

Spalling and Fragmentation

1 Introduction

One mode of material failure during high velocity impact is spallation. Historically, the spalling phenomenon was discovered during the development of steel armour plating. It was found that an impact on the outer surface which was not powerful enough to cause penetration, nevertheless, could cause the formation of spalls at the inner surface.

Reflected shock wave is generated when the incident shock hits the material boundary. The interaction of the incident and reflected shock waves causes the formation of spalls. Many spall events lead to the fragmentation of the material.

In this section on spall and fragmentation, we study:

- (1) The observed spall and fragmentation phenomena (part I); and
- (2) Using Rankine-Hugoniot equations of shock waves to study spall and fragmentation (part II).

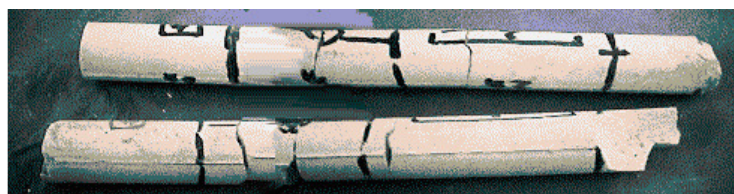
2 Spalling and Fragmentation Phenomena

2.1 Bar

In Figure 1, a high velocity impact is applied at the right end of the bar. Spalling starts from the free end. Multiple spalling is observed.



(a) Initial bar



(b) Spalling of the bar

Figure 1. Multiple spalling of a bar (from IMPEX at MACE).

The explanation is given in the following.

The compressive pulse is reflected from the free end of the bar as a tensile pulse. When the tensile pulse reaches the ultimate tensile strength of the material a spall is formed, and the end of the bar breaks off. A new free end is formed and the remained original pulse is reflected from this new free end. Once again the bar breaks when the reflected tensile pulse exceeds the ultimate tensile strength of the material, and again a new free end is formed. In this way multiple spalling is generated.

The reflected tensile waves can be pictured as originating from “Tensile Sources” mirroring the detonator position on the outside of the free edges.

2.2 Spall crack formation

Figure 2 shows the formation of spall crack during the high velocity impact. The impactor and the target are circular plates.

Sequential stages of the impact are shown in Figure 2. Figure 2a shows the initial stage before the impact. Figure 2b shows the appearance of micro-cracks. Figure 2c shows the coalescence of micro-cracks into one major crack. Figure 2d shows the spallation.

Spall is the process of internal failure or rupture of condensed media through the nucleation, growth and coalescence of defects, such micro-cracks, due to stresses in excess of the tensile strength of the material.

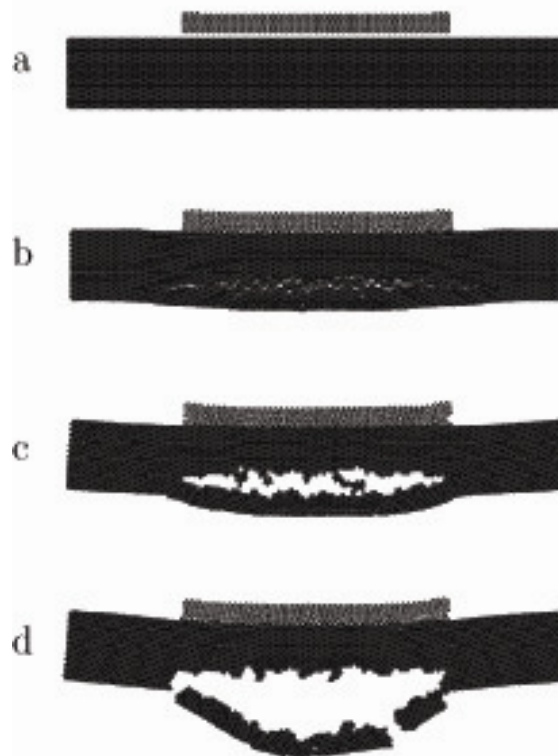


Figure 2. A simulation result shows the sequences of spalling (from Krivtsov, 1999).

2.3 Crack pattern

In Figure 3, spalling cracks are developed at a distance from the impulsive source, before the main cracks reach that location.

From the observation one can conclude that the velocity of the shock wave is considerably higher than the velocity for the propagation of main cracks, as the spalling crack is formed earlier and blocks the main cracks propagation.

Spalling cracks are a result of the compressive shock waves emerging from the explosion source and travelling towards the boundaries, and by the tensile waves reflected.

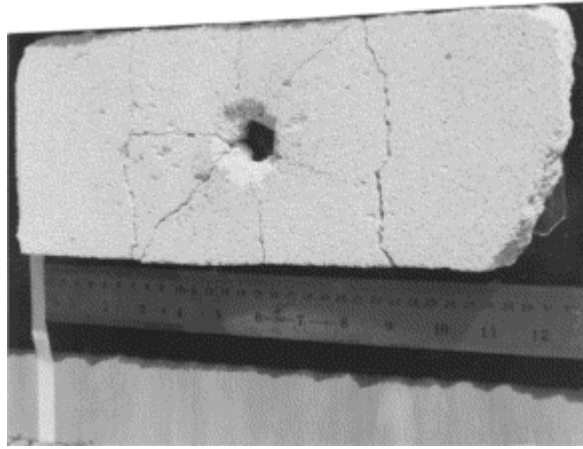


Figure 3. Typical cracking patterns for a concrete under explosive action. (from Yankelevsky and Avnon, 1998)

2.4 Square specimen

The reflected tensile waves can again be pictured as originating from “Tensile Sources” mirroring the detonator position on the outside of the free edges.

The follow shows the difference of the crack pattern, due to the position of the explosion source which affects the mirrored “Tensile Source”.

(1) Detonator positioned at the centre

In Figure 4, the left picture shows the specimen with the detonator mounted in a central hole, the right picture shows a pattern of radial cracks after explosion.

The mirrored “Tensile Source” for a square specimen with centre positioned detonator has a symmetric effect on the crack propagation.

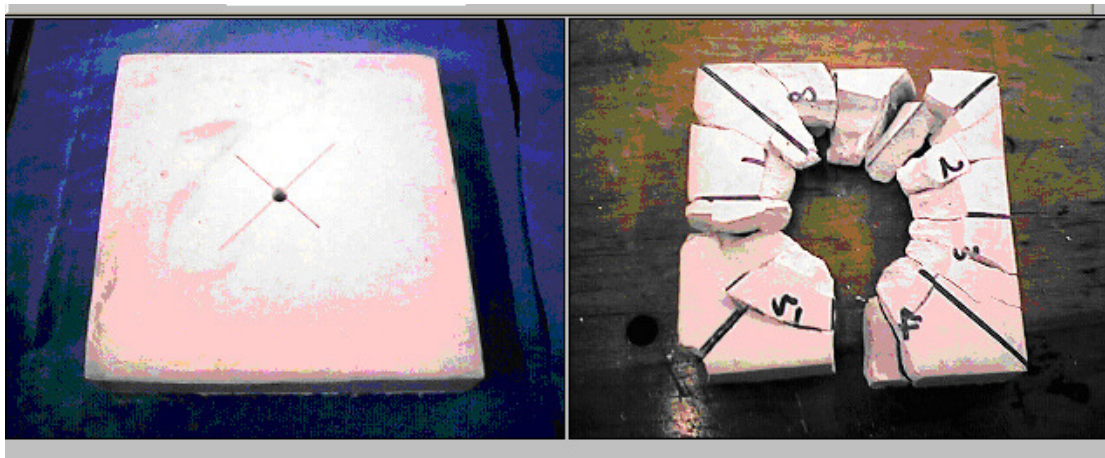


Figure 4. Square specimen, detonator positioned at the centre. (from IMPEX at MACE).

(2) Detonator positioned at the corner

In Figure 5, the square specimen had the detonator positioned at the lower left corner. The fracture pattern shows evidence of stress wave reflections from the free edges.

Spall failure in a material begins by the nucleation and growth of microscale defects, such as micro-cracks, along a spall plane rather than the propagation of a single crack, often causing a fracture surface with an appearance which is quite different from the quasi-static one.

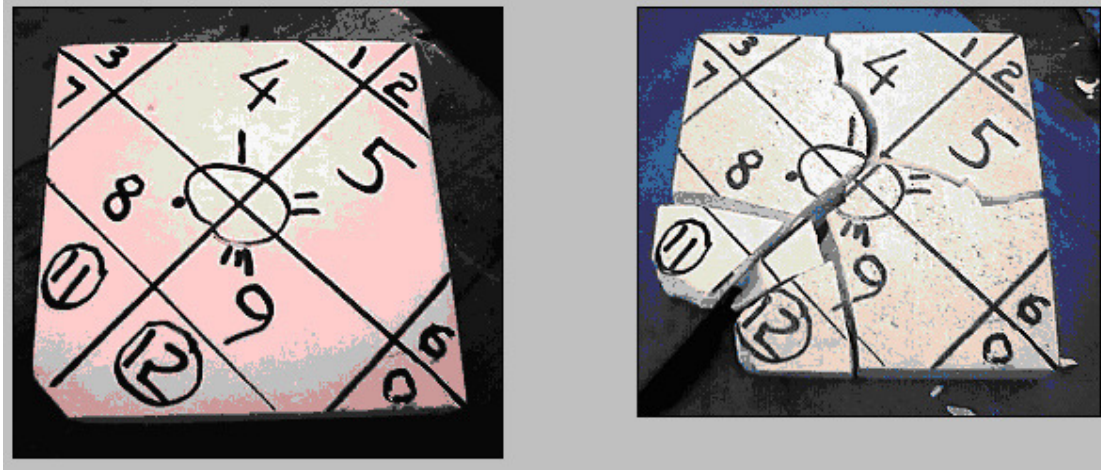


Figure 5. Square specimen, detonator positioned at the lower left corner. (from IMPEX at MACE).

2.5 Triangular specimen

Figure 6 shows crack patterns for triangular specimen with detonator placed at different positions.

The triangular specimen shown at the top had the detonator positioned at the apex of the triangle. The spalling behaviour is similar to the cylindrical bars.

The bottom picture shows a triangular specimen which had the detonator placed at the centre of the base. The fracture pattern is quite different. This is due to the reflection of the waves at the free edges of the specimen.

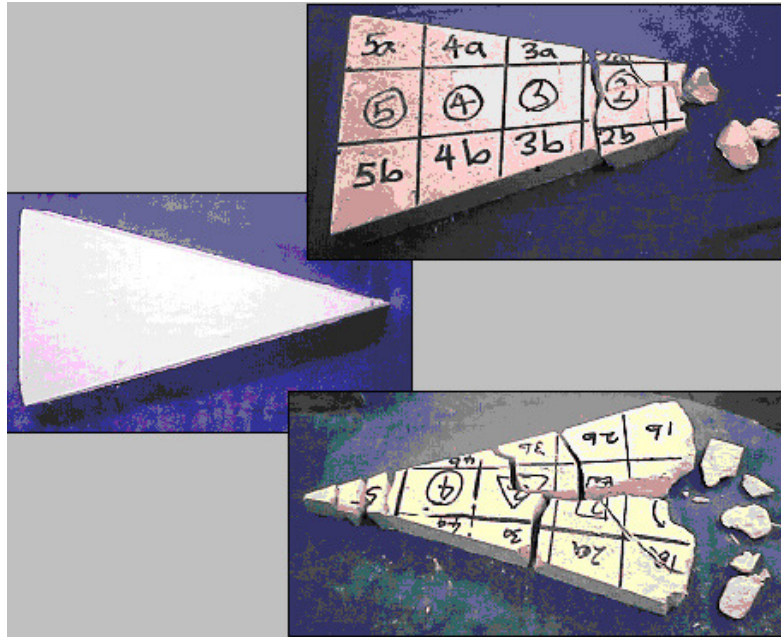


Figure 6. Triangular specimen (from IMPEX at MACE).

References

- Krivtsov, A.M. (1999) Computer simulation of spall crack formation, Structural Dynamics – EURO DYN '99, Balkema, Rotterdam, Russia, 1999.
- Yankelevsky, D. Z., and Avnon, I. (1998) Autoclaved aerated concrete behavior under explosive action, Construction and Building Materials, 12, 359-364.