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Dynamic fragmentation of concrete using electric discharge impulses

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HIGHLIGHTS

- We study dynamic fracture in concrete induced by electric discharge impulses (EDI).
- Crack propagation is initiated and guided by direct and reflected waves.
- Then crack openings are widened by gas pressurisation.
- Wave analysis for conventional blasting (explosives) is valid also for EDI crushing.
- Controlled, smooth dynamic fragmentation of construction materials is possible.

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ABSTRACT

We study dynamic fracture in construction materials induced by electric discharge impulses (EDI) that evaporate self-reactive liquid and produce high pressures in blast holes. Detailed observations utilising a high-speed digital video camera and a three-dimensional finite difference code show cracks generated in cylindrical concrete columns by means of EDI are controlled by direct and reflected waves and widened later by gas pressurisation, just as in the case of conventional blasting. Thus, wave-based analysis developed for blasting using explosives is valid also for EDI crushing, making it an ideal methodology to achieve controlled smooth dynamic fragmentation of construction materials and structures.

1. Introduction

As mentioned in our earlier study [1], the number of aged structures that are at the final stage of their average life has considerably increased during the last years. In dismantling such old structures or fragmenting rocks at construction/mining sites, blasting techniques using explosives are often employed. Although the blasting operation may be completed in a relatively short period of time, its technical details are still empirically determined and blasting destruction is usually avoided in developed urban areas for safety reasons. In recent years, instead of explosives, the use of “safer” electric energy to crush (geo)materials has been proposed, e.g. [2–10]. Fig. 1 shows a typical fracturing system utilising pulsed high-voltage electric discharge, the EDICS (Electric Discharge Impulse Crushing System) developed by Hitachi Zosen Corporation, and its principles. In EDICS, a cartridge containing self-reactive liquid (deflagration agent), e.g. liquid-nitromethane [10], is prepared, and the electric energy stored in a capacitor (e.g. 3000 V) is discharged in the self-reactive liquid within several hundreds of microseconds through an electronic switch. Then, high pressure is generated due to the rapid evaporation of the liquid. Although the electric method may be dynamically more controllable than conventional blasting methods, the physical process and mechanisms of dynamic fracture in solid materials generated by such electric discharge impulses (EDI) (and the quick evaporation of self-reactive liquid) have not been clarified yet.

Here, as a first step toward further understanding of fracture by EDI, we perform experimental and numerical investigations in the field and in the laboratory. First, we observe, in the field, dynamic fracture in concrete columns produced by EDICS. We prepare blast and empty dummy holes in cylindrical specimens and set

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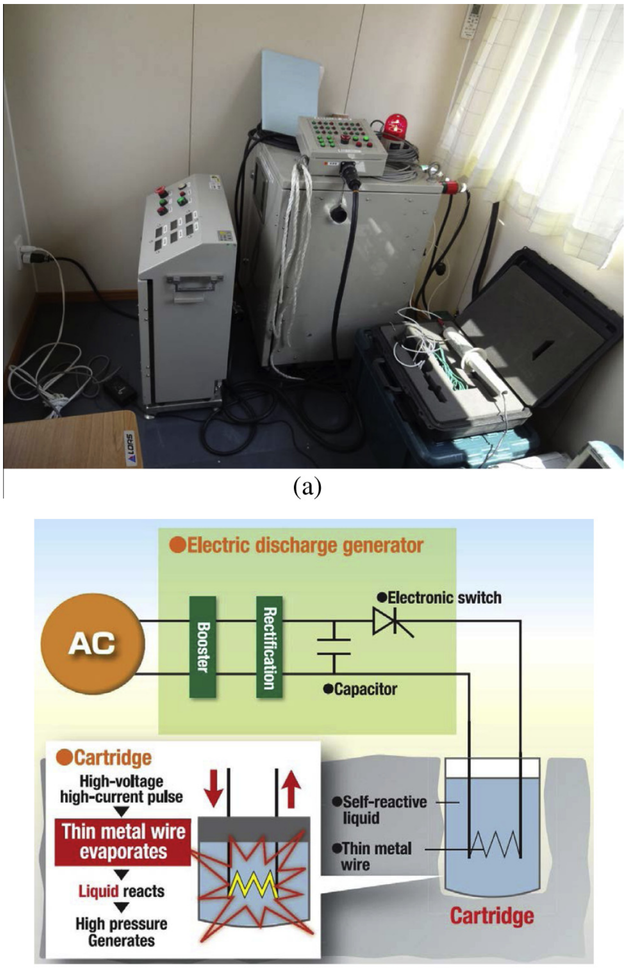

(a)

(b)

Fig. 1. (a) The Electric Discharge Impulse Crushing System (EDICS) developed by Hitachi Zosen Corporation, and (b) its principles.

cartridges containing a self-reactive liquid in the blast holes. Using a high-speed digital video camera system, we record the time-dependent development of fractures by evaporation-induced high pressures. Then, based on the finite difference method, we develop a fully three-dimensional numerical code available on a PC (Windows) that allows us to simulate rather complex dynamic wave motions in solid construction materials. Detailed computations and comparisons with the field observations may reveal the effect of wave expansion/contraction and blast hole pressurisation on dynamic crack propagation in and fragmentation of concrete.

2. Model experiments

We have prepared ten cylindrical specimens made of concrete (diameter 500 mm, height 500 mm; Fig. 2). No reinforcing steel bar is inside the specimens, and every specimen has one or more blast holes (diameter 12 mm, depth 280 mm) where cartridges (diameter 10 mm, length 60 mm) containing self-reactive liquid (2 cm^3 of nitromethane) and connected to the control unit of EDICS are placed and covered by a stemming material (silica sand). We have considered six different geometrical settings: Case 1 (Fig. 2(a)) has a blast hole at the centre along the vertical axis with the cartridge located at the very centre of the specimen. The model is symmetric with respect to the blast source (cartridge) except for the stemming section. In Cases 2 (Fig. 2(b)) and 3 (Fig. 2(c)) nonsymmetric loading conditions are introduced, while in Case 4 (Fig. 2(d)), two blast holes (and two cartridges) are arranged relatively close to the edge of the specimen. These three nonsymmetric cases are investigated in order to observe the possible effect of nonsymmetric blast wave reflections on the distributions of dynamic fractures. In the last two cases, one (Case 5; Fig. 2(e)) or two (Case 6; Fig. 2(f)) empty dummy holes (diameter 18 mm, depth 280 mm) are set in addition to the blast holes containing the cartridges. All the holes are located on a single plane that contains the vertical axis of the cylindrical specimen. Dummy holes are introduced so that we can check the controllability of the crack propagation directions.

In the field, each specimen is placed and subjected to EDI in a pit (diameter 3500 mm, depth 2100 mm) to minimise possible unwanted scattering of fragmented pieces of concrete. The pit itself is also covered by a protective sheet so that the broken pieces would not fly into the far field. The dynamic fracture process due to the action of EDI is recorded by a high-speed digital video camera (Photron FASTCAM SA5) at a frame rate of 50,000–100,000 frames/s, which is set 2680 mm above the top surface of the specimen (Fig. 3(a)). Fig. 3(b) shows typical development of dynamic fractures induced by EDI in a specimen with a single blast hole at the centre (Fig. 2(a)). The size of the black square marked on the top surface is 100 mm × 100 mm, and the photographs, here taken by a normal home video camera, indicate the rather strong power of the EDI (and the rapid evaporation self-reactive liquid) in dynamic fragmentation and scattering (noise levels recorded in the surroundings indicate the noise due to EDI themselves is negligibly small). We can immediately recognise a rather straight crack develops in the very middle along a horizontal plane and looking from the top, the specimen is divided simply into three or four main parts. According to the photographs in Fig. 3(b), the cracks on the top surface seem to have run unidirectionally from the central blast hole to the edge, but in reality, as we see later in Fig. 5, the cracks are formed by the combination of outbound (propagating from the centre) and inbound (moving from the edge to the centre) fracture propagation.

Fig. 4 illustrates the top and side view of the fracture patterns sketched after the experiments. For Case 1 (5 and 6), we have three (two) identical experiments, respectively, and we can confirm the repeatability of the experiments. Basically, a horizontal crack plane is found in the very middle section of the specimen (at a height of 250 mm). For Case 1 (Fig. 4(a)–(c)), although there are branched sections, the cracks are generated roughly in every 120 degree. In Cases 2–4 (Fig. 4(d)–(f)), the distributions of cracks are denser between the nonsymmetrically located blast holes and the edges than in the surroundings. Especially in Fig. 4(f), the sections around the two blast holes are totally fragmented. On the contrary, even when we have two or more blast holes (Cases 5 and 6; Fig. 4(g)–(j)), dynamic fracture may be more controlled if there is (are) dummy hole(s). Fig. 4(i)–(j) indicates the cracks may propagate rather straight along a vertical plane that includes dummy (and blast) holes. We shall see the effect of dummy holes later in Figs. 6 and 7 by referring to the photographs taken by the high-speed digital video camera.

Detailed observations of the crack development in a concrete cylinder with a single blast hole at the centre (Case 1; Fig. 5) reveal that cracks on the top surface may be initiated and propagated not in a simple way. For example, in Fig. 5(a) a crack extending outbound from the blast hole located at the centre as well as that propagating inbound from the edge to the centre may be identified. The outbound and inbound cracks may extend (and may or may not merge) at a later stage (Fig. 5(b)–(f)). After the crack development, we see the crack openings are widened by some gas pressurisation (Fig. 5(f)) Thus, like in conventional blasting using explosives [11–13], we may expect also in the case of EDI crushing that crack development from (to) the centre occurs first and is guided by direct (reflected) blast waves, respectively, and then gas pressurisation of cracks takes place. Similar discussion holds for the Cases 5 (Fig. 6) and 6 (Fig. 7), and the existence of both outbound and inbound cracks (Fig. 6(b)) as well as the gas pressurisation (Fig. 7(g) and (h)) is clearly visible. Also, particularly in Case 6 (Fig. 7(f)), we can confirm that dummy holes may well guide the wave-induced development of the main crack plane (as desired) and they are well suited for controlled smooth fragmentation of construction materials. In the next chapter, we shall consider the Cases 1, 5 and 6 in more detail by comparing the experimental results with some numerical calculations.

3. Discussion: Wave propagation in a cylinder

In the last chapter, we have found that the crack propagation may be initiated and guided directly by waves and not by gas pressurisation. Here, we try to investigate the connection between waves and cracks by simulating dynamic disturbances in a cylindrical specimen with our three-dimensional finite difference code (simulator running on a PC) [1]. Especially, we shall pay our attention to the development of the cracks on the top surface and those along the horizontal middle plane

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