Testing and simulation of local damage in a concrete plate by the impact of a hard projectile

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Abstract

This study is to investigate the mechanism of local damage in a concrete plate by the impact of hard projectile with a hemisphere-nose. Thus, to execute the experimental study, testing apparatus for launching the projectile was newly developed. Using this apparatus, a projectile with the mass of 100g is shot by at a velocity of about 500m/s. In this test, the relation between the impact velocity and the penetration depth and crater diameter were examined. The impacting appearance was recorded by a high-speed video camera, and then analyzed. Also, to find the mechanism of local damage in concrete, a numerical simulation by AUTODYN was performed.
Keywords: hard projectile, impact, concrete plate, local damage, AUTODYN.

1 Introduction

Recently everywhere in the world, explosive incidents due to terrorist's attack and accident have been increased. In case of such incidents, structures and people may be secondary damaged due to bombing fragmentation. To establish a reliable protective design method of structures against fragmentation, the mechanism of local damage subjected to high-speed impact of projectile should be investigated. However, only a few tests were carried out in Japan because the special apparatus or facilities to execute the impact tests were required. On the other hand, numerical simulations using FEM or FDM have been progressed rapidly with the development of computer technology. For example, Ito et al. [1] performed the 3-dimensional numerical simulation of local damage in concrete wall subjected to the collision of heavy aircraft [1]. It is well known that, in the numerical simulation, analytical results for concrete structures are strongly affected by the material constants and/ or the constitutive model of concrete material.

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Table 1: Test cases.

Thickness(cm)	Velocity(m/s)	Thickness(cm)	Velocity(m/s)
13	490	8	310
12	415	8	210
10	490	7	310
10	310	6	200
9	420	3	210
8	415	3	180

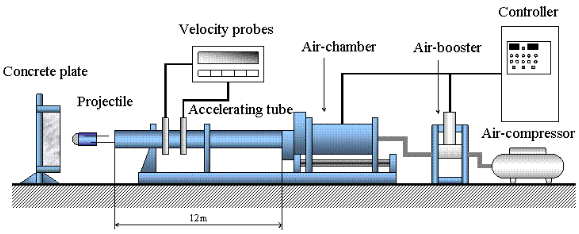


Figure 1: Projectile launching apparatus.

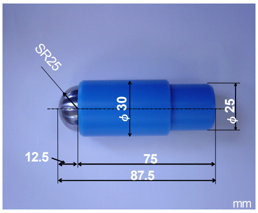


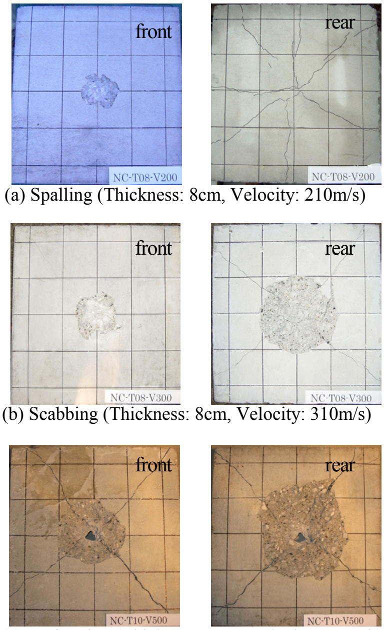
Figure 2: Head of rigid projectile.

In this study, the local damage in concrete plate is examined by impact tests and numerical simulation. First, the projectile launching apparatus by high-pressurized air was developed. This apparatus can launch projectiles with the mass of 100g to 1000g. Then, impact tests for concrete plates were carried out. In tests, the impact velocity of projectile and the thickness of concrete plate were employed for test parameters. The impact velocity of the projectile was varied between 180m/s and 490m/s. The types of local damage in the concrete were classified into three modes: spalling, scabbing and perforation. The mechanism of local damage is studied based on the failure process recorded by a high-speed video camera. Finally, numerical simulations of tests were carried out, and the effect of the material properties of concrete on the numerical results are discussed.

2 Experimental set up

2.1 Outline of impact test

The impact test is conducted to investigate the influence of projectile velocity and plate thickness on local damage. Test case is shown in Table 1. Test parameters are the impact velocity and the thickness of concrete plate. The impact velocity of projectile was varied between 180m/s and 490m/s. The thicknesses of concrete plates are 3cm to 13cm as shown in Table 1. The appearing process of local damage in each test was recorded by the high-speed video camera.



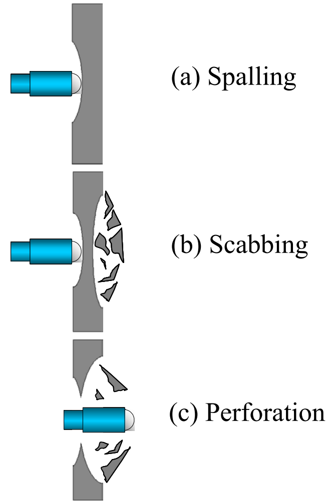


Figure 3: Local damage model.

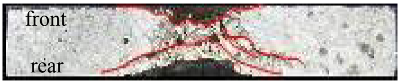


Figure 4: Local damage.

Figure 5: Inner crack.

2.2 Test apparatus

The apparatus of high-velocity projectile launcher used in this study is illustrated in Figure 1. The apparatus is consisted of accelerating tube (length of 12m, inner diameter of 35mm), air chamber, air booster and air-compressor. A hard projectile is launched by high-pressurized air. The configuration of the hard projectile is shown in Figure 4. The hard projectile consisted of two parts: a hemi-sphere steel head and a body of MC901-nylon. The diameter and mass of the head are 25mm and 50g, respectively, and that of body parts are 35mm and 50g, respectively. The velocity of the projectile before impact is measured by the velocity-sensor. A concrete target used in this test had a square plate of 500mm×500mm. The static compressive strength of the concrete was 25MPa. The target is set 1.0m ahead of the muzzle of launching tube, and then fixed the upper and lower edges of a target to the steel frame.

3 Experimental results

3.1 Local damage mode in concrete plate

Local damage in concrete is classified into three modes, i.e. spalling, scabbing and perforation as shown in Figure 3. Figure 4 shows the local damage in the concrete after projectile impact.

In this case, the thickness of concrete plate was 8cm. In Figure 4(a), spalling damage was appeared by the impact velocity of 210m/s. The diameter of spalling in the impact face was about 10cm, and radial cracks from the center of rear face were produced. Figure 4(b) shows the spalling damage in the impact face and the scabbing yielded in the rear face by the impact velocity of 310m/s. The diameter of scabbing was larger than that of spalling in the impact face. In this case, the inner cracks accompanied with scabbing were generated as shown in Figure 5. Figure 4(c) shows that the local damage spreads into the perforation for the impact velocity of 415m/s. The magnitude of both spalling and scabbing damage became larger than that for the lower impact velocities.

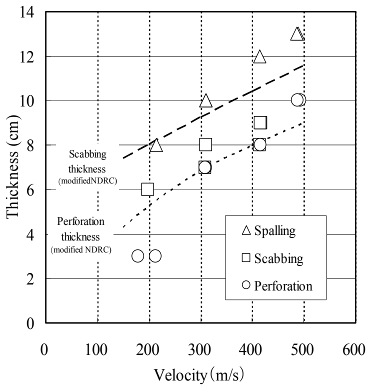


Figure 6: Comparison of local damage with that by the modified NDRC formula.

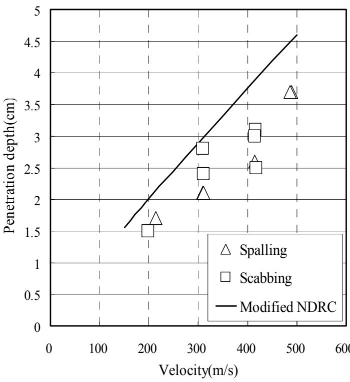
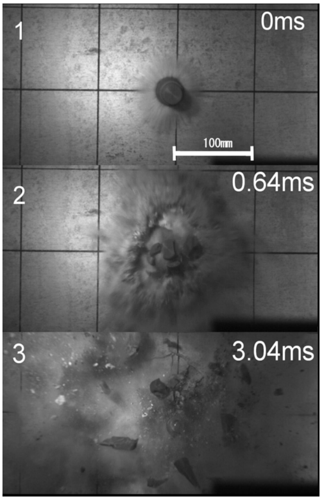


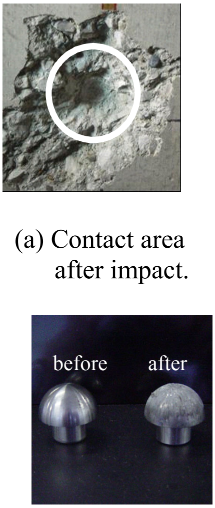
Figure 7: Comparison of penetration depth with that by the modified NDRC formula

Figure 6 shows the local damage modes in the relation between the thickness of specimen and impact velocity. From this figure, when the projectile velocity is increased or the thickness of plate is decreased, the local damage reduces. Figure 7 shows the relation between the penetration depth and impact velocity. The penetration depth increases in proportion to the projectile velocity. Figure 6 and Figure 7 also show the comparison with the numerical result by modified NDRC formulae [2] using the head mass of 50g in the calculation. The limit thickness of perforation and scabbing showed good agreement with the estimation by the modified NDRC formulae. On the other hand, the estimated penetration depth by modified NDRC formula is a little larger than test results.

3.2 Failure process

The failure process of local damage in a concrete plate impacted by a hard projectile was analyzed with the sequential photos recorded by high-speed video camera. Figure 8 shows the progress of spalling damage (using a plate thickness of 10cm and projectile velocity of 310m/s) at the time of 0, 0.64ms and 3.04ms. At the time of 0.64ms concrete in the impacted point was pounded and the body part of projectile was completely broken after impact. The damage to the impacted area is shown in Figure 9(a). The trace of the projectile head was observed at the impact point, see Figure 9(b). It is found that the head part of projectile after impact may be subjected to a considerable frictional force. Figure 10 also shows the process of scabbing damage (using a plate thickness of 10cm and projectile velocity of 488m/s). In the rear face of concrete plate, the crack was radiated in all directions from the center at the time of 1.0ms, then a lump of concrete was broken into pieces and scattered at the time of 3.0ms.





(a) Contact area after impact.

b) Head of Projectile.

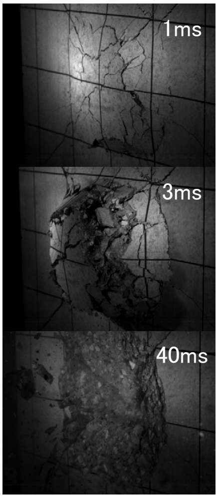


Figure 8: Spalling. Figure 9: After impact situation. Figure 10: Scabbing.

Table 2: Constitutive model of material.

Material	Equation Of State	Strength	Failure	Erosion
Concrete	Linear	Drucker-Prager	Cut-off	2.5
Steel	Linear	Von-Mises	None	None

Table 3: Set values for numerical simulation.

Strain rate(1/s)	Strain rate of effect		Strength(MPa)	
	Compressive	Tensile	Compressive	Tensile
10^{-5}(Static)	1	1	25.0	2.5
10^{-1}	1.25	1.70	31.4	4.25
10^{0}	1.43	2.44	35.9	6.11
10^{1}	1.69	4.05	42.4	10.15

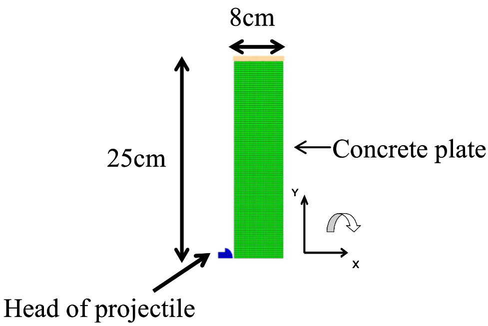


Figure 11: Analytical model.

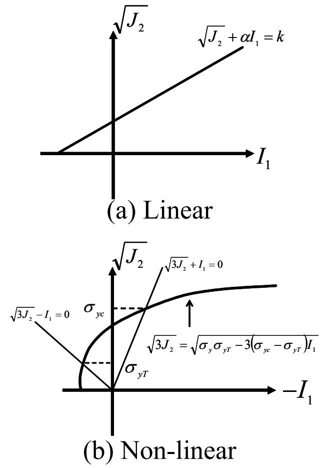


Figure 12: Two types of Drucker-Prager constitutive model.

4 Numerical simulation

4.1 Analytical model

Numerical simulations were performed using AUTODYN version.5.2, which is a multiple solver type hydrocode. Analytical model is set up in 2 axi-symmetric as shown in Figure 11. The concrete plate is modelled by 3200 elements, in which the element size is 2.5mm×2.5mm. The head part of projectile is consisted of 28 elements. In the numerical simulation, the plate thickness of 8cm subjected to the projectile impact velocity of 310m/s are analysed. In this case, the local damage mode was resulted to scabbing and the penetration depth of 2.4cm.

4.2 Material model

Material models of concrete and steel are shown in Table 2. The equations of state (EOS) are linear in both materials. The von-Mises yield criterion was used for steel. Two types of Drucker-Prager yield criterion (linear and non-linear) were used for the model of concrete material as shown in Figure 12. Herein, the limit tensile strength of concrete is set to 2.5MPa. The geometric strain was used for erosion criterion.

Concrete properties under the high strain rate show the increase of strength in both compression and tension. Therefore, it is necessary to consider the strain rate effect. In impact tests, the strain rate can be inferred 10^{-1}~10^{2} (1/s) from the fact that the failure process was completed at most within 1.0ms as shown in Figure 8 and concrete was damaged at hundreds to several thousand micro strain.

The equation of increase of the dynamic compressive strength of concrete is proposed by Fujikake et al. [3] as given in Eq. (1):

$$\frac{f'_{cd}}{f_{cs}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{0.006\left[Log\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)\right]^{1.05}} \tag{1}$$

where f'_{cs} is the static compressive strength of concrete, f'_{cd} is the dynamic compressive strength of concrete, $\dot{\varepsilon}_s$ is the static strain rate[1.2×10^{-5}(1/s)] and $\dot{\varepsilon}$ is the dynamic strain rate.

The Equation of increase of the dynamic tensile strength is proposed by Ross et al. [4] as shown in Eq. (2):

$$\eta(\dot{\varepsilon}) = \frac{f'_{td}}{f'_{ts}} = \exp\left[0.00126\left(Log\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{3.373}\right] \tag{2}$$

where f'_{ts} is the static tensile strength of concrete, f'_{td} is the dynamic tensile strength of concrete and $\dot{\varepsilon}_s$ is the strain rate [1.0×10^{-7}(1/s)].

In this numerical simulation, the test cases are shown in Table 3. The strain rates are assumed to be 10^{-5}~10^{1}(1/s) as shown in Table 3. The influence of strain rate on the material properties was considered in the numerical model.

Table 4: Results by numerical simulation.

Strain rate	Linear		Non-Linear	
	Local damage	Penetration depth(cm)	Local damage	Penetration depth(cm)
10^{-5} (Static)	Scabbing	0.5	Scabbing	2.5
10^{-1}	Scabbing	0.5	Scabbing	2.1
10^{0}	Scabbing	0.5	Scabbing	2
10^{1}	Spalling	0.5	Spalling	1.5

4.3 Results by numerical simulation

The numerical simulations for the different strain rates (10^{-5},10^{-1},10^{0} and 10^{1}) were executed. Figure 13 illustrates the damage state in the cross section of the concrete plate. From this figure and Table 4, in the case of linear model, the crack pattern becomes narrower and the penetration depth is smaller than that for the case of the non-linear model. As for the penetration depth, the results of the numerical simulation with the non-linear model show good agreement with test results compared to that with the linear model. In tests, when a projectile hit the concrete surface, the impacted area will be acted on by the greatest compressive stress. Since the yield stress of the linear model becomes larger for the hydrostatic stress state than that of the non-linear model, material with the linear model is hard to yield. According to a study on the mechanical properties of concrete under the tri-axial stress state [3], the failure criterion of concrete under the tri-axial compressive stress state is similar to the non-linear model. Thus, the results by this simulation may be appropriate. It is also found from the figure that the damage pattern is localized with the increase of strain rate in both models. Since the increase rate of tensile strength is much larger than that of compressive strength, cracks in the rear face will be reduced. It can be concluded that when the non-linear constitutive model of concrete and the strain rate of 10^0(1/s) are employed for the numerical simulation of concrete plate subjected to the impact of hard projectile, the damage state in concrete plate can be well simulated.

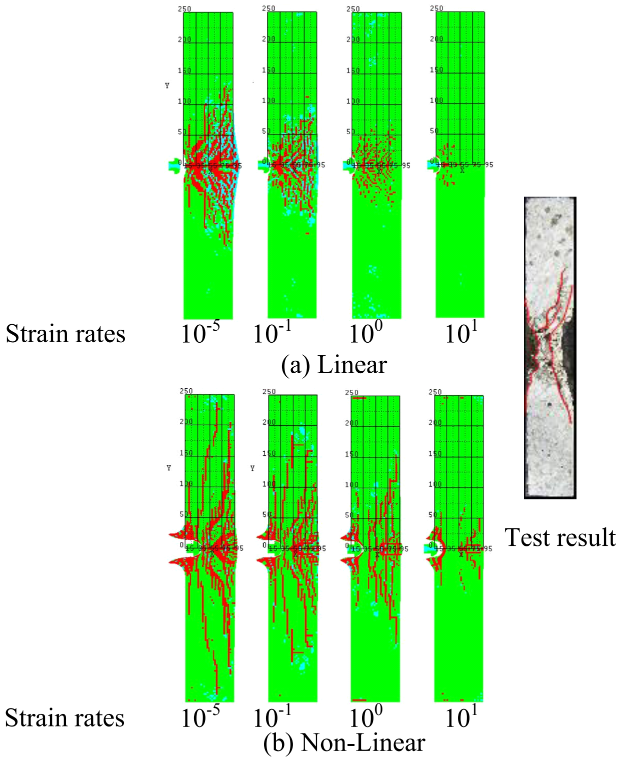


Figure 13: Result of damage pattern by simulation.

4.4 Simulation for all test cases

All test cases done in this study were numerically simulated for the non-linear material model and the strain rate of 10^0 (1/s). Figure 14 and Figure 15 show the comparison between the local damage mode and penetration depth, respectively. From these figures, the simulated results show a good agreement with the local damage and penetration depth by tests, although there is a small difference in the local damage. The effect of plate thickness on the local damage is shown in Figure 10. The penetration depth and damage of rear side became smaller with increasing plate thickness. These results indicate that an appropriate numerical model is required to simulate the local damage in concrete.

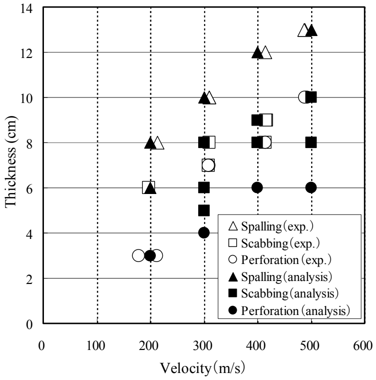


Figure 14: Local damage compared with simulation and test results.

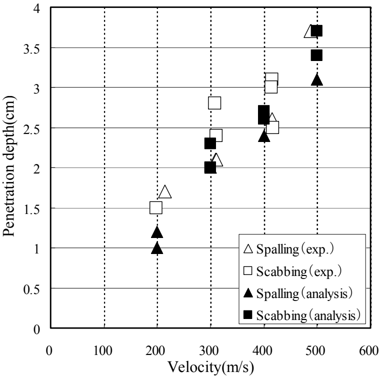


Figure 15: Penetration compared with simulation and test results.

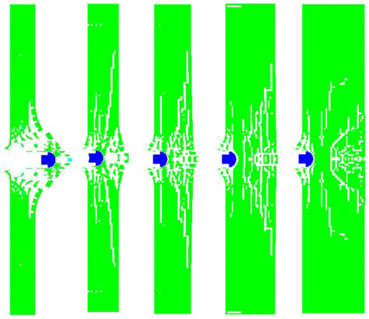


Figure 16: Effect of plate thickness on local damage.

5 Conclusions

This study presents a mechanism of local damage in a concrete plate subjected to the impact of a hard projectile. With the increase of projectile velocity and the decrease of plate thickness, the local damage becomes larger from spalling to scabbing or perforation. The penetration depth increases with the projectile velocity. It can be concluded that the constitutive model and the strain rate of concrete employed for the numerical simulation were the dominant factors in the results.

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