Non-Linear Analyses of Steel Plate Liner for LMFBR Cells

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Abstract

Carbon steel liners are provided in cells of an LMFBR plant to mitigate the effects of a radioactive sodium spill. The liner is anchored to the reinforced concrete walls and is subjected mainly to thermal loads during a Design Basis Accident (DBA) sodium spill. Because of high DBA temperatures the liner panels buckle and high plastic strains are induced in the vicinity of the anchorages. DBA design limits are based on the equivalent generalized Von Mises strain not exceeding a fraction of the liner steel uniform elongation. Different buckling patterns are investigated to determine the most critical strain condition, in the wall liner.

1. Introduction

The Radioactive Primary sodium system in a Liquid Metal Breeder Reactor Plant (loop type) is arranged in reinforced concrete cells to facilitate maintenance. These cells are provided with a steel liner anchored to the reinforced concrete walls and slabs and are normally inerted by means of a nitrogen atmosphere to mitigate the consequences of sodium spills. The cell liner protects the concrete structure by precluding the potentially hazardous chemical reaction between the sodium and the concrete. The cell liner has to be essentially leaktight before, during and after the sodium spill accident.

The typical wall liner consists of a carbon plate liner anchored to the concrete by means of stud anchors at 15 inch spacing in both directions, Figure (1). At the corners the liner is anchored to the concrete walls by means of special embedments with welded studs. Between the liner and the structural concrete a four inch layer of precast insulating concrete protects the structural concrete from the thermal effects and a 0.25 inch air gap between the insulating concrete and the liner allows for venting of the water vapor and other gases released by the heated concrete.

This paper discusses the analysis of the liner system, loads, analytical techniques, mathematical models and results.

2. Design Loads and Criteria

The liner design is controlled by the Design Basis Accident (DBA) that consists of a radioactive sodium spill in the nitrogen inerted atmosphere of a cell. The DBA is an extremely unlikely event that has conservatively been postulated in each of the cells having radioactive sodium systems. The entire sodium inventory of a loop has been conservatively postulated spilled during the DBA. As a consequence of the spill, temperatures of approaching 1000^{o}F and internal pressures up to 15 psi develop in the atmosphere of the cells. A behind the liner vent system is designed to limit the pressure on the liner due to water vapor and other gases released from the concrete to 5 psi. The maximum liner temperature is 770^{o}F during a DBA. The dominant effect on the liner are the thermal loads. Immediately after the sodium spill the liner heats rapidly and since it is anchored to and supported by the structural concrete which is still cold, it develops high thermal stresses that exceed the yield stress of the liner material. Yielding of the liner material is also accompanied with buckling of the liner panels.

As a consequence of this buckling, unbalanced forces act on the studs and liner producing large strains. When the sodium cools down, because of the permanent plastic compressive strains experienced in the heat up phase of the accident, tensile strains of approximately the same magnitude as the compressive strains are induced.

The criteria for Design Basis Accident (DBA) conditions is based on limiting the magnitude of the equivalent generalized Von Misses strains. The membrane strains are limited to 0.5 eu whereas membrane plus bending strains are limited to 0.66 eu. Where eu is the uniform elongation from the uniaxial tensile test of the liner material at the temperature (strain at maximum stress in the stress-strain curve). Table I provides the strain allowables for the liner.

Stress strain relationships of the liner material (SA516 Steel, Grade 55) at different temperatures were determined under a Base Materials Testing Program funded by the United States Department of Energy [1].

3. Method of Analysis

Finite element analyses were performed with the computer program ANSYS [2].

The analyses accounts for the material non-linearities by using elasto-plastic finite elements and for the geometric non-linearities by using large deflection theory. The analysis was conducted through an iterative solution technique where the plasticity load vector and the triangularized stiffness matrix were updated in each iteration to account for the combined plasticity and large deflection effects. Plasticity being non conservative and path dependent requires that the actual load history should be well followed. This results in very small load steps in the plastic range of the analysis. Convergence criteria for the plasticity and large deflection were carefully selected to optimize the cost of iterative procedures. Yielding was based on the Von Mises criterion and multiaxial effects were handled with Prandtl-Reuss flow equations.

Equivalent generalized Von Mises strains were calculated for comparison with the design allowables. Material properties used were in the form of temperature dependent stress-strain curves. Bilinear Kinematic hardening was used.

4. Mathematical Models

Various mathematical models were developed to examine different aspects of the liner behavior. Some models involved large areas with relatively coarse-elements while others considered high strain areas in particular at corners, penetrations and embedments in more detail. In general the liner was represented by elasto-plastic triangular shell elements (STIF48). The studs were represented by a combination of a spar element (STIF8) and a three dimensional pipe elements (STIF20) to properly account for the bending and axial stiffness of the stud. The liner-concrete interface was modeled using non-linear gap elements (STIF12 and STIF52). To investigate the strains at the vicinity of the stud when the liner buckles several buckling patterns were examined. A checkerboard pattern was considered the most likely although other patterns were investigated to determine worst possible effects on the strains. The following cases were considered:

a) Checkerboard Buckling: The model consists of a square panel (15 inch square) with a stud at the center. The boundary conditions at the edge of the plate are: free out-of-plane displacement and full restrained in-plane displacement and edge rotation. To induce the desired buckling pattern a one pound force outward force was applied at two opposite diagonal corners. While these corners deflected away from the concrete the other two deflected toward the concrete until they closed the gap. Figure (2) shows the mathematical model and the displacement contours at maximum temperature.

b) Diagonal Checkerboard Buckling: Another checkerboard buckling pattern was investigated with the model shown in Figure (3) Diagonal symmetry was utilized to reduce the model size. One of the corners on the diagonal was forced to deflect outward by a 1 lb. force while the other was deflected inward against the concrete by another 1 lb. force. Figure (3) also shows the displacement contours at the maximum temperature.

c) Asymmetrical Buckling: Figure (4) shows a case of asymmetrical buckling with half a panel and a boundary condition of symmetry along a plane through the stud. A one pound outward force was applied to one of the corners along the plane of symmetry. Displacement contours are shown in the same figure.

d) Axisymmetric Buckling: An axisymmetrical model was used to assess the effects of out-of-plane shear when the liner buckles against the concrete and tends to pull out the stud, Figure (5). STIF42 2D-Isoparametric Solid Elements were used in the plate and stud. The interface (gap) between liner and concrete was represented by STIFF12 elements. The maximum out of plane shear stress is 12.6 ksi or 45% of the yield stress of the material at the temperature whereas the average shear stress acrosss the cross section 8.3 ksi or 30% of the yield.

Similar models were developed in the vicinity of penetrations and embedments and other areas of high strains.

5. Results

In all the analyses performed, the calculated equivalent generalized Von Mises strains were well below the specified limits. Table II summarizes the maximum strains in the liner material. In no case did the maximum liner strain exceed 1/4 of the allowable limits.

References:

/1/ WARD D-0252 "Final Report on Base Materials Tests for Liner Steels" February 1980
/2/ Computer Program ANSYS, Rev. 4 - by Swanson Analysis Inc., Houston, Pa., USA, 1982

TABLE I

STRAIN ALLOWABLES FOR DESIGN BASIS SPILL CONDITIONS

Liner Temp. ($^{\circ}F$)	75	600	800	1000
Membrane Strain (0.50eu)	0.0955	0.1185	0.0815	0.0590
Membrane + Bending Strain (0.67eu)	0.1280	0.1588	0.1092	0.0791

eu = Uniform elongation or the strain at ultimate load. (Ref. 1)

TABLE II

SUMMARY OF MAXIMUM LINER STRAINS

	MAXIMUM STRAIN	
	MEMBRANE (in/in)	MEMB + BENDING (in/in)
Symmetric Buckling	.012	.020
Checkerboard Buckling	.010	.017
Diagonal Checkerboard Buckling	.010	.016
Non-Symmetric Buckling	.010	.022

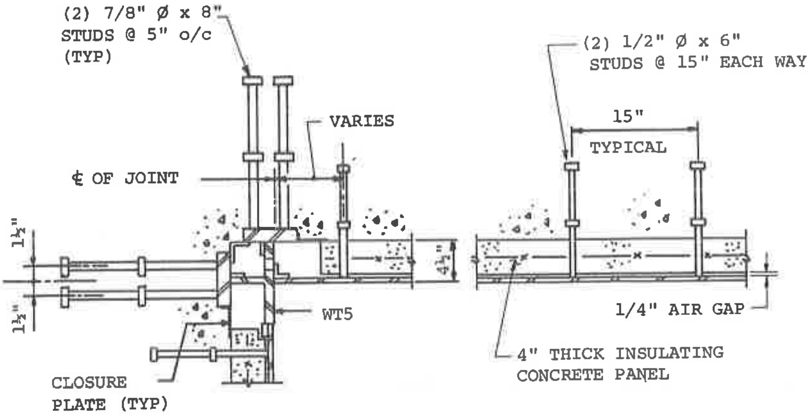

FIGURE 1 TYPICAL WALL LINER

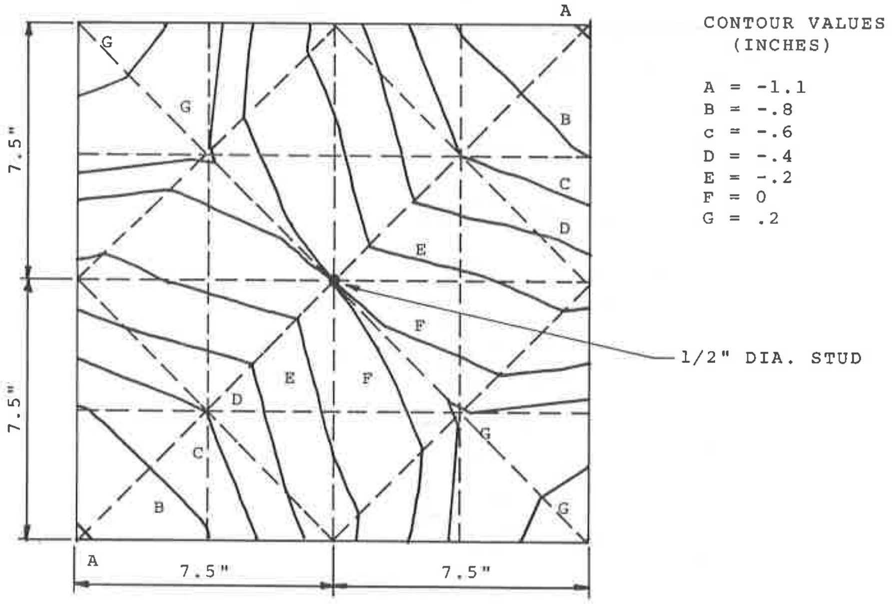

FIGURE 2 WALL LINER - CHECKERBOARD BUCKLING

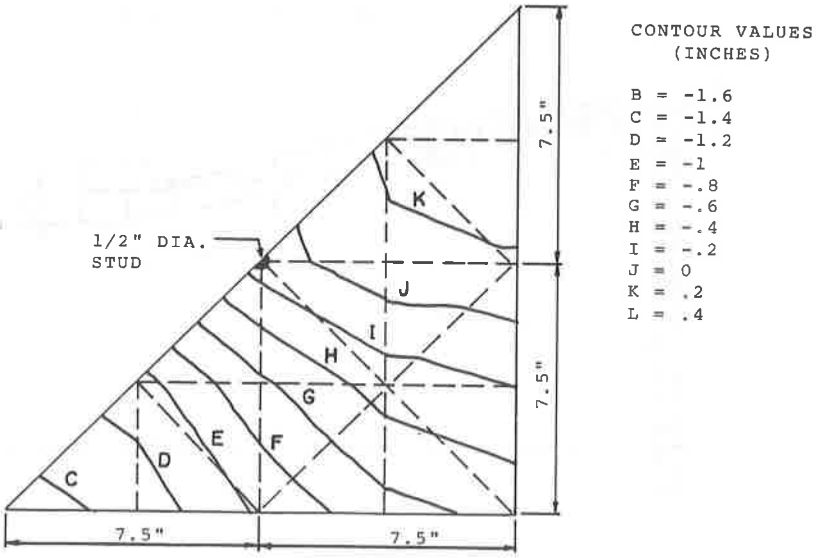

FIGURE 3 WALL LINER - DIAGONAL CHECKERBOARD BUCKLING

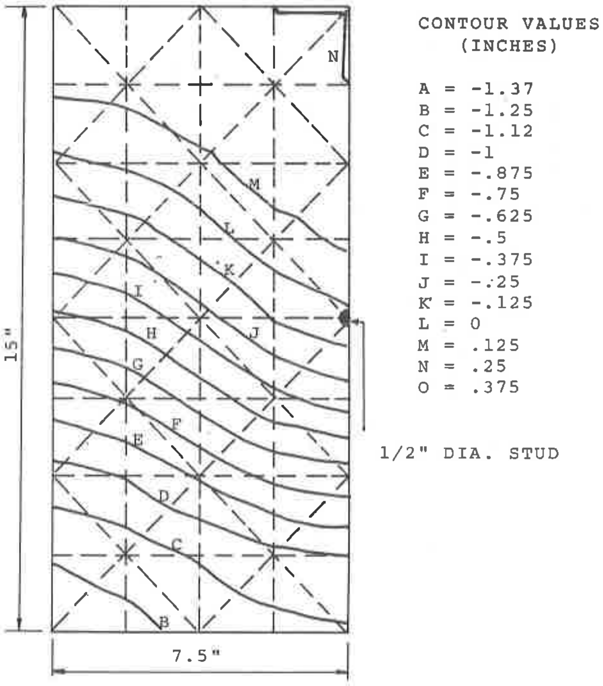

FIGURE 4 WALL LINER - ASYMMETRIC BUCKLING

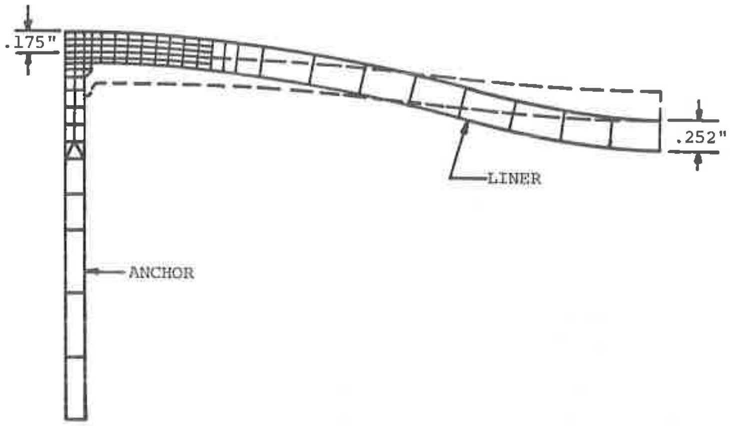

FIGURE 5 WALL LINER - AXISYMMETRIC BUCKLING