IMPULSIVE LOADING ON REINFORCED CONCRETE SLABS
- LOCAL FAILURE PROPAGATION -

Nebojsa Duranovic and Alan J Watson

Department of Civil and Structural Engineering
University of Sheffield, U.K.

ABSTRACT

This paper describes the fracture of reinforced concrete slabs under explosive blast loading. Local failure propagation has been filmed and the crack patterns, formed at an early stage of the slab response are reported. The time scale of events for the formation and development of local failure at the epicentral zone of the slab is presented.

INTRODUCTION

The blast pressure loading function generated by a close range explosion cannot be considered to be a transient point load. There are 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 which is as important in determining the salab response as its magnitude and duration. In blast tests the cracking extends further from the epicentre than in impact tests because of the spatial distribution of pressure.

Shear failure planes perpendicular to the plane of the slab have been reported in the impact and blast literature close to the slab supports. This type of failure has been described as direct shear and the failure criteria is determined from a direct shear resistance to shear slip function, along an actual or potential crack, ***Ross and Krawinkler,(1985).*** It would seem for the present experiments, that the direct shear failure resistance when blast pressure is applied to a local region of a reinforced concrete slab, is too high for this to be the dominant shear failure mode. The more critical shear failure mechanism was found to be diagonal tension cracking so forming a shear plug. Displacement of this plug was restrained by the slab reinforcement and the trapped concrete was fragmented by compression forces.

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.

Overall flexural response is a global response and the 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.

Local response produces a shear plug around the epicentral axis, but can also include, in addition to the shear cracks some or all of the following fractures which occur very shortly after the first application of pressure:

(i) The formation of radial and circumferential cracks centred on the epicentre of the blast but with most cracks on the surface of the slab away from the charge.
(ii) The formation of craters on both faces of the slab near the epicentre, with associated deformation or even fracture of the steel reinforcement within the boundaries of these craters.
(iii) The perforation of the slab near the epicentre.

This type of local response for RC slabs will be formed only for impact and close range explosive charges where there is a large curvature on the shock front. For far range charges, the curvature of the shock front will be small when it reaches the surface of the slab. The slab is then loaded with a uniformly distributed, though time varying pressure and any shear fractures would be confined to the local region adjacent to the supports.

When the duration of the load is much lower than the natural period of specimen vibration then almost all local response takes place before there is any significant overall response and can be decoupled from the overall response. The damaged area is relatively small and is unlikely to overlap with the supports.

EXPERIMENTAL TECHNIQUES

The reinforced concrete slab specimens used in this research are based on typical structural elements which can exist in various types of structure, for example industrial buildings. The models have been designed to represent approximately 1:4 scale and 1:10 scale models of typical prototypes. Thus the small specimens model the large specimens at 1:2.5 scale.

The concrete mix used for the production of the model slabs contained river sand, max size 4mm; the W/C ratio was 0.6 and the aggregate/cement ratio was 2.28. The average static compressive strength was $40N/mm^2$.

A constant percentage of reinforcement in the small and large specimens, which is one of the main modelling requirements, could have been achieved if the bar spacing and diameter were both scaled down by the 2.5 scale factor. Heavy Twilweld reinforcement meshes were used in the production of model slabs. The bar diameter was given by the manufacturer as 10 gauge (3.15mm) while the spacing was 76.2mm x 76.2mm. This mesh had a tensile capacity of about 113% of that required for the model slab whilst very importantly, the bar spacing was kept at about 95% of that required.

The slabs were all square shaped, had rectangular cross-sections and the overall dimensions of the model slab are given in Fig.1. All four sides of the slab had identical, fixed supports which prevent vertical and horizontal movement and almost all rotation in the support region of the slab.

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 $2.68 \times 10^7 kN/m^2$ and mass specific energy of $5111kJ/kg^2$ which gives it a TNT equivalence 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 for the 1:2.5 model scale.

The charge standoff distance to the specimen was measured as the clear spacing between the charge and the specimen. All the tests were, because of the amount of explosive involved, performed in open blast cells. The blast chamber was built of concrete blocks and was 2m wide, 5m long and 2.5m high with a concrete floor and no roof.

The shock wave initiated by the explosion of the PE4 will travel at close range distances, at about 7500m/sec (***Henrych, 1979***). 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.

A Photec IV - rotating prism 16mm high speed camera was used to film the damage on some of the tests. When recording in full frame mode the speed can vary from 100 to 10,000 pictures per second (pps) but half frame and quarter frame shutters are also available and these increase the speed by two and four times respectively. The camera has an internal lighting source that marks the edge of the film with a mark every millisecond. Two cables are provided with the camera; one to connect the camera to the event - synchroniser and the other for starting the camera. The event-synchroniser can be set to start an electrically controlled event, such as the explosion in our case, at any preselected point on the film. The camera was powered by a 15 volt 2A DC power supply and triggered the explosion as soon as the film had accelerated to the required speed.

The slabs were tested vertically so enabling direct filming of the area of interest. On all slabs, meshes were drawn before the test with squares of 36mm x 36mm, starting from the centre lines. The size and position of the field of view of the camera is approximately shown in Fig.2 and a typical film frame is given in Fig.3.

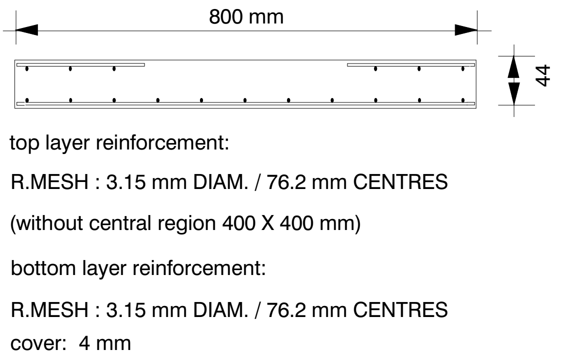

Fig.1 Model slab details

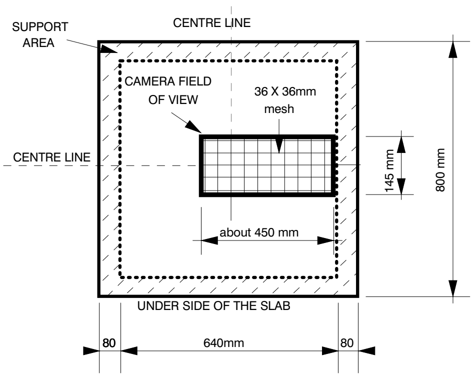

Fig.2 The area that was filmed by the High Speed Camera

plate/fig 3

Fig.3 Typical frame of the H.S. film

A half frame shutter and framing rates of up to 10,000 half frames per second were used to record the response of the slab. Ilford 400ASA HP5-plus Type 782, 30.5m long 16mm high speed films produced images of very high quality.

HIGH SPEED FILMS

Information about the local response of the slabs to blast loading was obtained mainly from the high speed films taken during the tests and inspection of the specimens after the tests.

The local response of a slab to an explosive charge at 75mm standoff from the centre was characterised initially by the formation of radial or fan shaped cracks on the underside of the slab, propagating from the centre of the slab. These cracks start to form by about 100μsec after detonation and the visible length of the longest crack after 190μsec was about 147mm measured from the centre of the slab. In addition to these radial cracks, a set of circumferential cracks was formed around the epicentre on the underside of the slab early in the response, in a region about 20mm radius from the centre. This was followed by extensive surface cracking inside that circle.

Another set of circumferential cracks forming a shear plug, with a radius of about 126mm on the under side of the slab and close to the boundary of the future scab region, was completely established by about 860μsec after the detonation. About 1.8msec after detonation the area of local response was fully defined within the circumferential cracks and inside that area extensive fan shaped cracking occurred and disintegration started to take place. New cracks then began to propagate, being initiated at the circumferential crack that borders the area of the scab.

The process that characterised the formation of the local damage in slab SE17 with the 78g charge at 50mm standoff was very similar to that described above but slab SE17 was perforated at the centre. Extensive radial cracking first occurred after about 100microstrain inside a circumferential crack at about 20 to 25mm radius from the epicentre. About 655μsec later, further circumferential cracks became visible at about 80mm radius from the epicentre. The establishment of the full circumferential crack around the epicentre took another 200μsec and the local scab area was then clearly established.

Not all explosively loaded slabs had significant scabbing and it was observed that the initiation of fan shaped cracks could be as much as 3msec before any visible circumferential cracks formed, usually at about 125mm from the centre. Although the circumferential cracks usually closed when the slab recovered, the fan shaped cracks remained open throughout the event and were combined with the scabbing that was observed after the test.

Some of the other explosively loaded slabs had diagonal cracking inside the area of the future scab before the circumferential cracks around that area became visible. These fan shaped cracks formed about 800μsec before the circumferential cracks and the area of the scab was square shaped with sides about 250mm long. The boundaries of the square were parallel to the reinforcement.

A typical failure pattern from high speed photography is shown in Fig.4 whilst the final shape of damage on the same slab is given in Plate 1.

Plate 1
Photograph 2

Plate 1
Photograph 3

Space for photographs 2 and 3.
They should be positioned side by side as shown on the example page

Plate 1. Failure shape on the slab SE15, top and bottom sides, respectively

space for the set of photographs “fig4”

Fig.4 Crack pattern as seen on H.S. films

DISCUSSION

In the static test on RC slabs, resistance mechanisms to shear or flexure followed response of the whole slab. A combination of shear-flexure failure occured after considerable central deflection of the slab. Impulsive load from a close range explosive charge produced both local and overall failure mechanisms changing the shape, location and characteristics of the damage from that produced by static load. In coupling local and overall failure mechanisms the transfer of energy to the specimen and the partition of energy between the failure mechanisms, becomes a major question.

Local response of the specimen is determined by spalling and scabbing mechanisms and by dynamic shear resistance. It starts long before the beginning of the overall response of the structure which is defined as a flexural response and is governed by the specimen's natural period of vibration. The energy absorbed in subsequent overall flexure will depend on the amount of energy transmitted to the rest of the slab across the shear plug boundaries of the local damage and transmitted by the dynamic shear resistance of the slab. When perforation of the slab occurs before the end of the shock pulse, some of the energy will be removed as the blast pressure exits through the hole in the slab.

The main features of local response are localised slab cracking and crushing resulting in shear failures and in top and bottom slab cratering or even perforation, followed by the local bending of the reinforcement. The cratering and scabbing occurs as the shock front reaches the structure, and the overpressure produces a compressive stress wave propagating into the slab. Internal reflections of that stress wave will produce tensile stresses which can produce scabbing before there is any flexure of the slab.

High speed photographs of the slabs show very clearly the pattern of scab disintegration under explosive blast loading. Radial cracking first started from the point on the back face of the slab below the epicentre. At about the same time a circumferential crack was formed at about 20mm radius from the centre.

The circumferential crack at about 20mm radius from the epicentre, bounded an area of scabbed or domed concrete, Fig.5, (Zone A) that completely disintegrated and fractured into random size and shape small pieces.

Another circural ring, (zone B), cracked and fractured into almost equal segments, Fig.6. These two zones approximately correspond to the size of the future scab region.

Radial cracks almost always propagated just to the circular cracks which define a shear plug, so giving the impression that the concrete within the circumferential crack deformed as a dome supported on the edges of the shear plug in a local flexural deformation. An alternative explanation of these radial cracks is that they are due to hoop stresses associated with an outwardly propagating compression pulse. In slab SE17 with a charge standoff of 50mm, there is more than just one Zone B ring, indicating larger stresses at greater distances from the epicentre.

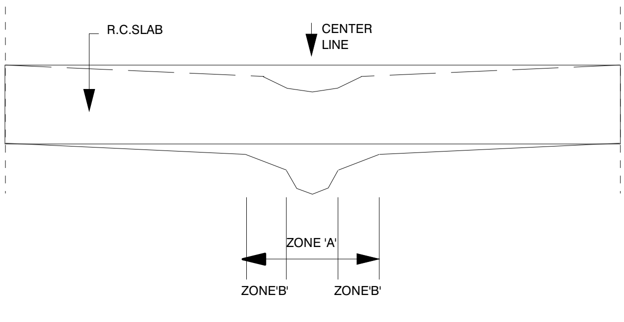

Fig.5 Development of area of local response

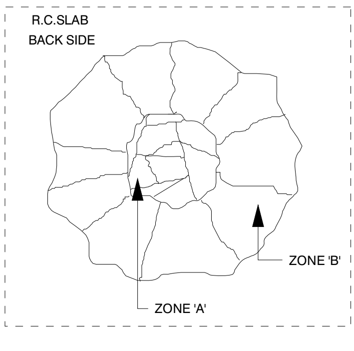

Fig.6 Symmetrical segmentation of the outer ring (ring B) and random segmentation of the inner ring (ring A)

The circumferential cracking on the surface of the slab around the epicentre may be associated with the formation of a spall crater on the front face and a scab crater on the rear face or may be the surface intersection of through-thickness cracks which form the frustum of a cone coaxial with the epicentral axis of the blast. This cone has often been described as a local punching shear failure surface, usually characterised by multiple inclined cracking.

The shear failure planes observed in these tests were always closer to the epicentre than to the support and their angle to the bottom slab surface of the slab was never greater than 35º.

The formation of a well defined cracked area of a circular shape can be caused by at least two different mechanisms. The concentric rings of identical pressures as the blast wave produced by the explosion of the hemispherical charge, spread across the slab, gave a load function that had radially varying intensities because of the curvature of the initial blast front. In addition the rate of loading necessitates the shortest paths of cracking and stress relaxation. Since the circle has the shortest length the first cracks will most likely be initiated along a circumference.

The high speed films show that the boundaries of the local damage are formed early in time and that most of the further damage then forms within that area. The circumferential cracks are then a limit on the size of the punching shear cone, the radial cracking and the future scab, and limit the transmission of further energy to the surrounding concrete.

Typical crack velocities observed from the high speed films were between 420 and 770m/sec but high speed films showed that the cracks did not propagate continuously with time but stopped and started for short periods. This could be explained by local increases in cracking resistance due to, for instance, a concentration of aggregate particles, or by the time needed for the stress to increase following stress relaxation due to the previous cracking.

The ultimate limit state conditions for local response are cracking and cratering in the area around the epicentre on both faces of the slab, and possible perforation. All these phenomena are mostly the product of the stress wave propagation through the slab but certain local damage may also occur as the result of overall deflection of the slab or local deformation of the reinforcement. Consequently the final shape of the local area occurred very early in the slab response with some further damage occurring much later, during the overall flexural response of the slab. The total time needed for the slab vibrations to be fully damped can be estimated from the deflection records measured by displacement transducers and for the 1:2.5 scale slabs it was up to 60msec while for the 1:1 scale slabs it lasted up to 150msec.

CONCLUSIONS

(a) High speed filming is a useful method for assessing failure mechanism in a slab under explosive blast loading. Filming at rates up to 10,000 pps in the blast loading tests produced a minimum of 150 frames or about 15msec of the film on which the visibility was very clear.

(b) To precisely measure the crack velocity from the high speed films the magnification has to be increased and so the film area is reduced. The film speed has to be increased to cover about 1mm of crack extension on every frame i.e. filming rates of up to 1,000,000 pps. This is possible using a rotating mirror camera but was not tried in these tests.

(c) In the blast tests the first cracks become visible 2 to 100 microsec after the blast pressure first reached the slab.

(d) The visible cracks on blast tested slabs occurred in the following order:

(1) Radial cracks were initiated under the epicentre of the slab on the rear face, in less than 100 microsec after the blast and had a length after 190microsec of about 147mm.

(2) The inner circumferential crack formed at about 10mm radius from the centre of the slab and appeared at the same time as the radial cracks.

(3) The outer circumferential crack formed at about 80 to 130mm radius and was established by about 800microsec after the blast.

(e) The area that was bounded by the inner circumferential crack disintegrated randomly, while the area inside the outer circumferential crack fractured into almost symmetrical ring segments.

(f) Typical crack velocities observed from the high speed films were between 420m/sec and 770m/sec.

ACKNOWLEDGEMENTS:

The interest and support of DRA Farnborough is gratefully acknowledged. The paper is published with permission of HMSO, Crown Copyright 1995/DRA.

REFERENCES:

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

ROSS, T.J. and KRAWINKLER, H., (1985), "Impulsive direct shear failure in RC slabs", ASCE Journal of Structural Engineering, Vol. 111, No. 8, Aug 1985.

WATSON, A.J. and DURANOVIC, N., (1994), "Validation of two-degree of freedom blast analysis algorithm ", Final Report to DRA Farnborough, University of Sheffield, 1994.