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EXPERIMENTAL STUDY ON LOCAL DAMAGE TO REINFORCED CONCRETE PANELS SUBJECTED TO OBLIQUE IMPACT BY PROJECTILES
–ANALYSIS OF EXPERIMENTAL RESULTS–

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ABSTRACT

The impact behavior of the reinforced concrete (RC) structure is an extremely complex phenomenon, and several empirical formulas based on experimental data were developed to estimate the local damage of the RC structure under various impact conditions. Several empirical formulas have been proposed to investigate the local damage to RC structures caused by the impact of a rigid projectile. The majority of these formulas were developed based on the analyses of normal impact to the target structure, whereas a few formulas related to oblique impact were studied. This study proposes a new formula to evaluate the local damage to RC panels caused by the oblique impact of soft projectiles, which should be considered as realistic impact conditions. In recent times, we performed impact tests to investigate the local damage to RC panels subjected to normal and oblique impacts caused by rigid and soft projectiles, respectively. In this study, we summarized the experimental results of impact cases conducted by us and compared the results with empirical formulas to determine the reduction effects related to impact angle and projectile stiffness.

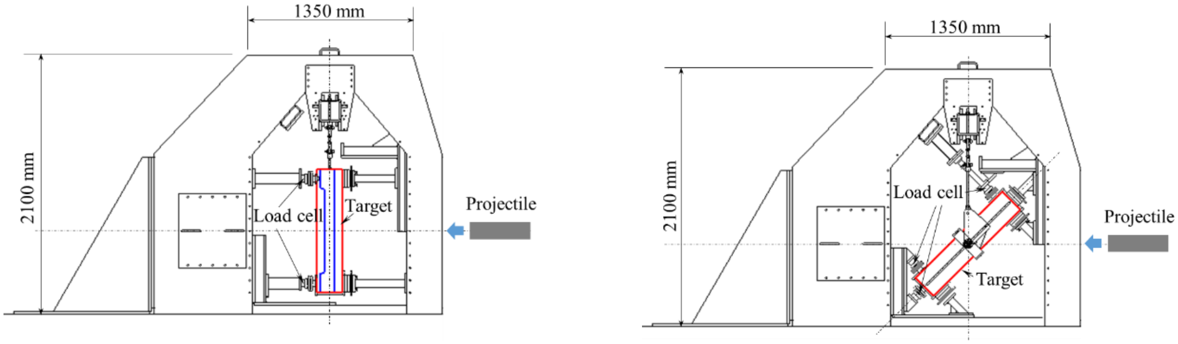
INTRODUCTION

The safety assessment of nuclear facilities subjected to projectile impact induced by tornadoes or aircraft is stipulated in the new regulatory requirements of the Nuclear Regulation Authority of Japan. It is necessary to conduct a safety evaluation on the local damage to nuclear facility buildings. To evaluate the local damage to a reinforced concrete (RC) structure subjected to projectile impact, several empirical formulas were derived to predict the ballistic parameters of the target, e.g., the depth of penetration, scabbing, and perforation limit thicknesses, and these formulas were summarized by Kennedy (1976) and Li et al. (2005). These studies focused on the normal impact caused by a rigid projectile, while Richard et al. (1943) conducted a few impact tests related to the oblique impact. Based on these test results, Ohta and Nishida (2017) proposed a modified formula to evaluate the penetration damage of RC panels subjected to the oblique impact of rigid projectiles considering the slip and rebounding effects of the projectiles. However, these experimental and analytical evaluations associated with oblique impact were conducted only for the rigid projectiles. At present, no oblique impact tests have been conducted on soft projectiles. Therefore, we focused on the numerical analysis of soft projectiles. Nishida et al. (2019) simulated the perforation damage to an RC panel subjected to the oblique impact and evaluated the effect of the impact angle of a flat nose-shaped projectile. The results indicated that the residual velocity after perforation in the case of the oblique impact is higher than that of the normal impact under certain conditions. It is assumed that the contact part of the flat projectile's nose changed accompanying the impact process. Therefore, to determine the effects of the impact angle and stiffness of the projectile, we designed impact tests to investigate the local damage to the RC panel subjected to oblique impact caused by rigid and soft projectiles (Okuda et al., 2022).

Based on the test results, we observed data that can be regarded as the scabbing or perforation limit under the oblique impact condition. Hence, the empirical formulas of Chang and Degen (Li et al., 2005) can be considered to determine the reduction effect of the oblique impact compared with that of the normal impact.

TEST APPARATUS

The impact testing facility is shown in Figure 1. The pressurized air is used to accelerate a projectile to reach its defined velocity. The designed apparatus can launch a 6-kg projectile up to a maximum impact velocity of ~170 m/s. The diameter of the projectile is limited to 200 mm. The RC panel to be tested is placed inside a shelter with a height of 2100 mm (Figure 1). The shelter can hold an RC panel of 1 × 1 m^2, and the RC panel can be fixed to the steel frame using the detachable angle steel. The acceleration tube is a 10-m long steel pipe with a diameter of 200 mm, and the pressure accumulator is installed beneath the acceleration tube. The pressure accumulator is made of steel and used to store compressed air, the volume of which is calculated based on the designed impact velocity and projectile mass. Pressure gradually increases in the pressure accelerator until it reaches a predefined value. The whole collision process was recorded using a high-speed camera located outside the RC panel.



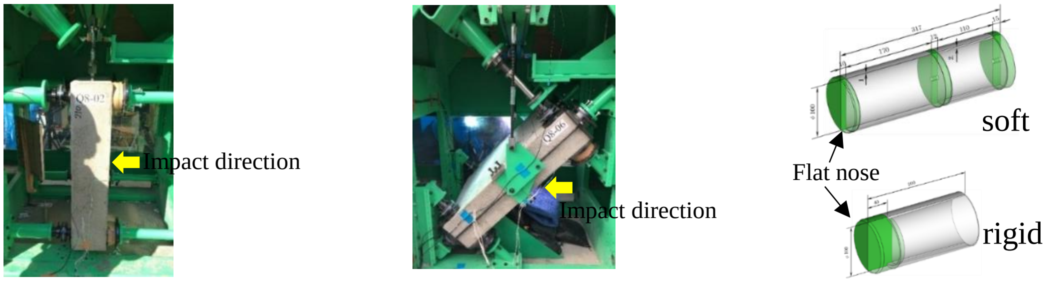
(a) Normal impact

(b) Oblique impact

Figure 1. Test apparatus.

The RC specimen was placed ~2000 mm from the front side of the accelerator tube. The newly designed shelter made of steel helps prevent the scattering of RC debris at the time of collision (Figure 2). The RC panel used in the impact test is a square plate with a side length of 1000 mm and thicknesses of 210 and 80 mm. The average concrete strength was 29.9 N/mm^2, and the maximum aggregate size was 10 mm. For the main reinforcement of the RC panel, the D6 steel rebar (deformed bars with a diameter of 6.0 mm) is vertically and horizontally placed with a spacing of 40 mm on the front and back sides. In addition, three reinforcing bars of D16 (deformed bars with a diameter of 16.0 mm) are placed at the periphery of the RC panel on each side. The target was restrained in the out-of-plane direction at the corners, and four load cells were installed to measure the reaction force. Moreover, the initial compressive force of 40 kN was considered to ensure the capability of recording the tensile reaction force induced at each support point.

A simplified 1/7.5-scale model of the GE J-79 turbojet engine installed in the F-4 Phantom fighter introduced by Sugano et al. (1993a) has been considered in this study. Two types of projectiles, rigid and soft projectiles, have been manufactured (Figure 2(c)). Both types possess the same diameter of 100 mm and the same weight of 3.4 kg to generate equal kinetic energy with an initial impact velocity of 200 m/s. The rigid projectile head was made of SS400 solid steel (Japanese Industrial Standards (JIS)), whereas its rear (a cylindrical shell component) was made of a thin aluminum alloy, A5056 (in JIS), which was employed to maintain stability during the flight. The soft projectile was constructed using steel SS400 for the front, middle, and rear disks and STKM 13A for the cylinder.



(a) Normal impact (b) Oblique impact (c) Projectiles

Figure 2. RC panel and projectiles.

MATERIAL PROPERTIES

The material properties of the RC slab are listed in Table 1. The static compressive strengths of the concrete and elastic modulus were tested using three medium-sized cylinders with a dimension of 100 × 200 mm, and the mean value was considered. The primary effect considered in the empirical formula to evaluate the local damage to the RC panel is the material property of the concrete, and the material properties of the steel rebar considered as the secondary effect are listed in Table 2.

Table 1: Material properties of the concrete.

	unit	value
Compressive strength	MPa	29.9
Young’s modulus	MPa	24,033
Aggregate size	mm	10

Table 2: Material properties of the steel rebar.

	unit	D6	D16
Yield stress	MPa	344	351
Tensile strength	MPa	506	472

EXPERIMENTAL RESULTS

The rigid and soft projectiles were used to impact the center of the RC panels with thicknesses of 210 and 80 mm at a designed impact velocity of 200 m/s. Impact angles were set to be normal (0°) and oblique (45°).

Table 3 lists the test results of the target after the normal and oblique impact of the rigid and soft projectiles. Focusing on the depth of penetration to the front face of the RC panel, the maximum depth of penetration was deeper for the oblique impact than for the normal impact at a plate thickness of 210 mm. It is assumed that the flat nose shape of the projectile impacted the RC panel from a corner during the oblique impact. However, with regard to the damage to the back face of the RC structure, a significant reduction in scabbing damage caused by the oblique impact was confirmed. In addition to the penetration, perforation, and scabbing damage behaviors, we obtained results that can be regarded as the scabbing (Case 5) and perforation limits (Case 8) (Figures 3–4).

Table 3: Test results of the RC plate structure.

Case No.	Projectile	Thickness of RC panel	Impact angle	Penetration depth	Damage mode
1	Rigid	210 mm	0°	25 mm	Scabbing (Debris scattering)
2	Soft	210 mm		6 mm	Penetration
3	Rigid	80 mm		—	Perforation
4	Soft	80 mm		—	Perforation
5	Rigid	210 mm	45°	37 mm	Scabbing limit (No debris scattering)
6	Soft	210 mm		24 mm	Penetration
7	Rigid	80 mm		—	Perforation
8	Soft	80 mm		—	Perforation limit

(a) Front face (b) Back face

Figure 3. Local damage subjected to the oblique impact caused by the rigid projectile.
(Case 5: Impact angle 45°, RC thickness 210 mm, and Impact velocity 202 m/s)

(a) Front face (b) Back face

Figure 4. Local damage subjected to the oblique impact caused by the soft projectile.
(Case 8: Impact angle 45°, RC thickness 80 mm, Impact velocity 200 m/s)

EMPIRICAL FORMULAS

Kennedy (1976) and Li et al. (2005) reviewed the progress in concrete design aimed at resisting missile impact effects. Commonly used formulas for predicting the local impacts, e.g., penetration, perforation, and scabbing, of rigid projectiles on targets were described and compared.

Based on existing research achievements, among several empirical formulas for evaluating local damage to RC panels, the formulas of Chang and Degen can predict the scabbing and perforation thicknesses for rigid projectiles, respectively (Sugano, et al. 1993b). Therefore, we adopted these two formulas in this study. The previous study (Sugano, et al. 1993b) indicated that the formulas of Degen and Chang enable a conservative evaluation of local damage to the RC structure. In particular, to predict the scabbing thickness, the Chang formula enables the most conservative evaluation in the high-velocity range compared with other empirical formulas.

Considering a flat-ended steel cylinder impacting an RC panel, Chang suggested that scabbing limit h_s should be calculated as follows:

$$\frac{h_s}{d} = 1.84\left(\frac{u}{V_0}\right)^{0.13}\left(\frac{M{V_0}^2}{d^3 f_c}\right)^{0.4} \tag{1}$$

Degen suggested the following formula to determine perforation limit e based on a statistical analysis of experimental data:

$$\begin{gathered}\frac{e}{d} = 0.69 + 1.29\left(\frac{x}{d}\right) \quad for\ 2.65 \leq \frac{e}{d} \leq 18\ or\ 1.52 \leq \frac{x}{d} \leq 13.42 \\ \frac{e}{d} = 2.2\left(\frac{x}{d}\right) - 0.3\left(\frac{x}{d}\right)^2 \quad for\ \frac{e}{d} < 2.65\ or\ \frac{x}{d} < 1.52\end{gathered} \tag{2}$$

where e is the perforation limit thickness (m), h_s is the scabbing limit thickness (m), d is the diameter of the projectile (m), u is the reference velocity (61 m/s), M is the mass of the projectile (kg), V_0 is the projectile impact velocity (m/s), and f_c is the unconfined concrete compressive strength (N/m^2).

THE PROPOSED FORMULA

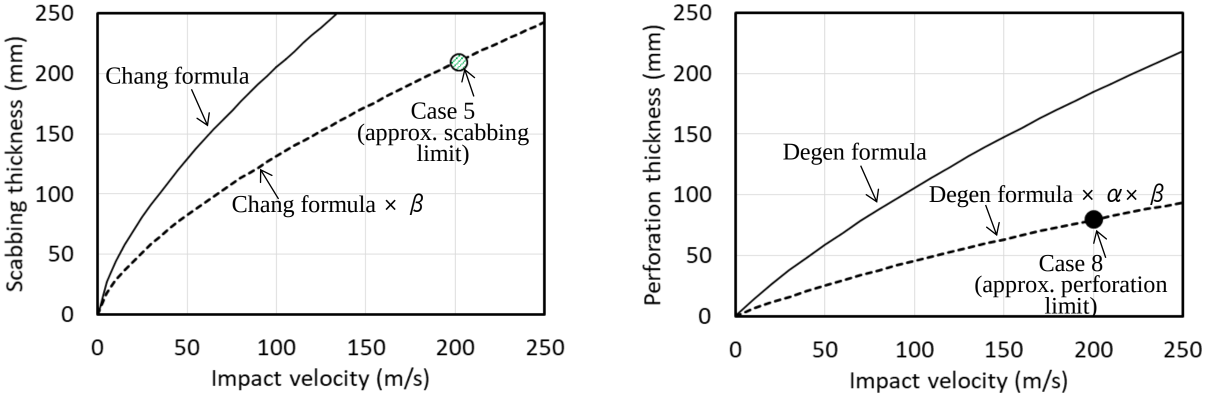
The University of Manchester Institute of Science and Technology (UMIST) formulas were developed to predict penetration depth, scabbing, and perforation limits of concrete targets (Li et al., 2005). As the linear formulation to reflect the effect of the nose shape was considered in the UMIST formula, we used the same implementation process, and the nose shape factor was defined based on the UMIST formulas. The estimation approach considering the reduction in the stiffness of the projectile and impact angle is expressed as follows:

$$Proposal\, formula = Existing\, formula \times N^* \times \alpha(\kappa) \times \beta(\theta), \tag{3}$$

where *Existing formula* comprises the Chang, Degen, and other formulas; N^* is the nose shape factor (0.72 for a flat nose; 0.84 for a hemispherical nose; 1.0 for a blunt nose; 1.13 for a sharp nose); $\alpha(\kappa)$ is the reduction factor caused by the stiffness of the projectile; $\beta(\theta)$ is the reduction factor caused by the impact angle; κ is the stiffness of the projectile; θ is the impact angle.

COMPARISON RESULTS WITH EMPIRICAL FORMULAS

To investigate the reduction effect on local damage to the RC plate structure caused by the soft projectile and oblique impact at 45°, the comparison results obtained using the empirical formula are plotted in Figure 5. The sharp nose shape factor (1.13) was considered in the formula, as the edge of the flat nose impacted the RC panel under the oblique impact test (Figure 6). For the rigid projectile, as Case 5 can be regarded as the scabbing limit for the oblique impact, the reduction factor based on the oblique impact at 45° was determined as $\beta_{\mathrm{Chang}}(45°) = 0.64$ based on the reference solution derived using the Chang formula (Figure 5(a)). Owing to the conservativeness of the Chang formula in predicting the scabbing damage of the RC panel described by Sugano et al. (1993b), the actual reduction factor caused by the oblique impact was considered to be less than 0.64 ($\beta \leq 0.64$), which should be verified based on sufficient test result data. The Chang formula was proposed as an upper level based on the scattering analysis with respect to impact test data; however, in this study, we did not consider the scattering influence of the test results. The variability owing to the uncertainty of the impact conditions should be further studied in the future.



$\beta_{\mathrm{chang}}(45°) = 0.64$

$\alpha(\kappa) \times \beta(45°) = 0.43$

$\alpha(\kappa) = 0.65$ (Sugano et al., 1993b);

$\beta_{\mathrm{Degen}}(45°) = 0.66$

(a) Scabbing damage (b) Perforation damage

Figure 5. Comparison results using the empirical formulas and test results with regard to the oblique impact at 45°.

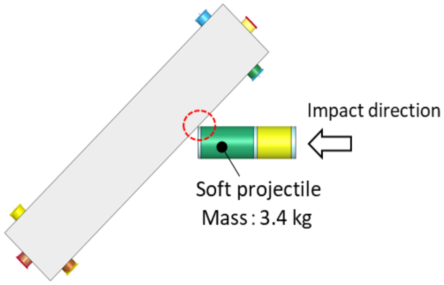


Figure 6. Oblique impact test (impact angle: 45°).

The previous study conducted by Sugano et al. (1993b) showed that the reduction factor of the perforation limit caused by the normal impact of a soft projectile can be conservatively regarded as 0.65. As the projectiles were manufactured based on the structure designed by Sugano et al. (1993a), the same properties have been assumed in this study. Therefore, referring to this reference solution, we plotted the Degen formula with the test result (Case 8) (Figure 5(b)) and calculated the reduction effect on perforation damage caused by the oblique impact at 45° as $\beta_{\mathrm{Degen}}(45°) = 0.66$. Similarly, the scattering influence of the oblique impact at 45° was not considered in the proposed formula owing to the lack of test data. The calculated reduction factors of the scabbing and perforation limits caused by the oblique impacts can be regarded as median values, which should be modified based on the investigation of variability.

CONCLUSION

In this study, we analyzed the impact test results to investigate the effects of the impact angle and stiffness of projectiles on the local damage to the RC plate structure, i.e., penetration, scabbing, and perforation. In particular, the scabbing and perforation limits of the oblique impact were observed in the test results. Therefore, we adopted the traditional Chang and Degen formulas for the prediction of scabbing damage and perforation damage, respectively, to determine the reduction factors of the oblique impact of the soft projectile compared with that of the normal impact of the rigid projectile. As we manufactured the projectiles based on the specifications presented by Sugano et al. (1993b), the same structural characteristics were assumed, and the experimentally obtained reduction factor of the perforation limit caused by the normal impact of the soft projectile was adopted to determine the reduction effect caused by the oblique impact. Finally, the reduction factors of $\beta_{\text{chang}}(45°) = 0.64$ and $\beta_{\text{Degen}}(45°) = 0.66$ for scabbing damage caused by the rigid projectile and perforation damage caused by the soft projectile under the oblique impact were calculated, respectively. The damage obtained from the experiment was realistic, and the calculated reduction factor based on the test results of the scabbing and perforation limits under the oblique impact can be regarded as a median value. To propose a reasonable evaluation formula, it is necessary to consider variability, so that it can be evaluated conservatively. Therefore, the database of test results is required to be enhanced to further verify the reduction effects of the impact angle and projectile stiffness in the future.

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