Experiments with Models of Reactor Containment Loaded by Internal Explosions

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SUMMARY

This work is concerned with the experimental assessment of the damage caused to the reactor containment structure by an internal explosion. This type of loading may arise when a penetrating warhead is detonated inside the containment, or in the case of accidental hydrogen release, which forms a detonable gaseous mixture.

The experiments modelled the geometry of a typical reactor with a cylindrical containment having a hemispherical dome. Internal partitions were included in the models to account for the blast wave reflection by internal walls. The auxiliary building was also modelled in the form of an annular structure.

The models were loades by suitable high explosive charges, placed at various locations inside the containment. The containment response was measured by several strain gauges ; The time-histories of these gauges were recorded. Wall pressures were also measured.

The experimental investigation had two major objectives :
The first was the verification of the computational model for axisymmetric loading, reported by Kivity and Falcovitz [2] . For this purpose, a set of experiments was carried out with charges placed on the axis of symmetry of the structure.

The second objective is concerned with the effect of asymmetrical loading. A computational model for off-axis charges would require extensive three-dimensional calculations of the resulting air-blast, which are presently very expensive.

To simplify the production of the models, an Aluminum alloy was chosen as the material. It was judged that dimensional accuracy and reproducibility of the experiments are more important than faithful reproduction of the material. The particular aluminum alloy chosen (6061T6) is fairly insensitive to strain rates and thus a simple elastic perfectly-plastic behavior was assumed.

The experimental results are judged to be in reasonable agreement with the code predictions. However, some inaccuracy of the blast computations was indicated by comparing them to pressure measurements.

1. Introduction

In previously reported works [1,2] the vulnerability of a reactor containment structure to the air blast resulting from the detonation of a high-explosive charge within the containment, was studied via the continuum-mechanics code DISCO. These computations comprised of two phases. In the first phase the time-history of the pressure on the containment wall is computed by an Eulerian processor, while assuming rigid (non-moving) walls. This information is stored on a mass-storage device, to be used as the wall-loading in the second phase, in which the structure is represented approximately as a multi-branch thin-shell. The purpose of the experimental investigation is two-fold. The first is a verification of the computations described above (both phases). The second objective is the effect of an off-axis explosion, for which there are no satisfactory computational codes; this is especially so in the air-blast phase. We shall reconsider this effect in chapter 3 below.

For the purpose of code verification, we conducted some axisymmetric experiments in a small-scale model, by detonating a miniature charge placed at various locations along the axis of symmetry. The time-history of strain and wall pressure were recorded. The model chosen for these experiments was an alluminum containment and auxiliary building replica of the structure that had been assumed in previous work by some of us [1, 2] , scaled down to about 1:220. There were two guidelines that led us to this choice : (1) Good reproducibility of the structural response : (2) A reasonable cost of the model. A concrete model would inevitably be much larger and hence much costlier. A larger metal model would be excessively costly if it were machine-tooled, or else - insufficiently accurate (for good reproducibility). Hence we were led to the choice of a relatively small-size aluminum model. Consequently, we are aiming at a partial verification of our computer codes, rather than a more conclusive proof which we may take up sometime in the future. The choice of small-scale model (D=196 mm), entailed a difficulty in the explosive simulation. Scaling down an explosive charge of 1 ton, we would obtain a miniature charge of W=0.1 gr. It seemed unfeasible to detonate such a small charge, since the detonator itself weighs about 0.2 gr. The minimal charge that would give a clearly reproducible air blast was about W=1 gr. of RDX. Obviously, we then have no similaritly in the air-blast; the charge of 1 gr. being equivalent to 10 tons in the full-scale case. A partial compensation for that would be to conduct the experiment in a compressed-air atmosphere within the model. A choice of ten times the ambient pressure (and hence, a ten-fold increase in density, while at room temperature) would maintain the same explosive-to-air mass ratio of the full-scale case. These experiments are currently under way, and the results reported here were conducted at an intermediate pressure of 3 times the ambient pressure. Thus, both the computational and experimental results are of a preliminary nature, and we are presently looking into ways of improving them.

2. The Experimental Setup

The Experimental setup incorporated a small scale model of the reactor containment and the auxilary building (see fig. 1). The model was made by machine tooling and welding 6061 Al alloy which can be closely approximated as an elastic perfectly plastic material. Pressure transducers as well as the explosive charge were inserted through holes in the model that were subsequently sealed-off. The explosive was a spherical charge of R.D.X which was detonated approximately at its center. The total weight of charge and detonator was W=1 gr.

Pressure measurements were taken via a commercial Kisler pressure trasducer connected with a low-noise cable to a charge amplifier.Strain meassurements utilized a commercial grid type gauge connected to a D.C amplifier.

Both pressure and strain signals were recorded by a digital transient recorder and were subsequently analyzed via a PDP-11 computer.

3. Experimental and Computational Results

Generally speaking, three types of experiments were carried out. These were :

P03 -- Detonation of a 1 gr. charge at the dome center, with an absolute pressure of Po=0.3 MPa.

P03S-- Detonation of a 1 gr. charge at a point half a radius below the dome apex, with an absolute pressure of Po=0.3 MPa.

P03A-- Detonation of a 1 gr. charge at a point half a radius to the right from the dome center (Asymmetric), with an absolute pressure of Po=0.3 MPa.

The corresponding computation were carried out on a scaled down model of the model in [2] , with the main difference being material properties. For aluminum we assumed young modulus=70 GPa, yield stress=0.14 GPa. Some typical results are shown in figures 2 to 5.

3.1 The Axisymmetric Experiments P03, P03S

Let us first consider the axisymmetric experiments. For these, we have both exprimental and computational results. A pressure time-history for P03 is shown in figure 2. The point of measurement and the charge location are identical to those reported in figrure 3 in [2] . (However, note that there is no exact symilarity in charge size and air presure). We note the large discrepancy of the measured and computed first pulse (about t=0.1 ms, in fig. 2). We beleive that this discrepancy, as well as the apparent frequency difference in subsequent pressure pulses is related to some shortcoming in the air-blast computation. The numerical scheme of the Eulerian processor (see ch. 3 of [2]) is notoriously inaccurate when the numerical gradients (i.,e.,the change across a single element) of the flow field are high. High numerical gradients were present in the initial stage of the spherical blast computation, which was obtained by a relatively accurate one-dimensional computation, and was subseqnently transformed into the cartesian Eulerian grid. The high dissipation of the initial stage of the blast, as well as the smearing of the shock front due to artifficial viscosity, explain the low first pulse of the computed pressure (fig.2).

It also helps to explain the apparent time lag in subsequent pulses. Due to high compressibility of air, the speed of propagation of shock fronts increases significantly with the pressure jump across the shock, so that the fact that the initial computed blast pressure is lower that the experimental one,may explain the moderate time lag of the second and subsequent pulses.

Let us now consider the strain time histories in P03S. Strain was measured at several points. At the upper location (50 mm along the dome from the apex), we measured longifudinal strain:points 1 and 2 in fig. 3). At the lower point (the tangent point of dome to cylinder), we measured the circumferential strain (point 3 and 4 in fig. 4). There is a fair agreement between the experimental and computed strain histories as to the typical range in amplitude and pulse frequency. In the longitudinal the computations correspond poorly to the measurements at early times (t = 0.3ms), and display a fair agreement at later times. In the circumferential strain, the agreement at early times is fair, while at later times it is poor. We do not have a good explanation for that. At the time intervals where correspondence of computed to experimental strain is poor, the difference is probably larger than the experimental error, as is hinted by the fact that two strain ganges give fairly close time histories (fig. 3). However, even in those instances where correspondence in amplitude was poor, it is interesting to point out that pulse frequencies which seem to be related to natural modes of the structure agree fairly well. What it all amounts to, is that in all likelihood, the structural dynamics is fairly well simulated by the thin-shell processor of the DISCO code.

3.2 The Asymmetric Experiment P03A

We now take up the matter of non-symmetric experiment, where the axisymmetric structure was loaded by detonating an off-center charge. The purpose of these experiments, is to asses the relative vulnerabilities of the containment to a symmetric blast (which we can compute) and to an asymmetric blast (which we cannot compute). It is conjectured, that at blast loadings which are considerably below those that would result in an ultimate structural failure, the difference between the structural response to a symmetric and to an asymmetric loading (of the same charge) may be rather moderate. As a demonstration we performed experiment P03A. We placed the strain gauges at points which are geometrically akin - 1, 2 in P03S vs. 3, 4 in P03A. The strain time histories (figures 3 and 5) display a fair resemblance in amplitude and frequency. We are contemplating of exploiting this approach in order to confirm containment integrity to asymmetric loading by combining axisymmetric vs. asymmetric experiments (scaled-down) with 2-dimensional computations.

4. Discussion and Conclusions

In spite of the small scale of the experiments and the preliminary nature of the results that were presented here, we feel that some reasonably-founded conclusions can be formulated. In regards to the experimental system, the results indicate a good reproducibility of strain and pressure histories. Some improvement is needed, though, particularly for the pressure measurements. As for the computations, the air-blast was found to be inaccurate in the early stage upto and immediately after the first reflection from the containment wall. An improvement of that phase in the computations is called for. The structural response, however, seemed adequate, and at any rate, can be tested in the context of present experiments, only in conjunction with an improved blast-loading computation.

The concept of analyzing the case of non-symmetric explosion in the containment by combining both symmetric and asymmetric experiments with two-dimensional computations, seems to have some merit.

References .

[1] Y.Kivity, J.Falcovitz and M.Ben-Artzi : "Response of Reactor Containment to an Internal Explosive Blast", Presented at the 3rd International Seminar on "Extreme Load Design of Nuclear Power Plant Facilities", 20-21 Aug. 1979, Berlin, W. Germany.

[2] Y.Kivity and J.Falcovitz : "Vulnerability of Reactor Containment to an Internal Explosive Blast", SMIRT 6 (paper J10/13), 17-21 Aug. 1981, Paris, France.

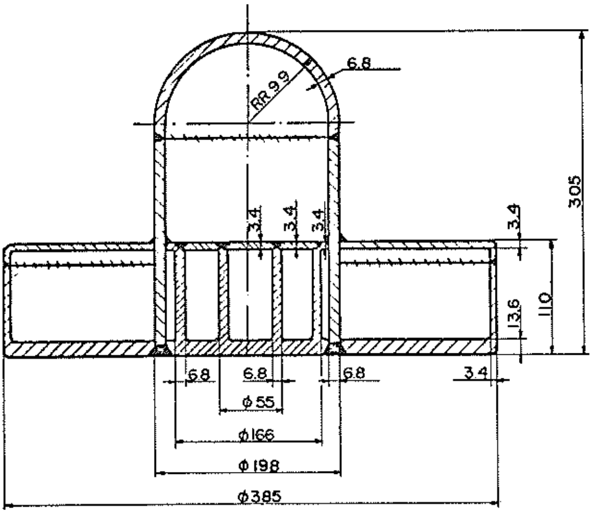

Fig. No. 1: The Aluminum Containment Model.

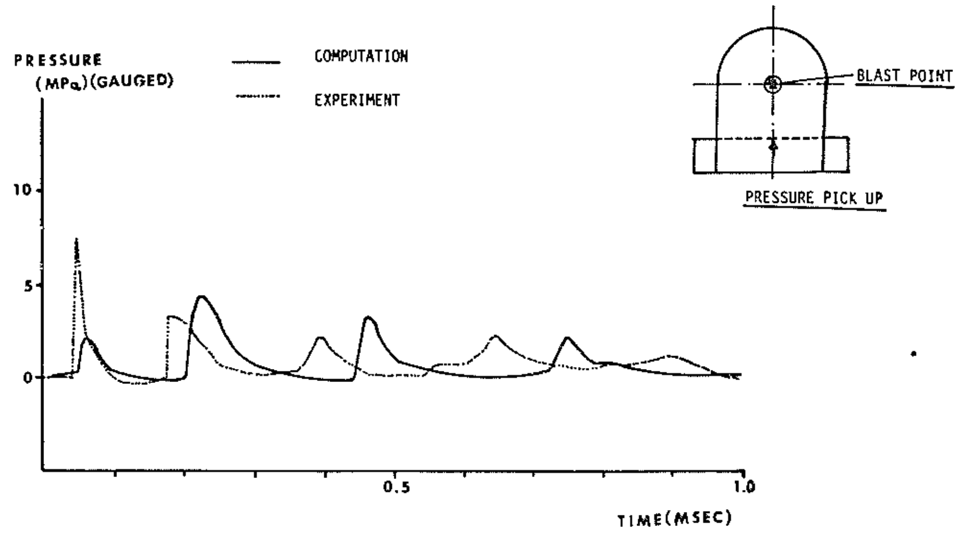

Fig. No. 2: Experiment P03. Wall-Pressure Time-History.

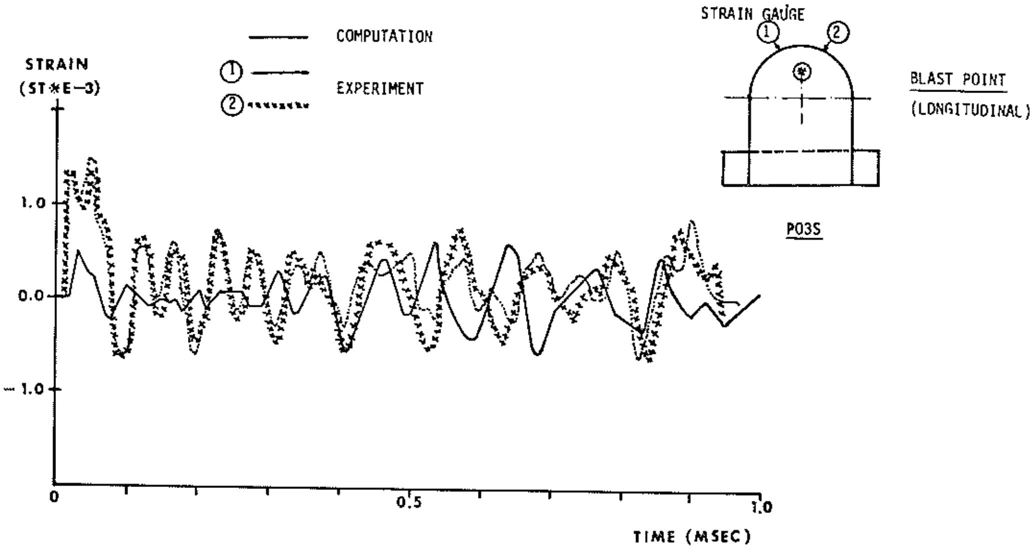

Fig. No. 3: Experiment P03S. Longitudinal Strain Time-History.

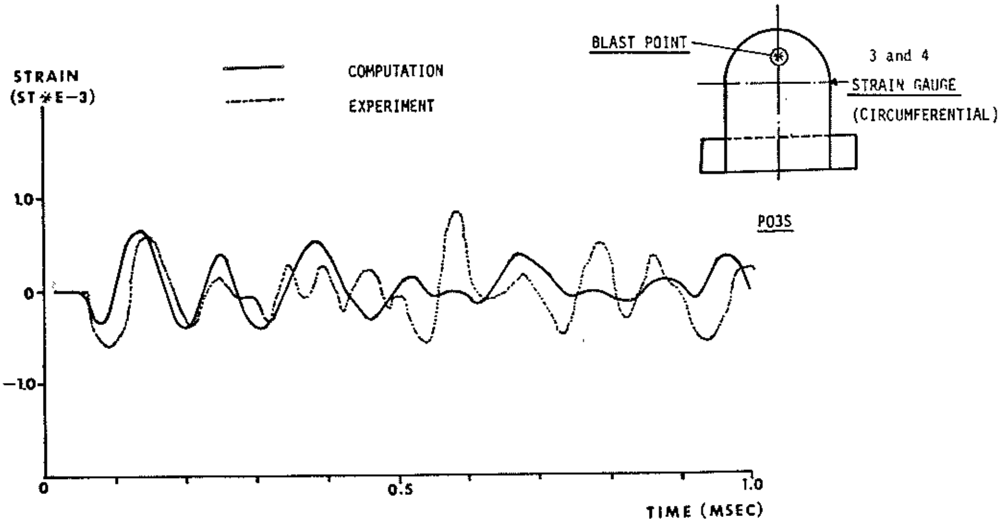

Fig. No. 4: Experiment P03S. Circumferential Strain Time-History.

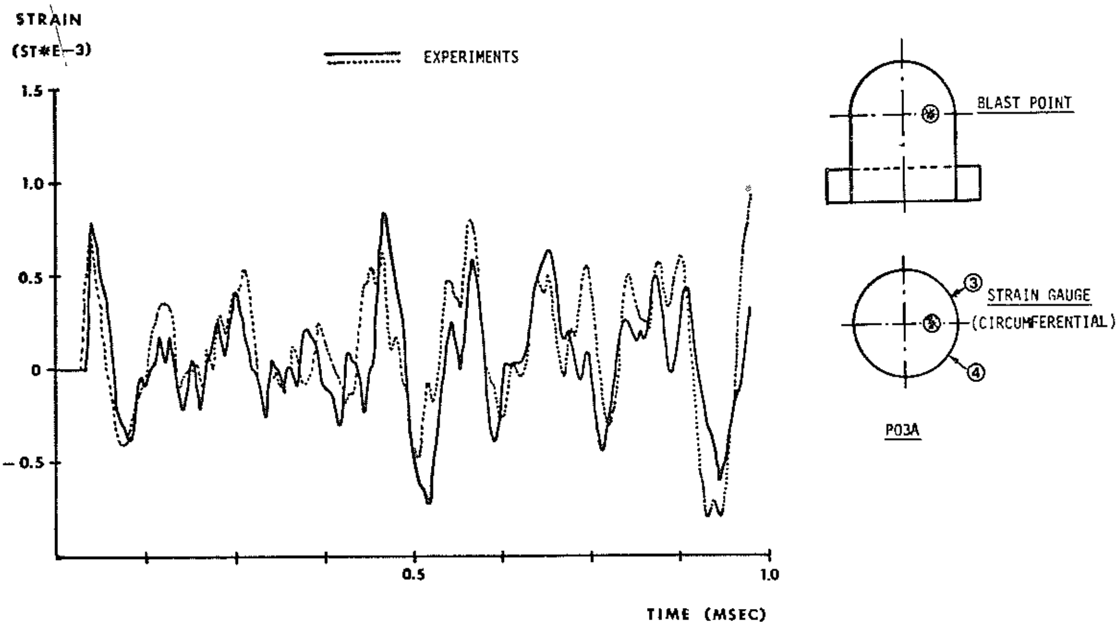

Fig. No. 5: Experiment P03A. Circumferential Strain Time-History.