FULL-SCALE TORNADO-MISSILE IMPACT TESTS*

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SUMMARY

This paper describes a test program in which reinforced concrete panels were impacted by poles, pipes, and rods propelled by a rocket sled. The objective was to generate full-scale data for use in designing nuclear facilities against postulated impacts from tornado-borne debris. Of particular interest was the determination of impact velocities below which reinforced concrete walls are invulnerable to backface scabbing. The panels had thicknesses typical of nuclear power balance-of-plant walls and roofs and were constructed to current minimum standards. Test missiles and velocities included representing current design standards.

The four missile types tested were:

- 1500-pound 35-foot-long utility pole
- 8-pound 1-inch reinforcing bar
- 78-pound 3-inch pipe
- 743-pound 12-inch pipe

The test panels were 12, 18, and 24 inches thick with 15-foot-square unsupported spans. They were constructed with a concrete design strength of 3000 psi (actual strength averaged about 3700 psi) and 0.3% reinforcing steel area each way at each face (12-inch spacing). Panel edges were supported against a 3-foot deep, 1-foot wide reaction beam with grout between the beam and panel to assure uniform support. Load cells behind each corner of the reaction beam measured impact loads transmitted to the 40-ton fixed backup structure.

Desired impact velocities were attained by a rocket-propelled sled which pushed the missile along a 130-foot, wide-flange beam aimed at the center of the panel between reinforcing bars. The sled and rockets were stopped by a bumper at the end of the launcher rail leaving the missile in free flight to the test panel. Test velocities ranged from 92 to 435 fps, bracketing current design velocities.

Test results showed that the utility pole, 1-inch rebar, and 3-inch pipe impacting at greater than current design velocities do not produce backface scabbing even in the thinnest (12-inch) panel tested. The front several feet of the poles disintegrated upon impact without damaging the face of the panels. The 12-inch pipes penetrated the face of the panels, but at the current maximum design velocity (154 fps) caused no backface scabbing (secondary missiles) in 18- and 24-inch panels. For a 12-inch panel the threshold velocity for scabbing was about 95 fps.

Also examined in the 18-test program were the effects of concrete strength and the location and angle of impact. No significant effect of concrete strength was observed over a range from about 3300 to 4500 psi. Local panel response was similar for impact by a 12-inch pipe at the center and near an edge. A 45-degree 222-fps impact of a 12-inch pipe into an 18-inch panel produced only cracks on the backface, whereas perpendicular impact produced scabbing.

The tests included high-speed photography of the impacts and measurements of reaction forces, missile deceleration, panel velocity, and rebar strain during impact.

Measured penetration depths and scabbing thresholds were compared with those calculated with traditional impact design formulae. Only a modified NDRC formula gave results in reasonable agreement with the test data.

* Work sponsored by the Electric Power Research Institute in cooperation with the U.S. Energy Research and Development Administration.

I. Introduction

Until now the design of nuclear power plants for hypothetical impact from tornado-borne missiles had to rely on subscale data [1-3] and empirical formulas derived from military tests [4-6]. Since these tests involved nondeformable projectiles at high velocities (>500 fps), the applicability of the formulas to deformable missiles such as pipes and utility poles at significantly lower velocities has been open to question. The test program described in this paper provides data from full-scale simulated tornado-missile impacts of reinforced concrete walls that can be used directly in plant licensing. In addition, the data can be used to aid the development of improved design and analysis techniques.

The test program consisted of reinforced concrete panels impacted by poles, pipes, and rods propelled by a rocket sled. A specific objective was the determination of impact velocities below which the panels do not experience backface scabbing (generation of secondary concrete missiles). Another objective was to assess the adequacy of conventional penetration design formulas for predicting penetration and scabbing. The panels were constructed to current minimum standards and had thicknesses typical of auxiliary buildings of nuclear power plants. (Reactor containment buildings have 3- to 5-foot thick walls that are more than adequate for tornado missile protection.) Test missiles and velocities included those representing current design standards [7-9].

It is important to interpret the data in this paper recognizing that the test conditions represent conservative assumptions regarding maximum wind speeds, missile injection, aerodynamic trajectory and orientation of missile at impact. For example, tornado experts now agree that maximum wind speeds do not exceed 250 mph [10-12] whereas current design velocities are based on 360-mph winds [9]. Also, during a recent severe tornado in Kentucky [11] utility poles stacked in a position favorable for injection were merely blown off a rack. Thus, it is still questionable whether heavy, slim objects could even become airborne at all.

Even with these severe assumptions, the tests described here demonstrate the ability of prototypical nuclear plant walls and roofs to provide adequate protection against postulated tornado missile impact.

2. Test Description

2.1 Missiles

The four types of missiles evaluated in this program represent a spectrum of debris postulated for design [7]:

- Wooden Utility Pole. 35-foot-long pine pole with a front-end diameter of 13.5 inches. To meet the design criterion, the pole's weight was increased from 920 to 1500 pounds by attaching a ten-foot length of 12-inch pipe as a sleeve on the small (back) end of the pole.
- Steel Reinforcing Bar. 1-inch-diameter, 36-inch-long, grade 60 rebar weighing 8 pounds.
- 3-Inch Steel Pipe. 120-inch-long Schedule 40 pipe weighing 78 pounds. Outside diameter = 3.5 inches; wall thickness = 0.216 inches.
- 12-Inch Steel Pipe. 165-inch long Schedule 40 pipe weighing 743 pounds. Outside diameter = 12.75 inches; wall thickness = 0.406 inches.

Yield strength of the pipes was approximately 75,000 psi.

2.2 Test Panels

The test panels were 12, 18, and 24 inches thick with 15-foot-square unsupported spans. They were constructed with a concrete design strength of 3000 psi (actual strength after curing ranged from 3300 to 4500 psi with an average of about 37000 psi). The panels had about 0.3% reinforcing steel area each way at each face (No. 6, 7, and 8 Grade 60 rebar at 12-inch spacing for the 12, 18, and 24-inch panels respectively; no shear reinforcing). Except for one test, the target point was midway between reinforcing bars.

2.3 Test Facility

As shown in Figure 1 the test facility included a missile launcher, a backup structure to support the test panels, and a reaction beam for determining impact loading.

2.3.1 Missile Launcher

The launcher rail for the rocket propelled pusher sled was a 130-foot, wide-flange I-beam mounted on pedestals for aiming the missile at the desired impact location. Impacts were within ± 0.5 inches of the target point. The beam also provided a support surface (top flange) for the larger missiles (12-inch pipe and utility pole). To prevent these missiles from falling off the top flange, a cage or guide system, attached to the beam, restrained the missile to the rail.

The desired speed for the missile was attained by selecting a launch position on the rail and the number of rockets (up to four) mounted to the pusher sled. The rockets used were High Velocity Aircraft Rockets (HVAR). Velocities attained were within ten percent of the desired velocities for the range covered by these tests.

At the impact end of the launcher, crushable aluminum honeycomb captured the pusher sled and the rockets, leaving the missile in free flight to the test panel. The reaction load from stopping the sled and the rockets was absorbed by a cross beam, anchored to a concrete abutment.

The adaption of each of the missiles to the launcher was made such that the total weight of the missile and attachments remained at the prescribed weight.

2.3.2 Backup Structure

The reinforced concrete backup structure reacted impact loads by means of both its mass (40 tons) and footings that transmitted forces to the ground. The 1-foot thick backup structure was 17-feet square and 8-feet deep. Test panels were supported at the bottom by eight 6-inch wide I-beams embedded in the concrete apron. In the first three tests, grout between the test panel and the backup structure assured uniform support. In addition, turnbuckle and cable ties held the test panel against the backup structure. Since this support arrangement did not permit measurement of reaction loads, a reaction beam was installed for subsequent tests.

2.3.3 Reaction Beam

A 3-foot deep, 1-foot wide reinforced concrete reaction beam was placed between the test panel and the backup structure as indicated in Figure 1. Load cells between the reaction beam and the backup structure at all four corners recorded the total reaction force history caused by the missile impact. This history is a measure of the loading that would be transmitted away from the impact area in an actual structure. The test panel was grouted to the reaction beam and a turnbuckle tie was attached to the test panel, holding both the panel and the reaction beam against the load cells on the backup structure. Load cells were preloaded to prevent liftoff during dynamic response of the panel.

2.4 Instrumentation

Measurement of reaction forces, panel backface velocity, rebar strain, and missile deceleration was achieved by means of both electronic and photographic instrumentation as described below. Electronic data were recorded on digital magnetic tape. The data system provided a 300 Hz recordable response.

Reaction forces were recorded at each corner of the reaction beam by four 150,000-pound capacity load cells. Each cell was preloaded between 6000 and 28,000 pounds by the turnbuckle ties to allow load measurement when the panel tends to rebound from the supports.

An array of six velocity transducers recorded the velocity of the backface of the test panels in the direction of the impacting missiles. These gages consisted of a magnetized core mounted to the test panel and a coil held approximately 1/2-inch from the panel, so that velocity could be measured to a displacement of 1/2 inch.

Three strain gages welded to reinforcing bars measured strain during impact. The gages were specially designed and jacketed for use in concrete.

High-speed motion photography (up to 3000 frames per second) was used extensively in each test to record (1) the motion of the missile before, during, and after impact; (2) the motion of backface spall products; and (3) documentary coverage of the test. Photographic measurements provided missile velocities before impact and missile deceleration histories during impact. These data were used to determine the force history applied to the panels. (See Section 5).

2.5 Test Velocities

In general, test velocities for each missile type were selected to be equal or less than currently postulated tornado-missile design velocities. In the early stage of the test program design velocities were specified by the USNRC as 317 fps for the one-inch rebar and 211 fps for the other three missile types [7]. Therefore, test velocities were selected from among nominal velocities with 40 percent increments: 100, 150, 210, and 300 fps. Near the conclusion of the program the USNRC lowered design velocities to 167 fps for the one-inch rebar, 180 fps for the utility pole, and 154 fps for the 12-inch pipe [8]. Fortunately, the revised velocity of the 12-inch pipe was close to the nominal test velocity of 150 fps used in several tests. Because the other three missiles produced only minor panel damage at the original high design velocities, there was no need to repeat the tests at the revised lower design velocities.

With one minor exception, each panel was impacted only once.

3. Test Results

A summary of the conditions and results for the 18 full-scale tests is given in Table 1. As indicated in the table, impact response experienced by the test panels can be categorized in terms of backface damage as follows:

- No Damage
- Cracks
- Flaking
- Scabbing
- Perforation

Secondary missiles generated

In both the flaking and scabbing categories, pieces of concrete are dislodged from the backface. The term flaking means that the pieces merely dropped to the base of the wall. The term scabbing means that the pieces were imparted a velocity and were thrown some distance from the wall. Since nuclear plant walls and roofs must be designed to prevent the generation of secondary concrete missiles inside the plant, response categories up to and including flaking satisfy the impact design requirement.

Data from the tests with normal midpanel impact are shown graphically in Figure 2. The results show that the utility pole, 1-inch rebar, and 3-inch pipe impacting at greater than current design velocities do not produce secondary missiles even in the thinnest (12-inch) panel tested. The front several feet of the poles disintegrated upon impact without damaging the face of the panels (Figure 3). The 1-inch rebar and 3-inch pipe penetrated the face of the panels and produced only minor cracks on the backface.

Impact tests with 12-inch pipes showed that at the current Region I design velocity (154 fps [8]) no secondary missiles are produced in 18- and 24-inch panels. A 202-fps impact caused only backface cracking in a 24-inch panel (Figure 4). A 152 fps impact caused backface flaking in an 18-inch panel; i.e., a piece of concrete became dislodged and fell to the base of the panel (Figure 5). For a 12-inch panel, the threshold velocity for scabbing was about 95 fps, which is slightly greater than the current design velocity for Region II.

To examine the effect of concrete strength on impact response, three panels (test numbers 12, 17, 18) were fabricated with a 5000 psi concrete mix instead of the 3000 psi mix used for all of the other test panels. However, the average strength of the "high strength" panels on the day of test was only 4490 psi. Nevertheless, some conclusion regarding the effect of concrete strength can be obtained from the data. Consider the following results of two tests with a 12-inch pipe impacting 18-inch panels:

Test No.	Velocity	Concrete Strength	Penetration	Missile Deformation
4	198 fps	3560 psi	6.8 inch	3.8 inch
12	203 fps	4535 psi	7.5 inch	4.0 inch

Although conventional impact formulas (see Section 4) would predict a smaller penetration for the higher-strength panel, the opposite was observed. Thus, we note that over the range tested (about 3300 to 4600 psi), the effect of concrete strength was too small to be detected.

To examine the effect of location of impact, a 12-inch panel was impacted by a 92 fps, 12-inch pipe both at the center of the panel and 30 inches from one edge along the panel centerline. Examination of the test results (Nos. 14 and 16) shows virtually the same response in each. Both had backface flaking (small pieces of concrete fell to the base of the panel). Penetration was 3.5 for central impact compared with 3.9 for near-edge impact.

To examine the effect of off-normal impact, an 18-inch panel was struck at its center by a 12-inch pipe at 222 fps with its line-of-flight inclined 45 degrees with respect to the panel surface (test No. 19). As expected, penetration was reduced appreciably--4.3 inches compared with 7 to 9 inches from normal impacts at slightly lower velocities (test Nos. 3, 4, 12, 18). More important, backface damage was reduced from scabbing (with normal impact) to cracks (with off-normal impact).

4. Comparison With Penetration Formulas

Traditionally, empirical penetration formulas have been used in the tornado impact design of nuclear power plant facilities. The most commonly used penetration formula for concrete has been the Petry formula [6]; however, the National Defense Research Committee (NDRC) formula [13] is presently coming into wider acceptance. Both were derived by empirical means from military tests of nondeformable projectiles at relatively high velocities (>500 fps). Thus, the applicability of these formulas to deformable missiles such as pipes and utility poles at lower velocities has been open to question. In this section we compare the results of the full-scale tests with the prediction of the Petry and NDRC formulas.

Since both formulas include the diameter of a solid missile, the question arises as to what diameter to use for hollow pipe missiles. Two alternatives exist: (1) the outside diameter of the pipe or (2) an effective diameter based on the actual metal area of the pipe. The first of these alternatives is the one most often used in design practice.

Presented in Table 2 is a comparison of measured and computed penetration depths for the steel rebars and pipes.* Computed penetrations are based on the outside diameter of the pipe, with values based on the actual metal area of the pipes shown in parentheses.

It is apparent from the values in Table 2 that the NDRC formula, using the outside diameter, predicts the actual penetration depths remarkably well. On the other hand, the Petry formula predicts penetration depths which have little resemblance to measured values regardless of which diameter is used.

No comparisons are shown for the utility poles because the formulas are inapplicable to these highly deformable missiles. The formulas would predict several inches of penetration, whereas the poles did not penetrate the panels at all.

The Petry and NDRC formulas have also been extended to predict the minimum thickness t_s of a concrete panel needed to prevent scabbing. Neither formula as used conventionally was able to match the test data for scabbing. However, if one takes t_s as three times the penetration depth predicted by the NDRC formula, reasonable agreement with the data for 12-inch pipes is obtained. It is important to note that because the threshold of scabbing was determined only for the 12-inch pipe missile, the adequacy of the conventional formulas for predicting scabbing from other missile types was not determined.

5. Structural Response Data

In addition to the full-scale data on local impact response reported above, the tests provided information regarding overall structural response of the panels. The extensive electronic and photographic data on structural response collected in this program are reported in [14]. Among the most useful data are the time histories of the impact force acting on the missiles and the resulting panel reactions.

The impact force on the missiles was found by multiplying the missile mass by the acceleration obtained by double differentiation of displacement histories read from high-speed film. A typical acceleration versus time curve for a 12-inch pipe impact is shown in Figure 6. As indicated by the dashed lines, the acceleration (or force) history can be approximated by an isosceles triangle (in contrast to the commonly made assumption of a rectangular impact force history). For the 12-inch pipe impacts, the missile force duration ranged from about 9 msec for a 24-inch panel to 15 msec for a 12-inch panel. For the utility pole the force duration increased to about 70 msec.

Typical records of panel reaction histories at the four corners are shown in Figure 7.

*The measured strength of each panel was used to compute the penetration depths with the factor N in the NDRC formula taken as 0.84.

For the 12-inch pipes the duration of the main reaction pulse ranged from 20 to 30 msec and the sum of the four peak reactions was typically about one half the peak applied impact force.

The force data described above, together with panel velocity/strain measurements and observed damage, indicated that structural response of the panels was much less than would be predicted by current nuclear plant design methods. The data showed that for the typical panels tested in this program, provision of adequate thickness to prevent scabbing will assure adequacy on the basis of overall structural response.

Acknowledgment

Results from impact penetration calculations were provided by Professor E. Burdette of the University of Tennessee.

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Table I

SUMMARY OF TORNADO IMPACT TEST DATA

TEST NO.	MISSILE	WEIGHT (lb.)	VELOCITY (fps)	MAX. MISSILE DEFORMATION (in.)	PANEL THICKNESS (in.)	CONCRETE STRENGTH (psi)	FRONTFACE PENETRATION (in.)	BACKFACE DAMAGE
6[(a)]	Utility Pole	1500	205	50.5	18	3770	0	Cracks
7	Utility Pole	1470	204	69.4	12	3620	0	Cracks
1	1" Rebar	8	303	0	18	3650	3.6	No Damage
13	1" Rebar	8	435	0	12	3545	5.8	Cracks
5	3" Pipe	78	212	1.9	12	3340	4.6	Cracks
8	12" Pipe	743	202	1.8	24	3795	6.8	Cracks
3	12" Pipe	743	202	3.8	18	3350	7.0	Scabbing
4	12" Pipe	743	198	3.8	18	3560	6.8	Scabbing
12	12" Pipe	743	203	5.0	18	4535	7.5	Scabbing
18[(b)]	12" Pipe	743	213	2.5	18	4420	9.1	Scabbing
19[(c)]	12" Pipe	743	222	9.1	18	3900	4.3	Cracks
17	12" Pipe	743	157	0.25	18	4070	4.1	Flaking
15	12" Pipe	743	152	0.13	18	4205	5.3	Flaking
9	12" Pipe	743	143	2.1	18	4325	5.0	Cracks
10	12" Pipe	743	143	0	12	3690	12.0	Perforation
11	12" Pipe	743	98	0	12	3595	4.5	Scabbing
16	12" Pipe	743	92	0	12	3350	3.5	Flaking
14[(d)]	12" Pipe	743	92	0	12	3545	3.9	Flaking

(a) Ballast pipe attachment broke; full weight not effective.
(b) Impact at rebar intersection
(c) Impact 45^{o} to panel face.
(d) Impact near panel edge.

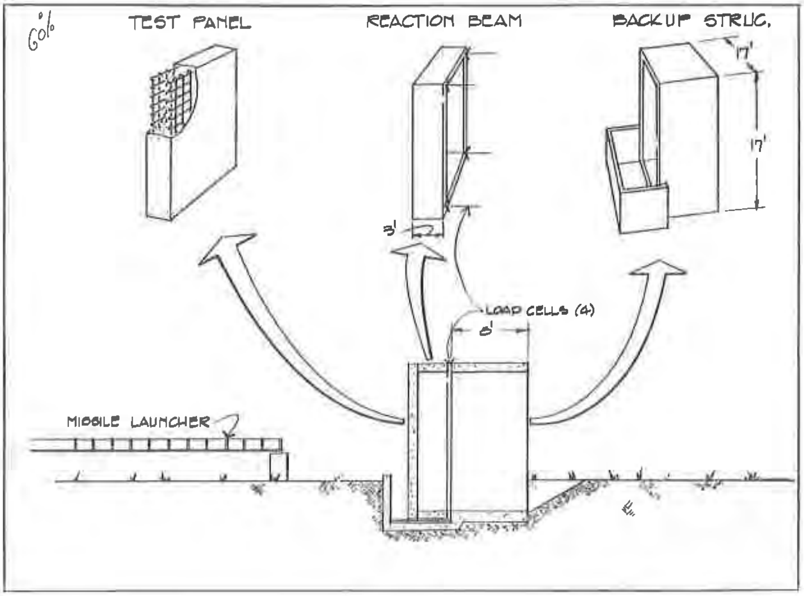
Table II

COMPARISON OF MEASURED AND COMPUTED PENETRATION DEPTHS

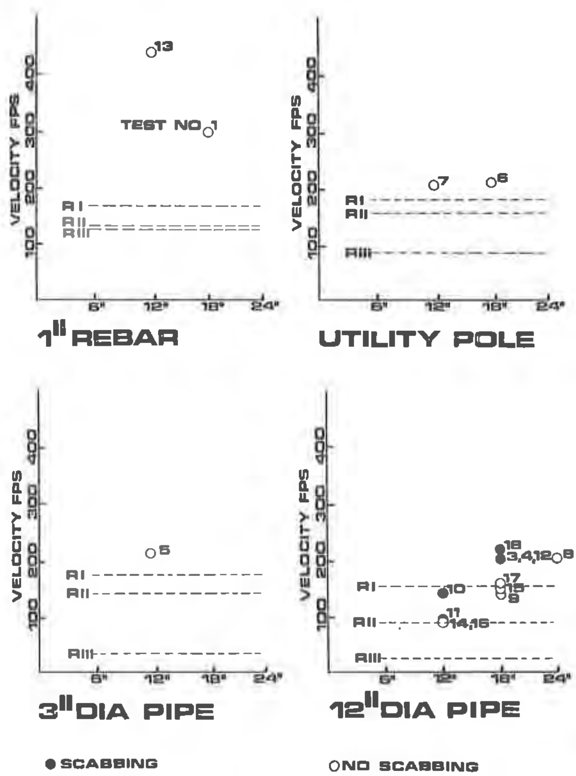
		MISSILE CHARACTERISTICS		PANEL CHARACTERISTICS		PENETRATION (in.)		
NO.	TYPE	WEIGHT (lbs.)	VELOCITY (fps)	THICKNESS (in.)	CONC. STRENGTH (psi)	ACTUAL	NDRC[a]	PETRY[a]
1	1" rebar	8	303	18	3650	3.6	3.2	13.0
13	1" rebar	8	435	12	3545	5.8	5.0	12
5	3" pipe	78	212	12	3340	4.6	4.2 (6.2)	3.7 (>12)
3	12" pipe	743	202	18	3350	7.0	7.6 (11.4)	2.4 (>18)
4	12" pipe	743	198	18	3560	6.8	7.3 (11.1)	2.4 (>18)
12	12" pipe	743	203	18	4535	7.5	7.0 (10.7)	1.7 (>18)
8	12" pipe	743	202	24	3790	6.8	7.3 (11.1)	2.2 (>24)
9	12" pipe	743	143	18	4320	5.0	5.2 (7.9)	1.1 (12.9)
10	12" pipe	743	143	12	3680	Perforated	5.4[b] (8.2[b])	1.2 (>12)
11	12" pipe	743	98	12	3595	4.5	3.9 (5.8)	0.5 (4.3)
14	12" pipe	743	92	12	3545	4.5	3.7 (5.6)	0.5 (4.5)
15	12" pipe	743	152	18	4205	5.3	5.5 (8.4)	1.2 (>18)
16	12" pipe	743	92	12	3350	3.5	3.7 (5.6)	0.5 (4.6)
17	12" pipe	743	157	18	4255	4.1	5.6 (8.6)	1.3 (>18)
18	12" pipe	743	213	18	4690	9.1	7.2 (11.1)	2.0 (>18)

[a] Parentheses denote use of metal area ($d = d_e$) in formulas.

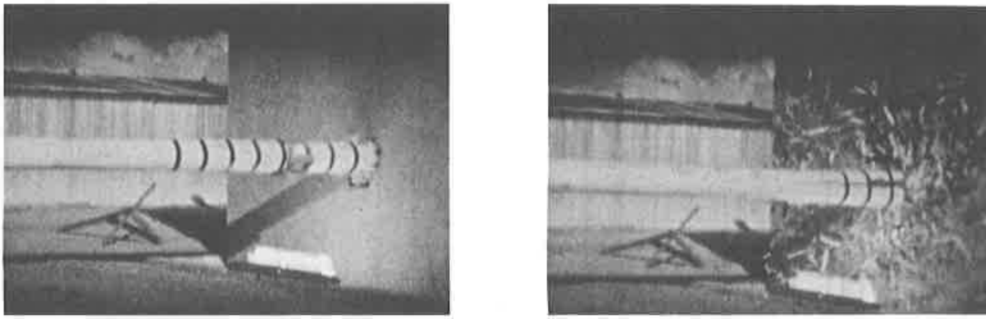
[b] NDRC predicts performation.



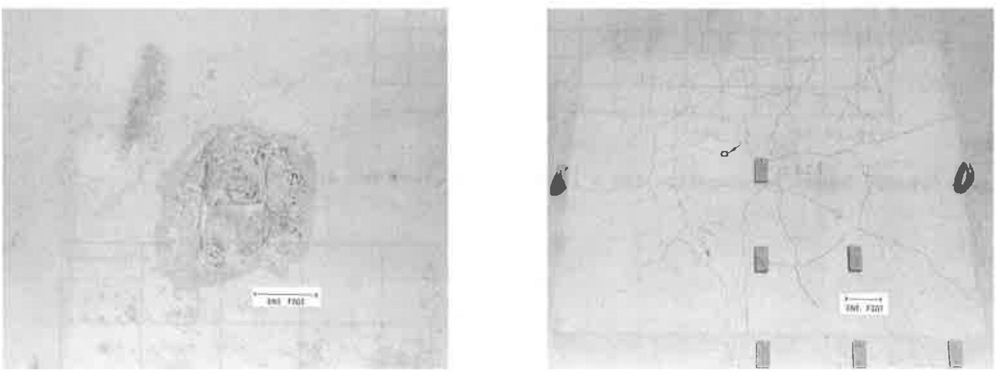
1. Arrangement of Test Facility



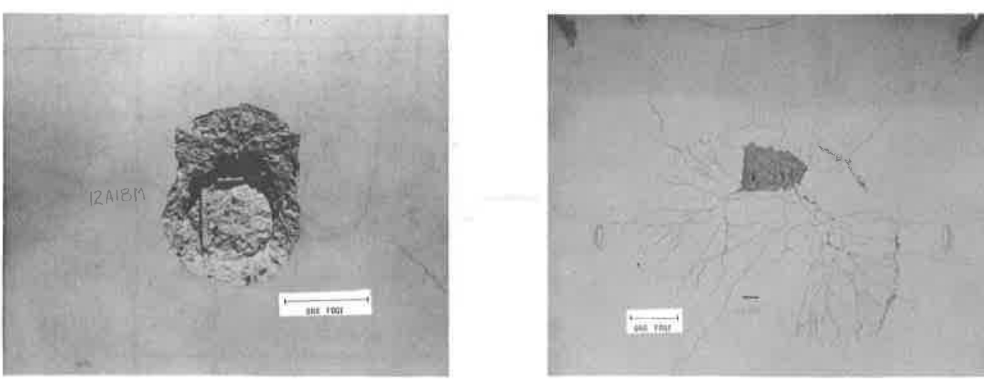
2. Graphical Summary of Results



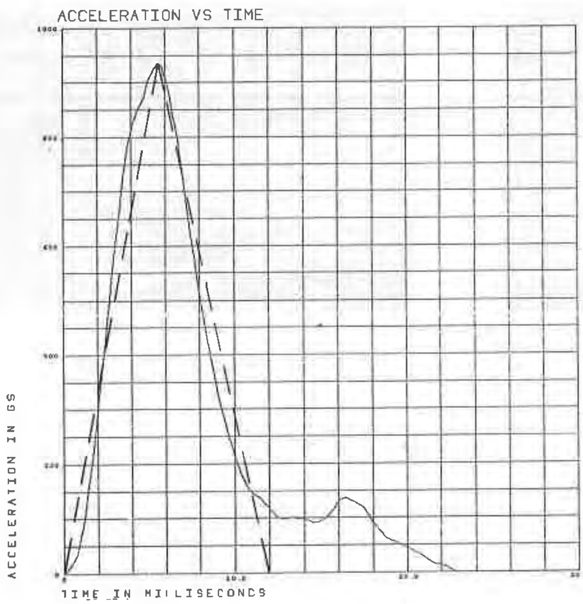
3. Frames from High-speed Film of 204 fps Utility Pole Impact (Test No. 7)



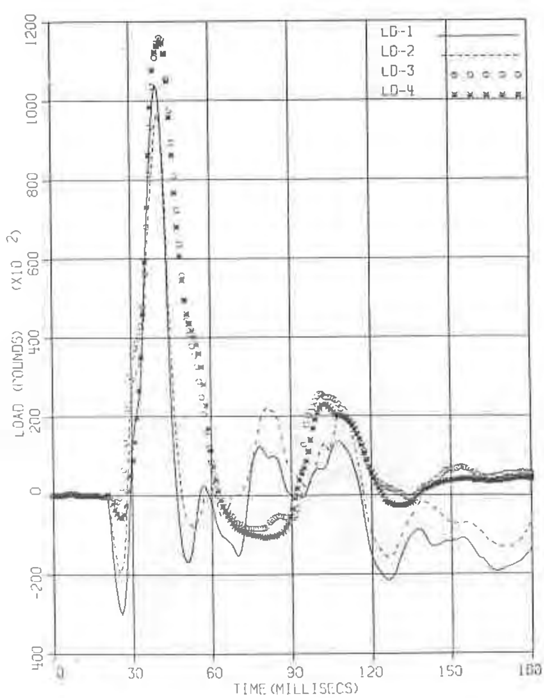
4. Impact Response of 24-inch Panel to 202 fps 12-inch Pipe (Test No. 8) (a) Front (b) Back



5. Impact Response of 18-inch Panel to 152 fps 12-inch Pipe (Test No. 15) (a) Front (b) Back



6. Typical Impact Acceleration for a 12-inch Pipe (Test No. 4)



7. Typical Reactions from a 12-inch Pipe Impact (Test No. 4)