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Citation	International Journal of Fracture, 180(2), 163-175 https://doi.org/10.1007/s10704-013-9809-4
Issue Date	2013-04
Doc URL	http://hdl.handle.net/2115/55291
Rights	The final publication is available at link.springer.com
Type	article (author version)
File Information	FRAC-D-12-00112_fukuda.pdf

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Numerical simulation of the fracture process in concrete resulting from deflagration phenomena

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Abstract

This paper investigated the mechanism of fracture in concrete due to the deflagration phenomenon. For this purpose, the electric discharge impulse crushing method was selected, with liquid nitromethane (NM) taken as the deflagration agent. Employing this technique, NM is set inside charge holes and initiated by electric discharge. The pressure generated by the deflagration of NM in a steel chamber was modeled using the Jones–Wilkins–Lee equation of state. The modeled and measured pressures agreed well and the applicability of the pressure model was validated. Then, assuming controlled splitting along the expected fracture surface in concrete, dynamic fracture process analysis (DFPA) based on two-dimensional dynamic finite element method was conducted. The results showed that fracture patterns predicted in the DFPA agreed well with those obtained from experiments. The mechanism of fracture in concrete due to deflagration was then discussed in terms of the fracture process in the controlled splitting. Owing to stress interference from each charge hole, compressive stress zones (CSZs) formed above and below the middle regions between charge holes where maximum and minimum principle stresses were both in compression. The CSZs was found to be important in obtaining a flatter fracture surface in the case of controlled splitting. In conclusion, the proposed method was shown to be useful for the investigation of the fracture mechanism in the case of the use of deflagration agents and could be useful for the design optimization of such controlled splitting.

Key words: *Dynamic Fracture Process Analysis, Deflagration, Nitromethane, Finite Element Method, Concrete, Material Heterogeneity*

1. Introduction

Understanding the mechanism of dynamic fracture in rocks and rock-like materials such as concrete in response to rapidly applied loads is of considerable importance in a wide range of engineering disciplines. Especially in civil and mining engineering, control of fragmentation caused by rapidly applied loads in the case of detonation has been a significant issue because of frequent applications of blasting in, for example, tunnel and mining excavations. Many research papers and books on this topic have been published (e.g., Bhandari 1970; Borovikov and Vanyagin 1995; Bulson 1997; Stiehr and Dean 2011).

However, because of the occasional limitation of the application of blasting, alternative high-speed fracturing techniques have been proposed and developed. One such technique is the use of pulsed high-voltage electric discharge, which has been extensively studied and implemented for various purposes, such as the disintegration and fragmentation of rock-like materials (e.g., Andres 1989; Weise and Loffler 1993; Bluhm et al. 2000; Hofmann and Weisse 1997; Lisitsyn et al. 1999; Rim et al. 1999; Cho et al. 2006; Narahara et al. 2007; Shao et al. 2010). In addition, the application of deflagration agents has been proposed and the legal regulations relating to such application are more relaxed than those relating to blasting. Examples of deflagration agents are powder mixtures of metal oxide with aluminum causing thermite reaction, and nitromethane (NM). However, there has been no report of investigations of the fracture mechanism based on the detailed modeling of the deflagration process, which could be of engineering interest.

Generally, the process of dynamic fracture in rock-like materials is characterized by the initiation, propagation and intersection of multiple cracks. The resultant fracture pattern in the case of dynamic loading is quite different from that in the case of quasi-static loading. In the case of quasi-static loading, a few predominant cracks and large fragments form, while in the case of dynamic loading, the number of initiated cracks increases with increasing loading rate and many smaller fragments form. Previous studies (e.g., Rossi et al. 1991; Hanchak

et al. 1992) have shown that the main parameters affecting dynamic fracture include the applied loading rate and material heterogeneity. The loading rate has been shown to be a significant factor, especially in the high-strain-rate regime, in characterizing fracturing in concrete (e.g., Abrams 1917; Malvern et al. 1985; Ross et al. 1995; Brara et al. 2001; Grote et al. 2001) and rocks (e.g., Bacon 1962; Rinehardt 1965; Birkimer 1970; Zhang et al. 2000; Cho et al. 2004). Large strength increases were observed with the increasing applied loading rate. In addition, Cho et al. (2003b) reported that such strength increase was affected by the material heterogeneity of rock-like materials in the higher strain-rate regime.

Thus, in the investigation of fracturing in rock-like materials due to deflagration, it is necessary to characterize the corresponding loading rate and consider material heterogeneity.

Recently, numerical methods have been increasingly applied in analyzing fracturing, including extensive use of finite-element-method (FEM)-based simulations. These methods include the FEM featuring the element deletion method (e.g., Hallquist 1998), the FEM featuring the interelement crack method (e.g., Xu et al. 1994; Camacho and Ortiz 1996; Carol et al. 1997; Ortiz and Pandolfi 1999; Ruiz et al. 2000; Gálvez et al. 2002; Segura and Carol 2010) and the extended FEM (e.g., Belytschko and Black 1999; Moës et al. 1999; Belytschko et al. 2001; Stolarska et al. 2001; Song and Belytschko 2009). It has been reported that the latter two methods perform reasonably well (Song et al. 2008) with a careful choice of mesh size and fracture energy. On this basis, we carried out dynamic fracture process analysis (DFPA) based on the two-dimensional (2-D) FEM featuring the interelement crack method (Kaneko et al. 1995; Yamamoto et al. 1999; Cho 2003a; Cho et al. 2003b; Cho et al. 2003c; Cho and Kaneko 2004; Cho et al. 2006; Cho et al. 2008). DFPA simulates multiple crack initiations, crack growth including crack bifurcation, and crack coalescence. The code considers material heterogeneity and the size effect of the strength of the material, both of which play an important role in the simulation of the fracturing process in rock-like materials.

With the above background, this paper investigates detailed loading characteristics and the fracture mechanism relating to deflagration. As a research target, we selected a high-speed splitting method for rock-like materials, termed the electric discharge impulse crushing method (EDICM), which uses both

electric discharge and the deflagration of NM (Sasaki et al. 2011).

The paper is arranged as follows. In the next section, we describe the characteristics of a generated pressure profile obtained from pressure measurement and a method for modeling the pressure resulting from the deflagration of NM. Section 3 introduces the DFPA and, in section 4, we simulate the fracturing in concrete through DFPA with the proposed pressure model, and show that the resultant fracture patterns simulated in DFPA agree well with those obtained in experiments. We also discuss the mechanism of fracturing of a concrete block due to the deflagration of NM. Finally, we close the work by presenting conclusions in Section 5.

2. Modeling of pressure arising from deflagration

2.1. Overview of the EDICM

Pertinent information on the EDICM is presented in the following. For further details, see Sasaki et al. (2011). In the EDICM, the initiation cartridge shown in Fig. 1 is prepared. The cartridge consists of a cylindrical plastic bottle, a cylindrical plastic cap and liquid NM. The cartridge also has a thin metal wire. Initiation is controlled by an electric discharge generator, and electric discharge of 2500 A and 1500 V is applied to the wire through cables. The wire is then vaporized by the electric discharge. As a result, plasma is generated and the deflagration of NM commences. Thus, by setting the initiation cartridges in charge holes (CHs) drilled in a target rock-like material, gas expansion due to deflagration causes fracturing in the target. Although the EDICM uses both electric discharge and deflagration, it has been revealed that the electric discharge itself only acts as an initiator for the deflagration of NM and makes little contribution to the resultant fracture (Sasaki et al. 2011). Thus, this paper only focuses on the deflagration.

2.2. Modeling methodology

We consider it essential to understand the characteristics of the generated pressure. The characteristics of pressure generated in a CH were identified by a simple pressure measurement using a hollow austenite stainless-steel chamber (ISO TR 15510 L No. 6). Figure 2 shows a schematic diagram and photograph of

the chamber. The initiation cartridge for the volume of NM, $V_{\text{NM}} = 12 \text{ mL}$, was set inside the chamber. The hollow interior (i.e., the CH) was confined by upper and lower flanges. The outer diameter, inner diameter and length in the axial direction of the chamber were 120, 20 and 70 mm, respectively. The generated pressure was measured by piezofilm (PVF₂ 11-125-EK made by Dynasen, Inc.) set immediately below the initiation cartridge. Poly (methyl methacrylate) (PMMA) was set below the piezofilm to minimize the undesirable interference of reflected stress waves in the obtained data.

Figure 3 shows the measured pressure profile. The horizontal and vertical axes indicate the time after the electric discharge was applied and the measured pressure, respectively. The pressure spike observed approximately 120 μs after the electric discharge was attributed to both the vaporization of the wire by the electric discharge and the generation of plasma by vaporization of the wire (Sasaki et al. 2011), and the subsequent gradual rise in pressure was due to the deflagration of NM. The effect of the pressure spike on the resultant fracture was found to be negligible. The pressure due to deflagration peaked approximately 130 μs after the pressure spike that corresponds to the electric discharge peak and then decreased. Data were no longer obtained approximately 50 μs after the maximum pressure was attained because of the cutoff of the piezoelectric system. In addition, the inside of the chamber could not be observed after the measurement because of large plastic deformation of the chamber. By conducting preliminary experiment, we obtained the pressure profile in case that the piezoelectric system was cut off. In that case, significant signal errors were observed as irregular and quite steep signal changes. Because the obtained pressure profile in Fig. 3 did not correspond to such case before $t = 310 \mu\text{s}$ and pressure decrease was also successfully captured, it was not considered that the piezoelectric system was cut off before $t = 310 \mu\text{s}$ in Fig. 3.

Although consideration of the lack of reproducibility in the reaction kinetics of deflagration phenomena is generally quite important, we considered that such lack of reproducibility could be minimized in the case of the deflagration of NM due to applied electric discharge under 1500 V and 2500 A, i.e. the condition of very high voltage and high current. Thus, to model the pressure resulting from the deflagration of NM, we used the measured pressure profile in Fig. 3. Considering that the expansion of gaseous products via deflagration can be regarded as a

thermodynamically isentropic process, we applied and extended the Jones–Wilkins–Lee (JWL) equation of state (EOS) (Lee et al. 1973). The JWL EOS has been extensively used to express the isentropic expansion of gaseous products generated by various explosives. In the EOS, a decoupling effect (e.g., Rustan 1998) can also be considered where the pressure acting on the CH dramatically changes with a change in V_{NM} .

It was assumed that the deflagrated volume of NM, $V_d(t)$, increased with elapsed time, that all NM was in the state of deflagration at time t_{peak} after the initiation, and that the maximum pressure was attained at t_{peak} . In other words, by expressing the initial volume of a CH by V_0 , $V_d(t)$ became V_0 at $t = t_{\text{peak}}$. Considering that NM may have commenced deflagration around the vaporized metal wire installed approximately in the middle of the initiation cartridge vertically, it is reasonable for $V_d(t)$ to be modeled by 2-D expansion with constant propagation velocity; i.e., a quadric function with respect to time. $V_d(t)$ thus has the form

$$V_d(t) = Dt^2 \quad (0 \leq t \leq t_{\text{peak}}), \quad (1)$$

where the constant D was determined such that $V_d(t)$ becomes V_0 at $t = t_{\text{peak}}$, and a monotonically decreasing function was used for $V_d(t)$ after $t = t_{\text{peak}}$. Figure 3 shows that $t_{\text{peak}} \sim 130 \mu\text{s}$.

By incorporating $V_d(t)$ into the JWL EOS, the applied pressure $P(t)$ at time t is expressed in the form

$$P(t) = A \exp \left\{ -R_1 \left(\frac{V(t)}{V_d(t)} \right) \right\} + B \exp \left\{ -R_2 \left(\frac{V(t)}{V_d(t)} \right) \right\} + C \left(\frac{V(t)}{V_d(t)} \right)^{-(\omega+1)}, \quad (2)$$

where $V(t)$ is the volume of the expanded gaseous products at time t divided by V_{NM} . The JWL parameters for NM are $A = 348.504 \text{ GPa}$, $B = 9.021 \text{ GPa}$, $C = 1.225 \text{ GPa}$, $R_1 = 5.38881$, $R_2 = 1.39179$ and $\omega = 0.29475$, all of which were calculated using the 2003 version of Kihara–Hikita–Tanaka (KHT) code (Tanaka 1985; Tanaka 2003).

2.3. Validation of the pressure model

To investigate the applicability of the proposed pressure model, the pressure profile obtained from Eq. (2) with $V_{\text{NM}} = 12 \text{ mL}$ was compared with the measured pressure in Fig. 3. Because the measurement was conducted inside the chamber

under high pressure, it needs to be interpreted with consideration of the deformation of the chamber. Thus, $P(t)$ was calculated through DFPA (see the next section) assuming deformation of the chamber.

A numerical model for a cross section of the chamber shown in Fig. 2 was employed. Figure 4 shows the 2-D finite element mesh and its size. The cross section was assumed to be perpendicular to the axial direction of the CH in the chamber and to include the initiation cartridge. Linear triangular elements were used. There were 28,292 elements and 14,328 nodal points. All outer boundaries of the mesh were treated as free faces, and $P(t)$ in Eq. (2) was applied to the CH. The physical properties of the chamber used in the analysis were P-wave velocity of 6000 m/s, S-wave velocity of 3100 m/s, density of 8000 kg/m³, Young's modulus of 200 GPa and Poisson's ratio of 0.3. The analysis was conducted under a plane-strain condition. Tensile fracturing and shear yielding were considered. The onset of yielding was judged using the von Mises criterion. The post-yielding behavior was treated using a perfect elastic-plastic model. Tensile strength and yield strength were 500 and 200 MPa, respectively.

Figure 5 compares the modeled pressure $P(t)$ with measured pressure. Deflagration was considered to commence when the pressure spike due to the electric discharge attained its peak value; i.e., $t = 0$ in Fig. 5. The figure shows good agreement between modeled and measured pressures. Thus, $P(t)$ modeled in this section was applied in the DFPA conducted in Section 4.

3. DFPA

The methodology of DFPA is briefly introduced here. For details, see the literature (Cho 2003; Cho et al. 2008). DFPA is based on a 2-D dynamic FEM and can simulate multiple crack initiations, propagations and coalescences mainly in rocks and rock-like materials such as concrete, while considering material heterogeneity and the size effect. The viscosity of the material is treated using a quality factor, Q (e.g., Kolsky 2012). Tensile and compressive fractures are simulated.

In the case of tensile fracture, different tensile strengths were given to each finite-element boundary such that the strengths satisfied Weibull's distribution (Weibull 1951). Introducing a notion of mean microscopic tensile strength $S_t(V)$ in a given volume V , a cumulative probability function, $G(V, S_t(V))$, is expressed as

$$G(V, S_t(V)) = 1 - \exp \left[\frac{V}{V_{\text{ref}}} \left(\frac{S_t(V)}{S_t(V_{\text{ref}})} \right)^m \Gamma^m \left(1 + \frac{1}{m} \right) \right], \quad (3)$$

where $\Gamma(\cdot)$ is a Gamma function; m , a coefficient of uniformity; V , a volume given by the area of each element having unit thickness in the context of the FEM; V_0 , a reference volume; and $S_t(V_{\text{ref}})$, the mean microscopic tensile strength in V_{ref} . Random numbers satisfying Eq. (3) were generated to give the spatial distribution of $S_t(V)$ for each finite element. The microscopic tensile strengths on each boundary were calculated by taking the average of its surrounding elements' strengths. Application of Eq. (3) is equivalent to considering material heterogeneity and the size effect of strength characterized by m and the ratio of V to V_{ref} , respectively.

When the calculated tensile stress normally acting on the element boundary exceeded the boundary's tensile strength, crack initiation was expressed by separation of the element boundary. Non-linear behavior in the crack opening was considered and modeled by a tensile softening curve (or cohesive law) (Hillerborg et al. 1976) of a bilinear model (Peterson 1981) illustrated in Fig. 6. The horizontal and vertical axes indicate crack opening displacement, w , and cohesive traction, σ , of each crack, respectively. The area under the w – σ curve is referred to as fracture energy, G_f (Hillerborg et al. 1976). σ_0 is the initial cohesive traction of each crack and equivalent to the element boundary's tensile strength, and w_1 and w_2 correspond to w when $\sigma = (1/4)\sigma_0$ and $\sigma = 0$, respectively.

The compressive fracture in concrete was judged by Mohr–Coulomb criteria for each element because the strain rate corresponding to the deflagration could be regarded as almost quasi-static condition in the literature (Cho et al. 2004) due to the fact that the deflagration is slower phenomena than detonation by one order. The compressive strength of each element was calculated as the product of S_{tb} and the ratio $S_c(V_{\text{ref}})/S_t(V_{\text{ref}})$, where S_{tb} is the mean value of microscopic tensile strengths of the three boundaries of each element and $S_c(V_{\text{ref}})$ is the mean microscopic compressive strength in V_{ref} . After the stress exceeded the Mohr–Coulomb criteria, which relate to the internal friction angle ϕ and compressive strength of each finite element, the stress state was successively modified to express the plastic strain by applying the opposite sign of the excessive stress from the Mohr–Coulomb envelope to the corresponding finite elements in the next time step.

All DFPA in the next section were conducted under the plane-strain condition.

4. Investigation of the fracture process in concrete

We investigated the process of fracturing in concrete due to the deflagration of NM. Specifically, controlled splitting of the concrete structure along CHs as shown in Fig. 7 was investigated because it is a representative application of the EDICM. In this case, attaining a flat fracture surface between CHs and minimizing damage to the remaining structure are of particular interest. Field-scale experiments simulating the controlled splitting of concrete were investigated by DPFA.

4.1. Overview of the experiment and analytical conditions of DFPA

Figure 8 is a photograph of a concrete block used in the experiment. The experimental configuration allows application of the EDICM with electric discharge to three CHs. V_{NM} was set to 12 mL and each CH had a diameter of 20 mm and a height of 400 mm. The initiation cartridge was set at the bottom of the CHs, and the remaining upper space in each hole was tamped firmly with silica sand.

Figure 9 shows a 2-D finite element mesh corresponding to the experiment specimen in Fig. 8. The mesh consisted of linear triangular elements and the analyzed plane was assumed to include each CH. There were 146,840 elements, and 74,094 nodal points before the crack initiation. The DFPA applied the interelement crack method and the total number of nodal points thus increased with the progress of fracture. The element size in the mesh was carefully chosen to be small enough to minimize the dependency of the crack path on the mesh. Table 1 shows the physical properties of concrete used in the DFPA. The P-wave velocity was measured and, assuming a Poisson's ratio of 0.20, other elastic constants were calculated according to the theory of elastodynamics. The coefficient of uniformity m was set small enough to express the heterogeneity of concrete. The calculated distribution of the tensile strength over the mesh is shown in Fig. 10. The mean value of the tensile strength was calculated as 13.5 MPa according to the size effect considered in Eq. (3). Although the Q value in the very close vicinity of charge hole was unknown under the extreme condition of the deflagration, we considered that such zone is quite limited (e.g. Cho et al.

2003c; Cho et al. 2004) and the problem could be approximately treated as elastodynamics problem for some distance away from the charge hole. Thus the constant Q was applied. All perimeter boundaries of the mesh were treated as free boundaries. $P(t)$ in Eq. (2) was applied to all CHs. Because the EDICM applies electric discharge, simultaneous initiation was assumed in the DFPA. In addition, considering that the tamped silica sand remained in the CHs after the fracturing and the required time for the fracturing due to the stress wave induced by the deflagration of NM to complete was estimated to be shorter than that for the tamped silica sand to be blown away, the effect of the stemming was not considered in this paper.

4.2. Fracture process in the controlled splitting of concrete

Figure 11 presents the results of DFPA. The figure shows the maximum principal stress distribution and crack propagation. The cold and warm colors show compressive and tensile stresses, respectively. The black lines changing with elapsed time indicate cracks initiated by the applied pressure, $P(t)$. The time $t = 0$ corresponds to the commencement of the deflagration of NM (see Fig. 5).

Between $t = 0$ and $40 \mu\text{s}$, the stress waves propagated outward from the CHs with their maximum and minimum principle stresses being in the circumferential and radial directions, respectively, as shown in Fig. 12. Around $t = 40 \mu\text{s}$, cracks initiated around the CHs and propagated in radial directions owing to the circumferential tensile stress, $\sigma_{\theta\theta}(t)$. With time, some of these cracks became predominant and extended toward the outer free faces while remaining cohesive.

Around $t = 80 \mu\text{s}$, the predominant cracks around each CH reduced in number to 4–6. Additionally, four compressive stress zones (CSZs) formed immediately above and below the middle regions between adjacent CHs where the stress states were in biaxial compression. Then, around $t = 100 \mu\text{s}$, the intensity of the CSZs increased, leading to the arrest of any crack propagation toward the CSZs. Because the CSZs did not form along the CHs, predominant cracks between CHs extended. In addition, the extension of predominant cracks from CHs 1 and 3 toward the perimeter boundaries continued because these cracks were not affected by the CSZs.

Around $t = 160 \mu\text{s}$, the crack extensions continued and some predominant cracks between the CHs coalesced as the pressure began to decay after $t_{\text{peak}} = 130$

1 μs . With the decay of the applied pressure, the CSZs disappeared around $t = 160$
2 μs . After crack coalescence between CHs, there was little crack initiation in these
3 regions, and there was only the extension of predominant cracks from CHs 1 and
4 3 toward the perimeter boundaries. Finally, around $t = 240$ to $260 \mu\text{s}$, these
5 predominant cracks reached the left and right perimeter boundaries, respectively.
6 In addition, the pattern of the open cracks with zero cohesive traction among the
7 predominant cracks showed little change after $t = 240 \mu\text{s}$. Thus, we consider that
8 the entire fracture pattern resulting from the stress wave was geometrically
9 determined by $t = 260 \mu\text{s}$, and we stopped the simulation and estimated the final
10 fracture surface; i.e., at $t = 260 \mu\text{s}$, we extracted the predominant open cracks
11 shown by white dotted lines. In addition, considering that the gaseous products
12 generated by deflagration could selectively flow into these predominant open
13 cracks (Cho 2003), it is reasonable to assume that the predominant open cracks
14 propagating from CHs 1 and 3 could continue to extend as shown by the white
15 dotted arrows, thus forming the final fracture surface.

16
17 According to the above estimation of the resultant fracture surface, the region
18 above the fracture surface could remain a concrete mass and the region below
19 could fragment into a few pieces with the help of gas flow. Cracks other than the
20 predominant open cracks are cohesive and thus should be interpreted as damage to
21 the remaining concrete mass.

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23 Because the heterogeneity of concrete could be an important factor affecting
24 the resultant fracture patterns, we conducted three DFPA to consider the effect of
25 concrete heterogeneity using different spatial strength distributions with the same
26 mean value and variance as the distribution in Fig. 10.

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4.3. Comparison of experiment and DFPA results

Figure 13 shows the resultant fracture surface obtained from the experiment (see Fig. 8) and the fracture surfaces predicted in three DFPA for the different spatial strength distributions. For the DFPA results, predominant open cracks were extracted as white dotted lines and arrows following the same procedure used in the previous subsection and other black lines are cohesive cracks. Next, we mainly focus on the fracture surface between the CHs.

A fracture surface with predominant open cracks connecting CHs was observed in both the experiment and DFPA. In the three DFPA conducted to investigate

the heterogeneity of concrete, there was the same trend that fracture surfaces formed between CHs, even though the detail of the fracture geometry was slightly different in each case. Thus, the geometry of the fracture obtained by experiment and that obtained by DFPA were in good agreement. This indicates that the form of the fracture surface connecting CHs could be attained if additional experiments are conducted under the analysed condition.

The above results verify the applicability of our pressure model and demonstrate that the fracture process resulting from the deflagration of NM can be evaluated by DFPA. Thus, the simulation of the fracture process by DFPA could clarify the mechanism of concrete fracture due to the deflagration of NM. We discuss the DFPA result in the following.

4.4. Discussion

In terms of material heterogeneity, it is clear that, even for the same model geometry under the application of the same external force, the fracture pattern depends on the strength distribution. This dependence is due to the difference in positions of crack initiations around the CHs and the difference in the directions of crack growth after the crack initiations depending on the strength heterogeneity of the concrete. Thus, the shapes of fracture surfaces that form between the perimeter boundaries and CH 1 or 3 were completely different in each model. However, the fracture surfaces connecting the CHs were flatter and had only minor shape differences. As described in subsection 4.2, the results can be explained by the formation of CSZs associated with the stress interference and the prevention of crack growth toward them. Thus, if the main aim is to attain a flatter fracture surface along the CHs and avoid crack growth in unexpected directions, there should be smaller spacing between the CHs to minimize the time required for the formation of the CSZs considering that this may be the only measure to control the directions of crack growth. Otherwise, the flatness of the resultant fracture surface between CHs could be compromised. To investigate the validity of this idea, we conducted additional experiments and DFPAs for different spacings between CHs.

Figure 14 shows the fracture patterns for different spacings of CHs. A photograph of the fractured concrete block and the three DFPA results for varying distributions of the material strength are shown. The experimental and DFPA

1 results clearly agree with each other, demonstrating the applicability of the
2 proposed method. It is seen that the roughness of the fracture surface between the
3 CHs increases with increasing spacing of the CHs. In particular, the flattest
4 surfaces were obtained between CHs in the case presented in Fig. 14(a) with the
5 smallest spacing. In contrast, the roughest surfaces were obtained in the case
6 presented in Fig. 14(b) with the largest spacing owing to the relative delay of
7 formation of CSZs. Hence, the larger spacing leads to a rougher fracture surface
8 because of the greater effect of heterogeneity on the shape of the resultant fracture
9 surface between CHs. In addition, the effect of the free face on the fragmentation
10 size weakens in the loading rate corresponding to the deflagration; i.e.,
11 fragmented pieces became larger even for the smallest spacing in Fig. 14(a).
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13

14 Finally, it is worth mentioning that the result presented in Fig. 14(a) was
15 obtained by applying the proposed pressure modeling method in the case that V_{NM}
16 = 2 mL, using a setup similar to that shown in Fig. 2 and following the same
17 procedure described in Section 2. The value of t_{peak} was also 130 μs in this case.
18 This result indicates that our pressure modeling method is not limited to the
19 particular case discussed in this paper but can account for variation in the volume
20 of deflagration agent.
21
22

23 5. Conclusion

24 We investigated the mechanism of fracture in concrete due to the deflagration
25 of NM when employing a high-speed splitting technique for rock-like materials
26 (namely, the electric discharge impulse crushing method). For this purpose, we
27 applied dynamic fracture process analysis (DFPA) code based on the 2-D FEM
28 utilizing the interelement crack method. By proposing a new pressure modeling
29 method based on simple pressure measurement and incorporating it into the
30 DFPA, the fracture patterns obtained from several experiments assuming the
31 controlled splitting of concrete along charge holes were found to be expressed
32 well.
33

34 In discussion of the fracture process assuming the controlled splitting of
35 concrete due to the deflagration of NM, it was clarified that CSZs formed above
36 and below the middle regions between CHs where maximum and minimum
37 principle stress states were both in compression. These CSZs were found to be
38 essential if flatness of the fracture surface along CHs is the main requirement. It
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was also found that smaller spacing between CHs is required for the successful utilization of the CSZs because the time required for the formation of CSZs increases for larger spacing.

Finally, considering the difficulty of both considering the chemical reactions inherent in deflagration of different deflagration agents and calculating the generated pressure, our approach is advantageous in that the generated pressure can be easily expressed according to a simple pressure measurement and application of the JWL equation of state, where the JWL parameters for individual deflagration agents can be readily calculated using, for example, KHT code.

Acknowledgment

The first author appreciates support received in the form of Research Fellowships from the Japan Society for the Promotion of Science for Young Scientists.

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Title of Table

Table 1 Physical properties of concrete used in DFPA.

Figure captions

- Fig. 1 Schematic diagram of the initiation cartridge used in the EDICM.
- Fig. 2 Schematic diagram (left) and photograph (right) of the pressure measurement using a stainless steel chamber; the volume of NM was 12 mL.
- Fig. 3 Measured pressure profile.
- Fig. 4 2-D finite element mesh for a single cross section of the chamber.
- Fig. 5 Comparison of measured and modeled pressures.
- Fig. 6 Tensile softening curve used in DFPA (bilinear model).
- Fig. 7 Schematic diagram of the controlled splitting of a concrete structure along charge holes.
- Fig. 8 Concrete block before the application of EDICM.
- Fig. 9 Finite element mesh used in the analysis of the concrete block in Fig. 8.
- Fig. 10 Distribution of the microscopic tensile strength obtained from Eq. (3).
- Fig. 11 Result of the fracture process simulated by DFPA for chosen time steps.
- Fig. 12 Temporal change in radial and circumferential stress components on the wall of a CH before crack initiation.
- Fig. 13 Photograph of a fractured specimen and fracture surfaces predicted by DFPA.
- Fig. 14 Experimentally and numerically obtained fracture patterns.
- (a) The case for spacing of 80 mm.
- (b) The case for spacing of 600 mm.

Tables

Table 1. Physical properties of concrete used in DFPA.

P-wave velocity, V_p (m/s)	4000
S-wave velocity, V_s (m/s)	2450
Density, ρ (kg /m ³)	2200
Elastic modulus, E (GPa)	31.7
Poisson's ratio, ν (–)	0.2
Fracture energy, G_f (Pa m)	75
Quality factor, Q (–)	10
Mean microscopic tensile strength in reference volume, $S_t(V_{ref})$ (MPa)	3
Mean microscopic compressive strength in reference volume, $S_c(V_{ref})$ (MPa)	45
Reference volume, V_{ref} (m ³)	7.8×10^{-5}
Coefficient of uniformity, m (–)	5
Internal friction angle, φ (degree)	50

Figure1

Figure2

Figure3

Figure4

Figure5

Figure6

Figure7

Figure8

Figure9

Figure10

Figure11

Figure12

Figure13

DFPA :Strength Distribution 1

DFPA :Strength Distribution 3

DFPA :Strength Distribution 2

Figure14(a)

Experiment

DFPA :Strength Distribution 1

DFPA : Strength Distribution 2

DFPA :Strength Distribution 3

The results of DFPAs are $t = 110 \mu s$.

$$V_{NM} = 2 \text{ mL.}$$

Figure14(b)

DFPA: Strength Distribution 1

DFPA: Strength Distribution 2

DFPA: Strength Distribution 3

The results of DFPA are $t = 280 \mu\text{s}$.

$V_{\text{NM}} = 12 \text{ mL}$.