- *Technical Paper* -

POROMECHANICAL APPROACH TO BLAST-INDUCED DYNAMIC FRACTURE IN CONCRETE

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ABSTRACT

This study introduces a novel poromechanical approach to analyze blast-induced dynamic fracture in concrete considering gaseous kinetics. The objective is to establish a framework for examining the fracture mechanisms during demolition. The simulation employs finite element analysis, incorporating three-dimensional non-orthogonal multi-directional cracks induced by gas inflation, through which the gaseous media flows too. The study investigates the principles governing crack network development and the influence of pressurized gas using a multi-phase scheme and verifies its findings experimentally.
Keywords: blast-induced damage, poromechanics, deflagration, permeability, nitromethane

1. INTRODUCTION

The demand for quick and efficient partial or full demolition of existing structures, whether for reconstruction, planned deconstruction or disaster rescue operations [1], has significantly increased in recent years. Often, these operations need to be carried out in confined spaces with minimal impact on the surrounding environment. In such scenarios, choosing demolition based on dynamic fracture using explosives proves to be a suitable alternative to mechanical dismantling using tools and machinery.

Explosive demolition has been a subject in previous investigations [2] and although it is a complex process, its execution is usually based on empirical design, and it is error sensitive. To perform a safe and successful demolition, a detailed analysis is required that consequently leads to a good knowledge of impact, wave dynamics and fracture mechanism.

This study focuses on the numerical simulation of concrete fracture under blast loading caused by the deflagration of nitromethane. The aim is to develop impactive dynamic and nonlinear finite element (FE) model to analyze the mechanism of blasting-induced fracture in concrete. To address this objective, we employ a 3D multi-directional crack modeling, as blast-induced cracks exhibit geometric complexity. Unlike previous research, this study adopts a poromechanical approach, where the pressure of gas is the driving force of pore substances through variable voids and cracks, and accounts for nonlinear behaviors of both concrete and highly compressible gaseous media. This approach was fairly applied to ASR and fatigue of bridge decks [3] as well, and it is further discussed in Chapter 3.

In this research, the effects of three-dimensional confinement, rate-effect and anisotropic behaviors are considered. The influences of input parameters such as fracture energy, porosity, permeability of concrete, or influence of crack-guiding dummy holes are explained. The model verification is performed by comparing obtained blasting data and observations.

2. ELECTRIC DISCHARGE IMPULSE CRUSHING SYSTEM

An effective and controllable technique for precise demolition of concrete and masonry structures, which is known as Electric Discharge Impulse Crushing System (EDICS), has been developed [4] and is being in practice. This system consists of a power generator, control panel, electric discharge generator and a wire connected cartridge as shown in Fig.1. Inside the cartridge, there is a thin metal wire and a liquid explosive material - nitromethane (CH_3NO_2). It is an organic compound widely used as a safe and stable industrial solvent, monopropellant, liquid explosive, or fuel additive. Apart from normal combustion, it can undergo deflagration (combustion reaction at subsonic velocity) or detonation (supersonic combustion).

The electric discharge generator can provide a pulse of 3,000V. After an electric impulse is discharged into the cartridge within the hundreds of microseconds, the thin metal wire is vaporized, and the deflagration of nitromethane is initiated [4]. Then, a high pressure is generated by rapid volumetric expansion and applied to demolishing targets.

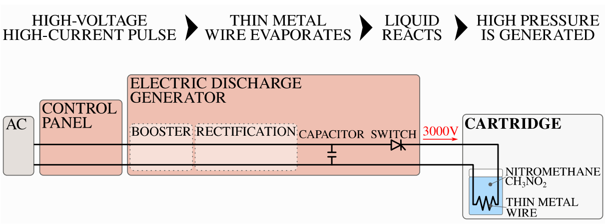

Fig.1 Schematic configuration of EDICS

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Since the pressure generated during the deflagration is lower than that of detonation, the destructive effect on a structure is rather mild. That makes the whole process more controllable compared to high explosives.

3. POROMECHANICAL APPROACH

The proposed modeling is a part of a multi-scale integrated system. For three-dimensional (3D) analysis of reinforced concrete (RC) subjected to arbitrary stress states, distinct constitutive models and modeling strategies may be indispensable [5]. For uncracked concrete fully in compression, 3D elasto-plastic fracture model is used to consider plasticity and softening of the total stress-strain relation. Concrete elasticity is conceptually modeled as an assembly of unit whose fracturing consequently develops plasticity (see Fig.2).

The cracked concrete is treated in a smeared model [5]. Based on previous research, a six-direction cracking model was formulated to represent multi-directional crack planes in 3D space by applying an active crack method [6]. This model was incorporated into non-linear FEM program and applied in practice.

By using smeared RC elements with multi-directional cracks, where the mesoscale migration of condensed water, vapor gas, and other substances can be incorporated [3], a multi-scale approach is developed. The scheme of this approach, where mechanical response of cracked concrete skeleton is considered based on the time-dependent non-linear constitutive laws [5], is briefly summarized in Fig.2.

3.1 Poromechanical approach

The governing equations of a coupled solid deformation-fluid flow through a porous media can be presented based on the two-phase model [7] and application to concrete engineering [3]. Here, we have the effective stress on the concrete skeleton as:

$$\sigma_{ij} = \sigma'_{ij} + \delta_{ij} p \qquad (1)$$

where, σ_{ij} : total stress, σ'_{ij} : effective stress, δ_{ij} : Kronecker's delta, p: pore pressure

Before cracking, it is reasonable to assume fluid isotropy inside the capillary pores of concrete. In formulating dynamic equilibrium equations of both concrete skeleton with cracks and fluid in pores, the interacting term between two phases is needed. Then, we have the tensorial form for equation of motion as:

$$\sigma_{ij,j} = \rho(\ddot{u}_i - g_i) + \rho_f \ddot{\omega}_i \qquad (2)$$

where, ρ: average density, $\ddot{u}_i$: acceleration of the solid part, g_i: gravitational acceleration, ρ_f: fluid density, $\ddot{\omega}_i$: acceleration of particle motion of fluid media, which is relative to the solid as kinetic deviation.

The momentum balance of pore media can be expressed by Eq. 3, where the last term represents the dragging action of pore substance based on Darcy's law, n is porosity, k is permeability and $\dot{\omega}_i$ is particle speed.

$$p_{,i} = \rho_f(\ddot{u}_i - g_i) + \frac{\rho_f \ddot{\omega}_i}{n} + \frac{1}{k}\dot{\omega}_i \qquad (3)$$

This model has been applied to non-compressible liquids with constant density, such as pore water in soil foundations. However, gas density varies with pressure p and temperature denoted by T. When Eq. 2 and Eq. 3 are further discretized, we encounter the multiplication of nonlinear variables, which may lead to complex solutions. As this multiplication means the mass transfer from the solid skeleton, we have the mathematical

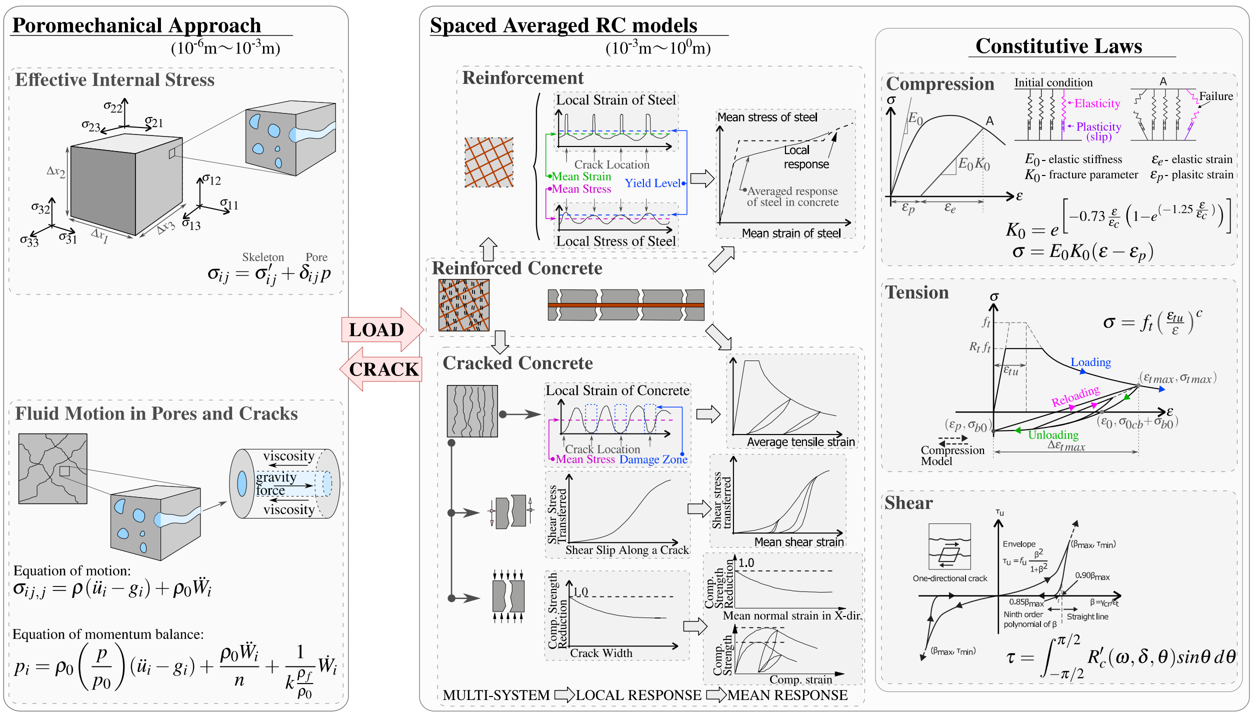


Fig.2 Multi-scale modelling of structural concrete with cracks [5]

conversion with mass transfer $\dot{W}$ and the referential density ρ_f as a function of pressure and temperature (see Eq. 4).

$$\rho_0 W = \rho_f(p,T)\omega \tag{4}$$

Then, the high nonlinear terms are handled by the material models of compressible gas with concrete. After implementing this conversion into the existing framework as stated previously, we have,

$$\sigma_{ij,j} = \rho(\ddot{u}_i - g_i) + \rho_0 \ddot{W}_i \tag{5}$$

$$p_{,i} = \rho_f(\ddot{u}_i - g_i) + \frac{\rho_0 \ddot{W}_i}{n} + \frac{\rho_0}{k\rho_f}\dot{W}_i \tag{6}$$

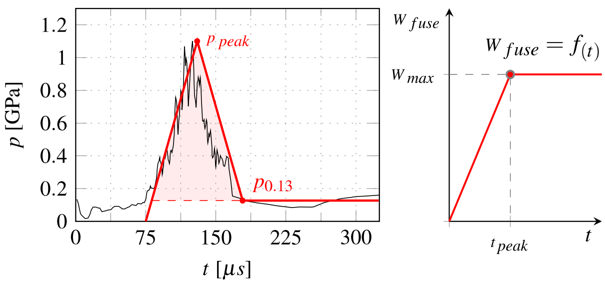
In this study, inflating gas which was vaporized from liquid nitromethane with density ρ_0 is assumed to be an idealized gas of thermodynamics where pressure is inverse proportional to the volume change as:

$$p = \frac{\overline{K}_f W_{i,i}}{1+\varepsilon_{ii}/n} \tag{7}$$

where, $\overline{K}_f$: average bulk modulus of the hole composite as a combination of bulk stiffness of solid part and pore substance, ε_{ii}: volumetric strain of concrete skeleton, n: capillary porosity, $W_{i,i}$: injected mass of compressible gas into the unit volume.

For cartridge with liquid nitromethane, the forced pressure under no volume change shall be added to the variable term of pressure as W_{fuse} which is produced during the deflagration (see Eq. 8). It is a function of time (see Fig.3b), where the maximum value W_{max} is reached by the time t_{peak} (when the maximum pressure is generated by deflagration). The pressure profile used is illustrated in Fig.3a, where maximum pressure p_{peak}=1.1GPa and its time t_{peak}=130μs. The residual pressure $p_{0.13}$ caused by the phase change from liquid to gas is equal to 0.13 GPa. This deflagration process was experimentally obtained under the confined volume.

$$p = \frac{\overline{K}_f(W_{i,i}+W_{fuse})}{1+\varepsilon_{ii}/n} \tag{8}$$



(a) Pressure profile used in this study (red), measured pressure by Sasaki et al. [8] (gray)

(b) Gaseous mass production

Fig.3 Pressure profile and gaseous mass production in time

3.2 Cracks and Anisotropy

The cracks bring about anisotropy of concrete permeability and a mutual interaction of pore substance

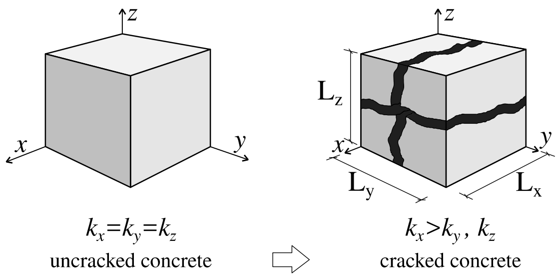


Fig.4 Permeability of cracked concrete

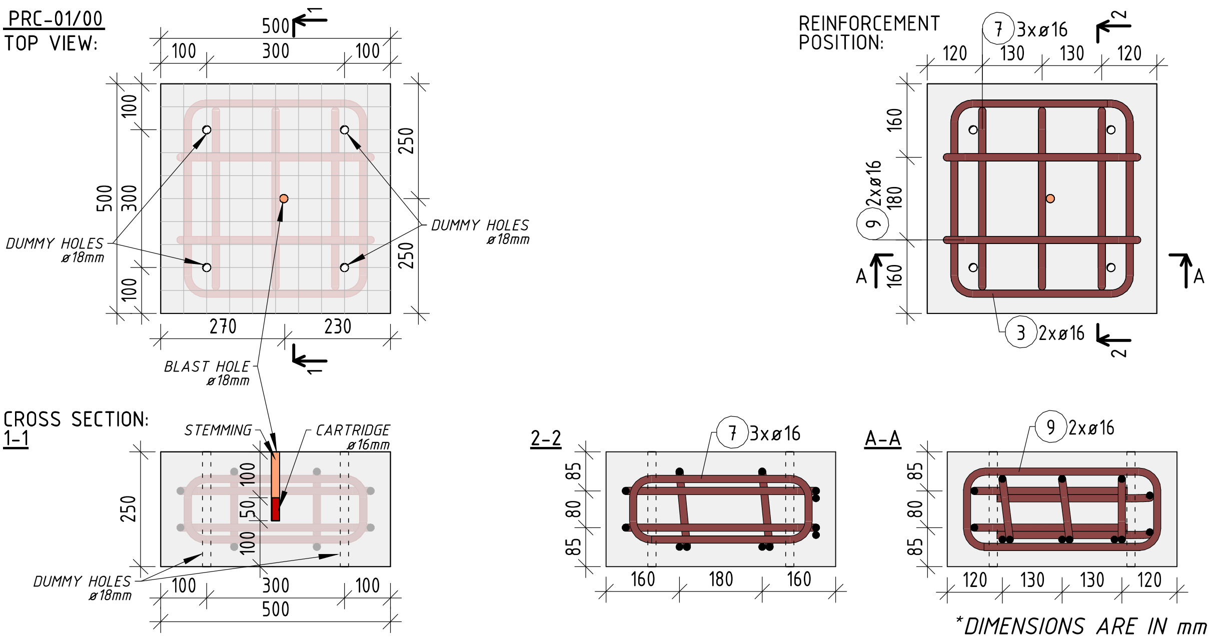


Fig.5 Dimensions and rebar position of specimen PRC-01/00

and cracked concrete. This is the coupling process of damage caused by gas and pressure release of it at the same time. With parallel cracking planes as shown in Fig.4, for example the permeability k_x along x axis will be larger compared to k_y and k_z.

Based on Hagen-Poiseuille law for a flow created between two parallel planes separated by a distance with a constant pressure gradient $-dp/dx$, the mass flow rate Q_x along x axis is described as a combination of the mass flow of two cracking spaces [9] as:

$$Q_x = \widetilde{Q}_z + \widetilde{Q}_y = -\frac{(L_z \varepsilon_{zz})^3 + (L_y \varepsilon_{yy})^3}{12\psi\mu}\frac{dp}{dx} \qquad (9)$$

where, L_z , L_y :dimensions of element, ε_{zz} , ε_{yy} : strain, ψ: tortuosity factor of crack plane, μ: gas viscosity [m^2/sec].

Then, we have the total mass transfer rate denoted by $\dot{W}_{x,tot}$ in x-direction as:

$$\dot{W}_{x,tot} = \frac{\widetilde{Q}_z}{L_z} + \frac{\widetilde{Q}_y}{L_y} = -\frac{L_z^2 \varepsilon_{zz}^3 + L_y^2 \varepsilon_{yy}^3}{12\psi\mu}\frac{dp}{dx} \qquad (10)$$

Permeability of cracked concrete is then defined as a combination of uncracked concrete permeability $k_{c,i}$ and crack permeability $k_{crk,i}$:

$$k_i = k_{c,i} + k_{crk,i} = k_{c,i} + \frac{L_j^2 \varepsilon_{jj}^3 + L_k^2 \varepsilon_{kk}^3}{12\psi\mu} \qquad (11)$$

4. NUMERICAL SIMULATION

The 3D non-linear FE analysis, in using constitutive models mentioned in the previous section, was performed to qualitatively verify the proposed framework to simulate the blast-induced fracture in concrete.

The experimental findings obtained on the specimen labeled as PRC-01/00, as presented by Yamachi and Nakamori [10], were utilized as a reference in this study. A concrete block with dimensions 500 × 500 × 250 mm was reinforced with steel bars (ø16 mm) as shown in Fig.5. One blast hole (ø18 mm, depth 150 mm) and four guiding dummy holes (ø18 mm) were drilled into the specimen. A cartridge (ø16 mm, length 50 mm) containing self-reactive liquid nitromethane was placed into the blast hole and covered by stemming with silica sand. The specimen was then fractured using EDICS.

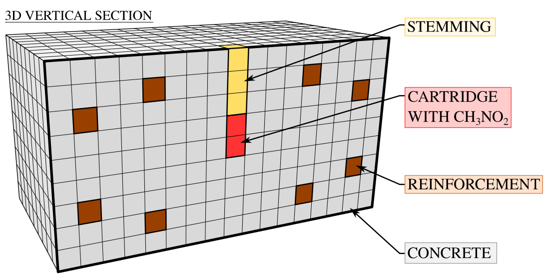


Fig.6 Schematic representation of FE discretization

The main purpose of guiding dummy holes is to prevent damage to the remaining part of a structure in case of the partial demolition. The surface of the dummy hole interacts with stress waves coming from the blast hole and creates the desired path for the main cracks.

4.1 Simulation Modeling

This section aims at the qualitative verification to realize the governing equations on the discrete finite degree of freedom. FE model was discretized using hexahedral finite elements as shown in Fig.6. Material properties were assigned to each element representing concrete, stemming, steel reinforcement and cartridge.

(1) Concrete and stemming

Material properties for concrete and stemming material are summarized in Table 1.

Table 1 Material properties

		Concrete	Stemming
E	[GPa]	34.2	0.08
f_c	[MPa]	31	1
f_t	[MPa]	2.6	0.1
ρ	[kg/m^3]	2300	1800
k	[-]	10^{-7}	10^{-1}
n	[-]	0.002	0.4
c	[-]	1.0	2.0

where, E: Young's modulus, f_c: compressive strength, f_t : tensile strength, ρ : density, k: permeability, n: porosity, c: tension softening factor,

We applied the 3D concrete model in considering the confinement effect and time-dependency [11]. The tension softening model for plain concrete is taken into account by c parameter [5], that is determined from fracture energy and the reference length of the finite element as described by Eq. 12 and shown in Fig.7. Considering the mesh size and nonuniformity of coarse aggregate distribution, c parameter was set to 1.0 for 1.4cm mesh size. We made the preliminary check with 5cm element mesh and confirmed the convergence.

$$\int \sigma_t \, d\varepsilon_t = \int f_t \left(\frac{\varepsilon_{tu}}{\varepsilon_t}\right)^c d\varepsilon_t = \frac{G_f}{l_r} \qquad (12)$$

where, σ_t: tensile stress, f_t: uniaxial tensile strength , ε_{tu} : cracking strain, ε_t : average tensile strain, G_f: fracture energy, l_r : finite element length

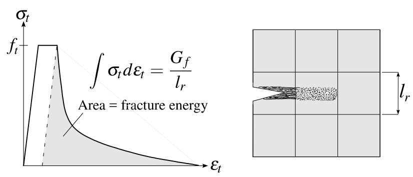


Fig.7 Tension softening behavior and implementation in FE analysis [5]

Capillary pores play a significant role in gas transport through concrete before cracking. In this study only interconnected capillary pores were accounted by setting the initial porosity n of 0.002. After cracking, porosity is increasing as a space where gas can stay [3].

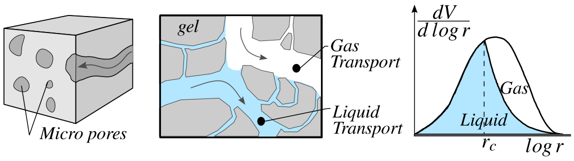


Fig.8 Capillary pores at microstructure level [11]

(2) Reinforcing bars

Steel reinforcing bars were defined by Young's modulus E=210 GPa and yield strength f_{yt} = 400MPa. The conventional smeared crack modeling was applied on the discrete fields of finite DOF, where the FE nodal displacement of steel and concrete is commonly shared and full adhesion on the interface as shown in Fig.2.

(3) Cartridge with nitromethane

The properties of nitromethane were defined by the time of initiation of deflagration t_{start} and t_{peak} when pressure reaches its maximum p_{peak} and by the density ρ. Pressure profile over time is illustrated in Fig.3a.

Table 2 Material properties of NM

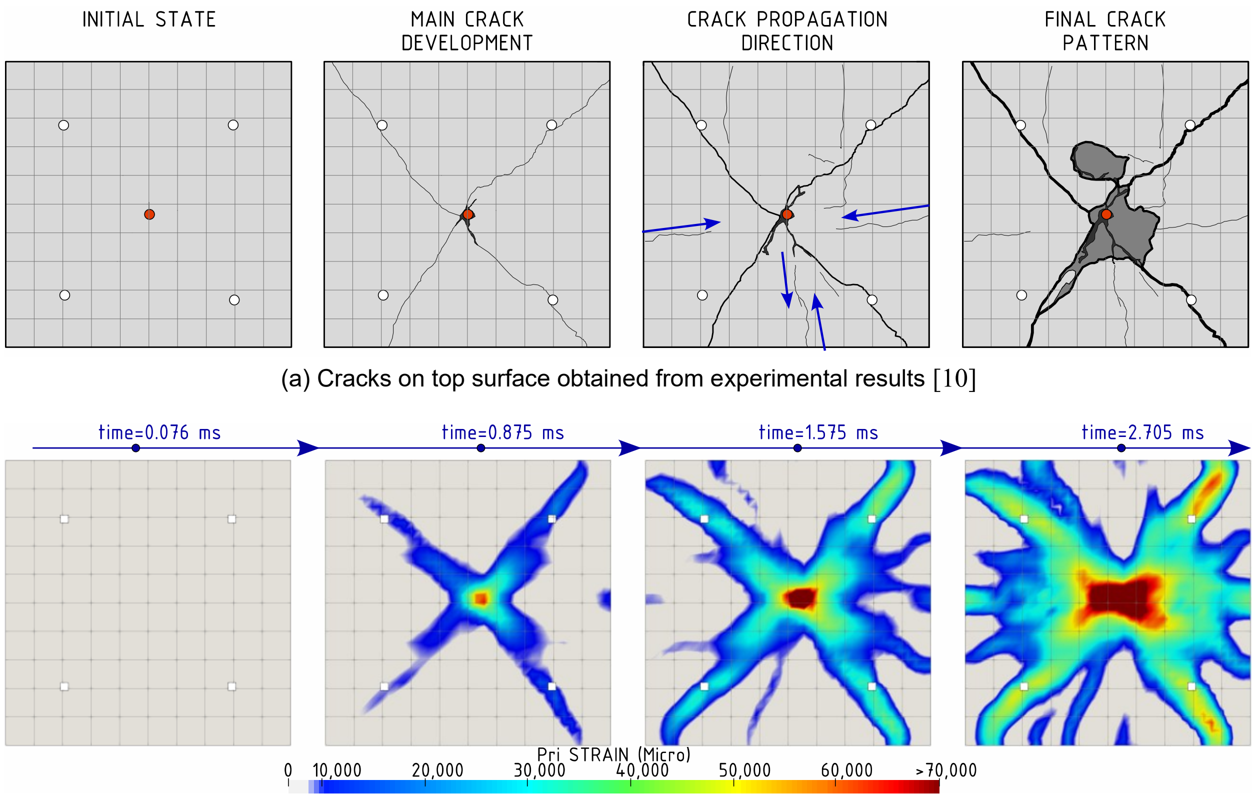
	t_{start} [μs]	t_{peak} [μs]	p_{peak} [GPa]	ρ [g/m^3]
NM	75	130	1.1	1.14

4.2 Qualitative Verification

As reported [10], the crack fracture development was recorded by a high-speed camera. The main cracks connecting the blast hole with the dummy ones were formed first, followed by the minor surface cracks with direction from surface to the center of the specimen as illustrated in Fig.9a. The principal strain, whose location and magnitude nearly coincide with those of active crack [5,6] and exactly matches when shear slip along crack is zero, is illustrated at different time-steps obtained from the numerical simulation in Fig.9b. At first, the greater tensile deformation is seen owing to the expansion of cartridge elements by nitromethane's inflation.

The computed pore pressure which was obtained by Eqs. 7 and 8 with solution of the governing equations of motion indicates that at first, the pressure is concentrated inside the cartridge, and gradually released through developing cracks (Fig.10). The pressurized gas then widens the cracks, and the stemming nitromethane is numerically ejected. The simulation indicates the coupling of crack development by gas pressure and the subsequent pressure drop owing to gas release through cracks. This predicted event shall be experimentally validated in a future study.

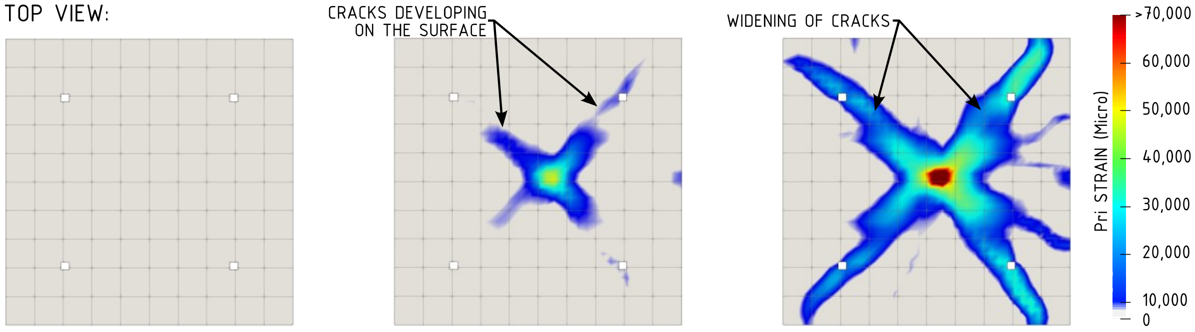
It is noted that the impact action affected by blasting is considered by the high strain rate model of the time-dependent constitutive law [5] and the graveling models as an extreme erosion of concrete composites [12] [13]. The temperature rise of gas is considered indirectly by the experimental data inside the cartridge as shown in Fig.3 and ignored for other elements. Heat energy transfer by high-speed flowing gas will be discussed in further.



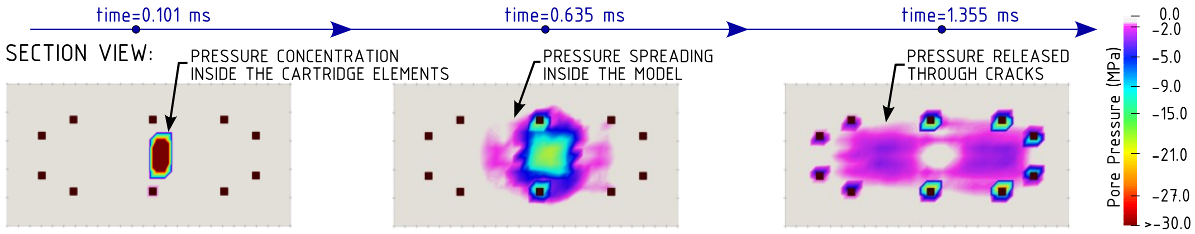
(a) Cracks on top surface obtained from experimental results [10]

(b) Numerical simulation results – maximum principal strain

Fig.9 Crack location of experiment and analysis in specific time-steps. The value 35,000 micro (green color) corresponds to 0.5mm which is thought to be the visibility of camera-photo resolution.



(a) Principal strain



(b) Pore pressure

Fig.10 Strain on the top surface and pore pressure inside the specimen

5. CONCLUSIONS

(1) The poromechanical simulation scheme has been applied to concrete engineering, focusing on un-compressive pore media such as condensed water in cracks, ASR, and corrosion gels. In this study, this framework is extended to include compressive gas media accompanying phase changes. This extension is applied to the dynamic fracture of structural concrete subjected to explosive actions, including inflating gas migration through cracks.

(2) Qualitative verification of the proposed simulation was conducted by the crack propagation related to the impactive phase change of nitromethane from liquid to gas. The computed gas pore pressure was found to be associated with concrete crack propagation, which also creates the pass of gaseous release. Quantitative validation is left for future, as measuring impactive gas pressure is challenging. Then, modeling was set up as much as simple and no crack was assumed as the initial state.

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