A study on the impact behavior of concrete slabs by SPH analysis

Kyushu University Student Member ○ Chi Lu
Kyushu University Fellow Member Yoshimi Sonoda

1. INTRODUCTION

In recent years, to prevent serious damage from natural disasters, the demand for protecting structures against the collision of flying objects is recognized in Japan. For existing studies, the perforation limit of a concrete slab has been examined by small scale experiments. Numerical analysis is a powerful alternative to study impact phenomena in term of scale and cost. In this study, SPH method (shown in Fig. 1) is used to express the local failure of concrete, and the effect of smoothing length and erosion limit to perforation process is discussed through the analysis results.

2. SPH analysis suitable for solid impact analysis

2.1 Adaptive smoothing length

The smoothing length h is very important in SPH analysis. In this study, to find a unified analysis method for both low and high velocity impacts, which require accuracy on local damages and overall response respectively, an adaptive smooth length h_a is utilized. The adaptive smoothing length h_a is changed during the analysis with the density of the particle, which is widely used in SPH analyses, shown in Eq. (1).

$$h_a = h_0 \left(\frac{\rho_0}{\rho_{current}}\right)^{\frac{1}{3}} \tag{1}$$

where h_0 is the initial smoothing length, ρ_0 is the initial density of the particle, $\rho_{current}$ is the density of particle calculated by SPH process. By the above calculation, the smoothing length h_a is decreased when the influence domain is compressed with the increase of density.

Especially, if two particles are positioned with smaller distance than h_0 at the beginning of the analysis, the two particles are "SPH-linked", and the SPH-link will break when the distance is larger than h_a, or the particles enter the crushing state explained in the next section. Since damage in solids is generally unrecoverable, if two particles are not SPH-linked, no SPH link will be generated even if the distance between particles become smaller than h_a, and contact forces are calculated when the particles overlap.

2.2 Concrete material model

To analyze the elastic-plastic behavior of concrete, pressure-dependent non-linear Drucker-Prager's yield function is applied in this study, represented by the following Eq. (2).

$$f(I_1, J_2) = \sqrt{J_2} - \sqrt{\frac{\gamma^2 - \alpha\beta I_1}{3}} = 0 \tag{2}$$

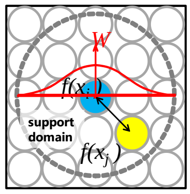


Fig. 1 SPH approximation calculation

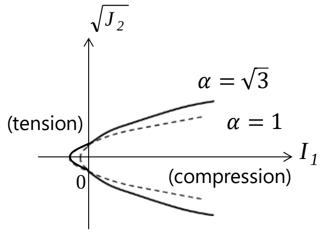


Fig. 2 nonlinear Drucker-Prager yield criterion

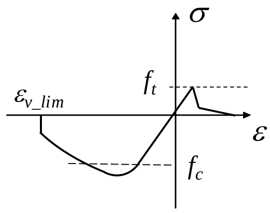


Fig. 3 Uniaxial stress-strain relationship of concrete

where I_1 is the primary invariant of stress, J_2 is the second invariant of deviatoric stress, α is a constant determining the yielding surface, f_c is the uniaxial compressive strength, f_t is the uniaxial tensile strength, γ is $\sqrt{f_c f_t}$ and β is $(f_c - f_t)$.Fig. 2 shows non-linear Drucker-Prager yield surface in the $\sqrt{J_2} - I_1$ plane. In this study, to achieve a wider yielding surface, $\alpha = \sqrt{3}$ in compression, and $\alpha = 1$ in tension are adopted, respectively.

Furthermore, bilinear softening of concrete is considered on the tensile stress side according to the Japanese specification[1], Compressive softening is also considered according to the Popovic's equation[2].

Hardening is considered on the compression stress side as shown in Eq. (3).

$$H = \frac{d\sigma}{d\varepsilon^p} \tag{3}$$

where dσ is equivalent stress increment, $d\varepsilon^p$ is equivalent plastic strain increment.

In this study, to avoid the unrealistic volume overlap between particles, when the volumetric strain of concrete particle ε_v reaches certain threshold value (we call it erosion limit) ε_{v_lim}, the particles are regarded as a crushing state

Keywords RC slab, SPH analysis, perforation, high-velocity impact

Address 744 Motooka Nishi-ku Fukuoka, Japan 8190395

and stress and stiffness of the particle are assumed to be zero, however, the particle itself is not erased in order to keep the mass conservation, and the kinetic energy and the momentum of the particle is also preserved. The uniaxial stress-strain relationship of concrete is schematically shown in Fig. 3.

3 SPH ANALYSIS FOR IMPACT PHENOMENA

3.1 The analysis object and model

An impact experiment is simulated by the proposed SPH method. The projectile and test specimens (concrete slabs) are modeled from the experiments conducted by Beppu et al. [3]. The size of concrete slab is 500mm×500mm, and the thickness varies in each test cases. It is assumed that two sides of slab are fixed in out of plane direction. The collision object is 100g in weight. The material properties of concrete are set as shown in Table 1. The impact velocity of the projectile varies from 180m/s to 500m/s.

3.2 Results and discussion

The maximum principal strain distribution after impact of case 60-300-06 (Slab thickness (mm)-impact velocity (m/s)-erosion limit (%)) and 60-350-06 are shown in the Fig. 4. The projectile with a velocity of 300m/s does not perforate the concrete slab, whereas the projectile with a velocity of 350m/s perforates the slab. Inclined shear cracks can be found in both cases, and the concrete damage is distributed along with the touching-surface of projectile. In case 60-300-06, although the concrete slab is not perforated, concrete at the back surface is damaged, which is similar to the scabbing phenomenon observed in the experiment. Thus, the perforation could be reproduced by the proposed SPH method.

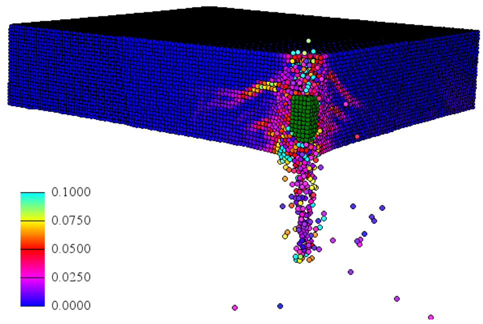
Next, the perforation in the analysis results are compared with experiment results, as shown in Fig.5. It can be found that the perforation in the experiment are almost reproduced by proposed SPH analysis. In this analysis, to achieve accurate predictions on the perforation limit, the erosion limit must be set to 6%. Larger erosion limit provides more impact resistance against projectile, and it gives large error on the perforation limit in this simulation.

4. CONCLUSION

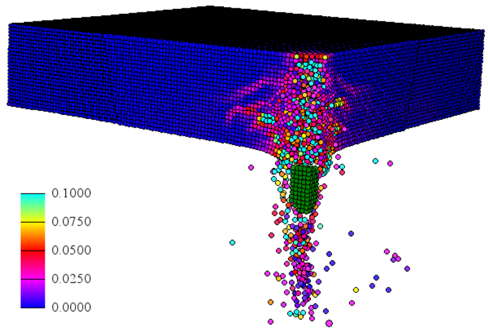
In this study, an analytical method to simulate elastic plastic impact behavior of perforation of concrete slab under the collision of a projectile is presented, and its accuracy was discussed using a comparison of existing experimental results. It was found that impact behavior with perforation is sensitive to erosion limit of concrete. Thus, in order to improve the analysis method that can simulate various problems (not only low velocity collision but also high velocity collision), it is desirable to adopt the best yield criterion of concrete (improvement of non-linear Drucker-Prager's yield function is needed) and erosion limit. In addition, perforation depth is also sensitive to the erosion limit. Thus, further study is needed to define the appropriate erosion limit with adequate yield criterion.

Table 1 Material property of concrete

Mass density (kg/m3)	2500
Young's modules (kN/mm2)	29.0
Compressive strength (N/mm2)	25.0
Tensile strength (N/mm2)	2.50
Poisson ratio	0.22



(a) 60-300-06



(b) 60-350-06

Fig. 4 Maximum principal strain distribution in analysis

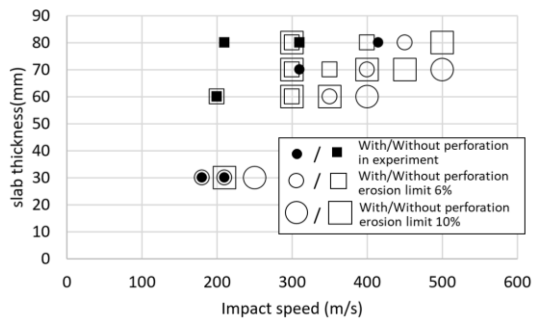


Fig. 5 Comparison of perforation results between experiment and analysis

4. REFERENCE

1) Japan Society of Civil Engineers Concrete Committee.: Standard specifications for concrete structures: Design, pp.37-38, 2012. (In Japanese)

2) Popovics, S. A numerical approach to the complete stress-strain curve of concrete. Cement and concrete research, 3(5), pp.583-599, 1973.

3) Miwa, K., Beppu, M., Ohno, T., and Katayama, M.: A study on local damage of concrete subjected to high-velocity impact by rigid projectile. Proceedings of the Japan Concrete Institute, 28(2), 835-840, 2006.