Evaluation of local damage to reinforced concrete panels subjected to oblique impact  
- Simulation analysis for evaluating perforation phenomena caused by oblique impact of deformable projectiles -

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Abstract
To date, oblique impact has not been studied and few experimental data on the local damage of reinforced concrete (RC) panels exist for oblique impact of deformable projectiles. The final purpose of this study is to propose a new formula for evaluating the local damage to reinforced concrete structures caused by oblique impact based on past experimental results and simulation results. As the first step of this final purpose, we validate the analytical method by comparison with the experimental results and simulate the damage caused by oblique impact using the validated method. First, we analyze and simulate the local damage of RC panel caused by a deformable projectile owing to an impact test normal to the target structure to verify the validity of the simulation analysis. Next, we perform simulation analyses for evaluating the perforation of RC panel due to oblique impact by the deformable projectile and present the results. Various response characteristics and perforation mechanisms to be the basis of examination of oblique impact evaluation were clarified in this paper.

Keywords: Local damage, Oblique impact, RC panel, FEM, Deformable projectiles

1. Introduction
Impact external force may act on structures in cases of collision with artifacts such as ships, vehicles, aircraft, and during events caused by natural disasters such as tsunami driftage, slope failure, flying objects from tornadoes. In recent large-scale natural disasters, collision damage to structures caused by volcanic debris, tornado missiles, slope failure, etc. have been reported. In the field of nuclear engineering, many collision problems such as turbine missiles and aircraft collisions have been discussed for a long time. The nuclear power regulatory committee published the “Tornado impact assessment guide of nuclear power plant” in June 2013 (NRA, 2013) and the “Review guide on aircraft impact assessment for practical nuclear power reactors” in September 2014 (NRA, 2014) to evaluate the impact of projectiles colliding with nuclear facilities. In particular, regarding the evaluation of impact on buildings by artifacts, the ISO 10252 standard is currently being developing for the design of structures against accidental action, along with EUROCODE (EN, 2006), JCSS (JCSS, 2001), etc. Moreover, “The concept of impact-resistant design of building” was published by the Japan Institute of Architecture (Design, 2015) in January 2015, and the part of impact load was introduced in “AIJ Recommendations for Loads on Buildings” for building design in March 2015 (Load, 2015). However, the importance of impact problems has continuously increased.

In general, local damage to reinforced concrete (RC) structures caused by projectile impact is classified into the following three modes according to the extent of the damage.

- Penetration: tunneling into the target by the projectile (the length of the tunnel is the penetration depth).
- Scabbing: ejection of fragments from the rear face of the target.
- Perforation: complete passage of the projectile through the target with or without residual velocity.
To date, many empirical formulas have been proposed for evaluating the local damage to RC structures caused by projectile impact. Most of these formulas were derived based on tests on rigid projectiles perpendicular to the target structures (normal impact). (Kennedy, 1976) and (Li et al., 2005) reviewed and summarized these empirical formulas. However, most of these evaluation expressions are empirical formulas introduced based on impact test results using rigid projectiles that do not deform at the time of collision, and can be applied only to collisions of rigid projectiles. Therefore, it cannot be applied to collisions of deformable projectiles, that is, the collision of projectiles that deform and absorb energy at the time of collision.

On the other hand, with regard to studies on the local damage to RC structures caused by collision with deformable projectiles, (Koshika, 1994) showed that local damage on the RC structure caused by a deformable projectile composed of a thin cylindrical shell can be calculated numerically using the axisymmetric buckling theory of a thin cylindrical shell by (Gerard, 1956). Although the object in this analytical method is a deformable projectile, its shape and structure are limited to a thin cylindrical axial symmetrical model; thus, it cannot be applied to a deformable projectile with more general configuration and structure.

In addition, there are few studies on the impact of deformable projectiles, for example (IRIS, 2014), and impact experiments on aircraft engines (Sugano et al., 1993) are one of few experimental cases that have been published. (Sugano et al., 1993) proposed a local damage evaluation formula for the collision of an aircraft engine, which is a deformable projectile, based on this experimental result. However, the proposed evaluation formula is applicable only to aircraft engines and not to other deformable projectiles. Therefore, in order to generalize the local damage evaluation caused by collision of these various deformable projectiles, the development of a local damage evaluation method by analytical approach is necessary in addition to experimental research.

On the other hand, regarding analytical studies on local damage occurring in RC structures due to collision with projectiles, (Morikawa et al., 1995) and (Sawamoto et al., 1998) showed that the local damage of an RC panel caused by collision with rigid and deformable projectiles can be evaluated using the discrete element method (DEM). In addition, simulation analysis of impact experiments on aircraft engines conducted by (Sugano et al., 1993) was carried out. This analytical method developed a two-dimensional model of the aircraft engine and an axisymmetric model of the target RC panel in order to accurately evaluate the local damage mode occurring in the RC panel. However, it is difficult to evaluate impact responses such as strain, deformation, reaction force, and even the non-axisymmetric collision phenomenon generated in the RC panel.

Focusing on the collision angle, in general, the influence of the normal impact is greater than the influence by the oblique impact. Thus, when evaluating the influence of projectile impact, it is often conservatively evaluated as normal impact. On the other hand, it is also conceivable that the approach direction of the collision is restricted from the oblique direction by the location or position of the structure to be evaluated. In such a case, it is desirable to not perform a conservative evaluation such as a normal impact but a rational evaluation that takes into consideration the approach from the oblique direction. However, research on oblique collision is currently limited.

In the case of oblique impact, the angle of impact is recognized to affect the local damage, particularly for angles greater than 20° from the normal (NDRC, 1946). Therefore, to establish a rational structural design method against impact loading, the proper evaluation of local effects caused by oblique impact is required. However, experimental data on oblique impact are limited and the only data currently available are from the works of (Beth et al., 1943) and (Tanaka et al., 2004), both of which were intended for rigid projectiles. There are also few experimental data on oblique impact by deformable projectiles. Therefore, more work is needed in order to propose new formulas for evaluating the local damage to RC structures subjected to oblique impact, especially by deformable projectiles.

The final goal of this research is to propose a new formula for evaluating the local damage caused by oblique impacts of deformable projectile. In this paper, as the first step to achieve this final goal, we validate the analytical method by comparison with experimental results, and simulate the damage caused by oblique impact using the validated method. First, we analyze and simulate the local damage sustained by an RC panel caused by a deformable projectile. We use an impact test normal to the target structure to verify the validity of the simulation analysis. Next, we perform simulation analyses for evaluating the perforation of the RC panel due to oblique impact by the deformable projectile using the validated analytical method. Furthermore, based on the simulation analysis results, we discuss the dynamic response behavior and energy history of the local damage of the RC panel caused by collision with the deformable projectile.
2. Evaluation of the validity of analytical method by comparison with experimental results

First, we analyze and simulate the local damage owing to an impact test normal to the target structure to verify the validity of the simulation analysis. This analysis was performed using the LS-DYNA R7.1.2 finite-element code with Lagrangian finite elements and explicit time integration.

2.1 Overview of Previous Experiments

Normal impact experiments on a RC panel using a deformable projectile were conducted by Koshika (1994). The experimental setup is shown in Fig. 1. The RC panel was a 1500 mm × 1500 mm square plate with thickness of 210 mm. D6 and D10 deformed rebars whose nominal diameters are 6 mm and 10 mm, respectively, were employed for the RC panel. The deformable projectile was a thin-walled cylinder with diameter of 101 mm and length of 317 mm. The RC panel was supported on all four corners behind the panel, and the reaction forces were measured by installing a load cell at each support. The measurement positions of the rebar strain and panel displacement and reaction forces are shown in Figs 2 and 3, respectively. The symbol @ in Fig. 2 means spacing of rebar. For example, D6@40 means that D6 rebar is arranged with 40 mm pitch. In addition, the material properties of the RC panel and projectile are given in Tables 1 and 2, respectively. The impact velocity was 201 m/s and the projectile neither scabbed nor perforated the RC panel.
Fig. 3 Measurement positions of the displacement and reaction force

Table 1 Properties of the RC panel used in the experiment (SD295A)

<table>
<thead>
<tr>
<th></th>
<th>Compressive strength (N/mm²)</th>
<th>Yield strength (N/mm²)</th>
<th>Tensile strength (N/mm²)</th>
<th>Young’s modulus (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>24.517</td>
<td>-</td>
<td>2.746</td>
<td>-</td>
</tr>
<tr>
<td>Steel rebar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D6</td>
<td>-</td>
<td>447.2</td>
<td>585.5</td>
<td>$2.05 \times 10^5$</td>
</tr>
<tr>
<td>D10</td>
<td>-</td>
<td>464.8</td>
<td>653.1</td>
<td>$2.23 \times 10^5$</td>
</tr>
</tbody>
</table>

Table 2 Properties of the deformable projectile used in the experiment (S45C)

<table>
<thead>
<tr>
<th></th>
<th>Yield strength (N/mm²)</th>
<th>Tensile strength (N/mm²)</th>
<th>Young’s modulus (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>411.9</td>
<td>705.1</td>
<td>214,000</td>
</tr>
</tbody>
</table>

2.2 Analytical model

(1) Reinforced concrete panel

The target reinforced concrete panel used in the simulation analyses is shown in Fig. 4(a). As shown in this figure, the target panel is a 1,500 mm × 1,500 mm square reinforced concrete panel. The thickness of the panel was 210 mm.

Steel reinforcement was provided in the form of deformed re-bars measuring 6.0 mm in diameter and placed equally at 40 mm c/c along two orthogonal directions on both faces. The concrete cover was 15 mm on both surfaces. The reinforcement ratio, which means the ratio of cross-sectional area of reinforcing bar per cross-sectional area of the RC panel, was 0.4% each way each face.

The reinforced concrete panel was fixed at its four corners and anchor plates were attached at four fixed points on both faces of the target panel; the anchor plates were connected by steel pipes measuring 30 mm in diameter.

For finite element analysis, concrete was modeled as a solid element and the steel reinforcing bar was modeled as a beam element. The anchor plates and the steel pipes attached at the four corners were modeled as shell and beam elements, respectively. The boundary condition of the target panel was set such that the four corner points were free along the out-of-plane direction and other freedoms at the supporting points were assumed to be fixed. In FE modeling, the spring elements were set in the out-of-plane direction at the four fixed corner points.

Figure 4(b) shows the finite element model of the target reinforced concrete panel. We set the element size of concrete to approximately 10 mm × 10 mm × 10 mm. It comprised 21 layers along the thickness of the panel.

The nodal point connecting the solid element of the concrete and the beam element of the reinforcing bar was
considered to be the same point. Therefore, in this analysis, we assumed a perfect bond between the concrete and the steel reinforcing bars.

(a) Arrangement of rebar, steel pipes, and load cells

(b) Sectional view

Fig. 4 Panel model

(RC panel, 1500 mm × 1500 mm × 210 mm)

(2) Projectile

The projectile was also modeled on the basis of the studies by Koshika (1994), that is, a simplified 1/7.5 scale model of the GE-J79 turbo engine installed in F-4 Phantom Fighters (Sugano et al., 1993). The configuration and size of the deformable projectile employed in this simulation analysis is shown in Fig. 5.

As shown in this figure, the deformable projectile is a cylindrical shell comprising three frames, namely, front frame, intermediate frame, and rear frame, and two thin cylindrical shells, namely, front and rear shell. The thicknesses of the front, intermediate, and rear frames are 10 mm, 12 mm, and 15 mm, respectively. The thicknesses of the front and the rear parts of the cylindrical shell are 1.0 mm and 2.7 mm, respectively. The diameter of this projectile is 101 mm, its total length is 317 mm, and its weight is 3.6 kgf.

The frames were modeled using solid elements, and the thin cylindrical parts were modeled using shell elements. The neutral surface of the shell element was positioned at an outer diameter of 101 mm.

The number of elements and nodes in the projectile and the target panel is summarized in Table 3.

<table>
<thead>
<tr>
<th>Model</th>
<th>Solid</th>
<th>Shell</th>
<th>Beam</th>
<th>Spring</th>
<th>Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC Panel</td>
<td>457,464</td>
<td>2,728</td>
<td>21,028</td>
<td>4</td>
<td>485,606</td>
</tr>
<tr>
<td>Projectile</td>
<td>768</td>
<td>896</td>
<td>-</td>
<td>-</td>
<td>2,137</td>
</tr>
</tbody>
</table>
2.3 Material properties

(1) Reinforced concrete panel

1) Concrete

The material properties of the concrete employed in the RC panel are listed in Table 4. The material model of the concrete employed in the simulation analyses is mainly the MAT_084 of LS-DYNA (Winfrith model). The MAT_072R3 of LS-DYNA (KCC model) was also used for comparison. The stress-strain curves for these two kinds of concrete model are shown in Fig. 6. This stress-strain curve is a basic curve for each concrete model that does not take into account strain rate dependence. In fact, in LS-DYNA, tensile / compressive strength and softening (stress reduction) curve after destruction change according to strain rate dependency for each individual element.

Given that the strain rate effect of concrete is calculated automatically in LS-DYNA, the DIF (Dynamic Increase Factor) is not multiplied to the compressive strength and the tensile strength of the concrete.

Table 4 Properties of concrete in the analysis

<table>
<thead>
<tr>
<th></th>
<th>(a) Winfrith model</th>
<th>(b) KCC model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength (N/mm²)</td>
<td>24.517</td>
<td>22831</td>
</tr>
<tr>
<td>Tensile strength (N/mm²)</td>
<td>2.746</td>
<td>0.2</td>
</tr>
<tr>
<td>Mass density ×10⁻⁹ (t/m³)</td>
<td>2.345</td>
<td>10</td>
</tr>
<tr>
<td>Young’s modulus (N/mm²)</td>
<td>22831</td>
<td></td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Aggregate size (mm)</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5 Projectile model (unit: mm)

Fig. 6 Basic stress-strain curves for concrete model
2) Steel Rebar

The material used in the steel rebar is S45C steel, and its material properties are listed in Table 5. The Poisson’s Ratio of the steel rebar was assumed as 0.3. The true stress–true strain relationship of the steel rebar material was determined by assuming an exponential function that passes the yield stress point and the maximum strength point.

\[
\sigma_y = A \varepsilon_p^n
\]  

(1)

where, \(\sigma_y\) is the stress after plasticity, \(\varepsilon_p^n\) is the plastic strain, and \(A\) and \(n\) are the material parameters. Figure 7 shows the true stress–true strain relationship obtained by this method. The strain-rate effect was considered for the steel rebar by applying the WES formula defined in WES-2808 (WES 2808, 2003).

![Fig. 7 True stress–true strain relationship](image)

Table 5 Properties of rebar in the analysis (SD295A)

<table>
<thead>
<tr>
<th></th>
<th>Mass density (t/m^3)</th>
<th>Young’s modulus (N/mm^2)</th>
<th>Yield strength (N/mm^2)</th>
<th>Nominal tensile strength (N/mm^2)</th>
<th>True tensile strength (N/mm^2)</th>
<th>True fracture strain (mm/mm)</th>
<th>Fracture strain (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D6</td>
<td>7.86</td>
<td>205,000</td>
<td>447.2</td>
<td>585.5</td>
<td>685.0</td>
<td>0.157</td>
<td>0.200</td>
</tr>
<tr>
<td>D10/D16</td>
<td>7.85</td>
<td>223,000</td>
<td>464.8</td>
<td>653.1</td>
<td>764.2</td>
<td>0.157</td>
<td>0.200</td>
</tr>
</tbody>
</table>

(2) Projectile

The properties of the projectile are listed in Table 6. The stress–strain relation was obtained by assuming an exponential law and considering the strain rate dependency as well as the steel rebar. The relationship is also shown in Fig. 6. The mass density of the projectile model was adjusted to equal the actual mass of the projectile because the kinetic energy of the projectile greatly affected the precision of the impact analysis.

![Fig. 6](image)

Table 6 Properties of the projectile in the analysis (S45C)

<table>
<thead>
<tr>
<th></th>
<th>Mass density (t/m^3)</th>
<th>Young’s modulus (N/mm^2)</th>
<th>Yield strength (N/mm^2)</th>
<th>Nominal tensile strength (N/mm^2)</th>
<th>True tensile strength (N/mm^2)</th>
<th>True fracture strain (mm/mm)</th>
<th>Fracture strain (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.136</td>
<td>214,000</td>
<td>411.9</td>
<td>705.1</td>
<td>846.1</td>
<td>0.1906</td>
<td>0.500</td>
</tr>
</tbody>
</table>

(3) Load cells

A 10-mm long spring element was placed at the load cell position and the spring force was considered as the impact reaction force. The load cell was modeled using the Maxwell 3 element model, which is a nonlinear spring element of LS-DYNA. The spring characteristics \(K(t)\) of the Maxwell 3 element model are defined by short-term spring constant \(K_0\), long-term spring constant \(K_\infty\), and damping constant \(\beta\). The relationship of these parameters is shown in Eq. (2).

\[
K(t) = K_\infty + (K_0 - K_\infty) \exp(-\beta t)
\]  

(2)
The three parameters were determined by parameter identification by the response surface method in order to obtain reaction force histories close to the results of the experiment. An example of the spring characteristics (elastic constant) of Maxell 3 spring is shown in Fig. 8.

Fig. 8 An example of the spring characteristics of the Maxell 3 spring (where $K_0=233159.0$, $K_\infty=13007.3$, $\beta=1000$)

2.4 Analytical conditions

(1) Contact condition

The contact conditions and the friction coefficients used in the simulation analyses are summarized in Table 7. To evaluate contact between the projectile and the eroded ruptured concrete, eroding contact for projectile–concrete contact was defined. Because contact between the projectile and the steel rebar was considered to be contact between the shell element and the beam element, node-to-surface contact was used to represent the projectile–steel rebar contact. Furthermore, we defined single-surface contact to represent self-contact of the projectile. All of these are based on contact calculation by penalty method. Since the value of each friction coefficient is not well known, we refer to reference (Architecture Handbook, 1977). The values used here are widely used in usual contact calculation.

<table>
<thead>
<tr>
<th>Object</th>
<th>Contact Condition</th>
<th>Friction Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projectile–Concrete</td>
<td>Eroding contact</td>
<td>0.30</td>
</tr>
<tr>
<td>Projectile–Steel Rebar</td>
<td>Node–surface contact</td>
<td>0.20</td>
</tr>
<tr>
<td>Self-contact of projectile</td>
<td>Single-surface contact</td>
<td>0.20</td>
</tr>
</tbody>
</table>

(2) Boundary condition

With respect to the panel structure model, the constraint condition was set for the steel pipe. The steel pipe is rigid and has six degrees of freedom; therefore, only the degree of freedom in the out-of-plane direction (x-direction) was allowed to vary, whereas the other degrees of freedom were fixed.

(3) Loading condition

The projectile impacted the center of the RC panel perpendicularly at 201 m/s, as in the experiment.

2.5 Analytical results and considerations

(1) Eigenvalue analysis

The eigenvalue analysis of the RC panel was performed before the impact analysis. The results are shown in Fig. 9. The natural frequency of the first mode of the rigid 210-mm-thick RC panel was about 200 Hz.
(2) Impact behavior

Figure 10 shows the simulation of the impact behavior of the projectile. The projectile completely penetrated into the RC panel at about 2.0 ms after the impact, and the shear cone crack in the direction of 45 degrees also occurred in the cross section of the RC panel.

(3) Damage mode of the projectile

Figure 11 shows the analytical results of the damage sustained by the projectile after impact. As shown in this figure, the thin cylindrical front shell part of the deformable projectile completely ruptured and separated from the remaining rear part; this part was approximately 100 mm in length. On the other hand, the length of the remaining rear part in the experimental results was approximately 110 mm, and almost the same result was obtained. Thus, it was found that damage of the deformable projectile by collision can be reproduced with appropriate accuracy by this simulation analysis.
Figure 12 shows the damage of the RC panel after the impact. The detailed dimensions of the crater on the surface of the RC panel are shown in Fig. 13. In addition, the size of the crater is given in Table 7. For comparison, the results for two concrete models (Winfrith Model and KCC Model) are also considered.

![Fig. 12 Damages to the RC panel](image)

(a) Winfrith model  
(b) KCC model

The local damage mode of the RC panel is the same in the simulations and the experiments. Craters caused by penetration occurred on the surface of the panel, and cracks on the backside occurred owing to the progress of the shear cone. In addition, as listed in Table 8, the experimental crater size is in good agreement with the analytical results. Moreover, there was not much difference between the two kinds of concrete models (Winfrith model and KCC model) in the damage situation and the size of the crater of the RC panel. From the comparison of the simulation and experimental results, it is clearly seen that the local damage on the RC panel caused by the impact of the deformable projectile is reproduced. Since the results obtained by the Winfrith model are capable of visualizing the cracks of the RC panel, the analytical results using the Winfrith model are shown in the following sections.

![Fig. 13 Damage modes of the RC panel](image)

Table 8 Crater dimensions in the RC panel

<table>
<thead>
<tr>
<th>Measurement area</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>Crater around 230 × 155 × 22</td>
</tr>
<tr>
<td>Analysis (Winfrith)</td>
<td>Crater around 140 × 130 × 30</td>
</tr>
<tr>
<td>Analysis (KCC)</td>
<td>Crack area around 200 × 220 × 30</td>
</tr>
<tr>
<td>Analysis (KCC)</td>
<td>Crater around 140 × 140 × 40</td>
</tr>
</tbody>
</table>
(5) Impact behavior of the RC panel

The simulation results for the strain in the D6 rebar of the RC panel are shown in Fig. 14. The positions of the strain gauges on the rebar are shown in Fig. 2.

First, the rebar at Y1U at the center of the impact surface on the panel is completely plasticized. This is consistent with the experimental results. The results for the rebar far from the central position (Y2U and Y2B) show the response behavior within the elastic range and suggest that the impact is a local phenomenon of either destruction or response. In addition, the periodic response of the strain at the end of the impact is confirmed. The period of the free vibration response is predicted 2-2.5 msec from Figs 14 (b) and (c). So the dominant frequency of this response is predicted as approximately 200–250 Hz, and this frequency corresponds to the primary natural frequency of the RC panel.

![Fig. 14 Time history of rebar strain](image)

(6) Time History of Energy Transfer Process

Figure 15 shows the time history of the overall energy transfer process for impact. The definitions of the symbols used in this figure are as follows:

TE: Total energy
PKE: Kinetic energy consumed by projectile
PIE: Internal energy consumed by rupture of projectile
TKE: Kinetic energy consumed by target panel
TIE: Internal energy consumed by rupture and deformation of target panel
SE: Sliding energy consumed at the contact surface between the projectile and the target panel.

The kinetic energy and internal energy are calculated using the velocity and mass density, and stress and strain of each element, respectively. The sliding energy is calculated using the virtual spring of the contact surface, and friction energy is included in it. As shown in these figures, the initial kinetic energy of the projectile was transferred to the internal energy consumed by rupture and plastic deformation of the projectile and the target panel, as well as other energy such as sliding energy. It is remarkable that the internal energy consumed by rupture of projectile PIE (Projectile) is approximately 60 % of the total energy after the impact (at t = 5.0 ms). It means that it is possible to reduce the impact load and damage to the target RC panel in comparison to a case of rigid projectile impact.

Here, it is observed that the total energy in Fig. 15 increased slightly during the collision (t = 0–2 ms), which can
be attributed to the effect of the artificial increase in contact energy. In fact, low artificial contact energy is preferable.

For this purpose, it is necessary to reduce the mesh size in order to reduce the local penetration of the projectile and the RC panel. However, from the viewpoint of the dimensions of the whole model, we believe that it is not reasonable to further decrease the mesh size. In this case, the error is approximately 6% and is regarded as acceptable.

(7) Comparison of experimental and simulation results

Time history of the reaction forces and displacements are compared with the simulation results. These experimental results were plotted using the value of the graphs in the reference (Koshika, 1994).

1) Time history of the reaction forces

The reaction forces at each corner of the panel from R1 to R4 as a function of time are shown in Fig. 16. The total reaction forces are shown in Fig. 17. The peak values of the total reaction forces of experimental results and analytical results indicate a good correlation despite the slight differences in the reaction force at each position.

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![Fig. 15 Time history of energy transfer process](image)

![Fig. 16 Comparison of the reaction forces of the RC panel](image)
2) Time history of the displacement

The experimental and simulated displacement of the RC panel as a function of time is shown in Fig. 18, which shows good correlation.

![Figure 18: Comparison of the displacements of the RC panel](image)

As described in this section, the experimental and simulation results were in good agreement and confirmed the validity of the proposed method.

3. Evaluation of effect of collision angle on local damage of the RC panel

Next, we present the results of simulation analyses for evaluating the local damage to reinforced concrete panels caused by normal and oblique impact of deformable projectiles, focusing especially on perforation phenomena. Based on the analytical results, we investigate the differences in impact response characteristics between normal and oblique impact.

3.1 Analytical Method
For the numerical analyses, we also used the finite element code LS-DYNA R7.1.2. As presented and discussed in the previous paragraphs, the validity and applicability of the analytical method for evaluating local damage to reinforced concrete panels subjected to deformable projectiles were verified and confirmed through the verification analyses results of a past experimental study (Sugano et al., 1993).

3.2 Analytical Model

(1) Reinforced concrete panel

The target reinforced concrete panel used in the simulation analyses is shown in Fig. 19. As shown in this figure, the target panel is a 1,500 mm × 1,500 mm square reinforced concrete panel. The thickness of the panel’s central region was set to 80 mm to ensure that the projectile perforates the target panel. To prevent overall bending failure of the panel, 200-mm-thick edge rib beams were attached to peripheral region of the panel and additional reinforcing steel bars were placed in these rib beams.

Steel reinforcement was provided in the form of deformed re-bars measuring 6.0 mm in diameter and placed equally at 100 mm c/c along two orthogonal directions on both faces. The concrete cover was 10 mm on both surfaces. The reinforcement ratio was 0.4% each way each face.

The reinforced concrete panel was fixed at its four corners and anchor plates were attached at four fixed points on both faces of the target panel; the anchor plates were connected by steel pipes measuring 30 mm in diameter.

For finite element analysis, concrete was modeled as a solid element and the steel reinforcing bar was modeled as a beam element. The anchor plates and the steel pipes attached at the four corners were modeled as shell and beam elements, respectively. The boundary condition of the target panel was set such that the four corner points were assumed to be fixed.

Figures 20 and 21 show the finite element model of the target reinforced concrete panel. We set the element size of concrete to approximately 10 mm × 10 mm × 10 mm. A finer element mesh was used for the central part of the target panel. It comprised eight layers along the thickness of the panel. A course mesh was used for modeling the peripheral region of the panel.

The nodal point connecting the solid element of the concrete and the beam element of the reinforcing bar was considered to be the same point. Therefore, in this analysis, we assumed a perfect bond between the concrete and the steel reinforcing bars.
(2) Projectile

The projectile employed in this paper is the same as the deformable missile shown in paragraph 2.2 (2). The number of elements and nodes in the projectile and the target panel is summarized in Table 9.

<table>
<thead>
<tr>
<th>Model</th>
<th>Solid</th>
<th>Shell</th>
<th>Beam</th>
<th>Spring</th>
<th>Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC Panel</td>
<td>141,936</td>
<td>800</td>
<td>8,952</td>
<td>4</td>
<td>161,957</td>
</tr>
<tr>
<td>Projectile</td>
<td>768</td>
<td>896</td>
<td>-</td>
<td>-</td>
<td>2,137</td>
</tr>
</tbody>
</table>

### 3.3 Material Model

(1) Reinforced concrete panel

1) Concrete

The material properties of the concrete employed in the reinforced concrete panel are listed in Table 10. The material model of the concrete employed in the simulation analyses is the "MAT_084 (*MAT_WINFRITH_COCRETE)" model installed in LS-DYNA. The strain rate effect of concrete was also considered in the same manner in paragraph 2.3 (1) 1).

<table>
<thead>
<tr>
<th>Compressive strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Mass density $\times 10^{-9}$ (t/mm$^3$)</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Aggregate size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.497</td>
<td>2.354</td>
<td>2.345</td>
<td>23,131</td>
<td>0.2</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass density $\times 10^{-9}$ (t/mm$^3$)</th>
<th>Young’s modulus (MPa)</th>
<th>Yield strength (MPa)</th>
<th>Nominal tensile strength (MPa)</th>
<th>True tensile strength (MPa)</th>
<th>True fracture strain (mm/mm)</th>
<th>Fracture strain (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.86</td>
<td>205,000</td>
<td>447.2</td>
<td>585.5</td>
<td>685.0</td>
<td>0.157</td>
<td>0.200</td>
</tr>
</tbody>
</table>
Table 12 Material properties of projectile (S45C Steel)

<table>
<thead>
<tr>
<th></th>
<th>Mass density $\times 10^{-9}$ (t/m$^3$)</th>
<th>Young’s modulus (MPa)</th>
<th>Yield strength (MPa)</th>
<th>Nominal tensile strength (MPa)</th>
<th>True tensile strength (MPa)</th>
<th>True fracture strain (mm/mm)</th>
<th>Fracture strain (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S45C Steel</td>
<td>8.136</td>
<td>214,000</td>
<td>411.9</td>
<td>705.1</td>
<td>846.1</td>
<td>0.1906</td>
<td>0.500</td>
</tr>
</tbody>
</table>

2) Steel rebar

The material properties of the D6 steel rebar used in the simulation analyses is same as shown in Table 11. The Poisson’s Ratio of the steel rebar was assumed as 0.3. The true stress–true strain relationship of the steel rebar material was determined by same procedure in paragraph 2.3 (1) 2), and the obtained true stress–true strain relationship is shown in Fig. 7. The strain-rate effect was considered for the steel rebar by applying the WES formula defined in WES-2808 (JWES, 2003), too.

(2) Projectile

The material used in the projectile is S45C steel, and its material properties are listed in Table 12. The true stress–true strain relationship for this S45C steel material was also shown in Fig. 7. The strain-rate effect was also considered for the S45C steel material.

3.4 Analytical Conditions

(1) Contact condition

The contact conditions and the friction coefficients used in the simulation analyses are same in paragraph 2.4 (1) and shown in Table 7.

(2) Boundary condition

With respect to the panel structure model, the constraint condition was set for the steel pipe. To set fixed boundary condition at the four corner points of the target panel, all degrees of freedom of steel pipe was fixed.

(3) Loading condition

Two cases of impact analysis, normal impact and oblique impact with the collision angle of at an angle of 45° degrees were executed. Figure 22 shows the definition of the collision angle. Figure 23 compares the state just before the collision of the projectile. As shown in this figure, in the normal impact, the rigid front frame of the projectile collides head-on to the target panel at first in the form of a flat nosed projectile. However, in the oblique impact, the edge of the rigid front frame collides to the target panel at first. Therefore, in this case the projectile collides in the form of a sharp nosed projectile.

The same impact velocity of 215 m/s was employed in both cases.
3.5 Analytical Results and Considerations

(1) Perforation behavior

A comparison of the perforation behaviors of the projectile under normal impact and oblique impact is shown in Fig. 24. Under normal impact, the projectile collided with the target reinforced concrete panel perpendicularly and then penetrated and perforated straight, maintaining its original posture. Under oblique impact, by contrast, the projectile was subjected to rotational motion during perforation. The projectile rotated by about 90° at 0.006 sec after the perforation, and it continued to move with rotational motion after that.

![Fig. 24 Perforation behavior of projectile](image)

(2) Damage Mode of RC Panel

Analytical results of the damage modes of the reinforced concrete panel are shown in Fig. 25. Under normal impact, a square perforation hole of approximately 120 mm side length, slightly larger than the diameter (101 mm) of the projectile, occurred. Under oblique impact, by contrast, a rectangular perforation hole was generated. The length of its long side is 200 mm, approximately twice the spacing of the reinforcing rebar. This result indicates that the perforation size was affected by rebar spacing. Furthermore, the volume of the perforation generated by oblique impact was larger than that of the perforation generated by normal impact.

(3) Damage Mode of Projectile

Analytical results of the damage modes of the projectile after perforation are shown in Fig. 26. For both normal impact and oblique impact, the front part of the cylindrical shell measuring 1.0 mm in thickness was ruptured and separated from the remaining part of the projectile. By contrast, the rear part of the cylindrical shell measuring 2.7 mm in thickness retained its original configuration in both the cases. For normal impact, especially, no buckling mode was observed in the rear part of the cylindrical shell. As shown in Fig. 26, however, for oblique impact, a non-axisymmetric buckling mode was extended to the rear part of the cylindrical shell. The final length of the remaining part of the projectile after perforation for normal impact was larger than that for oblique impact.
(4) Change in Projectile Velocity

The change in projectile velocity during perforation is shown in Fig. 27. From the start of collision to 1.0 ms, the reduction in projectile velocity was larger for normal impact than that for oblique impact. Thereafter, the velocity decreased at almost the same rate for both normal and oblique impact. For normal impact, it took 1.5 ms for the projectile to pass the target panel and the residual velocity of the projectile after perforation was 90.0 m/s. For oblique impact, however, it took more than 4.0 ms for the projectile to pass the target panel because the equivalent panel thickness, measured along the flight direction of 45° was large. In this case, the final residual velocity of the projectile after perforation was 8.0 m/s.

(5) Time History of Energy Transfer Process

Figure 28 shows the time history of the overall energy transfer process for normal impact and oblique impact. The definitions of the symbols used in this figure are same as shown in Fig. 15 in Section 2.5.

Here, it is observed that the total energy in Fig. 28 decreased slightly during the collision. Normally, explicit
Dynamic analysis uses various numerical attenuations to stabilize the calculation. For example, artificial viscosity or bulk viscosity is used to smoothly solve impact stress waves (discontinuities of pressure) within a finite number of elements (LS-DYNA, 2012). For this reason, the total energy (TE) tends to dissipate (decrease) slightly. In the case of Fig. 15, the TE is increasing because the increase in artificial contact energy is greater than the numerical attenuation. However, in the case of Fig. 28, the dissipation of TE owing to numerical attenuation is apparent because of the low contact energy. The errors in this case are less than 1% and less than 2% for normal impact and oblique impact, respectively, which is considered acceptable.

Figure 29 shows the energy contribution ratio after the projectile perforated the panel at t = 5.0 ms.

As shown in these figures, the initial kinetic energy of the projectile was transferred to the internal energy consumed by rupture and plastic deformation of the projectile and the target panel, as well as other energy such as sliding energy.

Because the residual velocity of the projectile after perforation under normal impact was larger than that under oblique impact, the final kinetic energy of the projectile after perforation PKE is larger than that for oblique impact. The internal energy consumed by rupture and plastic deformation of the projectile PIE for oblique impact is larger than that for normal impact because damage and deformation of the projectile for oblique impact is larger than that for normal impact, as discussed in section 6.3. The internal energy consumed by rupture and plastic deformation of the reinforced concrete panel TIE is almost same for both normal impact and oblique impact. As for sliding energy, however, a remarkable difference is observed between normal impact and oblique impact. That is, sliding energy for oblique impact is remarkably larger than that for normal impact. The reason for this increase in sliding energy for...
oblique impact is that for oblique impact, equivalent panel thickness measured along the flight direction of 45° was large and rotational movement of the projectile was generated, as discussed in section 6.1.

4. Conclusions

In this study, we proposed a method to simulate the impact and penetration of a concrete panel by a deformable projectile through comparison with experimental results. The experimental and simulation results were in good agreement and confirmed the validity of the proposed method. Furthermore, in comparison to a rigid projectile, a possibility for a deformable projectile to reduce the impact load and consequently the damage to the target was shown.

Also, we investigated analytically the perforation behavior of a reinforced concrete panel subjected to oblique impact by deformable projectiles. As the results, we clarified various response characteristics and perforation mechanisms such as perforation behavior, damage to reinforced concrete panel, rupture and deformation of deformable projectile, reduction tendency and residual of projectile velocity, and energy transfer process.

The advantages of oblique impact include the following:
- Energy due to damage of the projectile and friction during contact increases more than normal impact; hence, the strain energy of the RC panel is clearly reduced compared with normal impact, thus decreasing the damage to the target structure.
- By reducing the residual velocity, it is possible to reduce the influence area and collision velocity on the equipment installed in the inner space at the back of the RC panel.

On the other hand, the disadvantages are as follows:
- The damaged area due to penetration is enlarged by oblique impact.
- If penetration occurs, rotational motion may occur at the time of collision, making it necessary to consider the influence on the equipment installed in the inner space at the back of the RC panel.

As mentioned above, several features were clarified in oblique impact by deformable projectile, and it was found that there is an advantage in reducing the damage of the target structure compared with normal impact. However, this also merely analyzes the features of a particular test case.

Hereon, we will continue to perform simulation analyses by using various types of projectiles such as rigid projectiles and sharp-nosed projectiles. Finally, we will attempt to propose a new formula for evaluating the local damage to a RC panel due to oblique impact by deformable projectiles.

Acknowledgment

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