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# Investigation of blast and fragmentation loading characteristics – Field tests

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A B S T R A C T

The combined loading of blast and fragments on reinforced concrete (RC) elements has been studied in field tests of RC T-walls that were subjected to detonated cylindrical cased charges. Characterization of the combined loading has been experimentally studied and analyzed. This analysis includes the pressure time-history of a control bare charge and of the cased charges, the relation between them, and the distribution of the fragment masses and velocities over a vertical barrier that was impacted by them. The structural damage of the RC walls due to the fragmentation impact was also measured. The results indicate that while the detonation of a bare charge, without a casing, yielded negligible structural damage, major damage was caused due to the impact of the fragments. The importance of the findings that are reported in the paper relates to design of protective structures that are prone to be subjected to extreme loads caused by cased charges. Commonly, except for very small standoff distances, the fragments will reach the structure before the blast wave, which means that the damage that is created by the fragments should be considered for the global analysis of the element response to the blast load. Furthermore, the results reported here show that the smaller the standoff distance, the more significant the damage influence is on the response of the structure.

## 1. Introduction

Extreme loading on structures includes blast and fragmentation impact caused by detonated cased explosive charges. After detonation, the casing expands and then ruptures into a large number of fragments [1,2]. On the one hand, the blast wave from a cased charge would load a nearby structure with an impulse, which is lower than the one caused by the same bare charge (i.e., without a casing), because part of the energy is dissipated through the expansion and rupture of the casing [3–5]. On the other hand, a cased charge causes an additional load of fragments that strike the structure. While the load of the blast wave is due to the momentum (or impulse) which is transmitted to the structure, the fragments have a dual effect: the first is the transmitted momentum to the structure, which results in an additional impulse on the structure, and the second is the structural damage due to their penetration into the structure [1]. The times of arrival of the blast and the fragments are different, where for closer standoff distances, the blast wave reaches the structure first, while beyond a certain distance, the fragments reach the structure before the blast wave does [1,6–8]. This distance of simultaneous arrival is about few meters [1,8].

While there are researches that deal with the response of structures to blast loads [9–13], works that deal with combined loading of blast and fragments are less common [1,14,15]. Several studies mentioned that there is a synergistic effect of the combined loading of blast and fragments on structures [1,6,14–19]. This is mainly because in most cases, the fragments would reach the structure before the blast wave, and as a result, the structure that will be subjected to the action of the blast would already be damaged by the high velocity penetrating fragments. Consequently, its response will be more severe than that of a structure loaded by the same charge without a casing, even though the blast impulse of the cased charge is lower. However, studies rarely deal with this phenomenon and sometimes the synergistic effect is ignored or treated in a simplified manner.

Research works that deal with the combined loading of blast and fragments can be categorized into studies that deal with the loading itself (e.g. [20,21]) and studies that deal with the structural response to such load (e.g. [15]). The first group commonly refers to the blast performance of a cased charge, or the ‘equivalent bare charge’ that should be taken into account to simulate the blast effect of a cased charge [3–5,22–24]. The fragmentation is a more complicated phenomenon [1]. Although there are models for the fragment velocities (e.g. [2,25,26]) and masses (e.g. [27–29]), their spatial distribution and the way they load the structure is not widely investigated.

In a series of full-scale blast field tests, reinforced concrete (RC) T-walls and witness plates were exposed to the detonation of cylindrical cased charges and to a control bare charge. Thus, except for the control

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test (with a bare charge), the T-wall specimens were subjected to combined loading of blast and fragments. These field tests are a first stage in a study, in which reference (undamaged) and damaged walls are further tested in post-field, static flexural experiments to check their residual mechanical properties, such as stiffness, capacity, and ductility. This paper describes the first stage of this study, i.e. – the blast field tests and their results, focusing on the experimental investigation and characterization of the blast and fragmentation loading. A comparison between the blast characteristics of bare and cased charges is presented and compared with available models. The fragments are analyzed in terms of their masses, velocities and spatial distributions over the wall specimens and witness plates that were set at the arenas of these tests. Observations regarding the damage of the fragments to the RC walls are also presented.

## 2. Experiments

### 2.1. Tests data and materials

The main goal of the field tests was to examine the loading parameters of bare and cased charges and their influence on RC structures in a full-scale experiment. The experimental program consisted of four tests. The first two tests were aimed to study the detonation and fragmentation process of the cylindrical "pipe charges" that were used and to measure the pressure and fragmentation pattern before placing the RC walls against cased charges in the third and fourth tests.

The specimens were standard 'T-shape' RC walls that were made by a local precast contractor. The concrete strength was 33.7–51.2 MPa, measured at 28 days by standard $150 \times 150 \times 150\text{-mm}^3$ cubes. It consisted of 155 $\text{kg/m}^3$ water, 300 $\text{kg/m}^3$ Portland cement type CEM I-52.5 N, 245 $\text{kg/m}^3$ natural sand, 200 $\text{kg/m}^3$ crush sand, 1350 $\text{kg/m}^3$ aggregates, 150 $\text{kg/m}^3$ fly ash and 3 $\text{kg/m}^3$ water reduced agent (total 2403 $\text{kg/m}^3$). The height of the walls was 2.2 m, where the height of their base was 40 cm. They were reinforced with 8 mm deformed steel meshes, with rebars spaced at 150 mm at each side. The properties of the steel bars (from laboratory tension tests of their samples) were as follows: 200-GPa modulus of elasticity, ~580-MPa yield stress, ~680-MPa ultimate stress, and a rupture strain of 1.5–2%. Fig. 1 describes the plan of the walls and their casting process.

The charges were seamless steel pipes, filled with explosive that was made of 85% RDX and 15% plastic binders and oil. The interior and exterior diameters, length and thickness of the charge casing were 102.2, 114.2, 400 and 6 mm, respectively. The explosive and the casing were weighed, and their weights are listed in Table 1. The charges were placed on wooden boxes, such that their bottom was 79.5–85 cm above the ground level (see Table 1). The charge in Test 1 was bare (i.e., without a steel casing) but in order to maintain its cylindrical shape (as that of the cased charges) it was wrapped with a low weight plastic sheet.

The following paragraphs describe the aim, plan and instrumentation of each activation. The number of T-wall specimens, witness plates, and standoff distances of water containers that were placed to collect fragments, are summarized in Table 1.

### 2.2. Test 1

The test plan, illustration and photo of the test arena are shown in Fig. 2a. The main aim of first activation ("Test 1") was to check the detonation of the bare charge and to compare its performance with the cased charge in the other activations. Additionally, one T-wall specimen was placed 4 m from the charge (see Fig. 2a) to compare its structural damage with those of the T-walls in the other tests that included activations of cased charges. The charge bottom was placed at a height of 79.5 cm from the ground (see Table 1). Pressure gauges (Kulite, HEM-375-500G) were placed at horizontal distances of 2 and 4 m from the charge, at heights of 1.22 and 1.26 m, respectively. These gauges remained at the same instrumentation setup in all subsequent tests, and therefore protective poles were placed in front of the gauges to protect them from striking fragments in the other tests (which include detonations of cased charges). These poles were located at a distance of ~1 m from the gauges they protected (see Fig. 2). This test was captured by a high-speed camera (Phantom Miro M320 at 4000 fps), which was also used in all other activations.

### 2.3. Test 2

The test plan, illustration and photo of the test arena are shown in Fig. 2b. The main aim of the second activation was to examine the fragmentation of the cased charge, before placing the T-walls, and to compare its performance with the bare charge that was activated in Test 1. Two steel witness plates were placed at 2 and 4 m from the charge. Their width, height and thickness were 127 and 250 cm, and 1 mm, respectively. One of the witness plates, which was set at 4 m from the charge, was painted in black and a second high-speed camera (Phantom v1610 at 20,000 fps) was placed behind it to capture the fragment perforations for further analysis of their impact locations and arrival time. This setup of a witness plate, which was photographed by the second high-speed camera, was used also in Tests 3 and 4. In addition, two $1.1 \times 1.1 \times 0.8\text{-m}^3$ water containers were placed (one on top of the other) at a distance of 2 m from the charge, to collect the fragments.

### 2.4. Test 3

The test plan, illustration and photo of the test arena are shown in Fig. 2c. Two T-walls were placed 2 m from the charge and two more – 4 m from the charge. It was realized in the previous test that placing a water container to capture fragments, 2 m from the charge, is too close. Therefore, a combination of three water-containers was placed 4 m from the charge together with a witness plate in front of them, to slow down the fragments before they perforate the container plastic casing (see Fig. 2c).

### 2.5. Test 4

The test plan and photo of the test arena are shown in Fig. 2d. Two T-walls were placed 3 m from the charge and another one – 4 m from the charge. A tower of three water containers was placed 4 m from the charge together with two witness plates in front of it.

## 3. Results and discussion

### 3.1. General

No sliding of the walls was observed in all activations. Fig. 3 shows an example of the detonation process from Test 3, recorded by the high-speed camera. The fireball can be seen at $t \approx 0.75$ msec after detonation, and the fragmentation impact on the walls and witness plates located 4 m from the charge can be observed at $t \approx 2$ msec. At this time, the blast wave has not reach the walls yet, as indicated by both the high-speed cameras and the pressure gauges.

In Tests 2, 3 and 4 a second high-speed camera was set behind the witness plates that were placed 4 m from the charge and captured their perforation by the fragments at a rate of 20,000 fps. The charge detonation set a trigger wire for the commencement of the camera operation, which enabled monitoring and identification of the time from the moment of detonation, for each frame.

The following sections present results regarding the blast load, the fragment masses, velocities and spatial distribution, and the structural damage due to the fragmentation impact.