Scale Model Tests of Multiple Barriers against Aircraft Impact: Part 2. Simulation Analyses of Scale Model Impact Tests

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ABSTRACT

The objectives of this study were (1) to analytically investigate the effectiveness of multiple reinforced concrete barriers against aircraft impact through simulation analyses of the 1/7.5 scale aircraft model impact tests presented in Part 1, using a discrete element method (DEM), and (2) to examine the applicability and validity of DEM.

The analytical results accurately reproduced the fracture processes of the aircraft and the RC panel, velocity changes after impact, and the impact load on the second panel. The residual velocities of the aircraft and the impact loads on the second panels obtained in the analysis decreased markedly with increase in first panel thickness.

1. INTRODUCTION

In general, concrete structures suffer two types of damage under impact load: global damage and local damage. It has been more difficult to assess local damage analytically, but in recent years various analytical methods have been tried. The authors have proposed a new approach to assessing local damage characteristics, focusing on and experimentally applying the discrete element method (DEM). The feasibility of parameters used for DEM analysis, such as dynamic strength increase factors (D.I.F.), has also been confirmed through simulation analyses of a uniaxial compression test and a splitting tensile test on a concrete cylinder under static loading and high-speed loading. Furthermore, the process of local damage to a concrete structure has been quantitatively assessed by simulation analyses of impact tests on reinforced concrete (RC) panels subjected to rigid and deformable missiles [1-3].

In this study, simulation analyses by DEM were performed for the impact tests presented in Part 1, to analytically investigate the effectiveness of multiple reinforced concrete barriers against aircraft impact. Furthermore, we attempted to verify through simulation analyses the applicability and validity of DEM to complicated impact phenomena comprising penetration, scabbing and perforation of the first panel and impact on the second panel induced by an aircraft having a soft fuselage and a relatively hard engine.

2. METHOD OF ANALYSIS

The discrete element method idealizes the concrete/steel medium as an assemblage of
particles that have to satisfy equations of motion, and the dynamic characteristics of the whole body are expressed by the forces transferred between particles during contact. This method uses circular elements, with forces between elements expressed by non-linear springs and dashpots aligned in the normal and shear directions. Mohr-Coulomb’s failure criterion is applied to the springs between the elements. An explicit time integration method is used to solve the equation of motion, and the position (or center of mass and rotational displacement) of each particle is renewed for each time increment.

Details of the formulation processes are given in reference [3]. The spring constants for the springs connecting the particles were calculated on the basis of constitutive equation for a continuous system. For the D.I.F. dependent on strain rate effect, which plays an important role in impact analyses, equations proposed by Yamaguchi [4] were adopted for concrete members, and ACI Committee 439 [5] for reinforcing bars.

3. ANALYTICAL MODEL

3.1 Analytical cases
Analysis was performed for each of the cases with different first RC panel thicknesses, namely, 6cm (MP-6-47), 8cm (MP-8-47), and 10cm (MP-10-47). The time interval for the analysis was set at $5.0 \times 10^{-7}$ seconds, and analysis was performed for each case covering the entire duration of the aircraft impact and rebound. Axisymmetric models were used for the analyses. The aircraft, RC panel, and pendulum were modeled as follows.

3.2 Aircraft
The aircraft was modeled such that its mass and strength distribution in the axial direction corresponded to those of the aircraft model used in the experiments. The analysis model is outlined in Figure 1(a), the mass distribution in Figure 1(b), and the strength distribution in Fig. 1(c). Particles of equal diameter were arranged in two columns for the thin-walled tubular section of fuselage and engine, to enable the expression of buckling process. The axial dynamic strength of the projectile was evaluated on the basis of the results of experiments using a 16cm-thick RC panel. Fiberglass skin of the fuselage was modeled as a cylinder of equal diameter, and filling the cylinder with steel and fiberglass cloth as a diaphragm plate. The steel outer shell of the engine was modeled as a cylinder of equal diameter, hexcel inside as three cylinders, and aluminum plates inside as four plates.

3.3 First RC panel
The first RC panel was modeled as a disc fixed along its perimeter. The radius of the disc was determined such that its primary natural period equaled that of a 1.5m-square panel. The concrete was modeled as circular particles of equal diameter arranged in a hexagonal array, in 13 or more layers in the direction of thickness, to enable the expression of damage conditions. Under these conditions, the radii of the particles and the number of layers in the direction of thickness were adjusted for each analysis case. Static compressive strength was derived from the results of uniaxial compression tests on each specimen, and tensile strength was derived using Sen’s equation [6], based on the obtained compressive strength. Reinforcing bars were modeled in the required positions as bi-linear axial springs as connections between elements. The tensile fracture strain was set, taking into account the fact that the strain concentrates in the vicinity of the fracture, reaching a level 1.3 times the average strain obtained in material tests [7]. It was assumed that fracture occurs when the strain reaches that of the tensile fracture, following yielding of the material due to tensile stress. The element forces of reinforcement were assumed to be zero.

VII-146
3.4 Second RC Panel (Pendulum)
The second RC panel, the pendulum, was modeled as a rigid plate positioned 75cm from the impact surface of the first RC panel only to assess the impact load. The analytical model for the 8cm-thick RC panel are shown in Figure 2. Table 1 gives the physical properties used in the analyses.

4. ANALYTICAL RESULTS

Figures 3 through 5 show of (a) the fracture processes in which the aircraft perforates the first RC panel and reaches the second panel, (b) velocity time histories of the aircraft for the fuselage and engine and (c) impact loads on the second panel.

The principal experimental and analytical results are compared in Table 2.

4.1 Fracture process
The analysis results for cases MP-6-47 and MP-8-47 well simulate the fracture processes for each case where the aircraft perforates the first RC panel and then collides with the second panel, as well as the damage to the fuselage and engine after the impact tests. In the analyses, the crater diameters on the rear surface of the first RC panel are shown to be 45cm for MP-6-47 and 50cm for MP-8-47, which corresponds well with the experimental results. In the impact tests, it was difficult to visually confirm the fracture process of the aircraft perforating the panel, because of the spalling of concrete. However, the analysis results indicate well the process in which the aircraft perforated through the first panel and then collided with the second panel, accompanying the concrete mass of the first panel.

The analysis results for the fracture process of MP-10-47 indicate that the aircraft penetrated the first RC panel, the scabbing of concrete on the rear surface, and that the aircraft rebounded at 15msec after impact. In the experiment, the engine buckled approximately 20cm long, while the analysis showed buckling of 19cm. These analysis results are in good agreement with the experiments.

4.2 Aircraft velocity reduction curves
The velocity reduction curves show that the analytical and experimental results corresponded well for each case, indicating the appropriateness of the aircraft model for the analyses. However, the analytical results showed the start of drastic deceleration after engine impact on the first RC panel to be slightly delayed compared to the experimental results. This could be attributed to the possibility of forward shift of the engine relative to the fuselage upon impact of the edge of the fuselage on the first RC panel.

4.3 Impact loads
Since the aircraft did not perforate the first panel in the case of MP-10-47 and only a minute volume of scabbled concrete reached the pendulum, the analytical results for this case were compared with the impact load derived from Muto's equation [8] based on the mass and the strength distribution of the aircraft model. The impact load values shown in the figure are filtered using a 1001 Hz low pass filter, because the primary natural period of the pendulum is close to 300 Hz. The start-up time of the impact load on the second panel has been denoted as "0" msec.

The maximum impact loads for MP-6-47 and MP-8-47 occur early in the analysis results. This could be attributed to the fact that the second panel was placed closer to the first panel than in the experimental model in order to shorten the analysis time, which led to collision at
an earlier time of scabbed concrete. The experimental and analytical values of impulse indicated in Table 2 are very close. This indicates the appropriateness of the model which incorporated the residual velocity of the aircraft after perforation of the first panel, the mass of the aircraft when it reaches the second panel, and the mass and velocity of scabbed material from the first panel. Thus, the analysis method could be assessed as valid.

5. CONCLUSION

Highly complex phenomena of an aircraft model impact against multiple barriers were investigated by DEM. The analytical results accurately reproduced the fracture processes of the aircraft and the RC panel, velocity changes after impact, and the impact load on the second panel. The residual velocities of the aircraft and the impact loads on the second panels obtained in the analysis decreased markedly with increase in first panel thickness.

The analytical results confirmed the effectiveness of multiple barriers against aircraft impact, and the applicability and validity of DEM for analyzing an aircraft impact against multiple RC barriers.

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REFERENCES

5. ACI committee 439 “Effects of Steel Strength and Reinforced Ratio on the Mode of Failure and Strain Energy Capacity of Reinforced Concrete Beams,” ACI Journal, 1969
Table 1: Input Parameters

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<tr>
<th>Projectile</th>
<th>Panel</th>
<th>MP0647</th>
<th>MP0847</th>
<th>MP1047</th>
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<td>Foam</td>
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Table 2: Simulation Analysis Results

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<th>MP-10-47</th>
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<td>Analysis</td>
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<td>Concrete</td>
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<tr>
<td>Impact load to the Pendulum</td>
<td>Max value</td>
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<td>Crater of back surface</td>
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Figure 1: Aircraft Model

Figure 2: Analytical Model (MP-8-47)
(a) Fracture process of Aircraft Model and RC panel

(b) Velocity Time Histories

(c) Impact Loads to Pendulum

Figure 3  Simulation Analysis Results of MP-6-47
Figure 4 Simulation analysis Results of MP-8-47
(a) Fracture process of Aircraft Model and RC panel

(b) Velocity Time Histories

(c) Impact Loads to First Panel

Figure 5  Simulation Results of MP-10-47