S (and estimated feedwater (F/W)) penetrations posttest analysis. As a further observation on tendon friction behavior, the test measurements and analytical evidence support the conclusion that tendon friction is important to the tendon behavior, but traditional friction design formulas that predict tendon stress distribution begin to break down once pressurization exceeds the pressure that overcomes prestress (in this case, roughly $1.5 \, P_d$). The coefficient of angular friction appears to lessen, allowing sliding and force redistribution as the vessel expands, but more importantly, some parts of the tendon are forced to reverse direction of travel relative to the duct, and should be reversed from the direction of travel experienced during prestressing. Under this action, angular friction properties probably still hold, but the direction of friction must change sign from that assumed in a design calculation. Using the method of tendon friction modeling identified above for "Model 9" produced the tendon force distributions shown in Figure 6.

Posttest analyses were also performed for the penetration submodels. Liner strains measured in the vicinity of the E/H penetration collar were much lower than predicted by pretest analysis. Since the predicted high strain locations were fundamental to the failure predictions, significant effort was spent reanalyzing the E/H model after the test. As a result of this work, two hypotheses were developed.

**Hypothesis 1:** The liner in the E/H area had a high degree of bond-friction with concrete, preventing slippage of the liner relative to the concrete; relative slippage is required for elevated strains to develop near local discontinuities like T-anchors and stiffeners. This highly localized effect was not captured in the pretest analysis.

**Hypothesis 2:** A major crack near edge of E/H embossment further concentrated liner strains at edge of embossment.

Posttest analysis showed that by preventing relative slip between liner and concrete, the overall behavior of the system (concrete strains, tendon strains, liner strains away from the hatch) remained the same, but the elevated strains close to the collar were eliminated. In the final case, directed cracks were introduced to one row of elements, and a discrete crack was formed by adding double rows of nodes along an assumed crack line. This was found to create elevated liner strain. The additional strain concentration coincides with rat-hole weld seam details, and in the LST, elevated strains were measured and numerous tears occurred at those details. Based on results of detailed liner rat-hole analysis, the additional strains associated with such details is enough to exceed the liner tearing strain criteria. This shows that with discrete crack modeling and local rat-hole modeling, a liner tear could have been predicted to occur as early as $2.8 \, P_d$. Based on the evidence provided by liner strain gages and by acoustic monitoring, one of the tears along this embossment edge may have even occurred as early as $2.5 \, P_d$. (Note that this posttest analysis did not attempt to include as-built liner defects, such as local thinning or residual stresses resulting from initial fabrication or subsequent repairs.) The posttest E/H study thus presents a modeling strategy with results that correlate well with the LST measurements and observations. A somewhat higher strain prediction might be possible if a discrete crack (separate rows of nodes) were propagated all the way through the concrete wall, but this would require a change in rebar modeling strategy—one that is probably not practical even for very detailed analysis of containments.

The M/S and F/W penetration hot spots (both analysis and LST observations) occurred near the vertical T-anchor terminations and near the ‘equator’ of the thickened insert plate surrounding the penetration group, i.e. at the 3:00 and 9:00 positions. For the posttest analysis effort, no changes to the M/S model were necessary, other than updating the applied displacement versus pressure histories that were obtained from 3DCM posttest Model 9. After studying the F/W geometry in the posttest phase of the project, it was determined that the F/W penetration model was similar enough to the M/S penetration model that it would be assumed the posttest M/S model was reasonably representative of the F/W penetration. Several observations could be made from the well-instrumented M/S and F/W locations that are relevant to response predictions around containment penetrations.

- Many of the highest strains recorded during the LST are near the M/S and the F/W.
- There is wide variation in peak strain measurements, even at locations that are theoretically identical in geometry; factors contributing to these differences are: slight variations in liner thickness (due to manufacturing and weld repair grinding), gage position relative to the collar/weld, material properties (including welding heat effects), etc.
• The highest strain measurements can, but do not always, correspond to tear locations. Sometimes a gage can show evidence of rising strain prior to tear occurrence, then declining due to the stress relief caused by the tear; a gage located near a tear crack tip, on the other hand can show quite low strain up to 3.1 \( P_d \) and then suddenly jump.

Comparisons of analysis to the M/S and F/W liner strain gages showed that the posttest analysis of the M/S penetrations captured the strains measured in the LST quite well for both the M/S and F/W penetrations.

POST-TEST ANALYSIS OF LINER TEARS WHICH OCCURRED AWAY FROM PENETRATIONS

Detailed analytical investigation was conducted of liner tears that occurred away from penetrations but where welding details may have caused local liner strain concentrations. The PCCV model exhibited 16 distinct locations at which liner tears occurred. All 16 locations were near vertical weld seams, but with some variation in the configuration of a horizontal stiffener or rat-hole. By comparing "before and after" photos taken by SNL and with reference to a posttest metallurgical study [6], it was observed that liner-welding irregularities were present at almost all of the tear locations. These irregularities included points of extensive repair, such as grinding, points of discontinuous or missing back-up bars, or points with weld and liner seam fit-up irregular geometry. Some locations, where a seam and rat-hole existed and high strains were measured, but a tear did not occur provide additional evidence of the importance of the welding details to liner tearing. Ultrasonic measurements showed substantial reductions in thickness near many tears. Measurements showed around 23% thickness reduction in many locations, and more (up to 40%) in a few locations.

A posttest liner seam analysis study was aimed at quantifying effects of welding irregularities and distinguishing these from strain concentrations solely related to geometry. A mesh-size sensitivity study was conducted. Analyses were then conducted to assess material and geometry variations. The first variation implemented varying material properties near the weld areas. This included assignment of different material properties to the base metal, heat affected zone (HAZ), and weld fusion zone (WFZ) regions of the model. The second variation only modified the material in the WFZ. The final phase incorporated geometry modifications to the model near the weld lines. This included thinning of elements and varying the extent of thinning in the vicinity of the welds due to grinding. The geometry modifications were coupled with modified material properties ranging from uniform to including variations of base metal, HAZ, and WFZ regions. The conclusions of the liner seam-rat-hole modeling study are summarized below:

• By comparison with strain gages and posttest liner tear observations, some of the finite element weld seam analyses are able to generate strain fields in and around the rat-holes and liner welds which agree reasonably well with strain gage measurements and which exceed the liner tearing strain criteria at locations where tears were observed.

• Competing mechanisms between the weld zone and ends of stiffeners make yield and ultimate strength adjustments to the HAZ material properties necessary to correctly predict strain concentration location and intensity.

• The models with back-up bars, nominal geometric properties, and best-estimate material properties yielded the best simulations of defect-free construction of rat-hole/weld-seam details. However, even models without back-up bars also provided reasonable correlation with gages at these locations.

• A case with severe (~40%) amounts of thinning appears to provide the best simulation of the behavior of tear occurrences in which severe liner thinning (due to weld repair grinding) was reported.

• If a rat-hole/liner-seam detail is subjected to additionally elevated strain (i.e. strain across the liner model that is larger than free-field global strain) a tear even earlier than 3.0 \( P_d \) can be justified. In practice, such a prediction could approximately be made using a strain concentration factor approach. The strain concentration factors (\( K = \frac{\varepsilon_{\text{eff}}}{\varepsilon_{\text{global}}}, \text{peak} \)) implied by this liner seam study are as follows: \( K = 48 \) (tear at stiffener end, no back-up bar); \( K = 45 \) (tear at stiffener end, with back-up bar); \( K = 59 \) (tear at HAZ, no back-up bar, and 40% thickness reduction due to grinding); \( K = 91 \) if a short segment of horizontal weld seam back-up bar is missing.

• Using a model of the rat-hole/seam locations without defects showed that liner tears still would have developed by pressure of 3.4 \( P_d \), so liner tearing and leakage would still have been the failure mode (for quasi-static pressurization) even in the absence of liner welding irregularities.

ANALYSIS OF THE STRUCTURAL FAILURE MODE TEST

The LST resulted in liner tearing and leakage, but not a structural failure. Structural damage was limited to concrete cracking, and the overall structural response (displacements, rebar and tendon strains, etc.) was only slightly beyond yield. (Global hoop strains at the midheight of the cylinder only reached 0.4%, approximately twice the yield strain in steel.) In order to provide additional structural response data to compare with in-elastic response conditions, the PCCV model was resealed, filled nearly full with water, and repressurized during the SfMT to a maximum pressure of 3.6 \( P_d \) when a catastrophic rupture occurred as shown in Figure 7. The SfMT posttest analysis showed that good simulation of the PCCV global behavior through and including tendon rupture is possible with a 3D shell model as shown in Figure 8. The main limitations of the shell model were a lack of local liner strain concentration prediction and a lack of accuracy in the predictions of local wall-base-juncture behavior. However, accuracy in global behavior prediction did not seem to be lost when a bonded tendon assumption was used.
The SFMT model provided additional insight as to how the structural failure likely developed. Near the 0 - 6 degree azimuth of the cylinder, there is a reduction in inner and outer hoop rebar area of 38% (from alternating D19, D16 bars to a pattern of 1D16/3D13 bars). At 3.49 Pₜₐₜ, the wall and tendon strain at the 0 - 6 degree location is higher than all other azimuths as shown in Figure 8, and a tendon rupture occurs. The analysis then shows neighboring tendons rupturing and deformations spreading quickly along this azimuth. The secondary tendon ruptures spread upward. From review of test video, this appears to agree with observations. By 3.65 Pₜₐₜ, the analysis shows rupture to have spread over a vertical line spanning about 6 m. This also agrees with observations.

After wall rupture, a secondary event occurred in the SFMT: through-wall failure around the circumference of the wall at about 1.5 m elevation. While it is difficult to say at what azimuth this failure initiated, it seems clear that this was a shear or combined shear/ﬂexural failure of the wall. With the triggering event of a massive wall rupture, one of two mechanisms may have caused shear demand to exceed capacity: 1) a large deformation of the wall opening, creating large rotations near the base of the wall, would crush the outer concrete of the flexural section and thereby reduce the capacity, or 2) the water jet-induced momentum imbalance would cause added shear demand; this would create tangential shear at some azimuths and would be the maximum at the buttresses; such shear acting in combination with the already high radial shear stresses could have increased shear stress demand enough to induce the shear failure.

CONCLUSIONS AND LESSONS LEARNED

The 1:4 scale PCCV test showed that the response quantity driving the limit state of the vessel is cylinder radial expansion. This aspect of response must be predicted correctly in order to reasonably predict vessel capacity and predict, at least approximately, the many other local aspects of response (local liner strains, etc.) that are driven by the cylinder expansion. With this test, as with other steel-lined concrete vessel tests, many competing strain concentrations occur around the mid-height of the cylinder. Although it is difficult to predict which local liner detail will tear first, and although some particular response quantities, like basemat uplift, were not predicted exactly by the ANATECH/SNL pretest analysis of the PCCV model, the radial expansion of the cylinder was predicted very accurately. A response mechanism that also appears to have been well predicted was cylinder wall-base flexure and shear, another mechanism that, if predicted incorrectly, could lead to erroneous pressure capacity/failure mode conclusions. The minimum requirement for a containment overpressure evaluation should certainly be a robust axisymmetric analysis.

Other steps, guidelines, and lessons learned are provided in [7]. The lessons learned which may be most instructive are those related to tendon friction behavior. As a result of this project, the best calculation methods recommended for tendon friction modeling are, in descending order of preference, 1) an advanced contact friction surface between the tendons and the concrete, 2) pre-set friction ties applied in one direction during prestressing and then added in the other direction during pressurization (3DCM run 9) and 3) if neither of these methods are practical within the scope of the calculation, it is best to start with an “average” stress level (using a friction loss design formula), but assume uniform stress distribution in the tendons throughout pressurization, i.e., an unbonded tendon assumption, and finally 4) same as 3, but using a bonded tendon assumption. It should be recognized for method 4, however, that this can lead to a premature prediction of tendon rupture, because the tendon strain increments during pressurization will match the hoop strain increments of the vessel wall one-to-one, and this was not observed to be the case during the PCCV LST.

The relevance of this work to full size U.S. Containments is highly significant. All of the analysis methods tried, calibrated, and validated are applicable to full-scale structures. The posttest work also provides a reasonably simple liner-only mesh approach for predicting local strains near weld seams, and the test itself underscores the need for continuous back-up bars on all liner seam welds. Such is the requirement in the current U.S. design rules.

REFERENCES

Figure 1. Axisymmetric Model of PCCV and Locations for Plotted Output

Figure 2. Comparison of Pretest Prediction Analysis to Test Data
Figure 3. Comparison of Pretest (Upper) and Posttest Analysis (Lower), Vertical Displacement at Springline, to Test Data
Figure 5. HS3 Tendon Force Comparisons to Posttest Analysis

Figure 6. HS3 Tendon Force Comparisons to Posttest Run #89

Figure 7. PCCV SFMT: Photograph of Exterior of PCCV at Instant of Failure

Figure 8. PCCV SFMT, 3D Global Shell Model, Maximum Principal Strain. For Pressure at 1.381 MPa (3.51 Psig), Displacement × 10.