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EFFECT OF TORUS WALL FLEXIBILITY ON HYDRO-STRUCTURAL INTERACTION IN BWR CONTAINMENT SYSTEM

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ABSTRACT

The MARK I boiling water reactor (BWR) containment system is comprised of a light-bulb-shaped reactor compartment connected through vent pipes to a torus-shaped and partially water-filled pressure suppression chamber, or the wetwell. During either a normally occurring safety relief valve (SRV) discharge or a hypothetical loss-of-coolant accident (LOCA), air or steam is forced into the wetwell water pool for condensation and results in hydrodynamically induced loads on the torus shell.

Most test programs conducted to determine the hydrodynamic loads in a MARK I BWR containment system used very thick torus wall for the test models. The large shell thickness introduces significant wall rigidity which does not actually exist in real containment structures. Justification is clearly required to show that hydrodynamic loads determined by rigid-walled test models can be conservatively applied to flexible-walled prototype structures.

This paper describes an analytical program which employs the finite element method to investigate the influence of torus wall flexibility on hydrodynamically induced pressure and the resultant force on the torus shell surface. The shell flexibility is characterized by the diameter-to-thickness ratio which is varied from the perfectly rigid case to the nominal plant condition.

The general conclusion reached is that torus wall flexibility decreases both the maximum pressure seen by the shell wall and the total vertical load resulted from the hydrodynamically induced pressure. This conclusion is based on results of a comprehensive two-dimensional investigation and a more sophisticated three-dimensional confirmatory study of the hydro-structural interaction problem.

Numerous load cases are considered in the two-dimensional investigation for different combinations of pulse amplitude, pulse rise time, and diameter-to-thickness ratio. The calculated peak pressure decreases monotonically with increasing diameter-to-thickness ratio. The pulse shape is broadened and shifted in time as wall flexibility increases. In addition, the reduction of hydrodynamic loads due to the effect of the torus wall flexibility is found more pronounced for higher pulse amplitude associated with shorter rise time.

Results of the three-dimensional study compare qualitatively with two-dimensional results. However, the three-dimensionality of the torus configuration considerably reduces the magnitude of the peak pressure. This result appears reasonable when it is considered that the spherical bubble used in the three-dimensional study is significantly less energetic than the cylindrical source implied by the two-dimensional idealization.

The three-dimensional study leads to the belief that although the simple and fast two-dimensional finite element analysis is a good approach for generating qualitative results, it takes the more complex and hence more time consuming three-dimensional approach to produce realistic quantitative solutions of hydro-structural interaction phenomena associated with the MARK I BWR containment system.

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1. Introduction

This paper describes an analytical program that investigates, in a qualitative sense, the influence of torus wall flexibility on hydrodynamically induced loads in the pressure suppression chamber of a Mark I boiling water reactor (BWR) containment system. The degree of wall flexibility is characterized by the torus minor-diameter-to-shell-thickness ratio, which is varied from 0 (perfectly rigid) to 600 (nominal plant geometry).

The investigation is based on the geometry of the Monticello BWR power plant operated by the Northern States Power Company of Minnesota. A previous report [1] was issued to present some preliminary findings. This paper summarizes the final results of the analytical investigation. Other analytical and experimental studies closely related to this subject include works by Collins and Lai [2], Pitts and McCauley [3], McMaster, et al [4], Soulier and Krachman [5], Gross, et al [6], and Tang [7].

2. SRV-Induced Hydro-Structure Interaction

During normal BWR operation, steam is periodically discharged to the suppression pool through safety relief valves (SRV) to maintain reactor pressure within design operating limits. Each SRV line from the reactor vessel terminates at a discharge header located near the bottom of the suppression pool.

The two-dimensional finite element mesh utilized to model the SRV discharge problem (Fig. 1) represents an idealized plan section taken at a right angle through the wetwell torus. No motion is allowed at the shell waist, a reasonable boundary condition considering the torus support structures. The discharge of noncondensable air forced ahead of the steam flow is modeled by a single air bubble located at the exit of the discharge pipe. The inner surface of the bubble is loaded by a theoretical pressure pulse, derived using Rayleigh bubble arguments [8], which has a peak overpressure of 10.4 bars and a duration of 40 ms.

Linear finite element analyses of this model using the finite element code DTVT32 [9] for shell D/t ratios of 0, 100, 300, and 600 concluded:

- Increasing shell flexibility decreases the maximum pressure seen by the torus wall.
- Total vertical load on the torus shell diminishes with increasing wall flexibility.

The two-dimensional linear analyses were extended to include a pulse variation study and a limited investigation of nonlinear effects. In addition, the severe modeling constraints implicit in the two-dimensional modeling of the three-dimensional system were removed by a comprehensive series of three-dimensional calculations. These results, while still qualitative, provide a much improved basis for understanding the expected effects in real structures.

2.1 Two-Dimensional Pulse Variation Study

The pulse variation study confirmed previous conclusions (see [3]) and extended the data base for a wider range of pulse amplitudes and rise times. The general shape and total impulse of the pressure pulse were held unchanged, but pulse amplitude was increased or decreased by 30%, as shown in Fig. 2.

Numerical results were generated by the linear finite element computer code DTVT32 for D/t values of 0, 100, 300, and 600. The typical computed pressure histories at the wetwell pool bottom and the total vertical force acting on the torus shell are depicted.
by Figs. 3 and 4 for the +30% pulse amplitude. The effect of torus wall flexibility for different pulse amplitudes (on the pool bottom peak pressure and on the peak vertical force) is characterized by the sensitivity curves shown in Figs. 5 and 6. Peak pressures are normalized with respect to the peak input of the basic pulse (10.4 bars), whereas peak vertical forces are normalized with respect to that calculated for the rigid shell subjected to the basic pulse.

2.2 Two-Dimensional Nonlinear Analysis

Because of the relatively large fluid deformation observed in the two-dimensional linear analysis, the significance of nonlinear effects was assessed. A two-dimensional nonlinear finite element code NIX2D [10] was used to generate numerical results. The basic problem used in the analysis has a D/t ratio of 600 and uses the nominal input bubble pressure pulse. The linear and nonlinear comparison is depicted in Fig. 7, which shows the pool bottom pressure histories. It is seen that the nonlinear peak pressure is about 15% higher than the linear result. The nonlinear effect is therefore considered small for the following reasons:

- Only qualitative results are of interest in the idealized two-dimensional approach.
- There are other uncertainties; approximations resulting from model idealization and load definition, among other factors.

2.3 Three-Dimensional Investigation

The analytic model used for the three-dimensional SRV analyses (Fig. 8) is a one-eighth section of a right circular cylindrical shell 421.7 cm in radius filled with water to a level 91.4 cm below that of the shell centerline. The ramshied SRV discharge header used in the actual system is modeled by a quarter section of a single 25.4 cm diameter bubble, cut by the two planes of symmetry in the problem and located 279 cm below the elevation of the shell centerline. The 22.5-degree angle on the ends of the actual torus bay is neglected to take advantage of symmetry in the problem. The problem uses 1818 nodal points to form the finite element mesh. A total of 1425 eight-node fluid elements is used, 75 of which are defined as "zero shear" elements to simulate the slip condition at the fluid-shell interface. The steel shell is modeled by 85 four-node quadrilateral thin-shell elements. Model definition (i.e., material properties, bubble loading, etc.) is identical to that used for the two-dimensional planar model. The shell is rigidly constrained along its upper edge for all cases. The usual symmetry conditions (i.e., constraint of out-of-plane displacements and rotations) are applied to the xz and yz planes indicated in Fig. 8. A revised version of computer code SAP4 [11] was used to perform the analyses.

Results of the three-dimensional torus analyses compared qualitatively with the DTVIS2 planar calculations. Figure 9 shows the pressure history in the fluid at the pool bottom directly beneath the bubble, normalized to the peak source pressure, for shell diameter-to-thickness (D/t) ratios of 0, 300, and 600. As was predicted by the DTVIS2 analyses, the calculated peak pressure decreases with increasing D/t. However, the three-dimensionality of the torus problem reduces the magnitude of the peak pressure by as much as a factor of five (see Fig. 10).

3. LOCA-Induced Hydro-Structure Interaction

A hypothetical loss-of-coolant accident (LOCA) can be divided into two stages. During the early stage, LOCA downcomer clearing, air, followed by steam, is injected into the pressure suppression pool through pairs of downcomers connected to the reactor primary
containment through a ring header and vent pipes. LOCA downcomer clearing causes a large flow rate and large pool motion. On the other hand, chugging, which occurs during the later state of a LOCA, is caused by rapid condensation of steam bubbles formed at the downcomer exits.

Because of the large flow rate and pool motion involved, the LOCA downcomer clearing phenomenon presents an extremely complex hydro-structure interaction problem for analytical solution. Code development activities at LLL have been devoted to solve this problem by a new code, PELE-IC [4], which is based on an incompressible Eulerian formulation coupled with a thin-shell finite element code. Consequently, the activity in this investigation with regard to LOCA-induced hydro-structure interaction has been restricted to the LOCA chugging problem.

Linear two-dimensional LOCA chug analyses, using the nominal input pulse for torus D/t ratios of 0, 300, and 600, concluded that both the bottom pool pressure and the total vertical force on the torus shell were found to diminish with increasing wall flexibility. However, a lesser sensitivity was exhibited by the LOCA chug analysis as compared with the results of the SRV discharge results due to the reduced pulse amplitude and longer rise time associated with the chug pulse.

The chug pulse variation study holds the pulse shape and impulse constant while varying the pulse amplitude from -30% to +30%, as shown in Fig. 11. For +30% pulse amplitude, pressure histories at pool bottom are given in Fig. 12 and histories of the vertical forces in Fig. 13. The peak pool bottom pressures and the peak vertical forces, as they reduce with increasing wall flexibility, are illustrated in Figs. 14 and 15.

The pressure histories at the pool bottom are presented in Fig. 16 for both linear and nonlinear two-dimensional analyses. The basic chug pulse and D/t ratio of 300 are used in the analyses. As seen in Fig. 16, the nonlinear effect (about 15%) is of the same order as observed in the SRV discharge problem (Fig. 7).

4. Conclusions

The general conclusion is that torus wall flexibility decreases both the maximum pressure seen by the wall and the total vertical loads resulting from the hydrodynamically induced pressure. This conclusion has been supported by the results of the two-dimensional pulse variation studies and limited nonlinear effect investigations for both the SRV and LOCA chug problems and the comprehensive three-dimensional SRV analyses.

Numerous load cases were considered in the two-dimensional pulse variation studies for different combinations of pulse amplitudes, pulse rise times, and torus diameter-to-thickness ratios. In general reduction of hydrodynamic loads with increasing wall flexibility was found to be more pronounced for a higher pulse amplitude associated with shorter rise time. The two-dimensional nonlinear investigations indicated that including nonlinear effects due to large fluid deformation does not cause serious deviation from the linear analytical results.

Results of three-dimensional analyses compared qualitatively with two-dimensional results. The calculated peak pressure decreases monotonically with increasing diameter-
to-thickness ratio. In addition, the pulse shape is broadened and shifted in time as wall flexibility increases. The three-dimensionality of the torus configuration considerably reduces the magnitude of the peak pressure at all D/t ratios. This result appears reasonable when it is considered that the spherical bubble used in three-dimensional analyses is significantly less energetic than the cylindrical source implied by the two-dimensional idealization. It is important to note, however, that the relative pressure reduction offered by the flexible boundary over the rigid case is quite similar to that observed in the two-dimensional analyses.

5. References


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Figure 1. Two-dimensional finite element mesh

Figure 2. Variation of SRV pulse

Figure 3. SRV induced pool bottom pressure

Figure 4. SRV induced total vertical force
Figure 5. Effect of shell thickness on pool pressure

Figure 6. Effect of shell thickness on vertical force

Figure 7. Comparison of linear and nonlinear SRV analyses

Figure 3. Three-dimensional SRV finite element mesh

Figure 9. Pressure response at pool bottom

Figure 10. Comparison of peak pressure at pool bottom
Figure 11. Variation of LOCA chug pulses

Figure 12. Chug induced pool bottom pressure

Figure 13. Chug induced total vertical force

Figure 14. Effect of shell thickness on pool pressure

Figure 15. Effect of shell thickness on vertical force

Figure 16. Comparison of linear and nonlinear LOCA chug analyses