FRACTURE IN BRITTLE SOLIDS CONTROLLED BY WAVE MOTION

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We are developing a more precise and controllable technique for dynamic fracture of rock-like materials based on the theory of wave dynamics. Here, we investigate preferable geometrical and dynamic loading conditions for fracture of a given structure in the field. Detailed observations utilizing our high-speed digital video camera system and fully three-dimensional finite difference simulator indicate that crack extension in brittle rectangular specimens may be controlled by direct waves from energy sources and reflected ones, and optimal geometrical combinations of energy sources and empty dummy holes can indeed govern the dynamic wave and crack propagation and thus the dynamic fracture patterns in the specimens, even when waves are simultaneously radiated from all energy sources.

Key Words : *controlled dynamic fracture, wave dynamics, fracture mechanism, finite difference difference method*

1. INTRODUCTION

It is of crucial importance to develop controllable fracture and fragmentation techniques for safer and more efficient operation in construction and destruction (partial removal) of complex structures made of rock-like materials (geomaterials). Dynamic fracture by blasting (detonation of explosives) is one of the most effective ways in light of operational time and load to the surrounding environments, but its design details are still most often decided by experience[1)], and for a long time researchers and engineers in rock blasting have been attempting to find the best use of the energy from explosives for optimal fracture[2)]. Such attempts include experimental work in quarries for separating marble block from the in situ strata with various combinations of blast hole stemming, diameter, spacing, liner and explosive energy[3)] and a series of small-scale tests to utilize short delays for enhancing fracture of magnetic mortar blocks by wave interactions[2)]. However, the results using short ignition delay time of explosives showed, in comparison to the case without delays, no distinct differences or high improvements of the fracture when the delays were in the time range of wave interactions[2)].

Therefore, during this series of field experiments, instead of employing delay blasting, we simultaneously detonate all blast holes (energy sources) in a rock-like material and try to obtain an optimal geometrical and loading condition for controlling wave and crack propagation as well as fracture pattern in the material. Since it is difficult to handle explosives in urban areas, we apply modern, safer electric discharge impulses (EDI; pulsed high-voltage electric discharge) to break geomaterials[4)]. Our goal is to establish a more physics-based way of designing precise and more quantitatively predictable dynamic fracture of geomaterials based on the theory of wave dynamics, which can be used not only for large-scale fracture operations in isolated areas but also for construction / destruction of very intricate, relatively smaller but sensitive three-dimensional structures in densely populated regions. For this aim, we compare the experimental observations with the numerical results obtained by our fully three-dimensional finite difference code with the second order accuracy in time and space, and discuss the relation between wave propagation, interactions (e.g. reflection) and development of fracture network.

2. DYNAMIC CRACKING IN RECTANGULAR SPECIMENS

The previous series of experiments suggest that placing blast and empty dummy holes on a straight line (virtual single vertical plane) is effective for controlled three-dimensional fracture development by EDI, at least in cylindrical concrete specimens (diameter 500 mm, height 500 mm) without reinforcing steel bars. Here, we fracture more realistic, larger rectangular specimens made of concrete and try to find more preferable combinations (positions) of blast and dummy holes. This time, we prepare ten rectangular specimens with the dimensions 900 mm × 900 mm × 300 mm, but as before[4)], for testing purposes, no reinforcing steel bar exists inside the specimens that have one or more blast holes (diameter 12 mm, depth 185 mm). In every blast hole, a cartridge containing a self-reactive liquid (deflagration agent) is placed and connected to the Electric Discharge Impulse Crushing System (EDICS) developed by Nichizo Tech, Inc., where the electric energy accumulated in a capacitor is released in the cartridge in several hundreds of microseconds through an electronic switch and high pressure is produced by rapid liquid evaporation. All blast holes are filled with stemming material (silica sand). Each specimen has different geometrical and loading settings, but in this article, the results of two cases (IC-09/00 and IC-10/00) are shown.

The case IC-09/00 (Fig. 1(a)) has two blast holes, each of which is located on a (virtual) central vertical plane and surrounded by four empty dummy holes (diameter 18 mm, depth 300 mm). Seen from top, the four dummy holes, left empty, are situated at the corners of a square of side length 200 mm, and the blast hole with the self-reactive liquid is at the center of the square (see top view of Fig. 1(a)). The model is designed to be nearly symmetric with respect to the (virtual) central horizontal plane (at a height of 150 mm) as well as to the (again virtual) central vertical plane containing blast holes except for the stemming sections and screw holes for the carriage of the specimen. The case IC-10/00 (Fig. 1(b)) is similar to IC-09/00 and has the same geometrically symmetric nature, but now we have three blast holes. Again, seen from top, every blast hole is at the center of a square formed by four dummy holes that are left empty. Each specimen is carried by a crane into a pit (diameter 3,500 mm, depth 2,100 mm) that is covered by a protective sheet to avoid unnecessary scattering of broken

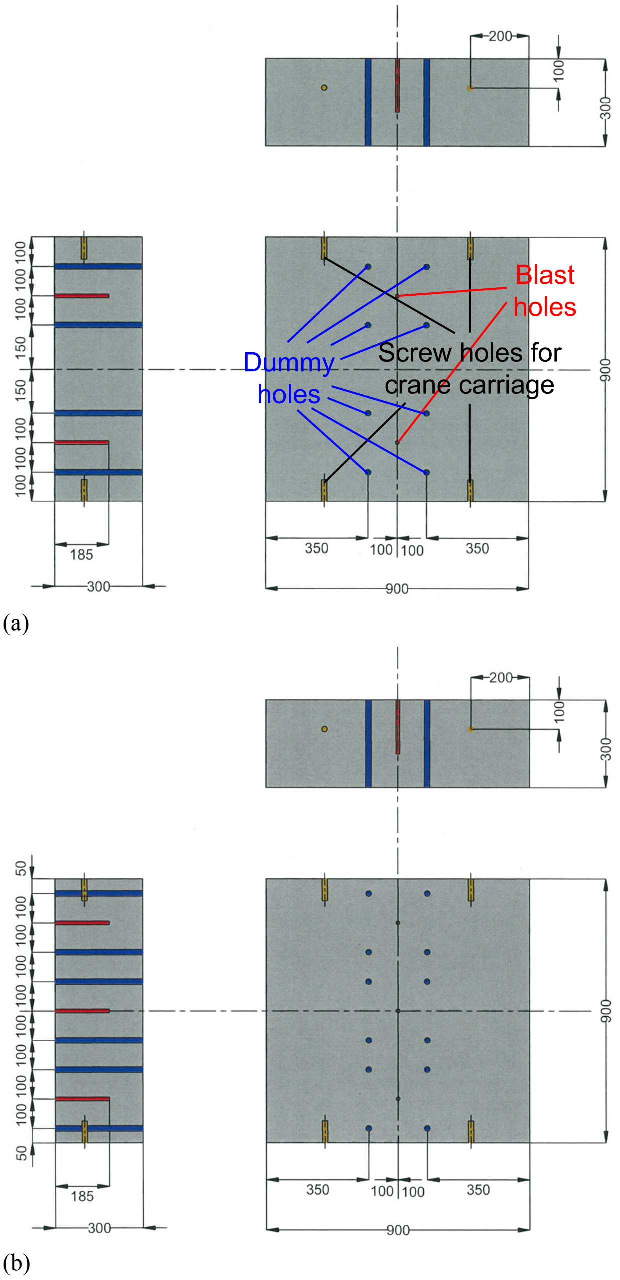


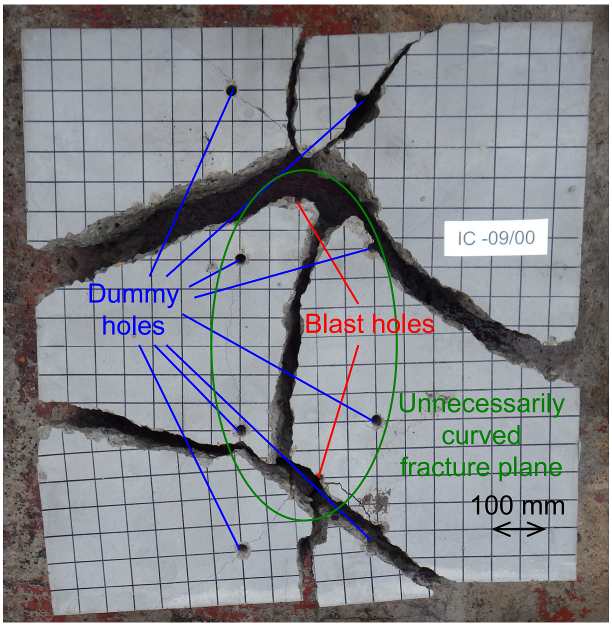
Fig. 1. The two (out of ten) rectangular concrete specimens prepared for the field experiments and modelled in the numerical simulations in this article: Top and side views for the cases (a) IC-09/00 and (b) IC-10/00 are shown [unit: mm]. Red, blue and yellow holes correspond to blast, empty dummy and screw holes, respectively. Screw holes are drilled for carriage of the specimens using a crane.

concrete pieces, and then subjected to EDI. The top view of the dynamic fracture process by the application of EDI is recorded by a high-speed digital video camera system (Photron FASTCAM SA5) at a frame rate of 50,000 frames per second. Considering the specimen size, observation area (some 350 mm × 850 mm) and the measured shear wave speed (2,400 m/s), this frame rate is sufficient for observing propagation of dynamic cracks that usually move much slower than shear waves. These two cases are studied in order to observe the possible effect of a set of dummy holes on the direction of dynamic fracture propagation. We expect that due to the superposition of the reflected waves from these dummy (and blast) holes, a main tensile crack extending rather straight and connecting only blast holes will develop, at least near the center of the specimen.

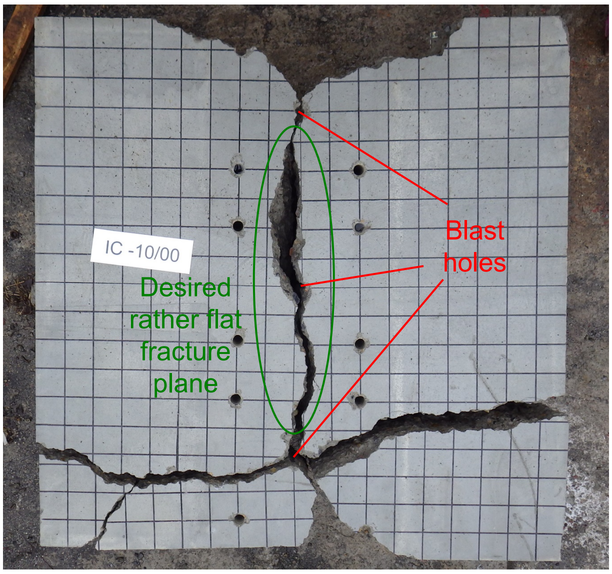
Employing alternately charged holes with a smaller diameter for dummy holes than blast holes[5] may be simply prepared and valuable in mining in isolated areas. However, instead of employing alternately charged holes, in this chapter we are using more complex geometry for the positions of blast and dummy holes in the real three-dimensional context: Dummy holes are not placed on the expected main crack path (fracture plane) and they are set rather to direct the main crack to connect the blast holes only. That is, the purpose of placing dummy holes is different from the previous ones[4), 5)]. Note that our current method is aimed more for critical situations to construct and destruct (parts of) structures made of rock-like materials in urban areas, which requires a very careful approach (No explosive can be used in such densely populated regions; Absolutely no damage to the surroundings is allowed, etc.) and a complex three-dimensional treatment is acceptable in actual fracture operation. We believe this is quite a new topic also in the field of rock mechanics, and also, it is important first to know whether the knowledge accumulated through our experience with, say, blasting by detonating explosives, is still valid for the modern safer technology (controlled dynamic destruction by application of EDI) or not.

Figures 2 shows the photographs of the top view of the fracture patterns taken after the experiments. The dimensions of the black square drawn on the top surface of the specimen are 50 mm × 50 mm. For the case IC-09/00 (Fig. 2(a)), we can identify an unnecessarily curved main crack (fracture plane) that (indirectly) connects the two blast holes. Since each of the two sets of a blast and four dummy holes is located rather close to the free surface on the side, we find unwanted cracks extending from the blast holes to the free surfaces as well as those to the screw holes through the dummy holes. In the case IC-10/00 (Fig. 2(b)), although the dimensions of the specimen remain the same, we notice that especially in the central part the main crack extends rather straight as desired. Also in this case, near the free surfaces and screw holes on the sides we see unwanted cracks but their extent looks smaller than the previous case. Crack propagation seems to be more strongly controlled in the case IC-10/00 than IC-09/00, and the geometry (positions of blast and dummy holes) used for IC-10/00 is more suitable for controlled fracture and does play an important part in real fracture process.

Further observations of the crack development in the rectangular specimens by the high-speed digital video



(a)



(b)

Fig. 2. The dynamically fractured specimens, cases (a) IC-09/00 and (b) IC-10/00, respectively, after the experiments. The (undeformed) grid spacing in this top view is 50 mm. While in (a) the crack (indirectly) connecting the two blast holes is unnecessarily curved, in the case (b) a desired, rather flat fracture plane connecting the three blast holes is generated.

camera system indicate that in the case IC-09/00 (Fig. 3) cracks on the top surface develop first in the squares bounded by the dummy holes and then the main crack (indirectly) connecting the blast holes emerges while for the case IC-10/00 (not shown here) the main crack running through the three blast holes and the cracks in the two squares formed by the dummy holes near the free surfaces on the sides appear almost at the same time.

It seems from Fig. 3 that dynamic fracture network induced by EDI develops first upon wave propagation in the specimen and then gas pressurization widens crack opening displacements and the stemming material is ejected, like noted in conventional blasting by explosives[6)-8)]. If cracks were generated due to gas pressurization from the beginning, the stemming material would be ejected at an earlier stage, simultaneously with the development of fracture network.

3. DISCUSSION

We have found that a main crack connecting blast holes rather smoothly may develop in a rectangular specimen if each blast hole is surrounded by four empty dummy holes and located not close to the free surface on the side. The influence of dummy holes and free surfaces on elongation of the main crack plane may be briefly confirmed also numerically. In this chapter, we use our fully three-dimensional finite difference simulator available on a PC (Windows)[1), 4)] and see the evolution of dynamic disturbances in the specimens. A homogeneous, isotopic and linear elastic concrete material, with the measured density 2,320 kg/m^3, Young's modulus 34.2 GPa and Poisson's ratio 0.25 (longitudinal and shear wave speeds $V_P \approx$ 4,200 m/s and $V_S \approx$ 2,400 m/s, respectively), is assumed. Orthogonal 91 × 91 × 31 grid points are arranged (constant grid spacing Δx = 10 mm) for efficient and fundamental calculations with the constant time step $\Delta x/(2V_P)$. Although different physical quantities may be chosen, for simplicity, the stemming material covering the cartridge and filling every blast hole is presumed to have the same material properties as concrete. The dimensions of the specimen and positions of the holes and cartridges are equivalent to those for the experiments except that now the width of each blast and dummy hole is the same (squares with sides of length Δx, but waves may be radiated cylindrically from the middle section and (hemi)spherically from the top and bottom

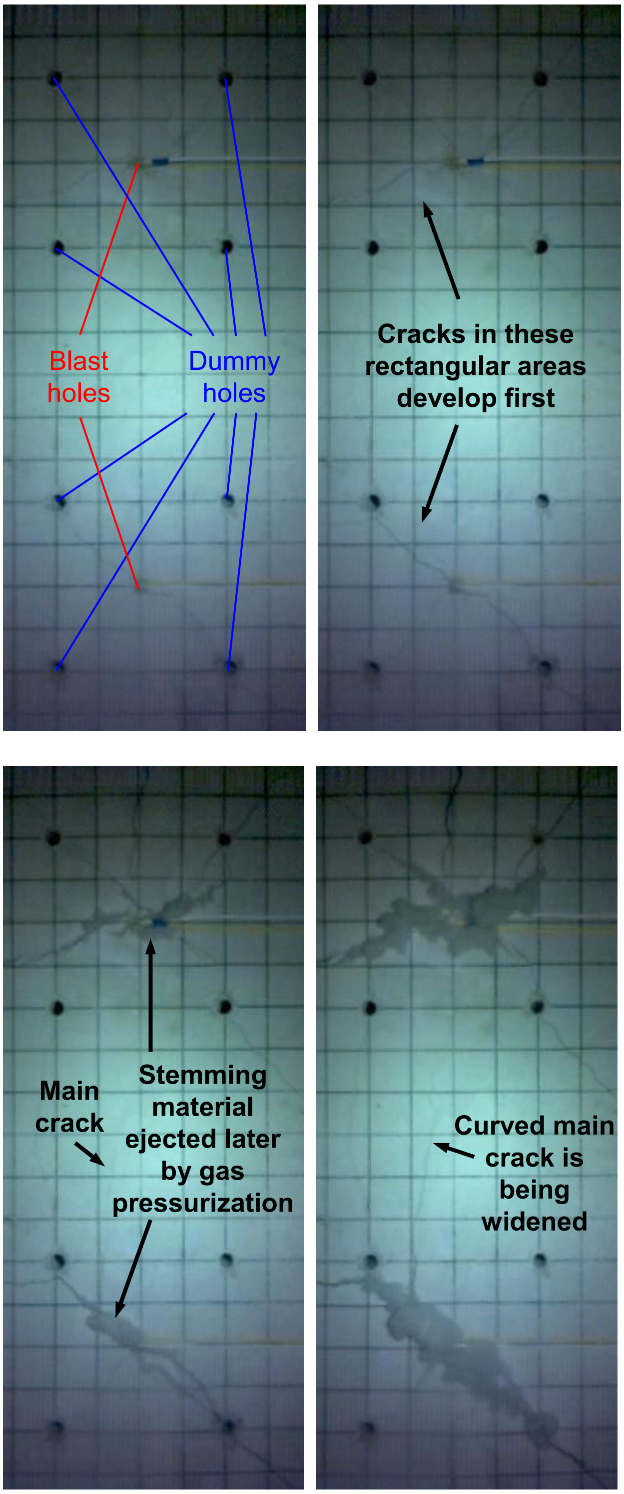
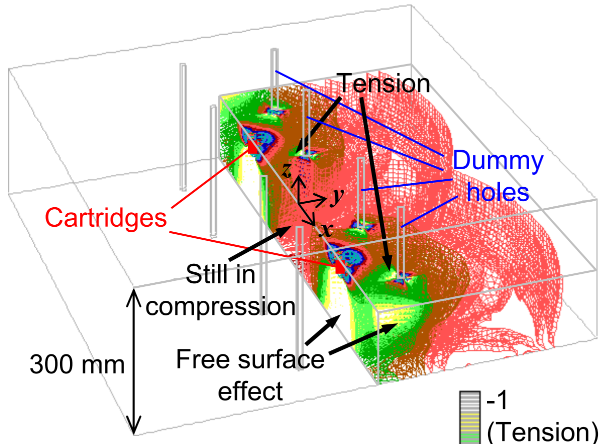


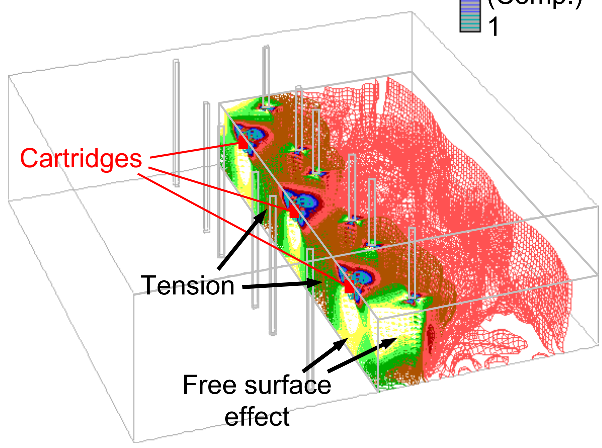
Fig. 3. Snapshots (top view), taken by the high-speed digital video camera at a frame rate of 50,000 frames/s, showing the fracture development for the case IC-09/00. As before, the spacing of the grid marked for a reference purpose is 50 mm. First, cracks propagate in each square region bounded by four empty dummy holes, and then the main crack connecting the blast holes develops. The time elapsed after the top left photograph is 200, 600 and 1,000 μs, respectively.

edges of the cartridges placed in the blast holes). Further, for the cartridges, a simplified form of the time-varying pressure $P(t)$ due to the application of EDI, $P(t) = A \sin^2(\pi t/T)$ (for $0 \le t \le T$) and 0 (otherwise), is employed, with A = 1 GPa and the duration of the pressure pulse T = 260 μs[4]. No specific fracture criterion is incorporated at this moment, because, first of all, we must know how waves generated by the new technique, application of EDI, propagate and interact with given inhomogeneities. We all know, normally, body waves propagate first and then fractures are induced. Before the rupture is initiated, our numerical simulations to observe wave propagation and interaction are valid even without introducing any fracture criterion. At least, we can see the most endangered sections in the model at an earlier stage using our current simulations without any unnecessary numerical contaminations. With the above presumptions and the geometrical and loading settings, the model becomes almost symmetric with respect to the virtual horizontal central plane (and the source cartridges) as well as to the virtual central vertical plane containing the blast holes, and we can recognize the essential effect of wave interactions on subsequent fracture development in a straightforward way by looking into only the quarter part of the specimen.

Figure 4 depicts the contours of normalized volumetric strain or relative variation of the volume (a strain invariant) for the cases (a) IC-09/00 and (b) IC-10/00, respectively. As stated above, owing to the symmetric nature of the models, only the contours for the lower quarter part of the specimen are shown, with a virtual cross-sectional view over the horizontal plane z = 0 (at a height of 150 mm) and the central vertical plane y = 0 that contains the centers of blast holes (cartridges). In the snapshots, dilatational (negative volumetric strain) and contractive (positive volumetric strain) elements in the rectangular specimen are clearly identified. In the case IC-09/00, first, compressive waves are generated and propagated simultaneously from the cartridges upon application of EDI. Then, wave reflection from the bottom/top and side free surfaces as well as the dummy holes gives tensile regions (and cracks, if a tensile fracture criterion may be assumed) near the blast holes, but the areas between the blast holes on the plane y = 0 are still in compression (Fig. 4(a)) if the distance between blast holes is rather large like in this case. Later, as the wave interaction process becomes more complex, tensile regions become larger and the section between the blast holes may be in tension and the main tensile crack may develop. On the other hand, in Fig. 4(b), with the shorter distance between the blast holes, tensile regions close to the free surfaces and dummy holes as well as those near the middle blast hole at $x = y = 0$ seem to appear almost simultaneously (possibly due to the existence of waves reflected from the nearby holes and propagated towards the middle blast hole), and a tensile crack plane connecting the three blast holes will emerge rather smoothly at a relatively earlier stage, as expected from the experimental results. Hence, (optimally located) blast and dummy holes may play a crucial role in controlled smooth fracture of geomaterials, and as demonstrated above, small difference between e.g. the



(a)



(b)

Fig. 4. Interactions of dynamic disturbances at an initial stage in a linear elastic rectangular specimen that models the case (a) IC-09/00 or (b) IC-10/00. Because of the symmetric nature of the models, contours of normalized volumetric strain (strain invariant) in the lower quarter part are depicted for the time approximately at 100 μs after initiation of the application of EDI.

distance of blast holes may become significant in crack development. Thus, wave-based analyses may be of powerful help in planning more precise and efficient dynamic fracture of materials including rocks. The discussion here holds not only for the modern method using EDI but also for the conventional blasting by explosives.

Of course, a fracture criterion should be included for post-failure analysis (technically very easy to be implemented in our code), and for example, observed dynamic fracture in a reinforced concrete beam by conventional, overcharge blasting can be well reproduced by our numerical method with the simple, maximum principal tensile stress fracture criterion[1]. However, even in that case, we must be cautious about our knowledge on real three-dimensional dynamic phenomena and fracture criteria for moderate (non-overcharge) blasting (by detonating explosives or applying EDI) in three-dimensional materials. Our fracture criteria are derived mostly from one- (or two-) dimensional experiments (e.g. one-dimensional frictional experiments for post-failure behavior), and for instance, we have still no consensus regarding fracture criteria for crack kinking and branching even for two-dimensional cases[9, 10]. Therefore, we must be very careful in implementing any fracture criterion for dynamic fracture by moderate blasting, especially in three-dimensional cases.

4. CONCLUSIONS

We have performed field experiments to dynamically fracture brittle specimens by electric discharge impulses (EDI) and recorded the fracture development by a high-speed digital video camera system. Our special attention has been paid to the effect of empty dummy holes on wave and fracture development in the rectangular test specimens. We have found that sets of blast holes surrounded by empty dummy holes may actualize main crack development in a desired direction. Our fully three-dimensional finite difference numerical code for a PC (Windows) may well (qualitatively) explain the results of the real field observations, and optimal positions of blast and dummy holes for predictable and controlled fracture may be determined for each specific geometry (structure) also by the established simulation techniques. Our ongoing further field application and experiments of dynamic fracture by EDI in urban and isolated areas suggest that in rock masses as well as in concrete specimens with reinforcing steels bars, fracture tends to propagate along planes of weakness in the materials and we can utilize this characteristic for more efficient destruction of a given structure, e.g. removal of only RC (reinforced concrete) lining segments from the surroundings in a tunnel. More detailed analyses employing more realistic models (structures) are required for quantitative evaluation of the influence of planes of weakness on dynamic disintegration of rock-like materials.

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