IMPULSIVE LOADING ON REINFORCED CONCRETE SLABS

submitted for the degree of Doctor of Philosophy
to the

Faculty of Engineering
Department of Civil and Structural Engineering
University of Sheffield
by

N. Duranovic

February 1994
## CONTENTS

| List of Figures | VII |
| List of Tables  | X   |
| List of Plates  | XI  |

1. **INTRODUCTION**
   - 1.0 General Introduction  
   - 1.1 Dynamic loading  
   - 1.2 Impact and impulse loading in the field of Civil Engineering  
   - 1.3 R.C. slabs under transient loading  
   - 1.4 Present investigation  

2. **LITERATURE SURVEY**
   - 2.1 Impact and blast loading of R.C. slabs  
   - 2.2 Material properties under high rates of strain  
     - 2.2.1 Concrete properties  
       - 2.2.1.1 Stress-strain diagram  
       - 2.2.1.2 Compressive strength  
       - 2.2.1.3 Tensile strength  
       - 2.2.1.4 Poisson ratio  
       - 2.2.1.5 Energy absorption and modulus of rupture  
     - 2.2.2 Reinforcement properties  
   - 2.3 Local response of R.C. slabs to impact and close range blast loading  
     - 2.3.1 Stress-wave propagation  
     - 2.3.2 Cracking  
     - 2.3.3 Penetration  
     - 2.3.4 Shear plug formation  
   - 2.4 Overall response of R.C. slabs to impact and close range blast loading
2.4.1 Inertial loading 40
2.4.2 Resistance function 41

2.5 Blast pressure characteristics 45
2.5.1 Introduction 45
2.5.2 Blast wave scaling and parameters 48
2.5.3 Interaction of shock waves with plane surfaces 49
2.5.4 Loading due to a short range explosion 51

2.6 Modelling considerations 54
2.6.1 Dimensional analysis 54
2.6.2 Theory of modelling for structures exposed to impact and blast 55

2.7 Some theoretical approaches to the problem 57
2.7.1 Timoshenko (1951) 57
2.7.2 Goldsmith (1960) 57
2.7.3 Norris (1964) 58
2.7.4 Ezra (Johnson, 1972) 59
2.7.5 Popov (1976) 60
2.7.6 Symonds (Watson, 1991) 61

2.8 Standard recommendations 62

3. EXPERIMENTAL TECHNIQUES

3.0 Introduction 65

3.1 Test specimen 66
3.1.1 Slab dimensions 66
3.1.2 Materials 68
3.1.2.1 Concrete 68
3.1.2.1.1 Microconcrete mix 69
3.1.2.1.2 Macroconcrete mix 73
3.1.2.2 Steel reinforcement 76
3.1.2.2.1 H.Y. grade 460 deformed reinforcement bars 77
3.1.2.2.2 H.Y. BS4483 square reinforcement mesh 77
3.1.2.2.3 Heavy Twilweld reinforcement mesh

3.1.3 Fabrication of the specimen
  3.1.3.1 Reinforcement mesh
  3.1.3.2 Preparation of moulds
  3.1.3.3 Concrete mixing, casting and curing
  3.1.3.4 Control specimen
  3.1.3.5 Preparations prior to testing

3.2 Test instrumentation
  3.2.1 Displacement transducers
  3.2.2 Digital storage oscilloscopes
  3.2.3 Strain gauges
  3.2.4 D.C.-Bridge amplifaer - 359 - TA
  3.2.5 Microswitches
  3.2.6 Slotted opto-switches
  3.2.7 Universal counter timer

3.2.8 D.C. Power supply

3.2.9 Photec IV - 16mm High Speed Camera

3.2.10 FS-10 Firing system
  3.2.11 Pressure transducers
  3.2.12 Hycam - K 2001 R - 16mm High Speed Camera

3.3 Test arrangements
  3.3.1 Support conditions
    3.3.1.1 Free supports
    3.3.1.2 Inner supports
    3.3.1.3 Fixed support
  3.3.2 Loading conditions
3.3.2.1 Impact test 96
3.3.2.2 Impulse test 98
  3.3.2.2.1 Test arena 98
  3.3.2.2.2 Explosive charge 99
3.3.2.3 Static test 100
3.3.3 Specimen response record 101
  3.3.3.1 Impact load measurements 102
  3.3.3.2 Hammer velocity measurements 105
  3.3.3.3 Blast pressure measurements 106
  3.3.3.4 Reinforcement strain measurements 107
  3.3.3.5 Deflection measurements 108
  3.3.3.6 High-speed filming 111
  3.3.3.7 After test damage assessment 113
3.3.4 Test set up, procedure and event synchronisation 113
  3.3.4.1 Impact test 113
  3.3.4.2 Impulse test 116
3.3.5 Experimental programme and variables 117

4. EXPERIMENTAL RESULTS

4.0 Introduction 120
4.1 Impact tests 121
  4.1.1 1:2.5 Scale slabs 121
    4.1.1.1 Pressure bar record and velocity measurement 122
    4.1.1.2 Displacement record 124
    4.1.1.3 Reinforcement strain record 125
    4.1.1.4 High speed films 128
    4.1.1.5 Crack patterns and slab cross-sections 130
  4.1.2 1:1 Scale slabs 132
4.1.2.1 Pressure bar record and velocity measurement 133
4.1.2.2 Displacement record 135
4.1.2.3 Strain record 137
4.1.2.4 Crack pattern 138
4.1.3 Conclusions 139
4.2 Impulse tests 140
4.2.1 1:2.5 Scale slabs 140
   4.2.1.1 Blast pressure records 142
   4.2.1.2 Displacement record 145
   4.2.1.3 Reinforcement strain record 147
   4.2.1.4 High speed films 149
   4.2.1.5 Crack patterns and slab cross-sections 152
4.2.2 1:1 Scale slabs 154
   4.2.2.1 Displacement record 154
   4.2.2.2 Reinforcement strain record 156
   4.2.2.3 Crack patterns 157
4.2.3 Conclusions 158

5. DISCUSSION
5.1 Introduction 160
5.1.1 Loading function 161
   5.1.1.1 Calculation of blast loading function 161
   5.1.1.2 Attenuation of the loading function and inertia 168
5.1.2 Dynamic character of material behaviour 169
5.1.3 Dual nature of the slab response 170
5.2 Local response 171
5.2.1 Formation of an area of local response 172
   5.2.1.1 High speed films 173
   5.2.1.2 Stress wave theory approach 175
5.2.2 Development of cracking within the area of local response 181
5.2.3 Ultimate state conditions in the area of local response and failure

5.2.3.1 Spalling, scabbing and perforation of the slab
5.2.3.2 Prediction of the damage

5.2.4 Load transfer from the area of local response to the rest of the slab

5.3 Overall response of the slab

5.3.1 Crack type analysis

5.3.1.1 Top surface cracks
5.3.1.2 Bottom surface cracks
5.3.1.3 Cross sectional cracks

5.3.2 Deflection analysis

5.3.3 Energy considerations due to close range explosion

5.4 Connection between local and flexural response

5.5 Time sequence of events in the blast loading of R.C. slabs and

5.6 Modelling

5.6.1 Local damage
5.6.2 Overall flexural damage

5.6.3 Displacement record

6. CONCLUSIONS

6.1 Modelling

6.2 Instrumentation

6.3 Dynamic properties of materials and the blast loading function

6.4 Local response

6.5 Overall flexural response

7. FUTURE WORK

REFERENCES

APPENDICES
Appendix A1 1:1 Scale impact test results
Appendix A2 1:2.5 Scale impact test results
Appendix A3 Impact tests - High speed films
Appendix B1 1:1 Scale impulse test results
Appendix B2 1:2.5 Scale impulse test results
Appendix B3 Impulse tests - High speed films
Appendix C1 Static test results
Appendix D1 Staff list, Expenditure and Publications
Appendix D2 Materials and equipment suppliers, and Summary of Equipment Specification
Appendix D3 Inventory of major items of expenditure for the experimental program
Inventory of explosive stores provided by DRA and used in testing program
SUMMARY

Reinforced concrete slabs were exposed to blast and impact loading in order to access modes of slab behaviour under these extreme dynamic loadings.

Two sizes of specimens were used and smaller slabs modelled the large slabs at 1: 2.5 scale.

Impact loads were produced by free falling hammer impacting coaxially onto a cylindrical bar of steel placed at rest in the centre of the slab. The steel bar was instrumented with electrical strain gauges which recorded the stress pulses produced by the impact.

Blast loads were produced by explosive charges made of Plastic Explosive PE4. In most cases the charge had the hemispherical shape and was placed centrally above the slab at close range standoffs i.e. up to 10 times the radius of the charge.

Additional blast tests were conducted in order to monitor the transient and spatial pressure distribution across the slab by using the pressure gauges placed in replica steel slab.

Transient deflections of the slabs under both types of load were obtained using long stroke displacement transducers, while transient strains in the steel reinforcement of the slabs were obtained using electrical resistance strain gauges bonded to the steel bars at mid span point.

A rotating prism high speed camera was used to film the damage on some of the small scale specimens at rates of up to 10,000 pictures per second.

The Hopkinson pressure bar tests were used to obtain dynamic characteristics of concretes of both scales at high rates of loading.

An analytical function of the spatial and transient blast pressure distribution based on detonation pressure of PE4 was established and is in close agreement to experimentally measured results.

The nature of the local and overall failure were discussed and time sequence of slab failure established for the case of explosive loading.
A crack pattern that occurs soon after the explosion in area of local failure has been established from the high speed films while the overall deflected shape was obtained from the displacement vs time records.

After test scab sizes and slab perforations were used to establish a relation between the slab thickness, amount of explosive and the slab damage in respect to scabbing and perforation.

The displacement records and the shape of after test damage provided the bases for comments on "gravity neglected - ultimate strength modelling law that was employed in this research."