# STRUCTURAL DEBRIS EXPERIMENTS AT OPERATION MILL RACE

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Abstract. Structural debris patterns as determined by the mechanisms of building collapse under airblast loading have been studied experimentally at MILL RACE, White Sands, N.M. Three near full-size buildings were instrumented to observe deflections, accelerations and air pressures and exposed to two different regimes of incident blast pressure produced by HE simulating 1 kt, viz., 10 and 30 psi; after the shot enough wall debris was located and identified to provide estimates of debris movement. Two of the test buildings were unreinforced, load-bearing masonry, one located at each of the two incident overpressures. The third buiding was made of reinforced concrete panels and was exposed to approximately 25 psi. Preliminary estimates of the effect of arching on debris energy and distribution are presented.

## INTRODUCTION

Knowledge of airblast debris distribution has many uses in civil defense planning. Moving debris is itself a hazard to structures and people; it may influence fire initiation and spread and its ultimate resting place will determine access to and usefulness of the site after attack. And certainly in regions of high blast overpressure the most plentiful kind of debris will be that originating in the buildings of the area. For the purpose of studying the production of structural debris three near full size buildings of two different types were exposed to airblast during the MILL RACE event in the pressure regime 10 to 30 psi. These buildings were instrumented with pressure and deflection gages and accelerometers to document the airblast loadings and the structural response. Final resting places of some of the debris also was recorded. Preliminary analysis of these data has told us how these particular kinds of buildings come apart in an airblast and where their parts go. More complete data than we can report here can be found in DNA Project Officer's Report 7077 soon to be published.

## DESCRIPTION OF THE BUILDINGS

Two of the structures were nearly identical load-bearing masonry retangular buildings facing ground zero, one at 10 psi free-field overpressure and the other at 30 psi. Plan dimensions were 16 by 12 feet, the short dimension aligned with the radius from ground zero. Height was 8 feet. The front wall contained two windows 40 by 32 inches in dimension. A heavy overburden on all four walls was supplied by a reinforced concrete ceiling 10 inches thick. There was a door in one sidewall.

The third building was a reinforced concrete "tilt-up" scaled down by a factor of two from an actual industrial design and located at approximately 25 psi. Dimensions were 13 by 17 feet in plan and 6 feet 8 inches in height. Ceiling was made of reinforced concrete "Double Tee" beams four feet on center. The structure was held together with embedded welding plates.

## POST-SHOT SURVEY

Airblast effects on the two load-bearing buildings were dramatically different. While 10-psi destroyed all walls and brought the ceiling down on the floor slab, the

30-psi blast blew front and sidewall material nearly 200 feet off the site, overturned the ceiling slab and carried it downwind of the floor slab.

Sidewalls at both sites travelled directly laterally (i.e., perpendicularly to the direction of the blast) in focussed streams while rear walls moved rearward. At 30-psi the rearwall was punched out by interior pressure and its fragments displayed a pattern on the ground devoid of evidence of hinging at the horizontal supports at top and bottom and only slight evidence of hinging at the vertical side articulations. At 30-psi the front wall however showed strong pivoting about horizontal junctures; the top half was lofted and outdistanced all other debris downwind. The bottom half appeared to have been pushed down into the floor after pivoting around its articulation with the floor slab. It barely travelled off the floor slab.

Although the tilt-up building suffered catastrophic collapse also, the rear wall was left standing after the shot. In fact, it showed no evidence of deformation except in a localized area impacted by a front wall fragment. The front wall and ceiling failed in bending; the sidewall connectors all ruptured or pulled out of the concrete. The side walls all were found outside the building; all but one appeared to have failed initially at the upper articulation and then fell exterior face down immediately next to its original location.

## INSTRUMENTATION

Each structure contained six air pressure and three wall deflection gages. The pressure gages were located to produce information about wall and ceiling loads; the deflection gages were intended to show wall motion in response to these loads. There was one deflection gage attached to a central point in the front, rear and one sidewall of each building. To document the interaction of a wall and its overburden, three vertical accelerometers were placed in the two masonry buildings: one in the ceiling directly over the front wall, a second in the middle of the ceiling, and a third in the footing directly under the front wall. A fourth observed horizontal displacement of the front wall parallel with a deflection gage.

Useful data was obtained from every gage. When these data are combined with the results of the post-shot debris survey, the movements of all structural components during building collapse can be deduced.

## GAGE RESULTS

Gage records show front walls moving steadily rearward. In the masonry building at 30-psi peak acceleration is reached in 7 to 8 ms and collapse is complete in 13 to 14 ms. "Collapse" here means that central deflection has equaled wall thickness. At the 10-psi masonry building acceleration lasts two to three times as long as at 30-psi and the front wall has collapsed in approximately 21 ms. In the reinforced building front wall collapse requires 22 ms. The final speeds of the central fragments can be calculated from the slope of the deflection gage records.

In all three buildings the sidewalls initially move inward then travel outward to collapse. The sidewalls in the two unreinforced buildings move inward between two and three inches before reversing direction; the reinforced sidewalls come in only 1.5 inches. The rear walls all behave differently. In the unreinforced building at 30 psi the rear wall moves directly outward at approximately half the speed of the front wall in the same building. In the unreinforced building at 10 psi rear wall collapse is marginal and appears to be influenced by ceiling behavior.

## INERTIAL ARCHING

McDowell, McKee and Sevin (1) during the 1950's showed that a masonry wall panel held tightly in a rigid frame developed arching forces under horizontal load, that is, the rotation of the wall created an opposing reaction in the frame. McKee and Sevin (2) applied the theory to walls impacted by nuclear airblast to account for their strength. Wiehle and Bockholt (3, 4) extended the idea to a wall loaded vertically by a static weight. Wiehle speculated that the actual stabilizing moment would be larger than that calculated from the weight of the overburden since wall rotation must accelerate the overburden upward. The present experiments with unreinforced masonry clearly show simultaneous front wall flexure and upward ceiling acceleration under the airblast impact on the front wall. This occurs despite the initial downward pressure of airblast on the ceiling. Preliminary calculations suggest that the stabilization is limited by crushing of the masonry and that an iterative, self-consistent calculational procedure should be capable of predicting it quantitatively.

The simplest evidence for the existence and magnitude of this stabilizing moment is seen in Table 1, which presents the gage data for all three front walls along with predictions based on Wiehle's response model using the dead load carried by the wall. For the two masonry buildings the Table demonstrates that actual behavior lags predictions, that is, front walls collapse later and with less kinetic energy than predicted. In sharp contrast, predictions for the reinforced front wall, whose response is controlled by the properties of steel and by its own mass and not by in-plane load, are quite accurate.

From double integration of the accelerometer traces the elevations of the front edge of the ceilings carried by the front load-bearing walls at the moment of collapse of the front walls are approximately 0.62 and 0.85 inches for the 30-psi and 10-psi sites, respectively. In the absence of crushing, rotation of the front wall segments, as illustrated in Figure 1, should raise the front edges of the ceilings approximately 1.2 inches. For this we assume four symmetrical crushing zones, one at the top and bottom of each of the two rotating blocks that make up the front wall as it approaches collapse.

Allowing for approximately 0.126 inches of elastic compression (to the elastic limit) there were approximately 0.45 inches and 0.68 inches of crushing in the front walls at the 30- and 10-psi sites, respectively. The energy dissipated in this crushing can be estimated indirectly from the data. The airblast in displacing the front wall does work of seven kinds:

(1) pushes the ceiling upward against air pressure
(2) gives kinetic energy to the front wall
(3) gives kinetic energy to the ceiling
(4) increases the potential energy of the ceiling
(5) causes the elastic compression of the front wall
(6) (probably) puts elastic energy into bending the ceiling
(7) contributes energy to the crushing of the front wall

The airblast work on the front walls and the first five dissipations above have been estimated (by hand) from the analogue data. The results are shown in Table 2. The final two (righthand) columns of Table 2 list (a) the crush energy calculated as the residual energy after subtracting from the airblast input the first five energy losses above and (b) crush energy as estimated from measured compressive strength of the masonry units (i.e., 1310 psi on the gross area), the distance of crush, and the area of the unit. The order of magnitude agreement between the final two columns suggests that it may eventually be possible to quantify the crushing process.

Table 3 lists the energy distributions found in the two buildings. Although more energy was dissipated in crush at the 30-psi site than at the 10-psi building, this form of loss amounts to approximately the same percent of the total input at both. The difference in the sites appears in the relatively large elastic component at the low pressure location. The Table indicates that the influence of the downward airblast on the ceiling is relatively minor in both cases.

In a rigid frame, crushing depth in this wall would presumably be 1.2 inches, corresponding to an order of magnitude estimate of crushing work equal to 192,000 ft-lb. This is slightly less than the airblast input at the 30-psi site but considerably more than the input at the 10-psi location, suggesting that at both overpressures rigid arching should be an extremely effective stabilization against airblast. Inertial arching appears to be intermediate between the case discussed by Wiehle and Bockholt on the one hand and that discussed by McKee and Sevin on the other.

## CONCLUSIONS

We are looking forward to more precise examination of the experimental data than so far undertaken. We believe it will confirm our tentative conclusions that the stability of the load-bearing wall is enhanced by inertial arching but the major effect of the phenomenon for our purposes may be the reduction of the kinetic energy of the wall fragments on collapse.

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This work was supported by the Federal Emergency Management Agency under contract EMW-C-0583, work unit 4113, through a subcontract with SRI International.

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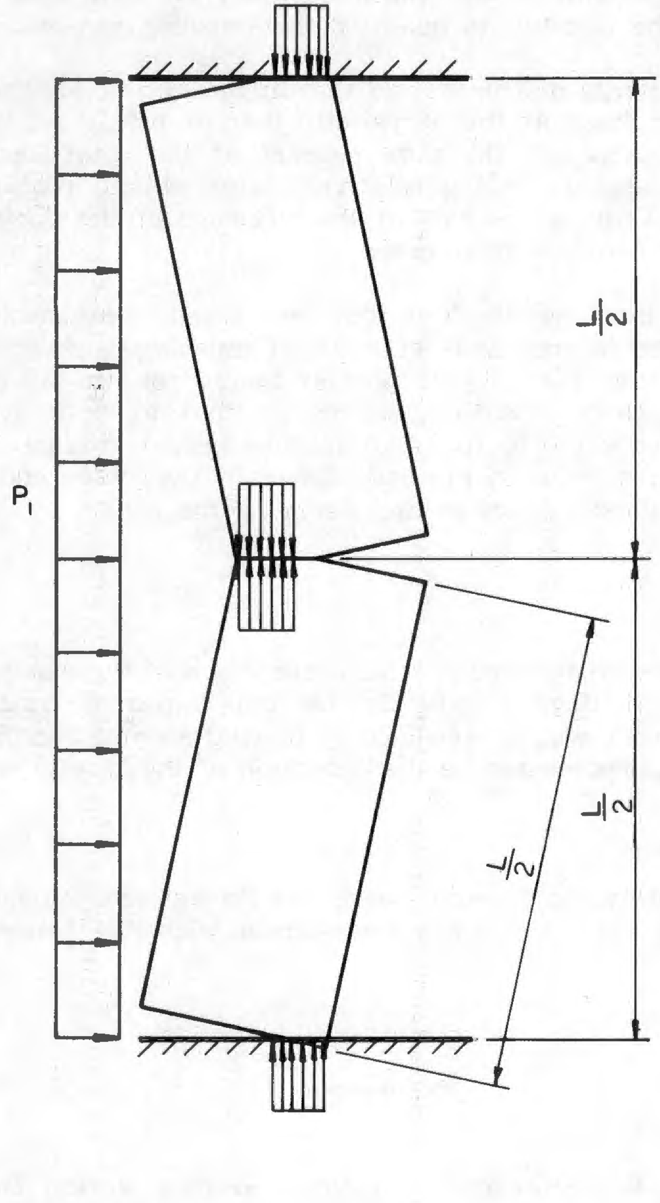


Figure 1 Assumed Arching Behavior of Masonry Wall.

## TABLE 1
## COLLAPSE OF UNREINFORCED FRONT WALLS

| EXPERIMENT NO. | ACTUAL | | COMPUTED | |
|---|---|---|---|---|
| | TIME OF COLLAPSE* (MS) | SPEED (FT/S) | TIME OF COLLAPSE* (MS) | SPEED (FT/S) |
| 5401 | 13. | 67. | 8.5 | 127. |
| 5403 | 26.5 | 29. | 19.5 | 53. |
| 5402 | 22. | 35. | 25. | 36. |

* Time of collapse = Time central deflection equals wall thickness

## TABLE 2
## UNREINFORCED FRONT WALL ENERGY DISSIPATION

| Site | Time to Collapse (ms) | Average Net Pressure (psi) | Vertical Displacement (in) | Energy (1000 ft-lb) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Airblast Input | Airblast Ceiling | Ceiling Potential | Ceiling Kinetic | Wall Kinetic | Elastic | Crush (a) | Crush (b) |
| DNA5401 (30-psi) | 13.5 | 36.4 | 0.62 | 197 | 11.8 | 0.46 | 3.11 | 80.9 | 10.0 | 90.8 | 81.8 |
| DNA5403 (10-psi) | 26.5 | 12.8 | 0.85 | 69.2 | 5.48 | 0.68 | 0.941 | 16.2 | 10.0 | 35.9 | 35.8 |

## TABLE 3
## UNREINFORCED FRONT WALL ENERGY DISTRIBUTION

| | DNA5401 (30-psi) | DNA5403 (10-psi) |
|---|---|---|
| clg airblast | 6.1 % | 7.9 % |
| wall K.E. | 45. | 23. |
| clg K.E. | 1.6 | 1.4 |
| clg P.E. | 0.24 | 1.2 |
| elastic | 5.1 | 14. |
| crush (est.) | 42. | 52. |