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A PHOTOELASTIC STUDY OF THE EFFECTS OF AN IMPULSIVE SEISMIC WAVE ON A NUCLEAR CONTAINMENT VESSEL

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SUMARIO

Si una estructura esta localizada cerca del epicentro de un terremoto, la energía impulsiva en una onda de compresion (onda-P) puede ser suficiente para debilitarla en lugares criticos, de manera tal que su habilidad para soportar futuras vibraciones del terreno es reducida. El manuscrito describe el movimiento progresivo de la onda dilatacional (onda-P) en un modelo de un tanque de almacenamiento nuclear por medio de un estudio fotoelastico dinamico. Las reflecciones de los soportes de la cascara son observadas, y la fuerte onda de flexion, que deforma la cascara misma, es estudiada por medio de fotoelasticidad y procedimento mediante el uso de indicadores de desplazamientos dinamicos.

SUMMARY

If a structure is located close to the epicenter of an earthquake, the energy in the impulsive wave (P-wave) can be sufficient to weaken the structure at critical locations such that its ability to survive subsequent vibratory ground motions ~~is~~ impaired. ~~The paper described~~ A dynamic photoelastic study of the progressive movement of a dilatational P-wave into a model of a nuclear containment vessel, is studied. The reflections at the dome abutments are observed and the strong flexural wave that deforms the dome itself is studied with photoelasticity and with dynamic strain gage procedures. (E.L.)

1. Introduction

Seismic analyses of large civil engineering structures generally consider the vibrational responses of such structures due to the horizontal and vertical ground motions as recorded by accelerograms. The possible dangers from the impulsive components of the dilitational or P-wave is usually considered to be minor. If, however, a structure is located close to the epicenter of a major earthquake, the energy in the impulsive waves can be significant and may be sufficient to cause structural damage. Such damage may be fatal by itself, but is more likely to weaken the structure at critical locations in such a way that it is less likely to survive the subsequent ground motions associated with the slower moving surface waves.

These impulse waves are amenable to study with the aid of dynamic photoelasticity involving the Cranz-Schardin high speed spark camera (1). This camera system can record the progression of an impulse wave as it moves into and through two-dimensional photoelastic models of various configurations. In order to evaluate the behavior and damage potential of such impulse waves on large structures, several series of dynamic photoelastic records were obtained for impulse waves in models of typical structures. The results for one specific case is presented in this paper because it represents a typical design for a large reactor containment shell (2).

The Cranz-Schardin camera and dynamic photoelastic procedures have been described elsewhere (1,3,4). The equipment normally operates as a light field polariscope with 16 spark gaps in air. The 16 arcs are fired sequentially with adjustable initial delay and variable intervals between arcs. The spectrum from the high voltage air arc is filtered through deep blue narrow band filters. Since the short wavelength blue light is emitted only during the peak intensity period of the arc, the resultant exposure is a short duration (600 ns) pulse of near monochromatic light on a film selected to be sensitive in the blue region of the spectrum. The film is pre-fogged to just before the knee of its density vs. exposure curve. It is then immediately responsive to the additional exposure from the short duration arcs and a single flash is enough to produce well exposed negatives. Sixteen sequential high speed photographs (at an equivalent framing rate of 1.7 million frames/s.) are obtained on a single sheet of 250 x 356 mm (11 x 14 in) film. The total event time spanned by these pictures can be varied, without changing the exposure times of the individual pictures, by adjusting the time interval between the discharges of the arcs.

The procedure described above was modified in two major ways to overcome the peculiar difficulties of interpreting the photoelastic data from this and other structural models. Dynamic color photos of the isochromatics were used quantitatively to obtain accurate interpretations of the fringes. Good color rendering required that the polariscope operate with white light in the dark field mode. To this end the polariscope was altered for dark field operation and the blue filters were removed from the field. The exposure at each individual frame is not adjustable with diaphram settings, as in other cameras. Since the precise energy and duration of the different arcs are not alike, the individual exposures had to be adjusted. This was done by inserting different neutral density filters behind each of the lenses until all 16 pictures were exposed correctly within the tight tolerances required for good color photography. Further color corrections were made with low level filters to compensate for the slightly different spectra at the arcs caused by variations in total discharge energy between different arcs. The color positive film could not be pre-fogged, so its "speed" was enhanced to 1100 ASA (32DIN) by special processing, requiring even tighter control over variations in exposure. Cibachrome process P-12 was used to make color enlargements from the color positive photographs.

The fringe orders of interest in this study were generally below 4 and at the times of greatest interest, below 3. At these levels, color photographs can be used effectively to estimate partial fringe order (5,6), provided a good monochromatic calibration standard is available. Two such standards were used here - a disk in diametral compression and a beam in pure bending. In both cases a model of the same material as was being used in the dynamic study was loaded statically to a useful fring order of 5. A full set of 16 photographs were then taken of the statically loaded model in the dynamic polariscope. The first with monochromatic light on black and white film (blue filters in place) and the second in "white" light as described above. After processing and printing, there was now an accurate calibration for each arc up to the 5th order blue fringe. This permitted partial fringe order readings to be estimated well, especially at levels up to 2.5.

For the dynamic photographs, black and white negatives were obtained from the color positive (Ektachrome) transparancies by the following procedure:

- Prefog a sheet of high contrast black and white film (Kodak 6127).
- Place film in film holder of camera underneath the color positive film previously obtained.
- Remove polarizers from the optical system.
- Place deep blue narrow band filters in place.
- Place previously selected neutral density filters in place for each individual arc.
- Fire camera (arcs) through any normal procedure (No model and No explosive).
- Develop the 6127 film in Kodak D-11 developer.
- Make black and white prints in usual manner.

The resulting photographs were sharp and of high contrast. They matched the color photographs exactly so that the two sets of pictures can be interpreted with confidence.

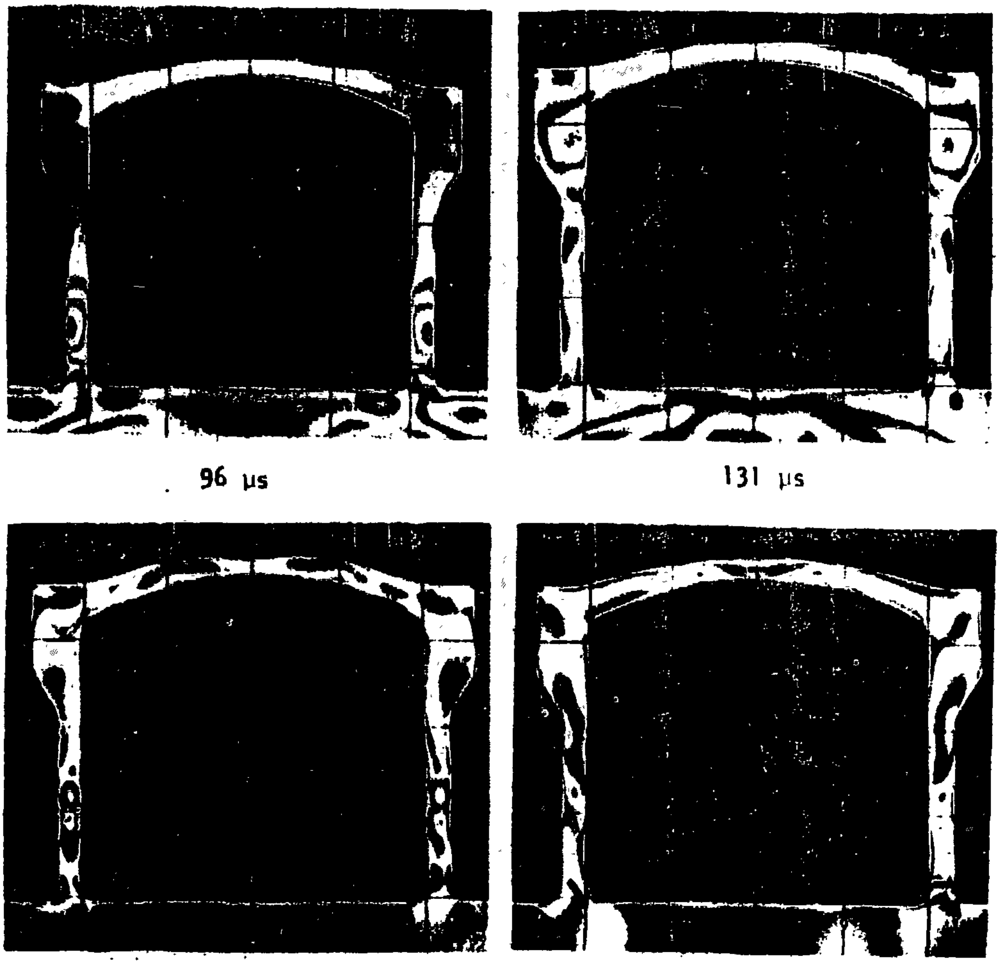
The photoelastic model of the reactor vessel was machined integral with the "ground" from a 6 mm thick sheet of CR39 photoelastic material (Homolite 120). A 25 mm square grid was scribed onto the model. Since interest centered on the behavior of the dome and its abutments, the side walls of the model was only half as high as they would have needed to be for accurate geometric modeling of the structure on which it was based. The impulse was generated with a 100 mg charge of lead-ozide (PbN_6) in a line load 25 mm long placed 130 mm below the base of the reactor model. This produced a reasonably flat wavefront at the time that the dilitational P wave entered the model.

Compressive explosive loading functions of this kind tend to have strong tensile unloading tails. To reduce this effect the line charge of explosive was packed into a separate block of CR-39 material which was attached to the lower surface of the model with a bond that is weak in tension (double sided masking tape). The tensile unloading wave then causes the small block to separate from the main body of the model so that only the main compressive pulse and a very low amplitude tensile tail passes on into the main model. There was no additional control over the shape of the incident wave. The model dimensions were chosen to be in reasonable ratio with the wavelength of the incident wave which represented a seismic shock wave.

The photoelastic data strongly suggested that the dome flexes in reverse bending (tension-compression-tension) under the influence of the impulse wave. The optical information alone is not conclusive. So, to confirm that bending does indeed occur and to obtain information on the sign of the bending stresses, strain gages were mounted at the crown of the dome, on the inside as well as on the outside. The strain gages were 120 Ω, 1.57 mm single element foil gages in a dynamic potentiometric circuit with 10.62V D.C. exitations and a 1kΩ balast resistor. The signals were recorded on a 2 channel oscilloscope with an input impedance of 1kΩ 15 pf.

2. Results

Two sets of dynamic pictures have been selected to illustrate how the impulse wave behaves in the structure and how it can induce serious and unexpected tensile stresses. In Fig. 1 the impulse source was deeper and of lower amplitude than in Fig. 2. In both cases the times are given in micro-seconds after the explosion. The effect of the shorter travel time and the difference in intensity can be seen in



96 μs

131 μs

170 μs

193 μs

Fig. 1. Dynamic Photoelastic photographs at four different times after the explosion.

the two frames at 96 and 94 μs. In the former case (96 μs, Fig. 1), the impulse has moved only about 35 mm up the legs of the model and the maximum fringe order is just over 3. In the latter case (94 μs, Fig. 2), the wave is already entering the crown abutments (≈64 mm from base) and the maximum fringe order in the first compressive pulse is almost 4. In both cases the pulse shape is similar with a leading ramp length (wave front to first compressive peak) of 25 mm. The two sets of frames were selected to show how the passage of the impulse through the dome introduces stress patterns which are similar to bending patterns. The analysis given here does not address the reflections in the abutments nor does it consider the apparent flexure of the walls.

All impulses were placed symmetrical with respect to the vertical centerline of the model. Consider Fig. 1:

- Frame 96 μs: The first compressive half-wave has just entered the walls. The light areas in the upper portions of the arch are residual values.
- Frame 131 μs: The extreme front of the wave has just started to reflect from the top of the wall. The reflection is, of course, tension and cancels a certain amount of the compressive stresses in the part of the wave which now lies immediately below the top. The reflected wave front is now 8 mm below the top and the expansion of the compressive pulse into the roof has just started.
- Frame 170 μs: The expansion into the dome has proceeded 75 mm; i.e., three quarters of the way across. The two compressive waves, which entered from opposite sides, reinforce each other so that maximum values are on either side of top center.
- Frame 193 μs: The tensile reflections now reinforce each other with peak stress values near top center.

Consider Fig. 2:

- Frames 80 and 94 μs: The wave enters and travels up the walls and into the expanded volume of material of the abutments.
- Frame 153 μs: The fronts of the waves have crossed at top center. They are now almost at the far walls ready to expand into the abutment.
- Frames 184 and 199 μs: The center of the dome experiences a complicated stress cycle.
- Frame 214: The top center portion of the dome is in a clear bending mode.

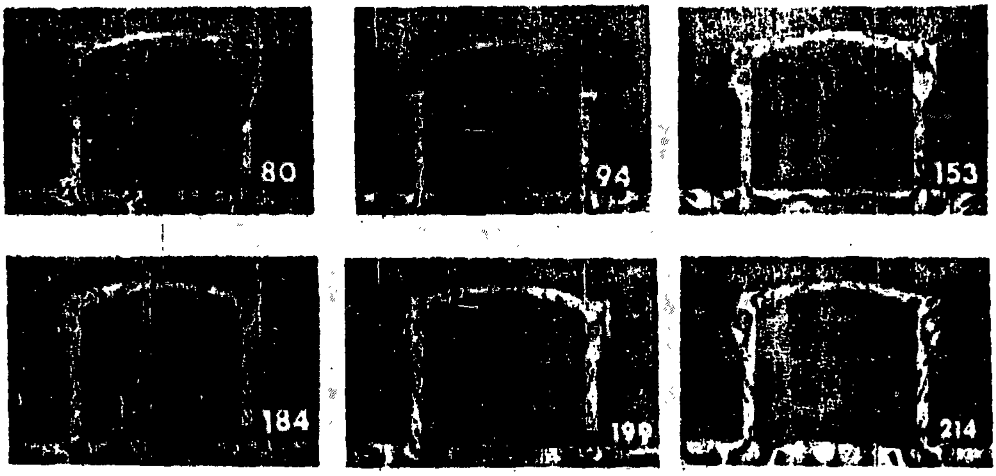


Fig. 2. Six dynamic isochromatic photographs for another model with a larger charge of explosive than in Fig. 1. Times are in micro-seconds after explosion.

In Fig. 3 the time histories at the top (outside) center and the bottom (inside) center of the dome are presented. The two central graphs compare the strains as recorded by the two strain gages. It is quite clear that from 200 μs on the dome experiences bending oscillations with the bottom surface in tension when the top surface is in compression.

The uppermost and lowermost graphs present the fringe orders at the upper and lower surfaces at the center of the dome. It is, of course, not possible to assign positive or negative values to the fringes; hence, the lack of sign on the scales above and below the zero lines. The information on sign from the strain gages was used to plot the fringe orders either above or below the zero level. Once that is done, the whole picture emerges in a consistent way and the previous interpretation of the photoelastic photographs is possible.

3. Conclusions

It is evident from this very simplified and admittedly distorted model that there is a strong possibility that the impulse component of seismic waves may be a threat to the reliability of large structures

The most important experimental difficulty in this modeling approach is posed by the limited extent to which the shape of the impulse wave can be modified to simulate a real seismic wave. This problem can be overcome by using non-polymeric model materials such as glass where the waves can be excited with piezo-electric crystals. The wave shape can then be modified to reproduce, on a reduced scale, the exact shape of seismic waves. Unfortunately, glasses have low birefringence; i.e., the models will display very low fringe orders. Present research at Iowa State University is concerned with developing a technique called half-fringe photoelasticity, which will permit highly sensitive photoelastic tests on glass models. If successful, the method will remove a major cause of distortion in the seismic photoelastic modeling.

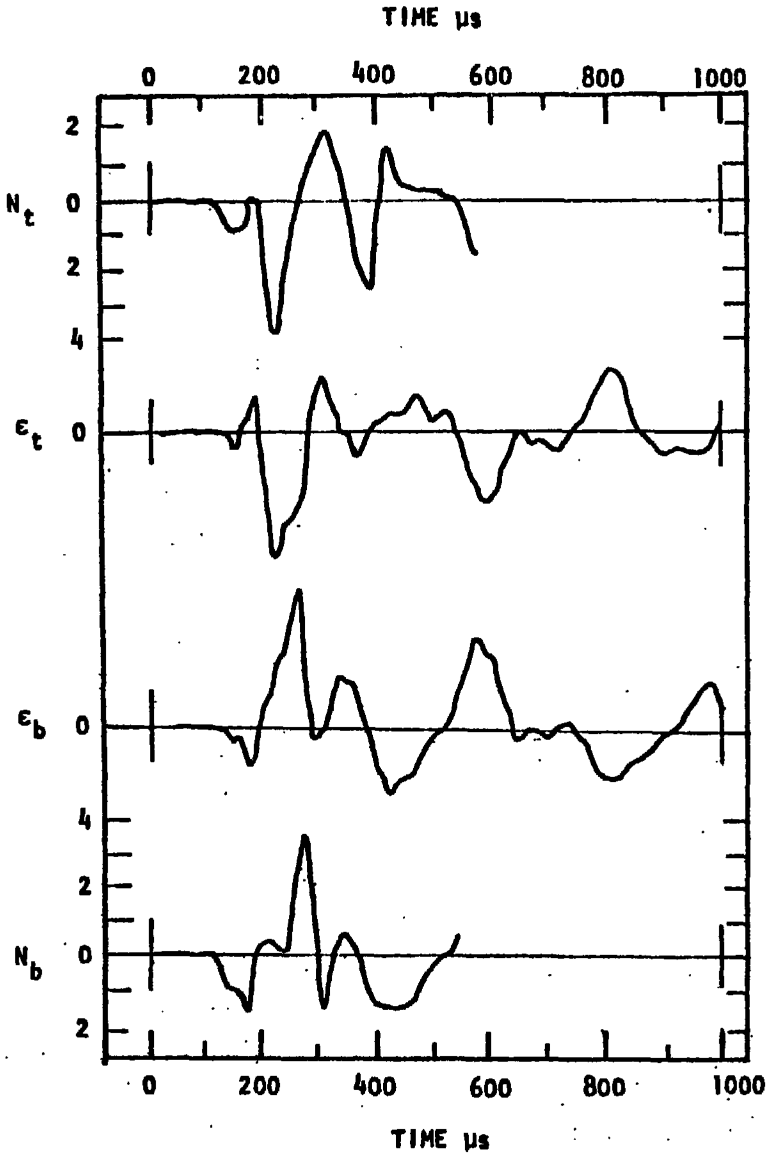


Fig. 3. Data for center of dome at times after explosion

N_t = Observed fringe orders on top of dome

ε_t = Measured strain on top of dome

ε_b = Measured strain on bottom of dome

N_b = Observed fringe order on bottom of dome

4. Acknowledgments

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