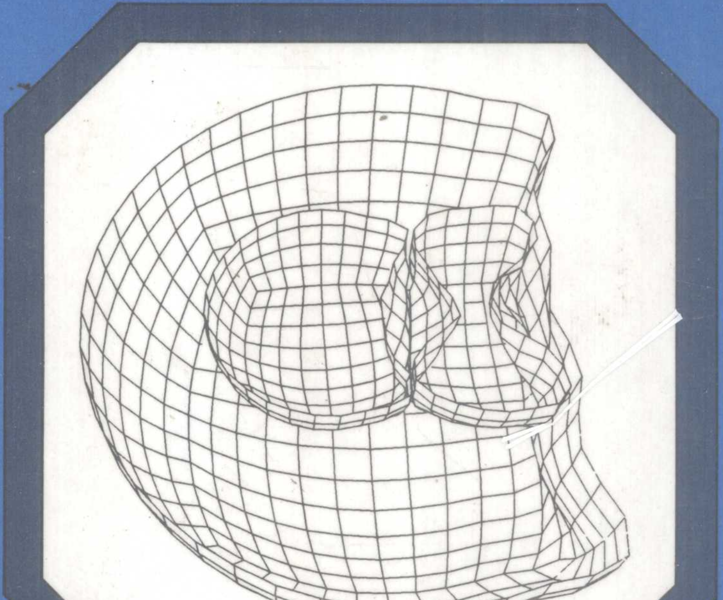
STRUCTURES UNDER SHOCK AND IMPACT

P.S. BULSON (EDITOR)



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PREFACE

The response of structures and structural elements to explosive shock or high speed impact is of growing interest to scientists, research engineers and designers throughout the world. Attacks on civil and military buildings, bridges and transport vehicles by terrorists mean that more attention has to be given at the design stage to the effects of explosions and impact, and to the high speed penetration of attack weapons. New design codes of practice need to be based on scientific research, both analytical and experimental, and there is a need for the cross-fertilisation of ideas between military and civil experts. This book brings together the experience of specialists in the behaviour of concrete and metal structures, both above and below ground, to the actions of blast, penetration and high speed collisions.

The book contains the edited versions of most of the papers presented at the first International Conference on Structures under Shock and Impact, held in Cambridge, Massachusetts, USA, in July 1989. This multidisciplinary meeting was held to bring together workers in a wide range of engineering activities, who employ common analytical and experimental methods in their estimation of structural response. The results of the meeting are of world-wide interest, and will help to stimulate future research and analysis.

P.S. Bulson
July 1989

CONTENTS

SECTION 2 - ANALYSIS

SECTION 3 - PENETRATION AND FRAGMENTATION

SECTION 4 - COLLISIONS

SECTION 5 - PLATES, PANELS AND SHELLS

SECTION 6 - BUILDINGS AND DEMOLITION

SECTION 7 - UNDERGROUND STRUCTURES AND SOILS

SECTION 8 - GENERAL STUDIES

SECTION 1 - CONCRETE STRUCTURES

Formation of Full Depth Cracks in Concrete Slabs subjected to Hard Impact

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ABSTRACT

This paper describes the likely causes of hard impact, then discusses briefly the various modes of impact damage found in concrete slabs. Experimental results from laboratory tests, undertaken by the authors on a large number of reinforced concrete slabs, are presented and the damage phenomena discussed in detail. The influence of the maximum contact force and the imput energy, measured during impact, on the extent of damage are discussed, and primary and secondary phases are identified. Further work by the authors on the provision of protection against hard impact by the use of low strength fender layers is summarized.

INTRODUCTION

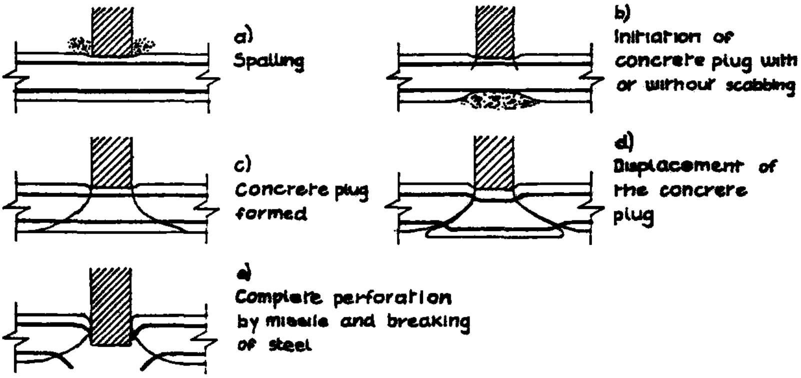
Preliminary design of civil engineering structures assumes, customarily, that loading is uniformly distributed. However, attention must sometimes be given to statically concentrated loads and, occasionally, to impact loading [1]. This is particularly the case when the consequences of local damage or possible penetration of a structural member are deemed to be sufficiently serious [2] and, also, when the risk of such loading is significant. Reinforced concrete slabs could be susceptible to intense hard impact loading in the low velocity range when, for example, rocks fall onto roof protection shelters in mountainous areas, the solidchassis of a forklift truck collides against a vertical column, or when objects are accidentally dropped onto offshore sub-surface storage tanks.

Several incidents, some of them major, have already been reported on oil platforms in the North Sea where objects such as drill collars, riser pipes, drill casings, drain caissons, mud pumps, reinforcing bars, scaffolding poles and even cranes have been dropped onto the roofs of base caissons [3,4,5]. Near normal, or vertical, impact of slender objects travelling at velocities up to 26m/s and weighing as much as 50 tonnes have been identified as being the most critical. Naturally, the velocity of the dropped object will depend on whether the terminal velocity has been reached during its free fall in water, and end-on impact velocities between 5 and 24m/s for objects weighing less than 20 tonnes are more likely to occur [5]. Impact loads at higher velocities (say 200m/s to 1000m/s - corresponding to aircraft and ballistic impact, respectively) can also affect protection requirements for aircraft shelters and nuclear reactor installations; but only the lower velocity range will be considered in this paper. Nonetheless, even a low-velocity impact can lead to environmental damage and complex repairs costing far more in monetary terms than the initial cost incurred for an adequate design. However, in order to be able to design structures that can readily withstand impact loading, a better understanding of load/-structure interaction, and the process of damage development within the structural material (in this case, concrete), must be obtained. Additionally, methods of providing protection against impact damage should be given consideration.

Hard impact of concrete is characterised by a sharply peaked force/time relationship (1 to $3x10^{-3}$ s), regardless of the approach velocity. This can lead to spalling, concrete plug ('shear' plug) formation, back face scabbing and, in the limit, complete perforation of both reinforced and prestressed concrete slabs. An extensive series of impact tests on concrete slabs and fender materials (in the 0-10m/s velocity range) was undertaken at the Imperial College of Science, Technology and Medicine under the general direction of Professor S.H. Perry [6] in order to investigate the different possible modes of damage, examine the parameters which govern internal concrete plug formation and study ways of furnishing adequate protection. Results, reported in detail elsewhere, are summarized here for tests on circular flat slabs [7,8] (1.5m diameter, 60-80mm thick and with two-way reinforcement in both faces) and lightweight concrete fender materials [9, 10].

CLASSIFICATION OF IMPACT DAMAGE

A standardized description of the different modes of damage caused by impact loading is necessary to allow accurate comparison between various experiments. Brown and Perry [6] define the following modes (Fig 1), <u>spalling</u>, cratering damage on the struck face; <u>penetration</u>, of the missile into the slab; <u>scabbing</u>, fracturing and expulsion of concrete, often at high velocities, from the face opposite the struck face; <u>perforation</u>, occurs when the missile passes completely through the slab; a <u>concrete plug</u> (sometimes refered to as a <u>shear plug</u>, and often in the form of a conical frustum) is formed by inclined cracking through the thickness of the slab. Scabbing may occur before plug formation or as a result of plug movement.



a) Spalling

b) Initiation of concrete plug with or without scabbing

c) Concrete plug formed

d) Displacement of the concrete plug

e) Complete perforation by missile and breaking of steel

Figure 1. Progressive development of full-depth cracks, and subsequent damage.

The form and degree of impact damage is heavily influenced by the ratio of slab thickness to missile diameter (t/d). Hence, using a small missile diameter in comparison with the slab thickness (high t/d values, for example, of the order of 6) will most likely cause penetration and spalling. Smaller t/d values, of about unity, are more likely to cause scabbing and concrete plug formation; all localized forms of failure. Impact will occur over a relatively large area of the slab for even lower values of t/d, and behaviour will be dominated by the global flexural response of the slab, although scabbing is still possible. Impactor shape, also, can affect the type of failure, and results for a pipe-shaped projectile have been discussed elsewhere [6]. Other factors influencing impact damage include the deformability of the projectile, the velocity of impact, the relative characteristics of the target and missile and also the severity of impact [11].

PROGRESSIVE DEVELOPMENT OF DAMAGE

Relatively low contact velocities with small (compared to that of the target) missile mass will lead to small contact forces and exercise the structure in the elastic range which, depending on the flexibility of the structure, velocity and missile mass, can be followed by a rebound of the impactor. This type of impact will generally not cause any perceptable damage to the target.

As the impact velocity increases, spalling, in the form of a crater with an area larger than the cross-sectional area of the missile, may occur (Fig 1). Further increases of missile velocity will result in penetration; with a depth greater than the depth of the spall crater, and a cylindrical penetration hole only slightly larger than the diameter of the missile. Some plastic deformation occurs within this increased velocity range, but the initial kinetic energy of the projectile is still, to a large extent, expended in rebound of the missile. Up to this stage, where target penetration occurs, the concrete slab as a whole can be treated as elastic for purposes of analysis. However, penetration of the target introduces predominantly inelastic behaviour.

A further increase in missile velocity may produce cracking of the concrete on the back face of the target, followed by the expulsion of concrete from the back surface (scabbing), initiated by the reflected tensile wave effect. Initially, impact loading creates a compressive wave which travels through the target; on reaching the free surface, the wave is reflected as a tensile wave of similar magnitude [12]. Generally, the area of scabbing will be much larger than the spall area, but not so deep; often only of the same depth as the concrete cover to the bottom steel [13]. Once scabbing begins, the depth of penetration will increase rapidly, usually causing a concrete plug to be formed by inclined cracking through the remaining thickness of the slab. However, scabbing may occur either before, or as a result of, the concrete plug movement.

Depending on the initial velocity, once the concrete plug is formed and displaced, the missile may break through the reinforcement, or may only deform it. This will depend, also, on the amount of, and size of, the reinforcement contained within the concrete plug. Finally, with a further increase in velocity, complete perforation of the target will occur.

Apart from the major damage caused at the point of contact during hard impact, radial cracks spreading from the penetration crater are usually formed on the back surface of a slab [13]. Some circumferential cracks can be formed, also, when the flexural tensile stresses produced by the vibrational response of the overall structural element (in this case, the slab) exceed the tensile strength of the concrete.

IDENTIFICATION OF THRESHOLDS FOR CRACK INITIATION

An extensive series of carefully controlled hard impact tests on reinforced concrete slabs (summarized in [8], detailed in [15]) has allowed identification of the actual contact force required for formation of an incipient concrete plug. This was achieved by cutting slabs through the point of impact revealing, in some cases, the presence of full-depth cracks (Fig. 2, scale in cm). Interpretation of the masses and velocities involved suggests that shear plug formation is not only dependent on the peak contact force but, also, on the input kinetic energy. This was demonstrated by comparing the peak contact force with the input kinetic energy at impact, $(mv^2)/2$. The results and observations of these tests imply that both requirements, namely, the peak contact force and the input impact energy, have to reach a certain, critical, value for damage to occur. Clearly, if a critical peak contact force is reached, yet the input impact energy is less than the critical value required, (which, for these tests, was approximately 500 J), the plug will not form. If, however, both requirements are satisfied, damage of the slab will occur by formation of a full-depth crack which will determine the concrete plug.

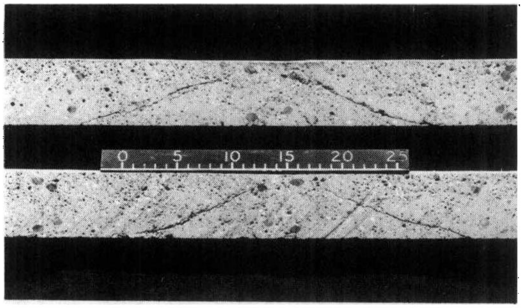


Figure 2. Section through a concrete slab after hard impact, showing an incipient concrete plug.

Examination of the results also showed that the contact force/time relationship for normal aggregate concrete (dome 6, Fig. 3) can be broken down into two distinct phases. The primary phase is characterised by a steeply ascending curve to the maximum load which, typically, occurs 0.2 to 0.3ms after contact. The descent is almost as rapid, and this phase is over in less than 1.0ms. The actual duration is largely "hardness" dependent; there is some evidence that it is influenced separately by contact velocity, impactor mass and target thickness, and that when penetration occurs, the duration of the primary phase decreases. Additionally, other parameters not examined in detail in this study, such as impactor nose shape, concrete strength and slab surface roughness, will certainly affect the primary phase behaviour. Nevertheless, it can be postulated that

$$t = f\ [v,\ m,\ d,\ \text{damage}]$$

where t is the duration of impact up to maximum contact force, v is the velocity, m is the mass of impactor, and d is the thickness of slab.

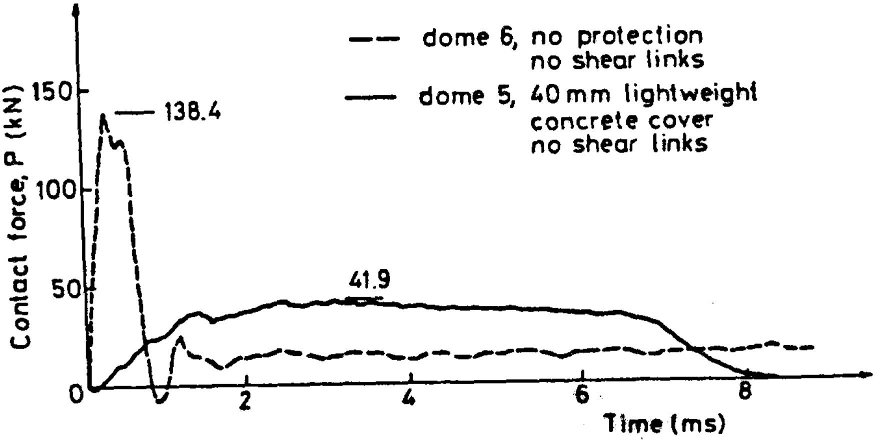


Figure 3. Contact force/time relationships for pipe impactor (mass of 37.85kg, velocity of 8m/s, dome thickness of 40mm).

The secondary phase describes the remaining duration of the impact event. Clearly, this also depends on the extent of damage caused by the impactor. When only cracking of the back face occurs the overall impact duration is approximately 1.75ms to 2.0ms. In this case, the slab reacts to the impact loading with a stiff response, representative