18 INTEGRATING SIMPLIFIED MODELLING WITH TEST RESULTS TO ASSESS THE EFFECT OF DYNAMIC LOADING ON REINFORCED CONCRETE SLABS AND BEAMS

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The Ministry of Defence, Mott MacDonald Group and the University of Sheffield are developing and validating a single degree of freedom model which is aimed at providing the design engineer with a simple and robust technique for assessing the response of reinforced concrete slabs and beams to blast loading. This paper provides the initial results of explosive and impact tests on reinforced concrete slabs and beams to assist in defining the failure modes and validating the model.

INTRODUCTION

Several complex numerical techniques, including finite element and hydrocodes, predict the response of reinforced concrete structures to explosive blast loading. These techniques can be computationally expensive, often taking many hours to run on a multi-processing computer system. There is also some doubt whether rate sensitivity is known accurately for reinforced concrete. Alternatively a 'mass, spring and dash-pot' single degree of freedom model can define the structure's behaviour.

Typical failure modes are shear and plastic moment flexural failures. These are described by Ross (1), and Crouch and Chrisp (2) but the mechanics of shear failure are not well understood. Model tests are currently being undertaken to develop new resistance functions and failure modes of reinforced concrete slabs and beams under impact and blast loading.

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EXPERIMENTATION

Reinforced microconcrete beams and slabs and their support conditions
The dimensions and reinforcement of the slabs and beams are shown in Fig. 1. The beams had a fixed amount of reinforcement, with high yield steel bottom bars and mild steel top bars and shear links. The mild steel bars were knurled to improve the steel/concrete bond and after knurling f_y = 260N/mm². Variable amounts of high yield steel, f_y = 460N/mm², were used in the slabs. The concrete water:cement ratio was 0.6 and maximum aggregate size 4mm. The 50mm cube crushing strength was 39-43N/mm² and the 50mm dia x 100mm cylinder splitting strength was 3.9-4.3N/mm².

The specimen supports, Fig. 2, had low moment restraint but prevented rebound after mid span impact or impulse load from an explosive charge at close range.

Equipment and instrumentation
The impactor was a 33.7kg drop hammer falling up to 1.76m onto a pressure bar 50mm dia x 500mm long, at midspan. Electrical resistance strain gauges (ERSG) on the bar measured the impact force. The impulse was from a 78g explosive

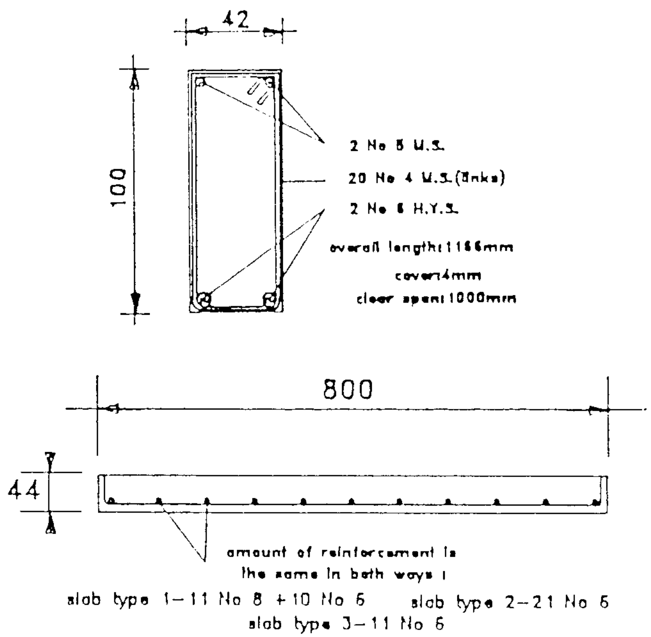

Figure 1. Dimension and reinforcement of beam and slab specimens

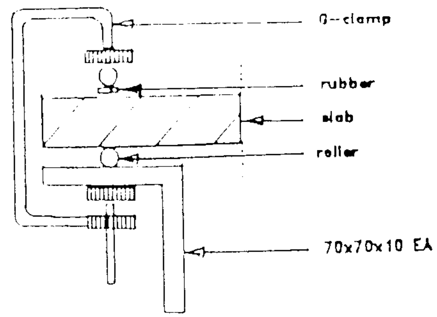

Figure 2. Typical detail of slab support

charge, hemispherical or cylindrical, placed 50mm to 100mm above the specimen mid span, Fig. 3. The blast over-pressures were measured by using piezo resistive gauges.

Deflections were measured at midspan and at one quarter span using linear variable displacement transducers (LVDT) connected to the steel bars, and reinforcement strains were measured at midspan using ERSG's.

RESULTS

Load and pressure
The distance between the explosive charge and the concrete was 50-100mm and pressure gauges placed on the surface directly beneath the charge could have

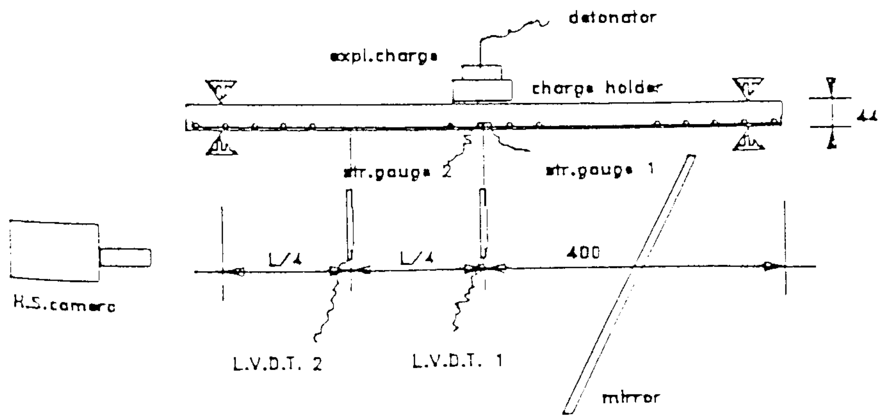

Figure 3. Arrangement for the impulse experiments

been damaged. For this reason the face-on overpressure-time profile was measured for three different explosive charge shapes at 1m standoff. At this range, the peak varied from 10 bar for a cylindrical or hemispherical charge with the hemispherical surface facing the gauge, to 30 bar for a hemispherical charge with the flat face facing the gauge, Figure 4. The duration of the positive phase of the pressure-time curve did not exceed 0.5ms at 1m. By extrapolation, the overpressure and positive duration at 100mm would have been 1650 bar (165N/mm^2) and 0.1ms for the charges with a curved surface facing the specimen.

In the impact tests the peak load was varied by altering the height of the drop and by placing a 27mm thick rubber pad between the hammer and the top of the pressure bar to produce a soft impact. Some typical slab results are shown in Fig. 5. The velocity of the hammer just before impact was 3.2 -5.88m/s depending on the drop height. The peak force for hard impact was 67-90kN and for soft impact was 20-31kN.

Deflections

Typical deflections for beams and slabs under impact are given in Figures 6 and 7. The deflection rate to maximum deflection for hard impact was 6500-1260mm/s at the midspan point and 1250-600mm/s at the quarter span point. For soft impact, rates of deflection were 1720 and 920-720mm/s respectively.

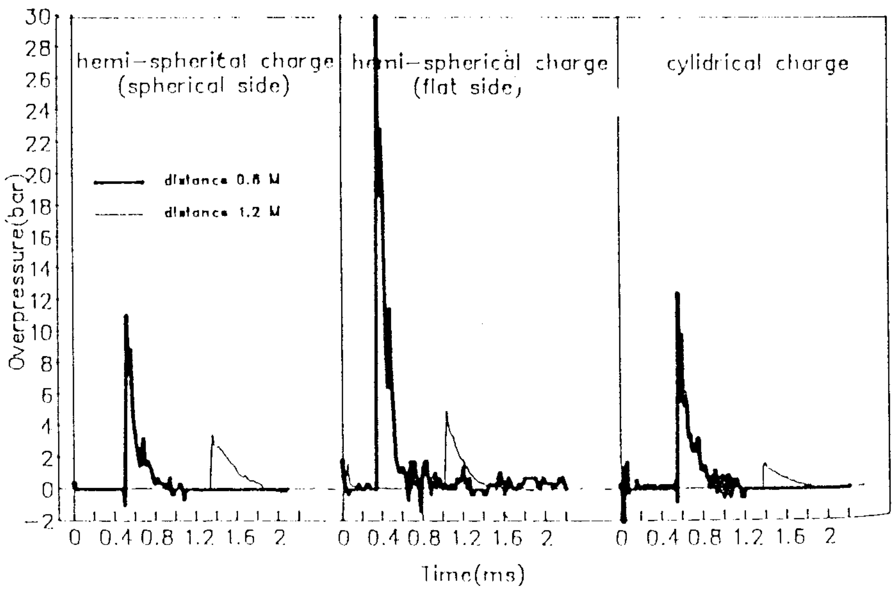

Figure 4. Face on blast pressure-time records at 1m standoff

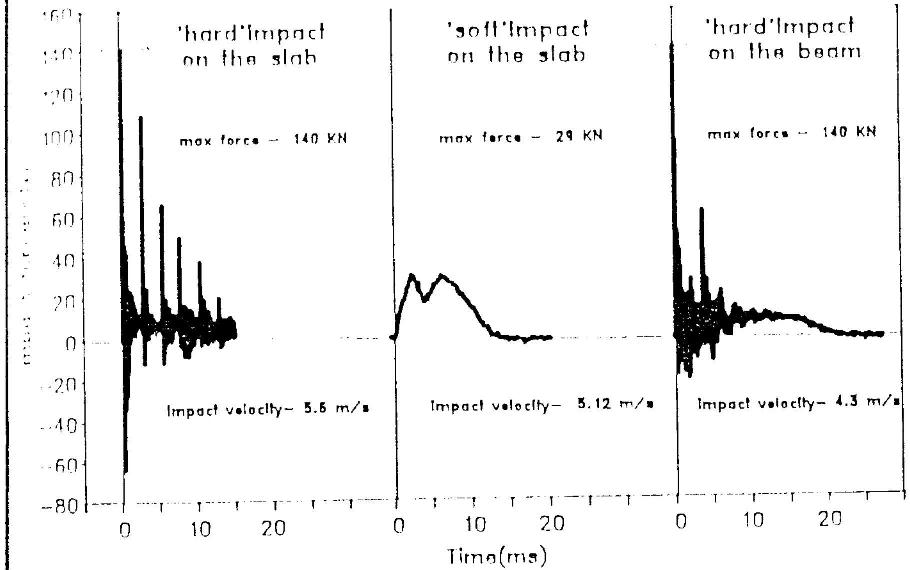

Figure 5. Typical impact force-time records

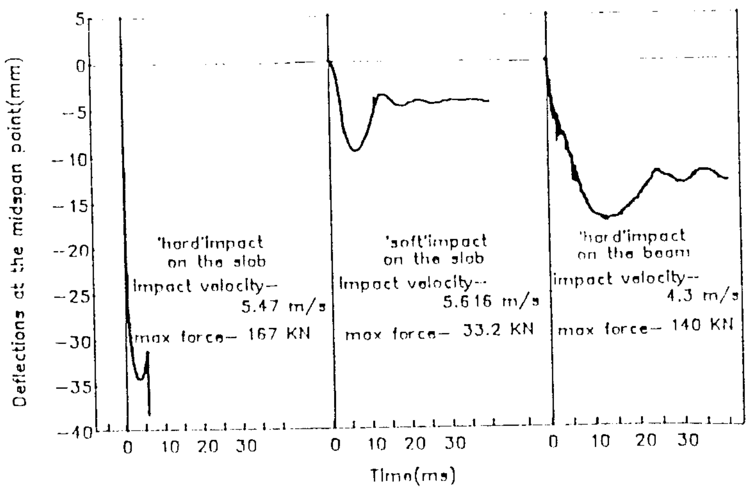

Figure 6. Typical deflection-time records for impact tests

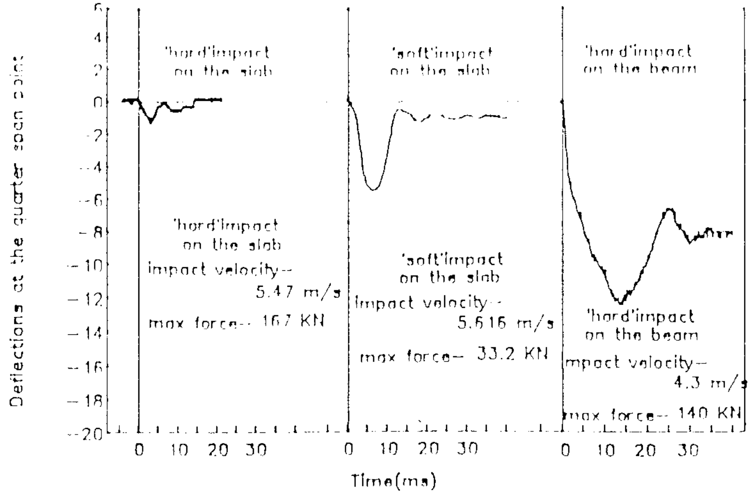

Figure 7. Typical deflection-time records for impact tests

Reinforcement strain

Typical strain-time curves obtained in the impact and impulse tests are shown in Figure 9 for both the beams and the slabs.

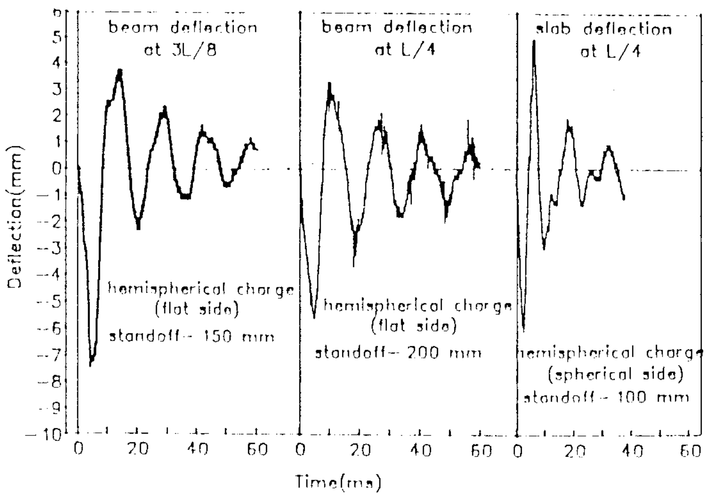

Figure 8. Typical deflection-time records for impulse tests

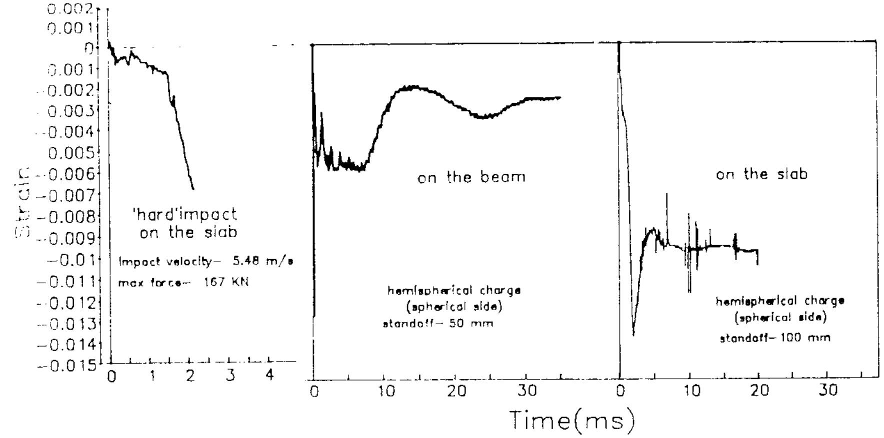

Figure 9. Typical strain-time records for impact and impulse tests

Cracking and failure modes

Typical cracks and spalls in the concrete slabs are shown for both hard and soft impact in Figures 10 and 11, and typical crack patterns from the impulse tests on beams and slabs are shown in Figures 12 and 13.

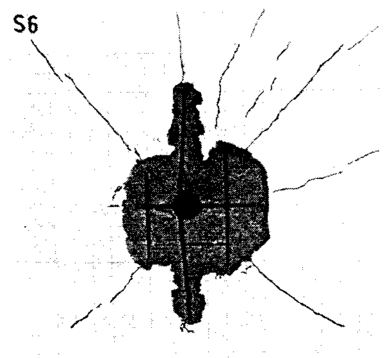

Figure 10. Slab Hard impact
(impact vel 5.47m/s max force 167 kN)

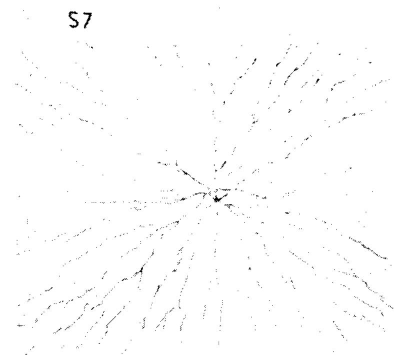

Figure 11. Slab soft impact
(impact vel 5.88m/s max force 31kN)

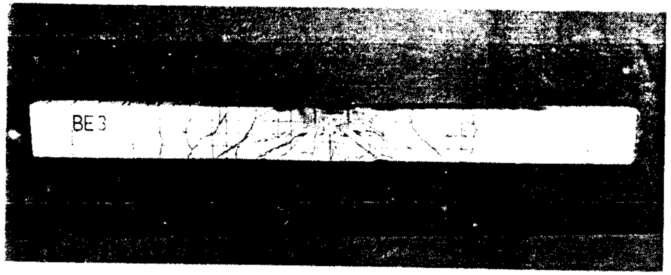

Figure 12. Impulse on the beam (hemispherical charge, flat side, standoff 150mm)

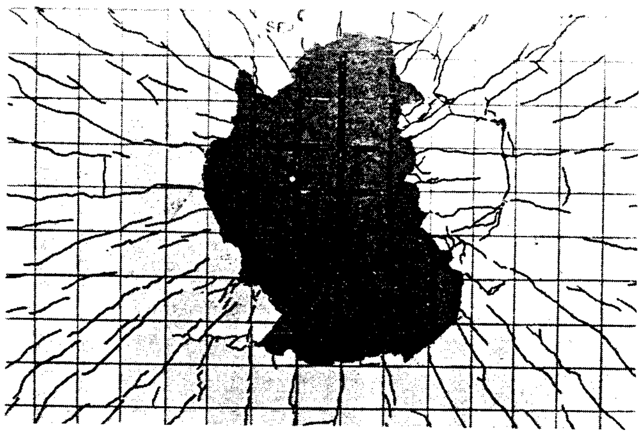

Figure 13. Impulse on the slab (cylindrical charge, standoff : 100mm)

DISCUSSION

The purpose of these experiments was to determine the shear and flexural modes of behaviour in the response of RC beams and slabs to dynamic loads. These were produced by either impact or by impulsive loads from the detonation of explosive charges at close range.

The loading conditions in both beams and slabs were varied in the impact tests by altering the drop height of the hammer and sometimes using a rubber pad to soften the impact. In the impulse tests the loading conditions were varied by altering the shape of the charge and the standoff distance.

Some of the SDOF models proposed by others, have indicated different modes of failure than were obtained in these experiments, particularly for shear failure under blast loading. Some models indicate that vertical shear cracks will form a shear plug, but in these impulse experiments the shear plug always had inclined cracks.

The form of the cracks throughout the beam and slab specimens and the fragmentation of the concrete in the region directly beneath the explosive charge, indicated that punching shear is only one of the active mechanisms of failure. In addition there are stress wave mechanisms which produce cratering and spalling, and flexural mechanisms which produced third mode bending deformations causing vertical cracking to form from the top downwards in the end section of the beams. All the beams tested impulsively had diagonal cracking and top surface cratering immediately under the explosive charge. The sides of the crater were steeply inclined and if these craters had intersected with spalls on the bottom surface, then the hole in the specimen would have had almost vertical sides. This could appear as a punching failure but a stress wave analysis indicates it is not a shear failure mechanism.

In all beams and slabs the bottom reinforcing bars were deformed locally in bending over a length equal to the width of the scab in the perforated slabs, or the length of beam between the inclined cracks. This indicates that although the concrete may crack and so form a potential shear plug, there is resistance to displacement of that shear plug from the dowel action of the bottom reinforcement. Before shear slip developed, the concrete in the shear plug had been fragmented by the high compressive stress applied by the blast pressure.

Shear failure planes perpendicular to the plane of concrete slabs have been reported in the literature but these are almost always close to the 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 (1985). It would seem for the present experiments, that the resistance to direct shear when blast pressure is applied locally on a reinforced concrete beam or slab, is too high for this to be the dominant shear failure mode. Instead the shear initiates diagonal tension cracking and forms a shear plug.

In all of the hard impact tests on the reinforced concrete slabs and beams, the pressure bar penetrated a short distance into the specimen. Diagonal cracks are visible on the sides of the beams from the edges of the pressure bar and on the underside of the slabs a circular crack pattern, or spall, was visible with a diameter much greater than the diameter of the pressure bar. The diameter was also smaller for hard than for soft impact.

CONCLUSIONS

The development of shear failure mechanisms in reinforced concrete beams and slabs under very rapidly applied dynamic load applied to a small area of the element, would appear to be greatly restrained by the longitudinal reinforcement. Diagonal shear cracks formed a conical plug but displacement of the plug could not occur because of the reinforcement and the compression forces then fragmented the concrete within the cone which was trapped above the reinforcement.

ACKNOWLEDGEMENTS

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REFERENCES

1. Ross, T.J., (1985) 'Characterizing impulsive failure in buried reinforced concrete elements'. Proceedings of the Second Symposium on the Interaction of Non-Nuclear Munitions with Structures, Panama City Beach, Florida, U.S.A., April 15-18, 1985.
2. Crouch, R.S., Chrisp, T.M., (1989) 'The response of reinforced concrete slabs to non-nuclear blast loading', Structures Under Shock and Impact. Bulson P.S.(ed), Elsevier Computational Mechanics Publications, p. 69-76, 1989.

K.S. Virdi, City University, UK
In carrying out the comparison with test results, was the effect of strain-rate taken into account in modelling the material behaviour? It is likely that a better material modelling, with appropriate consideration of cracking and crushing, better estimates of shear cracking would be obtained.

Author's reply
The effects of strain rate on the material properties are included in the 'resistance/displacement' function of the Single Degree of Freedom Model for the particular mode of deformation under consideration. Material properties under high strain rates have been measured by the University of Sheffield using the Split Hopkinson Bar tests.

We agree with the questioner that material modelling is an important factor in describing the behaviour of structural elements under high rate loading. However, the description of the correct deformation mode is not achieved by simply introducing rate enhancement factors into a typical quasi-static deformation in response. The effects of increasing the rate of loading may also introduce changes to the mode of deformation. Take, for example, the localised punching of a hole through a slab. Traditionally this type of deformation has been described by many as a 'punching shear' enhanced by some rate factor. The authors would, in fact, question whether this is actually a shear failure. Close scrutiny of the field trials undertaken at the University of Sheffield and the international literature describing trial results, suggests that the hole is produced by a combination of several mechanisms. These include reinforcement bending and dowel action; concrete spalling, cratering, confined crushing and local shear. The Special Services Division of Mott MacDonald is currently developing a mixed mode formulation to address this behaviour. We hope to produce a computer model in the near future, that will couple this local mixed mode punching response with the overall flexural response.

K.S. Elliott, University of Nottingham
As an experimentalist I am always interested in how one arrives at load magnitudes. How did you decide on charges of 78 gm and what equivalent surface pressure was measured on the specimens. How would you scale up the magnitude of these pressures in line with the geometric scaling of the beams.

Author's reply
The 78g charge was chosen as the smallest in a series of scaled tests.
The choice was based upon cube root scaling and a number of considerations such as the present maximum capacity of our test facility (about 1.3kg charge); a suitable linear scaling factor of 1:2.5, and our prediction of the expected level