IMPULSIVE LOADING ON REINFORCED CONCRETE SLABS - BLAST LOADING FUNCTION

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ABSTRACT

This paper describes the experimental methods used to study impulsive loads produced by close range explosive charges. Henrych's, [1], analytical relations have been used as a basis to develop the spatial and time distribution of blast overpressures across the slab surface and the charge standoff. The results of experiments are presented and comparison made between the measured and the calculated values of overpressures.

INTRODUCTION

In a static test on RC slabs, resistance mechanisms can usually be described as shear or flexural, and failure follows response of the whole slab. A combination between the two effects can also be present but shear-flexure failure occurs often after considerable flexural deflection of the member.

When an explosion occurs near to the surface of a R.C. slab, then the blast pressures are first applied very locally at the point on the slab closest to the charge, the epicentre, and then vary with distances and time across the slab surface because of the significant curvature of the blast wave front. As a result the response of the slab can usually be separated into a local and overall response which occur at different times.

Local response is basically characterised by the development of a central "shear plug" with all damage and deformation being localised, usually around the point on the slab closest to the explosive charge or impact point.

Overall flexural response is a global response whose main effects are the formation of failure lines similar to the yield lines characteristic of a static failure mode, and permanent displacement of the rest of the slab.

The characteristics of the loading function seem to determine the slab behaviour in both impulse and impact tests. There are, however, clear differences in the local response of the slabs exposed to impact, where the point load is transient at a fixed location, and close range blast loading where the load is transient but there is also a spatial distribution of the pressure function as important as its magnitude and duration. In impulse tests the amount of slab cracking furthest from the epicentre is greater than for the impact tests. The most probable reason is that although the charge was close to the target there was a large amount of distributed pressure over the slab surface.

EXPERIMENTAL TECHNIQUE

All explosive tests were performed at the laboratories for Civil Engineering Dynamics, University of Sheffield, CEDUS, in a blast chamber built of concrete blocks that was 2m wide, 5m long and 2.5m high with a concrete floor and no roof. The charge standoff distance to the specimen was measured as a clear spacing between the charge and the specimen.

The main problem in the evaluation of the blast pressure imposed onto the reinforced concrete slab specimens was that the blast pressure gauges could not be placed in R.C. slab because that would change the slab characteristics. For this reason a series of tests was conducted in which pressure-time histories from the charge were recorded using steel plate of dimensions equal to the R.C. slab. Two different test set ups were used and they are shown in Figure 1.

Figure 1: Pressure test set-up

The explosive charges used in the research were made of plastic explosive PE4 which had mass density of 1590kg/m^3, detonation velocity of 8189m/sec, detonation pressure of 2.68×10^7kN/m^2 and mass specific energy of 5111kJ/kg^2 which gives it a TNT equivalent of 1.13. Charges were of hemispherical shape, 57mm diameter, with the spherical side of the charge facing the specimen. In all tests the charges were initiated from the flat side and the charge mass was 78g .

Kulite miniature pressure transducers of two different types were used for all explosion overpressure measurement. They are both made as fully active four arm Wheatstone bridges that utilise either a metal (Kulite HKM-375-1,000) or a silicon (Kulite HKS-375-15,000) diaphragm that deforms under the blast pressure and has a piezo resistive sensor as its sensing element. Both were of a sealed type operational mode with rated pressures of 68.95 bar and 1034.25 bar respectively. The natural frequency of the metal diaphragm was 275kHz and of the silicon diaphragm was 700kHz. The sampling rates used were up to 1MHz. They were both usually powered with 5V DC and infinite resolution output signals were later amplified from 100 to 2500 times. 9.5mm thread allows very easy installation of the gauge and on all occasions they were mounted in steel holders facing the blast wave.

The influence of the charge shape and orientation was investigated using charges of three different shapes and orientations to a blast pressure gauge. The cylindrical charge was placed with its longitudinal axis parallel to the gauge, the hemispherical charge had the curved or flat side facing the gauge which was always on the axis central and perpendicular to the flat side.

TEST RESULTS

Typical results for all three types of the explosive charge are given in Table 1 and in Figure 2. In all of them the zero time has been taken as time of charge initiation.

	Charge stand off (m)	Pulse arrival time (msec)	Peak pressure (bar)	Duration of impulse (ms)	Specific impulse (bar msec)
Cylindrical charge	0.8	0.56	12.26	0.36	1.14
	1.2	1.38	1.54	0.50	0.27
	1.6	2.32	1.07	0.70	0.26
	2.4	4.42	0.44	1.53	0.21
Curved side -hem.sph. charge	0.8	0.52	11.05	0.44	0.95
	1.2	1.36	3.35	0.50	0.63
	1.6	2.20	1.25	0.76	0.37
	2.4	4.34	0.63	0.58	0.13
Flat side- -hem.sph. charge	0.8	0.36	29.94	0.28	2.40
	1.2	1.04	4.88	0.52	0.64
	1.6	1.90	1.14	0.78	0.30
	2.4	4.12	0.37	1.76	0.22

Table 1: Blast pressure test results for the cylindrical and hemispherical 78g PE4 charge

Figure 2: Typical pressure-time record for the 78g PE4 hemispherical charge - curved side facing the gauge

Additional tests with hemispherical charge -curved side facing the gauge- were carried out to establish the spatial distribution of pressure across the surface of the slab, Figure 1, and typical results are presented in Figure 3 and Figure 4.

Figure 3: Spatial pressure distribution from the 78g PE4 hemispherical charge

Figure 4: Blast pressures taken at 420mm off centre of the steel plate

As expected different shapes, orientation and positions of the charge gave different results. For instance, for a charge standoff of 0.8m when the flat side of the hemispherical charge faced the gauge, the peak pressure was much higher (29.94 bar) than for a hemispherical charge of the same mass of explosive but with the spherical side facing the gauge (11.05 bar), or for a cylindrical charge of the same mass (12.26 bar). The duration of the impulse varied inversely with the peak pressure so the impulse of the shortest duration was produced when the flat side of the hemispherical charge faced the gauge.

ANALYTICAL RELATION FOR THE BLAST PULSE FROM THE HEMISPHERICAL CHARGE

The blast pulse that produces the dynamic pressure on the slab was quantified using both experimentally obtained measurements and the theoretical approach of Henrych, [1].

The shock wave initiated by the explosion PE4 will travel at close range distances, at about 7500m/sec Henrych, [1]. Standoff distances used in this research were 250mm to 50mm for the 1:2.5 scale and 500mm to 200mm for the 1:1 scale slabs. Consequently the shock wave reaches the specimen after 7μsec to 33μsec in the case of the 1:2.5 scale slabs and after 27μsec to 67μsec in the case of the 1:1 scale slabs.

The shock front propagates in all directions from the charge but the "shock front vectors" that produce forces perpendicular to the slab are of greatest importance to the structural response. For example the shock front vectors from a charge at 500mm standoff will reach the 1:1 scale slab, at points 1m from the centre of the slab in about 150μsec and will act on the structure at an angle of 26.5º. The vertical component of force will then be much reduced due to obliquity and travel distance.

When the shock front reaches the structure, the overpressure produces a compressive stress wave propagating into the structure. Internal reflections of that stress wave will produce tensile stresses. These can produce some form of local fracture before there is any flexure of the slab.

If we denote the angle of incidence between the shock front vector and the line perpendicular to the slab surface as α (Figure 5),

Figure 5: Loading function

then Henrych,[1], gives the peak theoretical pressure $P_{(m)}$ at any point defined by α, as:

$$P_{(m)} = P_{\det} \cdot \left(\frac{R_w}{R} \right)^A \cdot \cos^2 \alpha$$

where $P_{\det}$ is the detonation pressure of a spherical, flat or cylindrical charge of radius R_w and standoff distance R. The parameter A is determined by the shape of the charge and is 2 for a spherical charge and 3 for a hemispherical charge with the flat side towards the slab.

Transient pressure distribution $P(t)$ is given by:

$$P(t) = P_{(m)} \cdot \left(1 - \frac{t}{\tau} \right)^A$$

If we consider a hemispherical charge initiated from the centre of the flat side as being similar to a spherical charge initiated from the centre of the sphere then the above relations can be directly implemented using $A = 2$. Since R_w = 28.5mm and 71.25mm for the 1:2.5 scale and 1:1 scale tests respectively and $P_{\det}$ is 26.8kN/mm^2 then the loading function can be written for the 1:2.5 scale 78g PE4 charge as:

$$P(t) = P_{\det} \cdot \left(\frac{R_w}{R} \right)^A \cdot \cos^2 \alpha \cdot \left(1 - \frac{t}{\tau} \right)^A ,$$

where t represents the time measured from the arrival of the blast front at the slab and τ is the positive duration of the pressure pulse. It is clear that τ will be dependent on the standoff distance of the charge and the position on the slab. It was therefore decided to relate τ to the charge inclined distance D(mm), Figure 5. The values for τ can be obtained experimentally and theoretically. For charge inclined distances of up to 560mm, which are of the greatest interest, (model R.C. slabs), the test results showed that the positive duration of the pulse was an almost linear function of the distance D. For calculation purposes τ has been taken as:

$$\tau_{(in\ \mu\sec)} = K \cdot D_{(in\ mm)}$$

where K = 0.715

It was experimentally established that the positive duration of the blast pressure pulse for the smaller charge placed at 300mm standoff was about 200μsec and this has been chosen as a maximum for calculation purposes.

Direct implementation of the Henrych relations gives results which do not compare well with the experimentally obtained results because no allowance is given for different pressure arrival times at different slab points. Instead an instantaneous pressure rise is assumed across the slab. This problem can be resolved by simply calculating pressures for each point taking pressure arrival time as zero time for that particular point but still relating it to the arrival time of the blast pulse at the centre of the slab. Peak pressures calculated using Henrych's values for A do not correspond to the experimentally measured ones. This may be due to the fact that the Henrych values for A refer to the spherical and cylindrical charges while values for hemispherical charges are applicable only to the flat side of the charge.

The values measured in these tests are the vertical components of the pressure on the slab but the Henrych calculations give full pressure values. After corrections the pressure function is:

$$P(t) = P_{\det} \cdot \left(\frac{R_w}{R}\right)^{2.65} \cdot \cos^3 \alpha \cdot \left(1 - \frac{t-L}{\tau}\right)$$

where: $L = \frac{D-H}{V}$, $V = 7.5 mm/\mu\sec$ and $\frac{D-H}{V}$ represents the delay which occurs due to the late arrival of the pressure at different points across the slab. The value of 2.65 for A has been chosen as the best fit to the available experimental results.

Figure 6: Calculated pressure vs. time profile for 78g PE4 charge at 50mm standoff

COMPARISON WITH THE EXPERIMENTAL RESULTS

Calculated results compare relatively well with experimentally obtained results when calculation is done at every 2mm of the slab and the comparison between them is given in Table 2.

Since the positive duration τ of the calculated pressure functions was chosen to be more or less equal to the experimentally measured results, it is not given in the table. The arrival time of the pressure pulse at a point on the slab must not be confused with the time of the pressure pulse arrival at the closest point on the slab which, if presented in the table, would vary because of the different bursting times for L2A1 detonators.

STANDOFF (mm)	DISTANCE TO THE EPICENTRE (mm)	PEAK PRESSURES	
		MEASURED VALUE (bar)	CALCULATED VALUE (bar)
600	420	26	21.2
500	0	100 to 140	116.14
400	0	180 to 280	202.2
400	350	45 to 55	48.8
300	0	290 to 320	407.9
300	350	35	63.6
200	350	40 to 52	74.2
100	350	55	57.8

Table 2 Comparison of measured with calculated pressures

CONCLUSIONS

(a) Blast pressure gauges with a metal diaphragm produced much better results than those with a silicon diaphragm. The amount of electrical noise from the metal diaphragm gauges was very minor.

(b) Henrych's,[1], pressure vs. time vs. distance relations given for spherical and cylindrical charges were adjusted for hemispherical charges and they then correspond to the measurements made from the tests, Table 2.

The pressure gauges were placed to measure the vertical component of the pressure at various points across the surface of the slab and the calculated pressure profiles for 78gr hemispherical charges placed at stand-off of 50mm is given in Figure 6. The blast pressures exerted on the slab by the curved side of hemispherical charge can be calculated according to:

$$P(t) = P_{\det} \cdot \left(\frac{R_w}{R}\right)^{2.65} \cdot \cos^3 \alpha \cdot \left(1 - \frac{t - L}{\tau}\right)$$

(c) Peak loading rates in explosive tests can be estimated from the calculated values of the pressure function and they are of the order of 17,000bar/microsec.

REFERENCES:

[1] HENRYCH, J., (1979), "The Dynamics Of Explosion and its use", Elsevier Scientific Publishing Company, Oxford, 1979.