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Fragment impacts into concrete

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Abstract

Massive concrete withstands blast wave and fragment impacts effectively, and consequently, reinforced concrete is commonly used for protective structures. An important issue is how the fragment impacts influence the concrete. It is well known that the behaviour of concrete exposed to fragment impacts leads to damage in the form of severe cracking as well as spalling. When fragments penetrate concrete deeply, scabbing may occur at the reverse side of the wall, or even perforation.

However, our knowledge of how the fragment impacts influence the material properties of concrete is quite limited. To study this, experiments have been carried out in order to examine to what extent the concrete, at various depths, is affected by the fragments. Spherical steel fragments of radius 4 mm were shot against concrete blocks with dimensions of 750 x 750 x 500 mm³ at a speed of approximately 1,650 m/s. The depth of penetration and crater size were measured. Thereafter, the concrete blocks were cut in two halves and the global macro-cracking was observed. Uniaxial compressive and splitting tensile tests were made from cylinders, which were drilled out from various positions in the block. Furthermore, specimens from the blocks were thin-ground and micro-cracking was analysed with a microscope. Experiments presented here show that the damage from fragment impacts is localized in the very front of the impact zone. The concrete strength below this zone at about 150 mm, though, is hardly affected at all. This indicates that it is possible to distinguish between the global load effects and the local damage effects which are caused by the fragment impacts. Consequently, it might be possible to separate the loads from blast wave and fragment impacts in design; thus, the structure could be analysed as a pre-damaged structure with decreased effective depth or width.

Keywords: concrete, fragment impacts, experiment.



1 Introduction

According to Swedish Shelter Regulations [1], a shelter shall be able to withstand: “the effect of a pressure wave corresponding to that produced by a 250-kilogram GP-bomb with 50 weight per cent TNT which bursts freely outside at a distance of 5.0 metres from the outside of the shelter during free pressure release”. Furthermore, according to these Regulations, the shelter shall withstand the effect of fragment impacts from the same bomb.

In design, normally, the thickness of concrete is designed to withstand the fragment impacts; and a static load, via a dynamic increase factor, approximates the blast load.

Experiments show that a concrete structure which is exposed to a combination of blast wave and fragments will collapse more easily than one that is exposed only to blast wave or fragment impacts; see Forsén and Edin [2]. The impulse density from fragment impacts is much lower than the impulse density from a blast wave; therefore, the slightly increased impulse density due to the combined blast wave and fragment impacts cannot explain the increased damage in the structure. It is believed that the reason for the increased damage is a combination of the spalling effect together with the increased impulse density; see [2].

Nevertheless, how the fragment impacts influence the concrete material properties is not known in detail. In earlier experiments – for examples, see Forsén and Edin [2] or Nordström [3] – the focus has been on the structural level, where beams, walls or whole structures have been analysed. In the study reported in this paper, the aim was to increase knowledge of how the material properties change after fragments are shot into concrete. To investigate this, experiments have been carried out, where steel fragments were shot against concrete blocks.

2 Experimental set-up

Concrete blocks with dimensions of $750 \times 750 \times 500 \text{ mm}^3$ were shot with fragments, which were spherical and 4 mm in radius, at a speed of approximately 1,650 m/s. The test set-up is shown in Figure 1. Totally, six blocks were shot, where the charge was placed with varying height over the concrete blocks. Results from three of these are discussed in this paper. Furthermore, single fragments were shot against concrete blocks. However, results discussed in this paper are limited to the multi-fragment impacts. For more details from the experiments, see Leppänen [4].

The charge was made by gluing bearing balls into a convex end of a cylinder. Two different explosives were used: octol and hexotol, with a weight of 1.3 kg. Totally, 7 charges were fired, 5 with octol and 2 with hexotol, and the height varied between 0.6 m and 1.0 m. The fragment velocity was measured with accelerometer and impact sensor. The impact velocity was approximately 1,650 m/s.



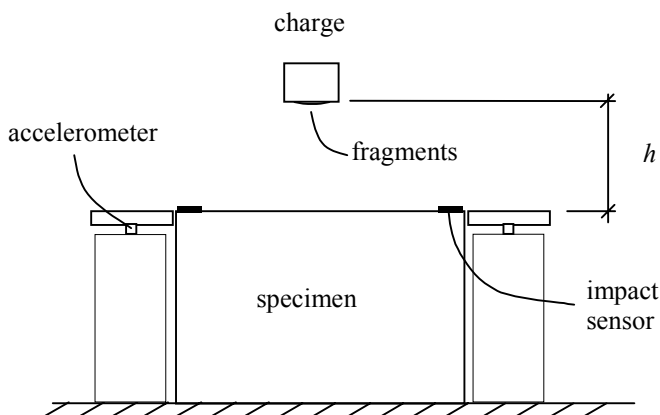


Figure 1: Test set-up for fragment impacts into concrete.

3 Analyses of fragment impacts into concrete blocks

The aim with the experiments was to increase the knowledge of the concrete material properties subjected to fragment impacts. After shooting the concrete blocks with fragments, photographs were taken; the depth of penetration, crater depth and crater diameter were measured.

To study how the material properties changed, drilled cylinders were used for uniaxial compressive and tensile tests. Furthermore, the concrete blocks were cut in two halves, from which the macro-cracking was observed. To analyse micro-cracking, thin-ground specimens were taken out from the blocks, and using a microscope the cracks could be observed.

The concrete blocks (numbered 3, 4 and 6), after the shot with fragments are shown in Figure 2. The height of the charge was 0.6 m for blocks 3 and 6, and 0.7 m for block 4. The depth of penetration varied between 30 and 50 mm, and the crater diameter varied between 45 and 60 mm. The concrete blocks were cut in two halves and the crack pattern was observed; it is also shown in Figure 2. All blocks had similar overall crack patterns, with clear spalling; the depth of the damage zone is approximately 50 mm. At the boundaries of the block, a global crack pattern was developed; this is due to reflections of the stress wave.

To study the change in material properties, uniaxial compressive and splitting tensile tests were carried out on drilled cylinders, with a diameter of 50 mm, from the concrete blocks. However, when drilling, most of the cylinders broke in two pieces. The broken cylinders were measured and drawn (for block 3), as seen in Figure 3. The broken cylinders correspond to the global crack pattern (compare Figure 2).

From the drilled cylinders, specimens were prepared at various distances for uniaxial compressive and tensile tests. Cylinders were drilled in two directions: both horizontally (perpendicular to the direction of the fragment impacts) and vertically.

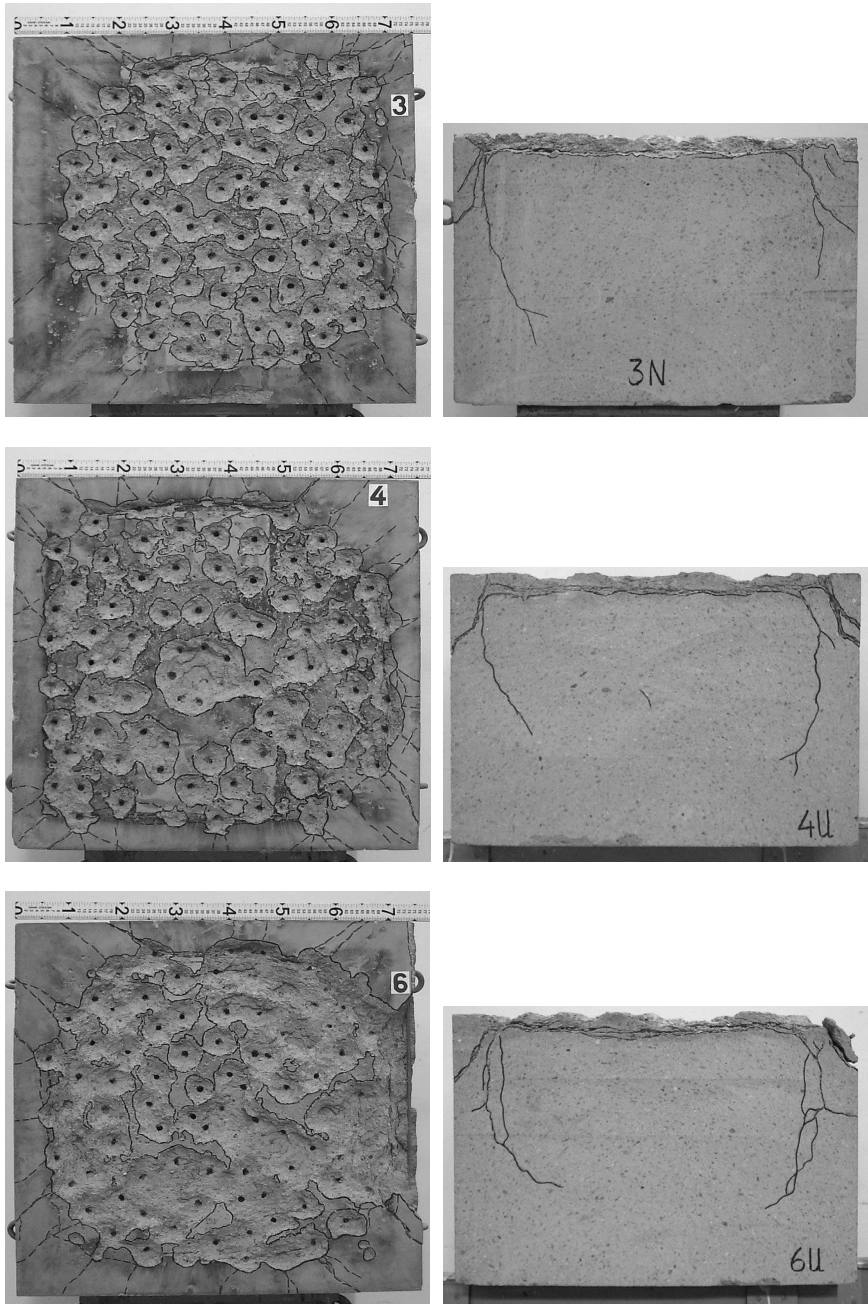


Figure 2: The concrete blocks (3, 4 and 6) after fragment impacts. To left: above, to right: cross section (after cutting the blocks in two halves).



For the uniaxial compressive test drilled in the horizontal direction, the strength was hardly affected by the fragment impacts. For the vertical drilled cylinders, at a distance of 140 mm below the surface of the fragment impact, as shown in Figure 4, the uniaxial compressive tests showed somewhat higher concrete strength compared to tests with references (specimen from a concrete block that was not exposed to any loading). This slight increase in strength is probably due to compaction of the concrete. However, the specimen that was taken out near the global crack pattern (as shown in Figure 2), in the middle and in the bottom of the block, had lower strength.

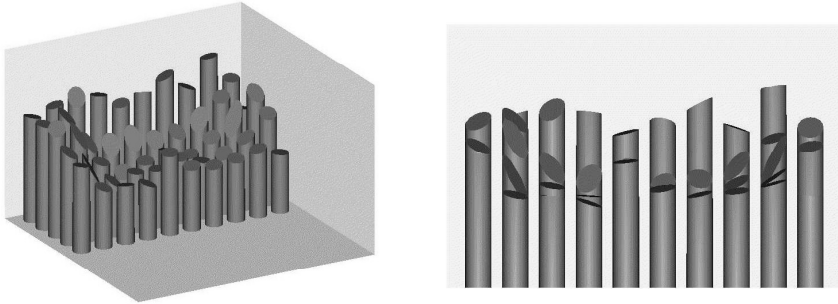


Figure 3: The global cracking (block 3). Drawn from the drilled cylinders.

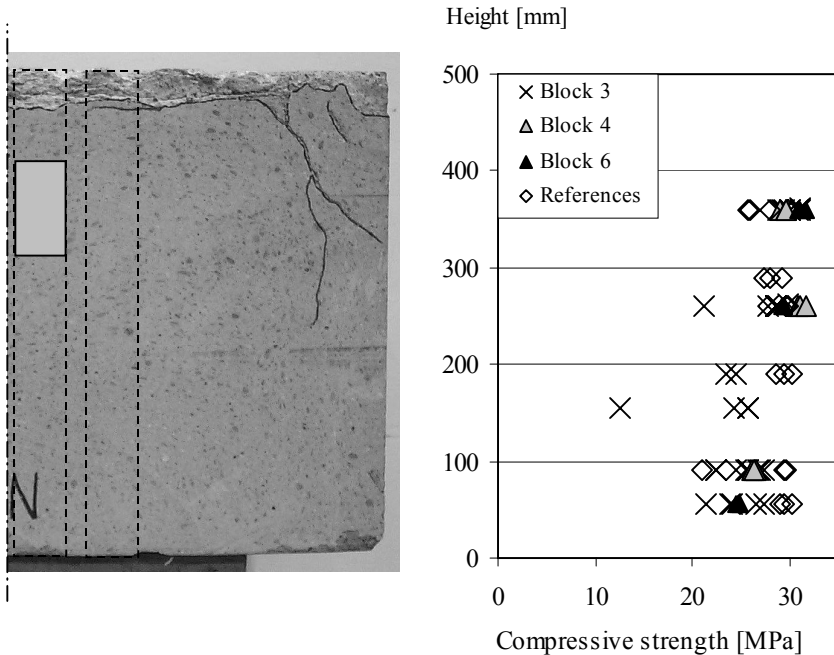


Figure 4: Uniaxial compressive tests from vertical drilled cylinders. The cylinders are taken out from marked areas. Results at different heights correspond to the cylinders' centres of gravity.

For the splitting tensile tests, the orientation when testing is important, as shown in Figure 5. If a specimen is loaded, where the cracks are parallel to the loading, the strength is decreased, and if the crack is orientated perpendicular to the loading, the strength will barely be affected.

However, for the first block (block 3), when drilling the cylinders, the orientations of the cracks were unknown. The results from the splitting tensile tests are shown in Figure 6. The strength was not affected at a distance of 150 mm from the impact. For the tests where the cylinders were drilled out near the global crack and in the bottom, the strength was highly reduced in relation to the references (for most of the tests).

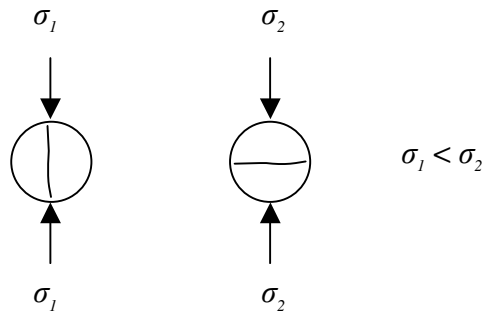


Figure 5: Effect of the orientation of the crack for splitting tensile tests.

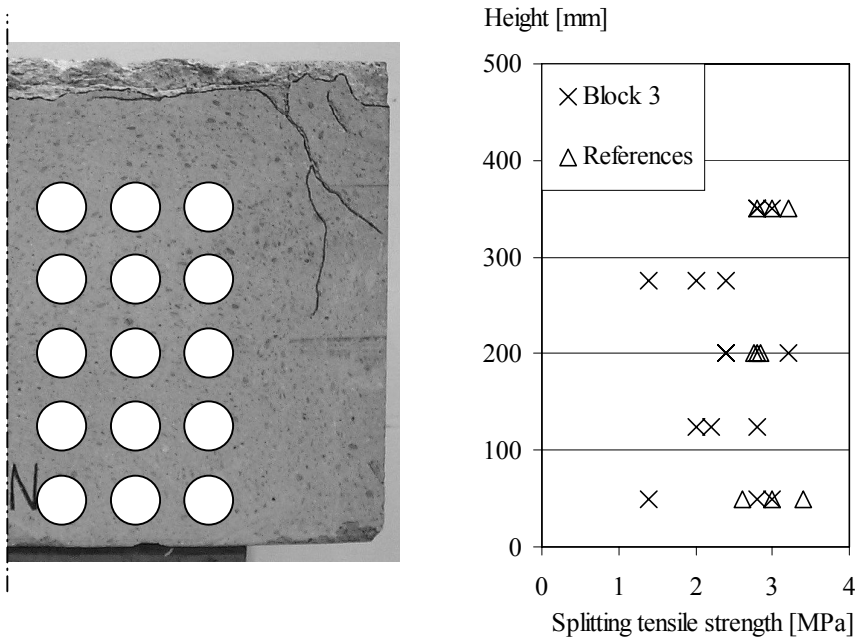


Figure 6: Uniaxial splitting tensile tests (block 3), from horizontal drilled cylinders, orientation unknown. The cylinders are drilled from marked areas.

For the next two blocks (4 and 6), the specimens were marked before they were drilled, so that the orientation of the crack would be known. The test where the crack was orientated perpendicular to the direction of the loading yielded a higher average strength than did tests where the cracks were orientated parallel to the direction of loading. The results from the splitting tensile tests from the horizontal drilled cylinders are shown in Figure 7. The overall behaviour was similar as for block 3. For the tests below at a distance of 150 mm, as for block 3, the strength was not affected by the fragment impacts (except for one test).

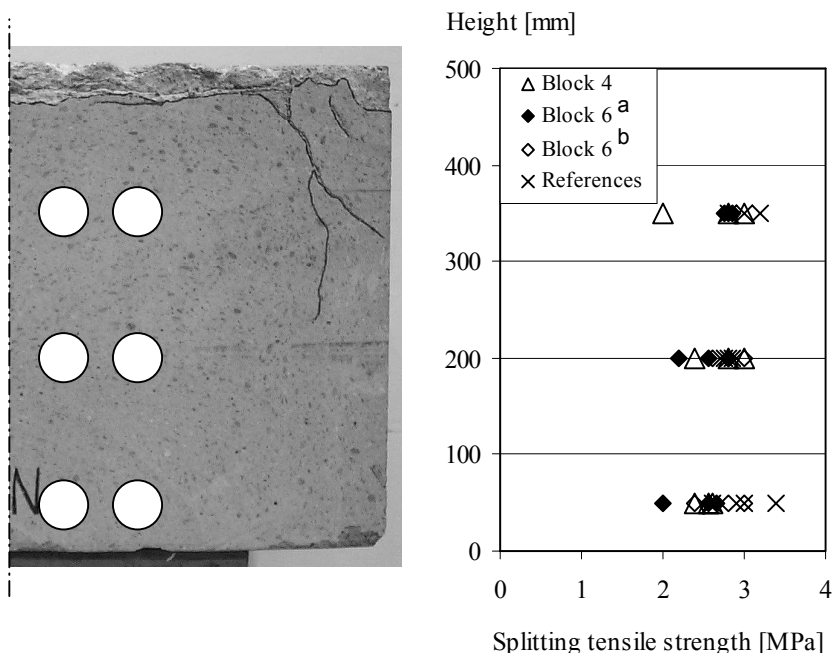


Figure 7: Uniaxial splitting tensile tests (blocks 4 and 6), from horizontal drilled cylinders. The cracks are orientated parallel to the loading direction for blocks 4 and 6^a. For block 6^b the cracks are orientated perpendicular to the loading direction. The cylinders are drilled from marked areas.

To study the concrete below the impact zone further, a thin-ground specimen was taken out at a distance between 80 and 170 mm below the surface. From the specimen, micro-cracks could be observed with a microscope. With a camera sited in the microscope, photographs were taken, and an example is shown in Figure 8. In the figure, micro-cracks can be seen, and similar micro-cracks could be found in the thin-ground specimen up to a level of approximately 120 mm below the surface of the fragment impacts. The width of the micro-cracks was up to approximately 0.02 mm.

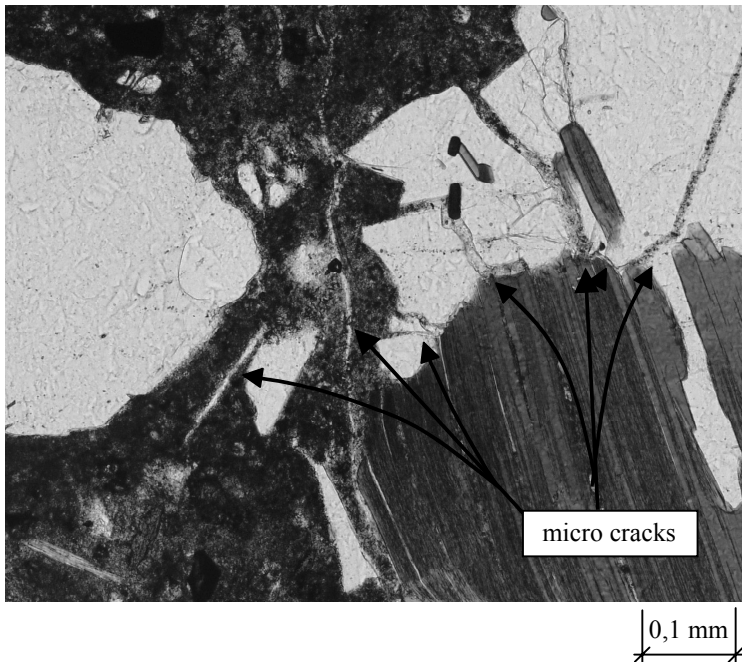


Figure 8: Photograph from the thin-ground specimen.

4 Conclusions and discussion

Experiments presented here show that the damage from fragment impacts is localized in the very front of the impact zone. Thin-ground specimens show that micro-cracking occurs up to a distance of approximately 120 mm below the surface where the fragments impact. The concrete strength below this zone, though, is hardly affected at all.

Uniaxial compressive tests showed some increase in strength at a distance of 140 mm from the surface of the fragment impacts; this is probably due to compaction of concrete. However, in the boundaries the strength was decreased due to reflections. From the splitting tensile tests, it was also found that the strength was not affected at a distance of 150 mm from the surface of the fragment impacts. Furthermore, it was noticed that the orientation when testing the drilled cylinders had an effect on the strength. If a specimen is loaded where the cracks are parallel to the loading, the strength is decreased. The tests which were loaded perpendicular to the cracks had almost no effect on the strength.

The experiments indicate that it is possible to distinguish between the global load effects and the local damage effects which are caused by the fragment impacts. Consequently, it might be possible for designers to separate the loads from blast wave and fragment impacts: the structure could be analysed as a pre-damaged structure with decreased effective depth or width, and the impulse from the fragment impacts could be added to the impulse from the blast wave.

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