

Results of Full Scale Turbine Missile Concrete Impact Experiments

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Summary

The overall objective of the subject experiments was to provide full scale data on the response of reinforced concrete containment walls to impact and penetration by postulated turbine-produced missiles. These data can be used to validate analytical or scale modeling methods and to assess the applicability of current design formulas to penetration by large, irregularly shaped missiles. These data and results will be used in providing more realistic estimates of turbine missile damage probability in nuclear power plants with a non-peninsula arrangement.

Four full scale experiments were conducted during the period from December 19, 1979 to June 12, 1980. This paper describes the results of the experiments. A separate paper [1] describes the derivation of the test matrix and the method of conducting the experiments.

Of the identifiable independent variables of the problem, only four were varied in this set of experiments. Missile velocity was varied from 90 to 132 m/s; missile mass, from 1476 to 2100 kg; missile attitude, to the two extremes of piercing and blunt; and panel liner thickness, from 0 (no liner) to 9.5 mm thickness. The latter three variables assumed only two values each. The target thickness, reinforcement, and concrete strength were the same in all experiments.

Since these experiments did not include perforations, a damage measure other than the perforation velocity (often called the "ballistic limit") is needed. Several measures of damage are possible. Historically, the most popular is the depth of penetration. Other possible measures include impact crater volume, backface cracking, liner deformation, and shear plug diameter. The use of each of these damage measures may contribute to the understanding of the complex failure mechanisms involved in impact of reinforced concrete structures by missiles of irregular shape.

Penetration depths into the 1.37 m thick panels ranged from 33 cm for the blunt impact of the 1476 kg missile at 92 m/s to 65 cm for the piercing impact of the 2100 kg missile at 115 m/s. The strongest correlation for penetration was with kinetic energy. Predictions using the modified NDRC penetration formula were moderately conservative, agreeing with measured values to within about 30%. Perforation and scabbing predictions were much less accurate, being extremely conservative.

Backface cracking varied greatly from test to test, even showing a marked difference in character with the presence or absence of the steel liner plate. With the liner absent, much superficial cracking was present on the rear face, while the presence of the liner seemed to inhibit such cracking. Impact with a sharp missile attitude caused significantly more severe backface cracking than with the blunt attitude. Intensity of shear plug cracking seemed to correlate most strongly with missile momentum for the same missile attitude. This is largely confirmed by measured strains on the reinforcing bars near the rear face.

Rear face kinematic quantities were measured on one quadrant of the panel. Displacements in excess of 6 cm and velocities in excess of 7 m/s were measured.

Attempts to analytically model the impact process have met with limited success using a finite difference code (CSQII) and no success in using finite element codes (NONSAP-C, MARC). The problem appears to be beyond the current capability of any existing finite element code.

Introduction

The objective of the subject experiments was to provide full scale data on impact and penetration of postulated turbine produced missiles striking reinforced concrete containment walls. These data can be used to validate analytical or scale modeling methods and to assess the applicability of current design formulas to penetration by large, irregularly shaped missiles. These data and results will be used in providing more realistic estimates of turbine missile damage probability in nuclear power plants with a non-peninsula arrangement. The experiments were conducted by Sandia National Laboratories for the Electric Power Research Institute.

The modeling and conduct of the four experiments are described in detail in another paper [1]. Briefly, the target panel in each of the tests represented a section of the wall of a reinforced concrete PWR reactor containment building. The 1.37 m thick panels were fabricated from heavily reinforced concrete with a nominal compressive strength of 26.2 MPa. For each of the last two tests, the panel had a steel plate 0.95 cm thick anchored to its rear surface during construction. This represented the leakproof liner plate installed in all United States concrete PWR containment buildings. The panels for the first two tests were fabricated without steel liners to allow any backface cracking to be visible.

The panels were cast horizontally next to the test facility and rolled into place for testing at the end of a rocket-sled track. They were suspended from a steel frame and supported against a massive concrete and soil backup structure. Tie rods held the panel in place against the 2 foot thick support-structure walls. Dynamic panel response was measured with acceleration, velocity and displacement gages on the panel backfaces, and with strain gages bonded to the reinforcing bars and liner plates.

The first three tests were performed with a 1477 kg, 120° sector of a Westinghouse last stage shrunk-on disk without blades. A heavier 2100 kg, 137° sector of a General Electric disk was used in the fourth test.

The impact velocity in the first test was 90 m/s. This is nominally the same as the exit velocity of the full-scale piercing casing test performed earlier by Sandia [2] and therefore accounts for the substantial energy loss in casing breakthrough. It represents an upper bound on the exit velocity of a fragment from a postulated failure at 120 percent overspeed in the sense that (1) of all possible orientations, the piercing orientation leads to the greatest exit velocity; and (2) the impact velocity in the casing test (150 m/s) was determined by lumping both the translational and rotational energy of the failed fragment into translational velocity. It is also expected that a missile leaving a casing would have a portion of its energy in rotation and would impact the containment building (if at all) in an oblique and non-sharp manner. Hence, the non-spinning, perpendicular, and sharp-end impacts in the concrete tests represent a conservative condition.

Test Results

The crater produced by the 90 m/s impact in the first test is shown in Figure 1 [the checkerboard on the surface has one foot (30 cm) squares]. The missile penetrated 47 cm, about one-third the panel thickness. Rear face damage was limited to cracking as shown in Figure 2 (cracks have been marked for visibility).

Since the impact orientation of a tumbling missile would be random, the effect of impact orientation was examined by turning the missile 90° to strike on its curved blunt edge in the second test. The same impact velocity as in the first experiment produced less penetration, 33 cm. Rear face cracking was similar though slightly reduced; no scabbing occurred in either of the first two experiments.

In the third test, the missile was turned again to strike sharp-end first and the impact velocity was increased to 132 m/s, which corresponds to a disk failure at about 150% overspeed. The missile penetrated 61 cm into the panel and produced a slight bulge (3.8 cm high) in the backface liner plate.

The fourth and final test in the series was performed with a 2100 kg General Electric missile impacting sharp-end first. The test velocity was specified to be the same as in the third test (132 m/s), to produce 40% greater missile kinetic energy. However, because 2 of the 16 rockets misfired, the actual impact velocity was only 115 m/s, producing only an 8% kinetic energy increase over the third test. The slightly greater impact energy produced slightly greater target response. The missile penetrated 66 cm into the wall and produced a 4 cm bulge in the liner plate. Therefore, although the desired increase in impact energy was not achieved, the test result was useful in its demonstration of consistency; even though the missile shapes in the third and fourth tests differed somewhat, a small increase in energy gave a consistently small increase in visible damage. The increase in interior damage from test three to test four, which was visible when the liners were removed from the panels, was more extensive. This difference may relate to the 24% increase in momentum from the third to the fourth test. (It is considered unlikely that the change from welded to hooked stirrups in panel four [1] would have had so significant an effect on the cracking.)

Figure 3 illustrates the rear face cracking found beneath the liner of panel four after its removal. Figure 4 shows a closeup of the area in the ten o'clock position of Figure 3 with some loose pieces of concrete removed. The knife is 14.5 cm in overall length. This dramatically illustrates the efficacy of the liner in containing potentially scabbed fragments. As a further diagnostic of the damage, not reflected in Table I, cores were drilled completely through the panel at ten locations within the damage cone. Figure 5 illustrates the results obtained for one panel. Measurements of the fracture angles at the cores fell within the 30° to 45° range with most being in the 40° to 45° range. Figure 6 schematically illustrates a typical cross-section of a tested panel. Note that the front face crater does not reach to the central layers of rebar and there

is no complete cone apex structure evident. The descriptors of cracking in Table I are in part related to the ability of the plug crack to carry a flow of water during core drilling. Flows indicated the continuous nature of the crack surface but the apex area was not cracked even though crushing was evident. Plug motion was almost precluded by the reinforcing mats.

Table I summarizes the results of all four experiments. Since so much data was recorded it has been necessary to distill it to the most concentrated form possible. Hence the single number entries in Table I require some explanation. Figure 7 is a typical sample of time histories measured for all the kinematic quantities and strains. The tabulated numbers represent maximum values taken from the aggregate of the time histories for each experiment. Figure 8 is a composite plot of the displacements from each displacement and (integrated) velocity record at a specific time. Examination of similar plots at one millisecond intervals clearly indicates the monotonic nature of the motion. The shear plug apparently moves with little bending motion, giving a strong confirmation that the cracking produced was almost entirely due to a shear rather than bending stress condition.

Figure 9 is a plot of missile displacement produced from photometric measurements. From these data the missile velocity at impact is extracted and, although with a lower confidence level, its deceleration during the impact may be inferred. Missile rebound data indicated a loss of kinetic energy greater than 99% during the impact. Figure 10 illustrates the pressure pulse measured internally during the impact. These pressure pulses, measured only on the first two experiments confirmed the greater internal damage potential of the sharp impact over the blunt one, a fact also evident in examining the rear face cracking in experiments 1 and 2.

Comparison With Design Calculations

Design calculations of impact effects are made traditionally using empirical formulas. The most widely accepted is known as the NDRC formula [3,4]. This formula gives penetration depth into reinforced concrete in terms of impact velocity, concrete strength, and missile diameter and weight. Although derived from data on circular cylindrical missiles, the formula is commonly applied to irregularly shaped turbine missiles by using an "effective" diameter. Another NDRC formula gives the wall thickness for incipient scabbing or perforation in terms of penetration depth and missile diameter.

NDRC predictions of front face penetration were close to measured values. For example, the first and third tests, the formula (with an effective diameter of 54 cm and a "nose factor" of 1.0) predicted depths of 47 cm and 68 cm compared with measured depths of 42 cm and 61 cm, respectively. Other standard formulas did less well.

The NDRC formulas were applied to appropriate mass missiles with piercing orientation to calculate the velocities required for scabbing (with no liner) and perforation (with or without a liner). These velocities are plotted against target thickness in Figure 11 and compared with the conditions in the first, third and fourth tests. In the first test no scabbing was produced at 90 m/s whereas the formula predicted incipient scabbing at 40 m/s. In the third test, with a 132 m/s impact, a substantial margin against perforation remained (penetration was less than half the wall thickness), whereas the formula predicted incipient perforation at 104 m/s. Similar results were observed in the fourth test where the 115 m/s impact produced only 65 cm penetration rather than the perforation predicted at 87 m/s. This additional resistance of the panels to scabbing and perforation over that predicted by the design formula may be due to the relatively large amount of reinforcing in the targets and to the inapplicability of the formula for predicting backface damage for missiles with highly irregular shape.

A limited effort was made to determine whether satisfactory analyses using finite element or finite difference techniques could be conducted. No success was obtained with the finite element codes tried (MARC, NONSAP-C) but some limited success was available through the use of a finite difference code (CSQ [5]). Figure 12 shows a two dimensional modeling of test number one which succeeded reasonably well in prediction of penetration but only moderately well in predicting backface kinematics, tending to overpredict displacements and underpredict accelerations.

References

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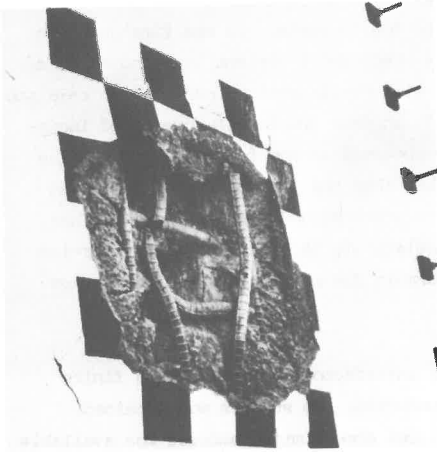


Figure 1. Front-face Crater, Panel 1

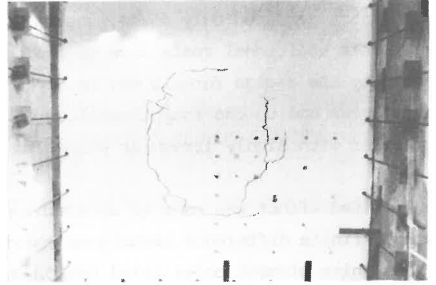


Figure 2. Rear Face Cracking, Panel 1

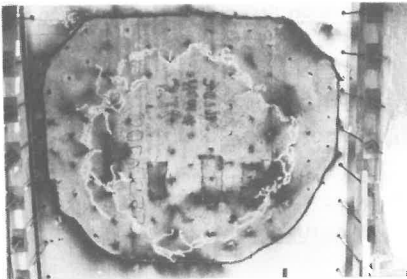


Figure 3. Rear Face Cracking, Panel 4

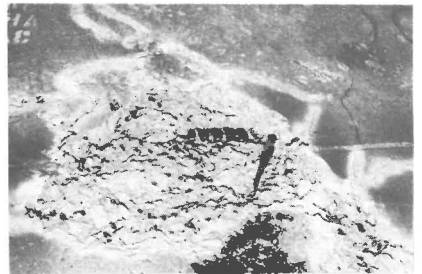


Figure 4. Rear Face Cracking, Panel 4, Closeup

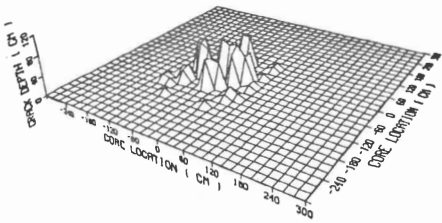


Figure 5. Core Sample Results, Panel 1

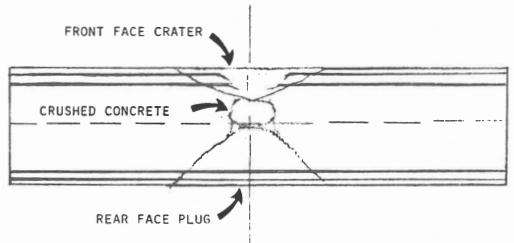


Figure 6. Cross-section of Panel, Schematic

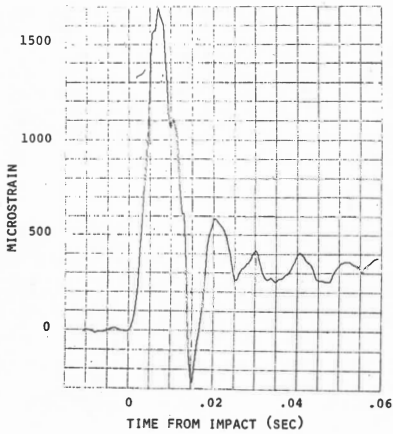


Figure 7. Sample Time History of Rebar Strain, Panel 1

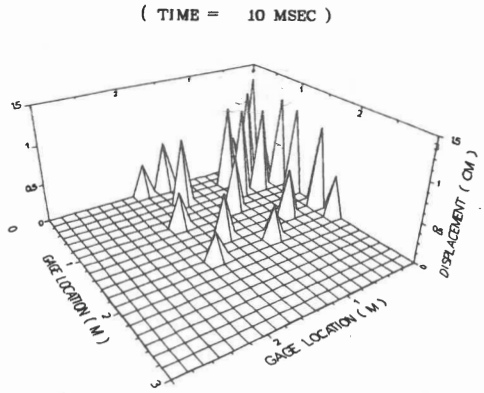


Figure 8. Rear Face Displacement Distribution, Panel 1

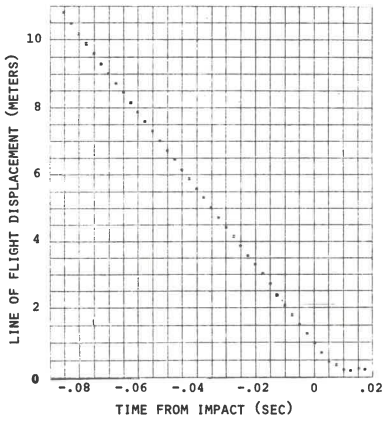


Figure 9. Missile Displacement During Impact Test 4

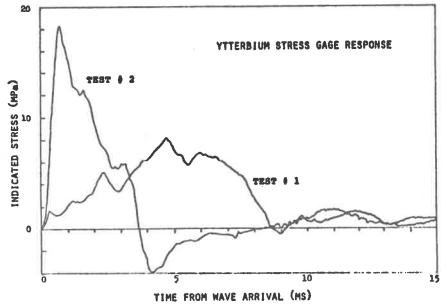


Figure 10. Pressure Pulse in Panel Interior, Test 1

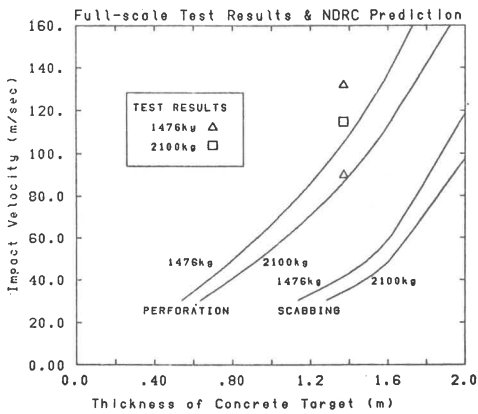


Figure 11. Comparison of Test Results with NDRC Formula Predictions.

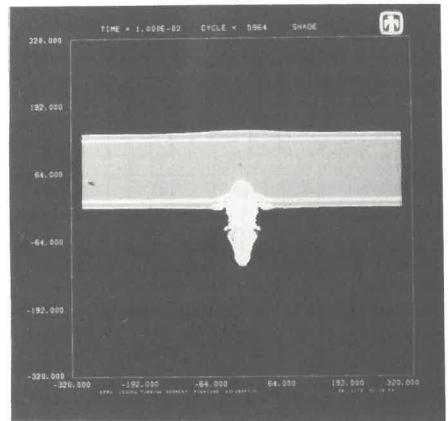


Figure 12. CSQ Penetration Calculation Results (Dimensions in cm)