ANALYSIS AND DESIGN OF CONTAINMENT LINER/ANCHORAGE SYSTEM

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SUMMARY

In the design of the containment structure for a Pressurized Water Reactor (PWR) Plant a steel liner plate is often attached to the inner surface of the concrete containment vessel by embedded anchors. The liner and its anchorage system are designed to maintain leak-tight integrity under all conditions of postulated loading. Under thermal loading, such as rapid temperature changes, the expansion of the liner is confined at the anchors by the concrete containment structure, which undergoes very small displacements. During accident conditions, the large thermal expansion stress resulting from constraining the liner at high temperature could result in liner buckling. Such buckling is undesirable, but is permitted for accidents or incidents above the service condition. However, the buckling has to be contained in a local region and progressive failure in the anchorage system must be prevented.

This study presents the stress analysis for pre- and post-buckling behavior in a liner/anchorage system. In the pre-buckling analysis, allowable buckling strains are determined for assumed buckled patterns. Variations in the arrangement of the liner and anchorage pattern and deviation in geometry resulting from fabrication and erection tolerances as suggested by US NRC Standard Review Plan 3.8.1 are also studied. Curves are plotted for such parameters as liner/anchorage geometric pattern, liner thickness, and other deviations to give design information for the system.

ASME Section II, Division 2, CC-3123 stipulates that the anchorage system shall be designed to preclude a progressive failure in the anchorage system in the event of a defective or missing anchor. In the case of a missing anchor, the unsupported length of the original assumed buckling pattern is doubled. Consequently, the allowable buckling strain in the liner will be lower. Hence, the panel which includes the missing anchor is more likely to buckle.

This study also includes an evaluation of the force and deformation in the liner anchorage to ensure that no further anchor failure is allowed in the vicinity of the buckled panel. Studies have been made by others on the design of liner anchorage using one dimensional models. Considering the biaxial stress state in the liner, a two dimensional plate model is used in this study to account for the Poisson's effect. The analysis shows that the thermal stress in the liner plate is concentrated around the buckled panel to the extent that yielding occurs in the adjoining liner panels. Thus, consideration of plasticity in the liner plates assures a more realistic and conservative design for the liner/anchorage system.

1. Introduction

In the design of the containment structure for a Pressurized Water Reactor (PWR) Plant, a steel liner plate is attached to the inner surface of the concrete containment vessel by embedded anchors. The liner provides an air tight seal for the containment in the event of a loss of coolant accident. Since the liner and anchorages are rigidly attached to the concrete, the deformations of the liner are the same as the concrete if the liner does not buckle. The liner plate is not designed to carry the applied mechanical loads since its rigidity is small compared with the rigidity of the concrete vessel. Under thermal expansion, however, the liner experiences a great deal of compressive load because its deformation is confined at the anchors by the concrete. During accident conditions, the large in-plane stress resulting from constraining the liner at high temperature could result in liner buckling. Such buckling is undesirable, but is permitted for accidents, and incidents above the service condition. However, once a panel buckles, large asymmetric forces are induced in adjacent anchors. If the force is sufficiently large to cause the separation of the plate from the anchor, progressive failures in the anchorage system could occur and the sealing effect of the plate could be lost.

Stability studies of a shell liner inside of a rigid cylindrical cavity have been investigated by many authors [1], [2]. Their analytical results in terms of interaction curves for allowable strains appear to be supported by good correlation with a limited number of experimental tests. Conclusions from those studies are valuable in the design of the liner, particularly in selecting a stud pattern based on the liner thickness, anchor size and other geometric parameters. Others [3], [4], have studied the anchor forces and displacements assuming buckling occurs in one of the liner panels. One dimensional models of a strip of liner plate between two rows of anchors were used, and the existance of a biaxial stress state was neglected. Those investigations provide design guidelines for the liner anchorage system for preventing an "unzipper" type of progressive failure between the liner and the anchors.

The present study considers the analysis of a liner/anchorage system for pre- and post-buckling behaviors. In the pre-buckling analysis, allowable buckling strains are determined for assumed buckled patterns using the method derived by Kicher and Schrader [1]. Variations in the arrangement of the liner/anchorage pattern and deviations in geometry resulting from fabrication and erection tolerances as suggested by US NRC Standard Review Plant 3.8.1 are studied [5]. In the case of having a defective or missing anchor, the buckling strain in the panel becomes lower because of the increase in the unsupported length. Hence, the panel which includes the missing anchor is likely to buckle. This study also includes the evaluation of the force and deformation in the liner anchorage to ensure that no further anchor failure is observed in the vicinty of the buckled panel. Considering the biaxial state of stress in the liner, a two dimensional plate model is established to account for the Poisson's effect. Due to the high thermal stress in the liner around the buckled panel, the effect of material-yield is also considered. It is believed that such a 2-D plate model with plasticity represents a more realistic analysis.

2. Pre-Buckling Analysis

2.1 Statement of Problem

To study the pre-buckling behavior of a liner anchorage system, the energy approach derived by Kicher and Schrader [1] is used. In that approach, several assumptions are made to simplify the analysis. First, the concrete containment vessel and the stud anchors are rigid. Secondly, no friction exists between the liner and the concrete containment vessel. Third, the cylindrical liner shell remains elastic. The liner considered in the present study has studs placed in a diamond shaped pattern.

For the assumed mode shapes, which are the same as the ones in Ref. [1], the total potential energy is formulated, and equilibrium states are determined from the total potential energy for various parameters of stud spacing and liner characteristics.

2.2 Discussion of Results

Figure 1 shows plots of the equilibrium states for the five assumed mode shapes for the nominal dimensions of the liner used in this analysis. The nominal dimensions are also shown in Figure 1. The low point of these curves represents the lowest strain ε_x at which buckling may be expected to occur, and it is this buckling strain which is used in the remainder of the discussion. Note that the higher portions of the curves to the left of the buckling strain represent unstable states of equilibrium which are not expected to occur. It is seen that the vertical trapezoid mode sets the minimum buckling strain at 1430 μ-strain for the nominal dimensions.

To investigate the effect of various construction tolerances on the buckling strain of the liner, similar curves were drawn representing variations in liner thickness, liner radius, and anchor spacing. The buckling strains plotted in Figures 2, 3, and 4 show that while buckling strain is relatively invariant with change in radius, decreasing the plate thickness and increasing the anchor spacing lower buckling strain significantly. For the three cases considered, the vertical trapezoid mode always controls the buckling strain.

To design the liner to withstand various combinations of loadings without buckling, a plot of buckling strain versus the ratio of circumferential strain to axial strain was used. Plots were made for the nominal dimensions of the structure and for all dimensions being at the most adverse end of the tolerances considered in this study. These plots are shown in Figure 5.

3. Post-Buckling Analysis

3.1 Statement of Problem

If buckling occurs in the liner due to either high temperature associated with accident conditions or a missing or defective anchor, the effect of this failure should be controlled and not propagate to the neighboring anchors. Therefore, in the post-buckling analysis, attention is given to the forces and displacements in the stud anchors. In this study, a one-dimensional model which is similar to the ones used by Doyle [3] and Winstead [4], is evaluated initially. An iterative procedure is used to find the forces and displacements in the anchors. This iterative procedure is required because the stress in the buckled panel depends on the displacements of the anchors next to the buckled panel. Hence, the stress in the buckled panel must be adjusted after every new set of anchor displacement is calculated. In the present study, the stud forces and displacemnts are smaller for lower yield values in the liner. Furthermore, the force and displacement in the head stud next to the buckled panel are found to be maximum for the case assuming no post-buckling capacity in the panel. These same observations were made by Doyle and Chu in their study [3].

An important aspect not considered in the one-dimensional model is the biaxial state of stress. Poisson's effect on the liner deformation may change the forces in the anchors, and the two-dimensional yield criteria may also predict different forces in the anchors. In this study, a quarter of a rectangular plate is modeled by plane stress elements using WECAN [6]. As shown in Figure 6, the plate model is fixed at the top and right-hand edges and roller supported at the left-hand and bottom edges with a buckled panel located at the lower left corner. The model includes sufficient panels to show that the effect of buckling on the panels not adjacent to the buckled panel is neglegible. The thickness of the plate is 0.375 inches with a uniform temperature rise of 266°F. The nonlinear force-displacement relationship for the 3/8 inch anchors used in the analysis is $F = 5660\ (1-e^{-18\Delta})^{0.4}$ [7]. The yield criteria used in the model is based on Von Mises' equivalent stress and strain definitions with the Prandtl-Reuss flow rule. The post-buckling capacity in the buckled panel is neglected for conservatism.

3.2 Discussion of Results

The analysis shows that the thermal stress in the liner plate is so concentrated around the buckled panel that yielding occurs in the adjoining panels. Since the material used for the liner has a large range of yield strength, several different analyses of the two dimensional model are performed. The analyses represent yield strength values of 38 ksi to 60 ksi, as well as an elastic case. The maximum anchor forces and displacements are plotted against yield strength in Figure 7.

Shown in the plot, the forces and displacements are higher for the plate considering plasticity. Because of the effect from the biaxial state of stress in the liner, decreasing the yield strength of the liner plate leads to higher loads in the anchors with an obvious peak occurring around the yield strength of 45 ksi. This result was not predicted by the one dimensional model, where higher yield strength gave higher anchor loads [3].

The importance of this result can be seen by examining the anchor displacements. The variation in the displacements is more pronounced than the variation in the forces due to the nonlinear nature of the force displacement relation for the anchor studs, with the peak value being about 145 percent of the elastic value. Since, for this type of loading, the anchor capacity is based on displacement, it is imperative that plasticity be considered when using a two dimensional model for liner plate analysis.

6. References

[1] T. P. Kicher and M. J. Schrader, "Design Selection of Patterns and Spacing for Stud Anchors Used on Liner Shells", Second ASCL Speciality Conference on Structural Design of Nuclear Plant Facilities, New Orleans, LA, December 1975.

[2] T. C. Esselman, "Buckling of a Point Supported Liner Shell Inside a Concrete Containment", Ph.D. Thesis, Case Western Reserve University, Cleveland, Ohio, June 1973.

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[4] T. L. Winstead, et. al., "Liner Anchorage Analysis for Nuclear Containments", Journal of the Structural Division, ASCE, October 1975.

[5] US Nuclear Regulatory Commission, Standard Review Plant 3.8.1,"Concrete Containment".

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[7] J. G. Ollgaard, et. al., "Shear Strength of Stud Connectors in Lightweight and Normal-Weight Concrete", AISC Engineering Journal, April 1971.

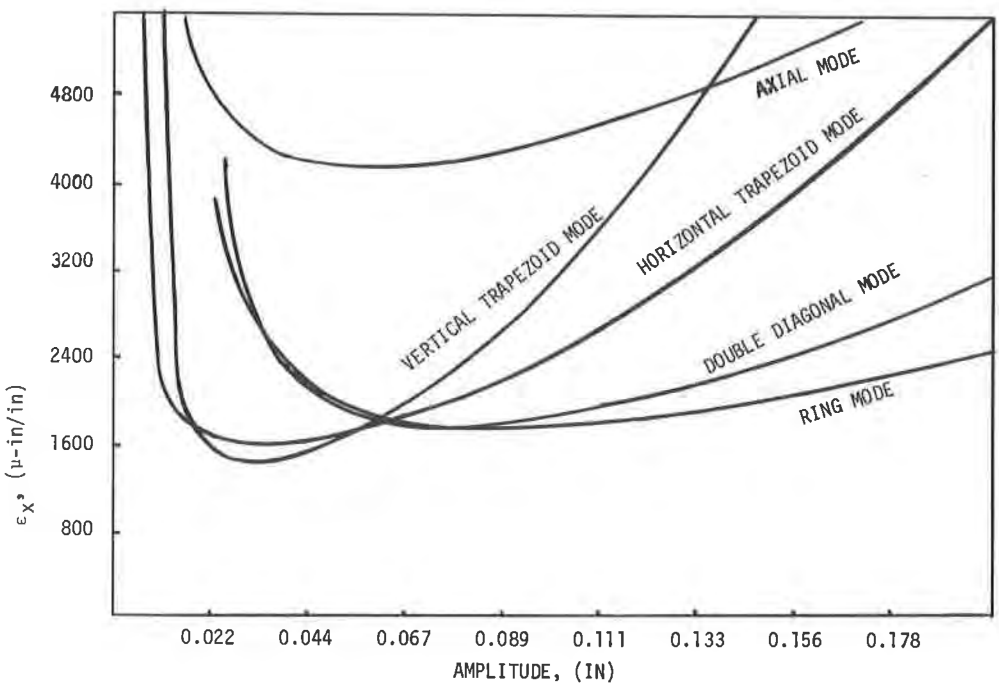
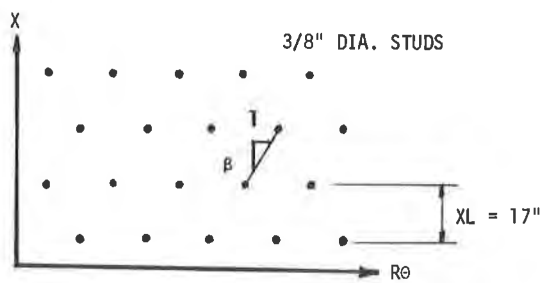


FIGURE 1A: EQUILIBRIUM STATES FOR NOMINAL DIMENSIONS



INSIDE RADIUS OF CONTAINMENT = 840"
LINER THICKNESS = 3/8"
β = 1.7
$\varepsilon_\Theta = \varepsilon_X$

FIGURE 1B: NOMINAL DIMENSIONS

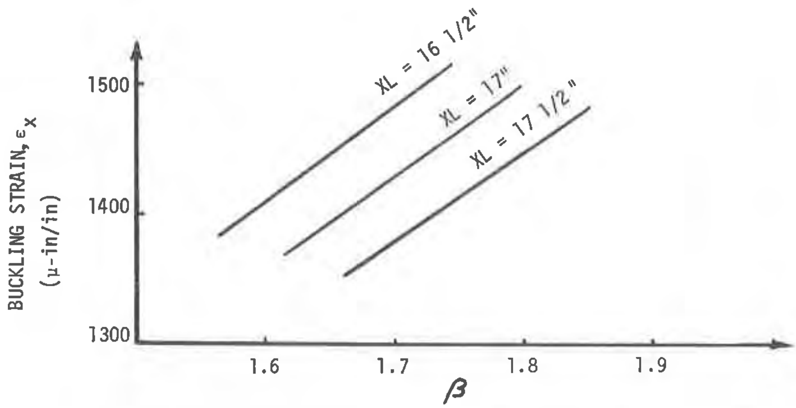


FIGURE 2: BUCKLING STRAIN VS. ASPECT RATIO

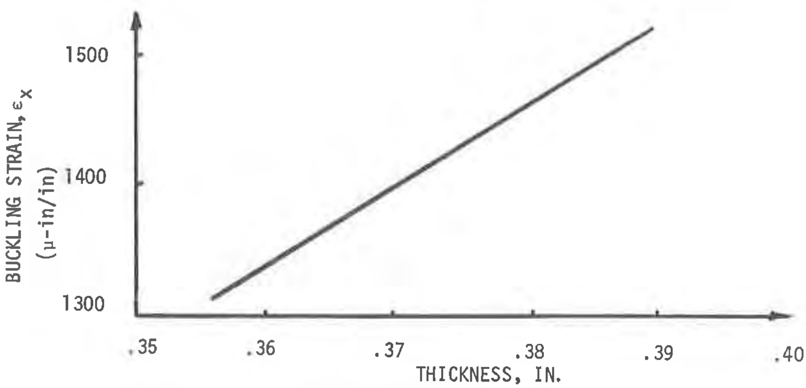


FIGURE 3: BUCKLING STRAIN VS. LINER THICKNESS

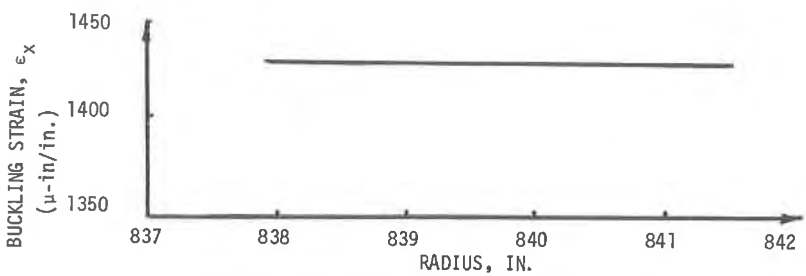


FIGURE 4: BUCKLING STRAIN VS. RADIUS

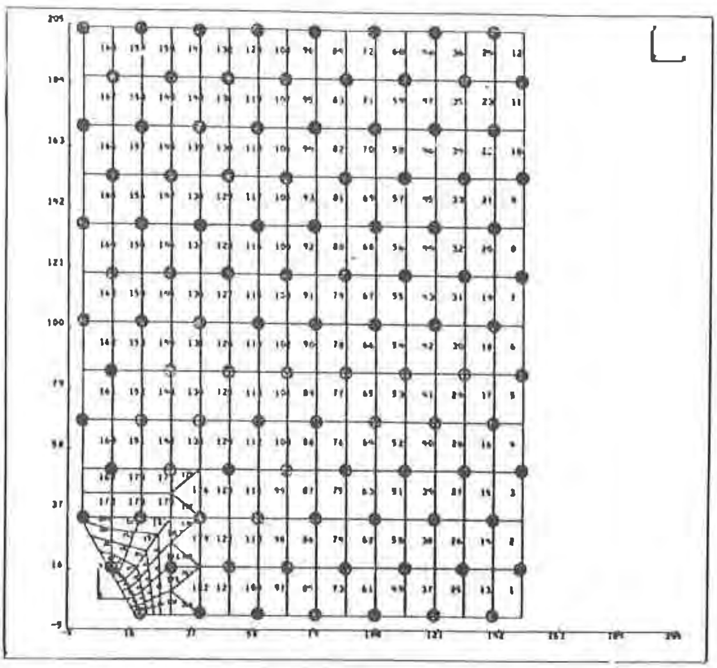


FIGURE 6: TWO DIMENSIONAL FINITE ELEMENT PLATE MODEL

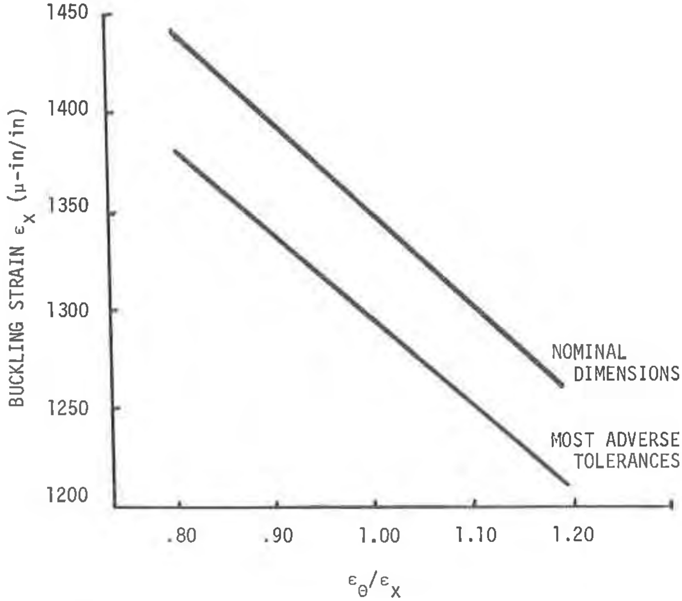


FIGURE 5: BUCKLING STRAIN VERSUS THE RATIO OF CIRCUMFERENTIAL STRAIN TO AXIAL STRAIN

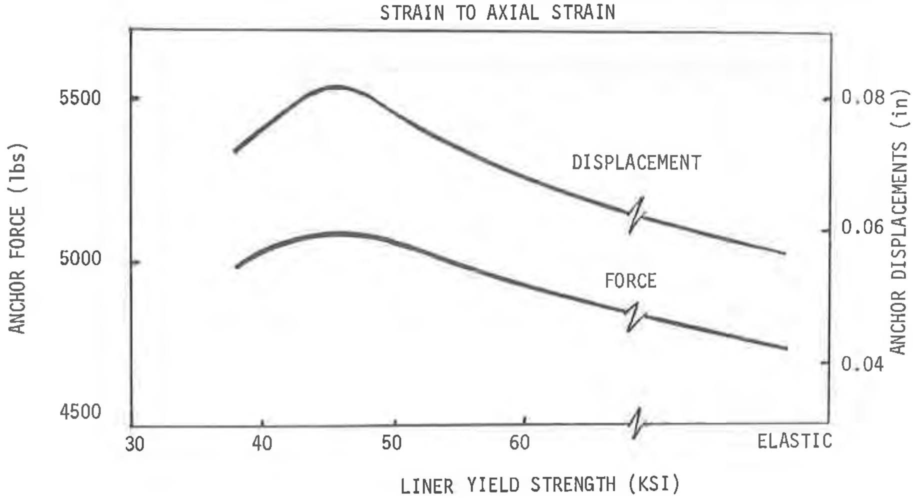


FIGURE 7: MAXIMUM ANCHOR FORCES AND DISPLACEMENTS VERSUS LINER YIELD STRENGTH