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Investigation of Liner Tearing Near Penetrations in a Reinforced Concrete Containment Under Severe Accident Loads

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INTRODUCTION

The inner surfaces of reinforced concrete containment buildings in the United States are lined with steel plate. During a severe accident, the liner plate serves as the main seal for preventing the leakage of radionuclides to the outside environment, while the reinforced concrete provides structural support for the liner. If the liner is torn or punctured during the accident, gases can easily escape through cracks in the reinforced concrete wall. An overpressurization test conducted on a 1:6-scale model of a reinforced concrete containment (Horschel, 1989) has demonstrated that the liner can tear before extensive structural failure occurs in the reinforced concrete.

In the 1:6-scale model experiment, the pressure inside the model was increased to 145 psig. At this point, leakage from the model became so great that the model could not be pressurized further. Inspection of the model revealed that this leakage was due to tears that had formed in the liner at several locations around the building. All of the liner tears observed in the 1:6-scale model initiated next to studs that were used to anchor the liner to the wall of the containment. These tears were located near thickened sections of the liner that were placed around penetrations in the containment shell. Most of the leakage occurred through a single large tear that had grown along the edge of a thickened plate that surrounded a cluster of piping penetrations. This tear is shown in Figure 1.

After the experiment, finite element analyses were conducted to determine the mechanisms that were the primary cause of the large liner breach shown in Figure 1. These investigations strongly suggest that the tear formed as the result of strain concentrations that developed at the base of stud anchors. The elevated strains near the studs were caused by concentrated shear forces that were introduced to the liner through the studs. These shear forces developed as the result of circumferential slippage between the liner and concrete. The slippage occurred because the thickened plate that surrounded the penetration was much stiffer than the thin liner plate.

DESCRIPTION OF THE PENETRATION REGION

The penetration where the largest tear developed was centered at the midheight of the cylindrical section of the containment building. A detail of the thickened region is shown in Figure 2. The liner plate in this region had a nominal thickness of 1/16 of an inch while the thickened plate immediately surrounding the penetration had a nominal thickness of 3/16 of an inch.

Both the liner and the thickened plate were anchored to the wall by headed studs that were welded to the outer surfaces of the plates. The studs in this region were 3/4 of an inch in length and 0.135 inches in diameter. As the concrete wall was cast, the heads and shanks of the studs became embedded in the concrete. The function of the anchorage system is to prevent buckling of the liner for cases in which the liner is exposed to elevated temperatures.

The studs around the penetration were arranged in a square grid pattern as shown in Figure 3. On the liner near the thickened plate and on the thickened plate itself, the studs were placed with a 2 inch × 2 inch spacing. Away from the penetration region, the stud spacing was 6 inches × 6 inches. The 2 inch × 2 inch spacing represents an accurate scaling from a typical full-sized containment, while the 6 inch × 6 inch spacing was used further away from the penetrations as a compromise to reduce the cost of construction. The first column of studs next to the vertical edge of the thickened plate was located approximately 0.5 inches from the edge of the thickened plate.

ANCHORAGE TESTS

Shear tests were conducted to determine the shear strength and shear force–deflection characteristics of the stud anchorage system (Horschel, 1988). The specimens used in these experiments were fabricated by welding studs onto strips of the 1/16-inch liner plate. Concrete was then poured against the face of each specimen so that after the concrete cured the studs were embedded within a concrete block. The specimens were tested by applying load along one edge of the liner plate so that the studs were put into shear. At the failure point, the average force on the studs was approximately 1450 lb. All of the specimens failed either at the weld between the liner plate and stud or in the shank of the stud. None of the specimens developed tears in the liner plate, and none of the liner plates were visibly deformed after the experiment.

FINITE ELEMENT ANALYSES OF THE PENETRATION REGION

Two separate finite element analyses were conducted to determine the primary mechanisms that caused the liner tear to initiate next to the piping penetration. In the first analysis of the penetration region, the anchorage system was entirely neglected. A second analysis was conducted in which the stud anchors were modeled with spring elements.

Only the liner was modeled in these analyses. The motion of the reinforced concrete wall was assumed to be identical to that of an infinitely long, internally pressurized cylinder. This infinite concrete cylinder was assumed to be reinforced by the same amount of vertical, hoop, and diagonal steel as used in the midsection of the 1:6-scale model and uniformly lined with 1/16-inch thick steel plate.

Analysis without anchorage

A quarter-symmetry plane stress model was constructed for the penetration region. In this analysis, it was assumed that the liner was unrestrained by the anchorage system and free to slip relative to the concrete wall of the containment. Displacement boundary conditions were applied along the outer edges of the model. The displacement history on these boundaries was matched to the displacement history that would exist on the edges of a similar section of the infinite cylinder described above.

Figure 4 shows the equivalent plastic strain in the liner at an internal pressure of 145 psig. In this analysis, the strain concentration near the edge of the thickened plate was caused solely by the difference in stiffness between the 1/16-inch thick liner plate and the thicker 3/16-inch plate surrounding the piping penetration. At an internal pressure of 145 psig, the maximum value of the equivalent plastic strain calculated in the analysis was 3%. Based on an empirical failure criterion, the magnitude of plastic strain necessary to initiate a tear is believed to vary from 18% to 30% depending on details of the stress state (Weatherby, 1988). Hence, the mechanisms modeled in this analysis were clearly not sufficient to cause the initiation of the tear.

Analysis with anchorage

In the second analysis of the penetration region, the stud anchors were modeled with an array of spring elements that were attached to a plane stress finite element model of the liner and thickened plate. Each spring element consisted of two nodes. One end of each spring was attached to the liner while the remaining end of the spring was assumed to follow the motion of the reinforced concrete wall. A force-deflection relationship for the springs was defined based on the results of the stud anchor shear tests that were described previously.

The infinite cylinder solution was again used to estimate the displacements of points on the cylinder wall thereby eliminating the need to model the reinforced concrete. The displacements of nodes on the outer boundaries of the model were specified so that the liner motion matched the motion of the reinforced concrete wall at these locations. In addition, the displacements of the nodes representing the concrete side of the stud anchors were prescribed to equal the displacements of corresponding points on the reinforced concrete wall. A more detailed discussion of the boundary conditions can be found in (Weatherby, 1988).

In the analysis, stud forces were generated as the studs tried to force the stiffer 3/16-inch plate to follow the motion of the cylinder wall. Figure 5 shows the relative magnitudes and directions of the forces that the studs exerted on the liner at 145 psig. Figure 6 shows how the load carried in the studs indicated in Figure 5 varied as a function of internal pressure. The ultimate strength was developed in studs on the 3/16-inch plate at pressures below 145 psig. This suggests that these studs may have fractured during the overpressurization test.

The most highly loaded studs on the thinner liner plate were located next to the vertical edge of the 3/16-inch plate. The ultimate shear strength was never developed in these studs. Instead the stud forces reached a limiting value of approximately 1400 lb and then began to decrease with further increases in the internal pressure. At the same time, the equivalent plastic strains in the liner elements directly connected to these studs began to increase at a rate that was much faster than the rate of increase in equivalent plastic strain at other locations in the liner.

Figure 7 contains a contour plot of the equivalent plastic strain in the thinner liner plate at an internal pressure of 145 psig. This figure shows the strain concentration that developed between the 3/16-inch plate and the first column of studs on the 1/16-inch plate. At 145 psig, the maximum principal strain in the thinner liner plate was 7% along the vertical edge of the 3/16-inch plate. The highest strains, however, developed in the liner elements that were directly connected to the studs located closest to the vertical edge of the thickened plate. The equivalent plastic strains in these elements were approximately 25% at 145 psig. Both plate thickness measurements and a visual inspection of the liner indicate that the strains immediately adjacent to the stud anchors were much higher than at other locations. When the calculated strains were compared against an empirical failure criterion, only the elements connected to this first column of stud anchors were found to exceed the failure criterion at 145 psig.

CONCLUSION

During an overpressurization experiment on a 1:6-scale reinforced concrete containment building, a large tear developed near a cluster of piping penetrations. Two finite element analyses were made of this region to develop an understanding of the factors that caused the tear to initiate and to develop an analytical methodology for predicting the initiation of such a tear.

The results of the present investigation suggest that two factors were primarily responsible for creating the tear. First, the higher stiffness of the thickened plate that surrounded the cluster of penetrations caused the liner to slip relative to the concrete. Second, this slippage was resisted by the presence of the stud anchors. The strain concentration induced by slippage alone was not sufficient to cause the liner tear. Concentrated forces from the studs produced the additional strain concentration necessary to cause the tear. The most highly strained areas were located in the 1/16-inch liner plate immedately adjacent to the studs located closest to the vertical edge of the 3/16-inch plate.

ACKNOWLEDGEMENTS

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Figure 1: Liner Tear Near a Piping Penetration in the 1:6-Scale Model

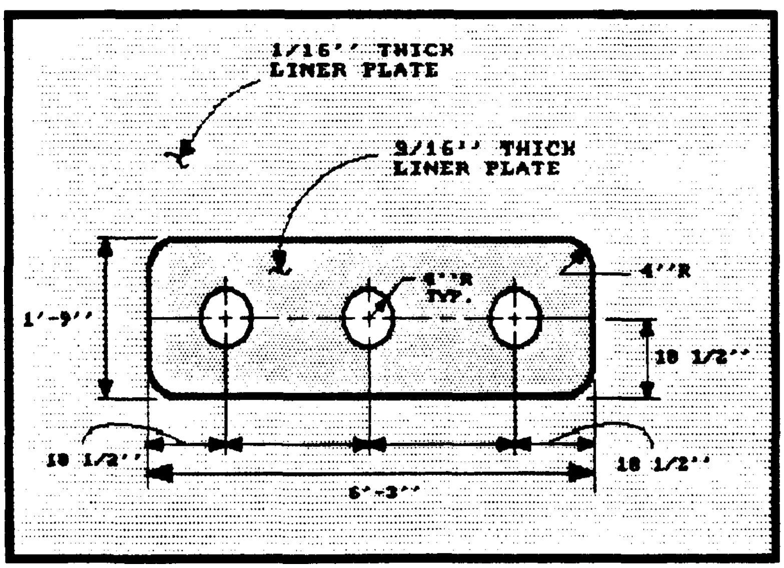

Figure 2: Schematic of the Area Around the Piping Pentrations

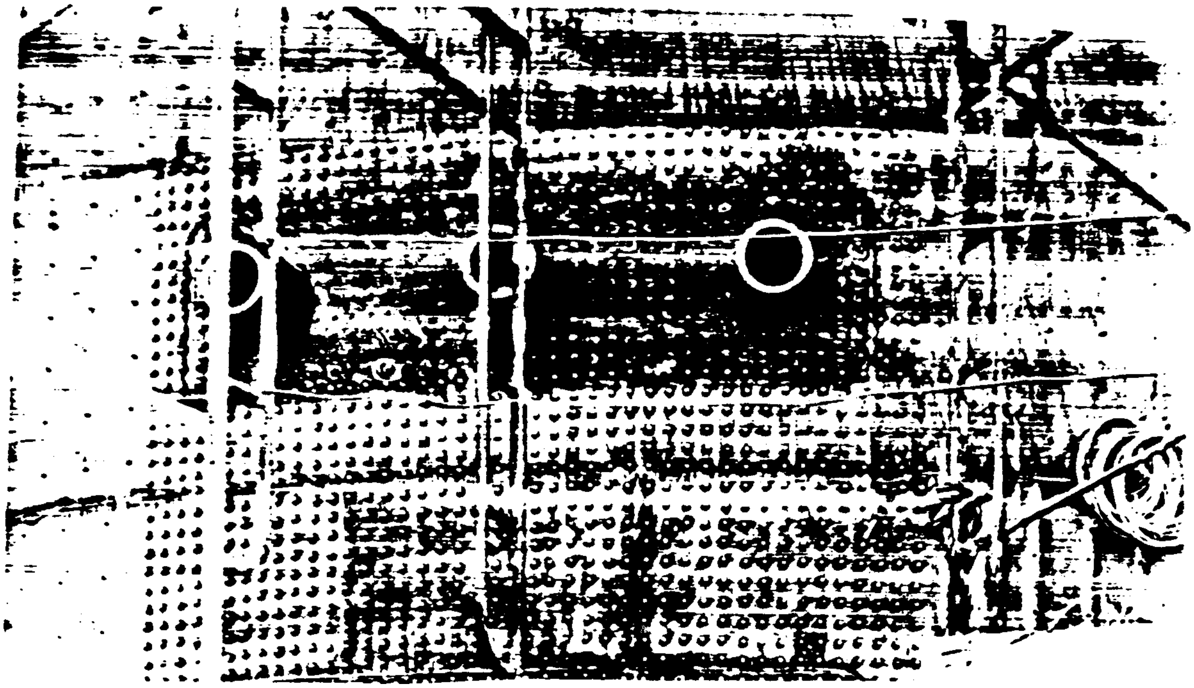

Figure 3: Arrangement of the Studs Around the Piping Penetrations

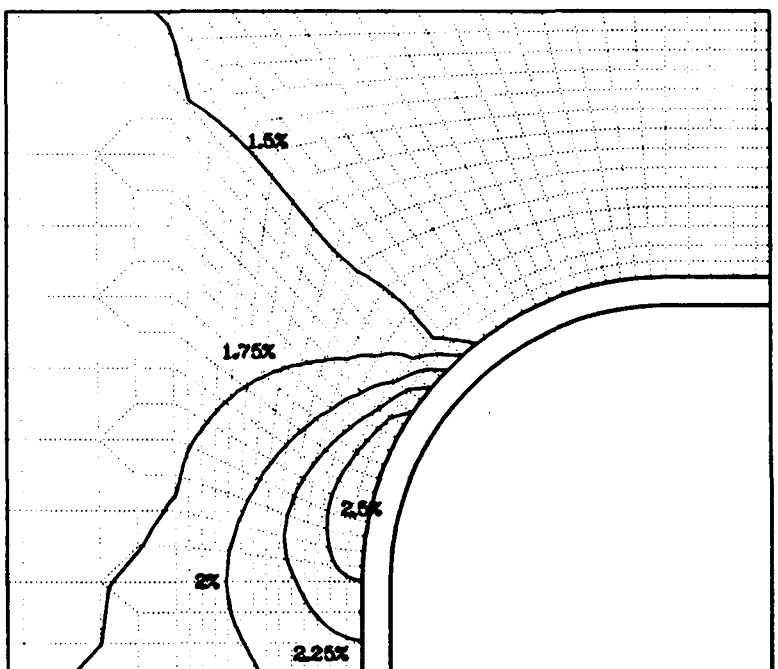

Figure 4: Equivalent Plastic Strain in the 1/16-Inch Liner Plate at 145 psig from Analysis Without Stud Anchors

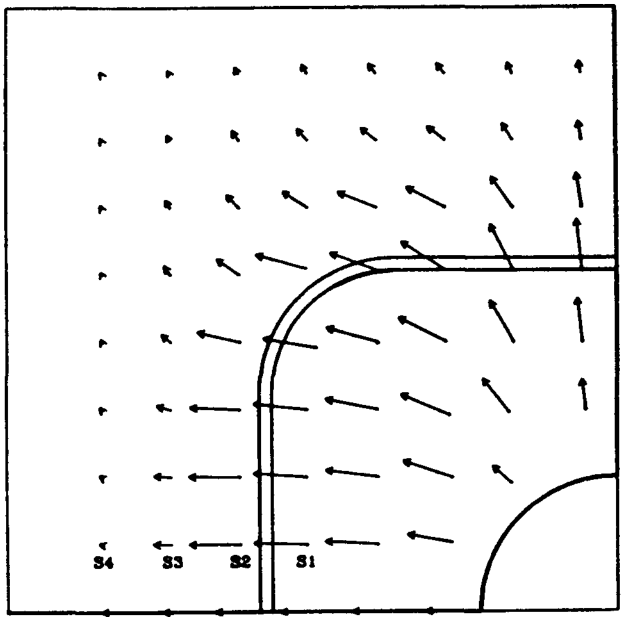

Figure 5: Magnitudes and Directions of the Stud Forces Acting on the Liner at an Internal Pressure of 145 psig

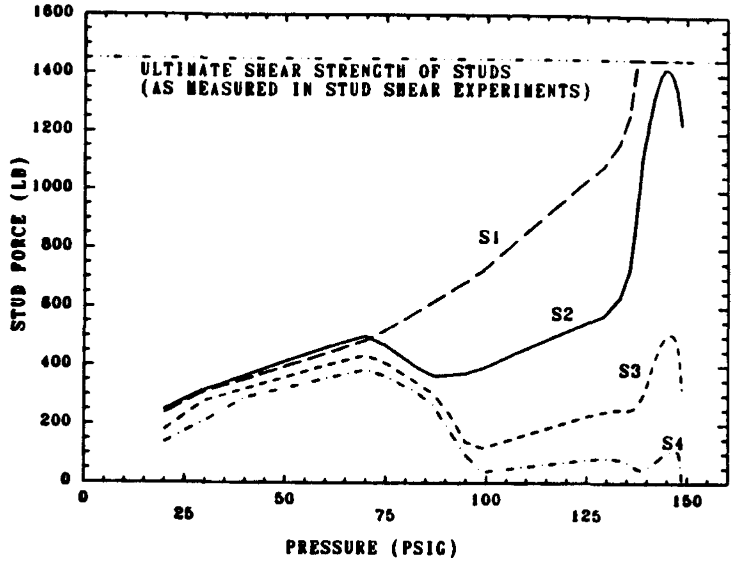

Figure 6: Stud Forces as a Function of Internal Pressure

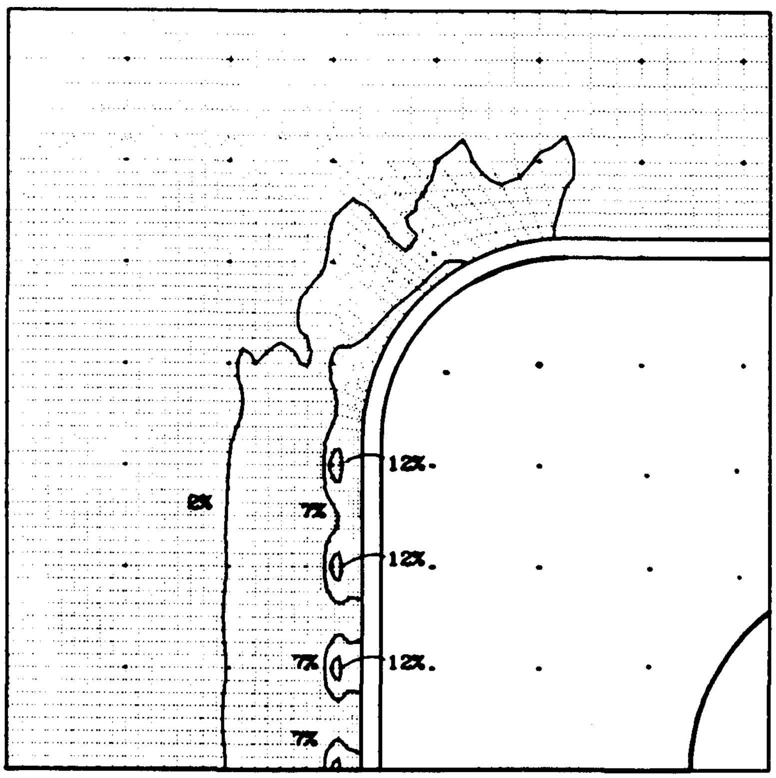

Figure 7: Equivalent Plastic Strain in the 1/16-Inch Liner Plate at 145 psig from Analysis With Stud Anchors