Numerical impact simulation of aircraft into reinforced concrete walls with different thicknesses

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Abstract
Aircraft impact analysis is needed for safety assessment of nuclear power plants. One of the items which should be analyzed for aircraft impact is physical damage to a reinforced concrete (RC) building and this can be estimated by numerical simulation. In the simulation, a simulation model which has been validated by some experimental data needs to be established. In 1988, an aircraft impact test using an F4 Phantom fighter was conducted at the Sandia National Laboratories in the US and a lot of important experimental data were measured. The numerical simulation results for this aircraft impact test are also introduced in this paper. The relationship between the thickness and the deceleration of the aircraft model is studied and then the differences in the deceleration between the simulation and test results are discussed. The relationship between the failure strain and the destruction modes of the aircraft and the target in the simulation are also studied, and then the differences between the simulation and test results are discussed as well. Through these parametric simulations, the validations of the aircraft and the target model are demonstrated. In evaluating the physical damage area inside the buildings, or discussing the necessary numbers of RC walls until the impacting aircraft stops, it is important to estimate whether the RC walls are perforated by an impacting aircraft. Besides numerical simulations, some empirical equations to estimate them are reported. One of them is the UKAEA equation. This equation estimates a dynamic punching strength of a RC wall. It is determined whether an impacting aircraft perforates a RC wall by comparing the dynamic punching strength with the dynamic impact load of the aircraft. In this paper, several aircraft impact simulations using the established aircraft model with different RC wall thicknesses are conducted. Dynamic punching strength of these RC walls are measured in each simulation. The obtained values in the simulations are compared with the estimated values by the UKAEA equation. The differences between them are investigated and the reasons of these differences are discussed.

Keywords: Aircraft impact analysis, Impact simulation, Simulation model, Empirical equation

1. Introduction

It is necessary to conduct a safety assessment analyzing the possible damage caused by an aircraft impacting into a reinforced concrete (RC) building at a nuclear power plant. The simulation model of an aircraft and the RC used in the walls of such RC buildings should be established before an impact simulation is conducted. And it is necessary to confirm whether or not the results of an impact simulation by these models agree with actual test results. Impact tests using actual aircraft are rarely conducted because a lot of preparational effort is needed for this kind of test. But an impact test using an aircraft (an F4 Phantom fighter) crashing into an RC target was conducted in 1988 (Sugano et al., 1993). After this test, several impact simulations based on this aircraft were conducted and their results were compared with the 1988 test results (Lee et al., 2014).
After establishment of simulation models, aircraft impact analysis by numerical simulations can be conducted. When an impacting aircraft hits the outer wall of a RC building, it should be evaluated whether the outer wall is perforated or not. When the outer wall is confirmed not to be completely perforated, the area physically damaged by the aircraft impact is limited to the outer wall and the outside of the RC building. When the outer wall is confirmed not to be thick enough to prevent the impacting aircraft from perforating the wall, the aircraft passes through the outer wall of the RC building and crashes into its inner walls. In this case, sequential impacts into the walls need to be considered for predicting how far the aircraft goes inside the RC building.

Besides numerical simulations, some empirical equations also estimate whether an impacting projectile perforates a RC wall. One of them is the UKAEA equation. One of the feature of the UKAEA equation is that this equation covers a soft missile including small aircrafts as a impacting projectile and estimates whether a soft missile perforates a RC wall or not. If the accuracy of estimation results on the UKAEA equation is sufficient, there is little need to conduct numerical simulations and it takes less times for aircraft impact analysis rather than conducting numerical simulations. However, it was reported that the estimated result included some errors when the UKAEA equation was applied under the condition that a diameter of a projectile was larger than a RC wall thickness × 1.3. When a diameter of a projectile is large and then the impacted area on the RC wall is large, RC wall thicknesses should be thick enough so that the above condition be satisfied. For example, when an small aircraft such as an F4 Phantom fighter impacts into a RC wall with wall thickness below around 2500 mm, above condition is not satisfied. RC walls with wall thickness below 2500 mm are often employed in a RC building in nuclear power plants. Thus, the causes of the errors in the UKAEA equations need to be investigated especially when the above condition is not satisfied.

In stead of the UKAEA equation, The Nuclear Energy Institute in the US published the guideline of a methodology for aircraft impact analysis to evaluate stability of nuclear power plants (Nuclear Energy Institute, 2011). This guideline also describes the evaluation method for sequential impact into RC walls by an aircraft. But this method only indicates a wall specifications which counted as a protection against an aircraft impact, and wall numbers for stopping an impacting aircraft are not clarified. Thus, this methodology is not referred in this study.

In this paper, at first, the impact simulation of the aircraft into the RC target is conducted. Various simulations with different thickness and failure strain of the shell of the aircraft are conducted and the influences of these parameters on the simulation results are investigated. These simulation results are also compared with the test results to check if the simulation reproduces the test results. These test and simulation results include the impact load history, the impulse by the impact, the deceleration and the crushed state of the aircraft, and the state of the RC target after the impact. Next, impact simulations of the aircraft model into a RC wall with different wall thicknesses are conducted. The average of the impact load which the aircraft receives from the RC wall during its perforating the RC wall should be same as the dynamic punching strength of the RC wall. Thus, the average of the impact load obtained in simulations are compared with the dynamic punching strengths estimated by the UKAEA equation. One of the causes of errors in the UKAEA equation might be that an average aircraft mean cross section diameter $D$ is used in the equation as an coefficient related to an affected area on the RC wall at impact. This assumption stems from the fact that a diameter of perforated area $D'$ at an impact is usually larger than an average aircraft mean cross section diameter $D$ when a RC wall shows severe bending failure. Then, we assume that a diameter of perforated area $D'$ is a better choice for the coefficient in the UKAEA equation. We measure a diameter of perforated area $D'$ after impacts in each simulation with different wall thicknesses and investigate whether a diameter of perforated area can be used for the coefficient in the UKAEA equation for the better estimation. Based on these investigations, influence of selecting a coefficient correctly to the estimated results by the UKAEA equation is revealed in this study.

The dynamic finite element analysis code LS-DYNA V971® is selected for running these numerical impact simulations, because many impact simulations into a RC target using this program have been previously reported (Agardh and Laine, 1999, Tai and Tang, 2006), and this program is recognized as one of the best for simulating impacts.

2. Aircraft and reinforced concrete model

2.1 Introduction

An impact test using the aircraft was conducted in 1988 at the Sandia National Laboratories in the US and a lot of valuable data were obtained. The test conditions and results are summarized in the study (Sugano et al., 1993). In our study, numerical simulation of this impact test was conducted and simulation results were compared with test results. For
numerical simulation, the simulation model of the aircraft needs to be established. In order to build the model, it is better to know all information about the aircraft design such as the shape of the stringers for the fuselage and the wing structure but it was not reasonable to obtain all this information in detail because the total number of parts for aircraft is enormous and some of the information is not publicly available. Therefore, it was decided to build a simple simulation model, which modeled the outer shape of the aircraft by shell elements and modeled the components inside the aircraft body (such as fuel) by Smoothed-Particle Hydrodynamics (SPH) elements.

2.2 Model configurations

Figure 1 shows the three-dimensional layout of the impact simulation model where the aircraft model impacts into the RC target. The RC target was 7000 mm in width and in height and 3700 mm in thickness. This target was composed of many layers of the concrete elements, and first layer was colored light green, second layer was colored sky blue and 3rd layer and layers after that were colored blown. Here, different colors were used for each concrete layer because it was easy to distinguish by colors which layer was destroyed at the impact. The aircraft configurations are summarized in Table 1. The aircraft model was established by using the shell elements and Smooth-Particle-Hydrodynamics (SPH) elements. Shell elements were used for modelling the outer shape of the aircraft such as fuselage, wings, engines and tails. Water was a substitute in the impact test for the jet fuel weight. Then, SPH elements were used for modelling water inside the fuselage and the material properties of SPH elements were same as water.

The mass distribution of the aircraft is described in Figure 2, where the solid line is the data measured in the test (Sugano et al., 1993) and the dotted line is the input data for the simulation model. The thicknesses of the shell elements were uniform in the entire aircraft model and then the densities of the shell elements were adjusted in according to the mass distribution. Aluminum alloy A7075 was assumed to be the material used in the shell elements of the aircraft model and the failure strain of this material was considered in order to model the shell elements breaking into pieces at the impact. The values of the thickness and the strain of the shell elements were discussed later in this section. Figure 3 shows the stress-strain relationship of the shell elements. A bilinear relationship was assumed. The stress-strain relationship did not change when a different failure strain was applied.

The RC target was modelled as concrete and rebar. Concrete was modelled by solid elements and rebar was modelled by beam elements. The material properties of concrete and rebar are shown in Table 2 and Table 3. These values were the same as those of the concrete and the rebar used in the test (Sugano et al., 1993). When the maximum principal strain of the concrete elements reached 20%, the elements were eroded so that the damage of the RC target in simulations be compared with the test results. Erosion criterion shown in Table 2 indicates this condition. When the maximum principal strain reached 20%, the concrete element did not have any strength against loads. Thus, the value 20% is high enough to erode the concrete elements without any harmful influence to the damage state of the RC target. The thickness of the target was 3700 mm, which was close to the thickness of the target used in the impact test, 3660 mm, and the size of the solid elements was 100 mm × 100 mm × 100 mm. The target was supported on air bearings in the test and then it moved freely in the impact direction. Thus, the RC target in simulations was set to move freely in the direction as well.

Table 4 summarizes the thickness and failure strain of the shell elements. The components of the aircraft modeled by shell elements were roughly separated into 3 parts, fuselage, wings and engines. In the case of fighters, engines are usually employed inside the fuselage; therefore, two kinds of failure strain were used for the simulation model of the aircraft as shown in Table 4. For the fuselage, the study (Lee et al., 2014) was referred to and failure strain of 1.8 was selected. For the wings, the nominal failure strain of A7075 in the uniaxial tensile test (Iwasaki et al., 2013) was referred to and failure strain of 0.1 was selected. For the shell thickness, two values were considered as shown in Table 4.

In order to check the influences by the changes of failure strain and thickness of the shell elements, the sensitivity analysis for these values was conducted by comparing results of different strains and thicknesses in cases No. 1-2, No. 1-3 and No. 1-4 with the results in case No. 1-1. The influence of failure strain of the shell elements was considered in cases No. 1-2 and No. 1-3, and that of thickness of the shell elements was considered in case No. 1-4. Here, the densities of the shell elements were adjusted when the thicknesses were changed from 1.0 mm to 2.5 mm so that the mass distribution of the shell components did not change.

For the impact simulations, explicit dynamic simulations using LS-DYNA were conducted. A contacts among each object were simulated by penalty method and friction coefficients among them were assumed to be 0.3.
Table 1 Configuration of aircraft

| Item            | Value   |
|-----------------|---------|
| Aircraft length | 17.74 m |
| Wing span       | 11.77 m |
| Aircraft height | 5.02 m  |
| Weight          | 17.5 tons |
| Impact velocity | 215 m/s |

Fig. 1 Impact simulation model

Fig. 2 Mass distribution of the aircraft from nose to tail

Fig. 3 Stress-Strain relationship of shell elements

Table 2 Material properties of concrete

| Property                  | Value   |
|---------------------------|---------|
| Density                   | 2500 kg/m³ |
| Poisson ratio             | 0.19    |
| Young modulus             | 23 GPa  |
| Compressive strength      | 23.5 MPa|
| Erosion criterion         | Max principal strain: 20% |

Table 3 Material properties and installation conditions of rebar

| Property                  | Value   |
|---------------------------|---------|
| Type                      | Vertical rebar | Horizontal rebar |
| Diameter                  | 32.1 mm  | 35.8 mm          |
| Density                   | 7850 kg/m³|
| Poisson ratio             | 0.3      |
| Young modulus             | 206 GPa  |
| Yield strength            | 489 MPa  | 467 MPa           |
| Ultimate strength         | 744 MPa  | 733 MPa           |
| Failure strain            | Effective strain: 6% |
| Amount of rebar           | Vertical: 35×35 (1 layer each at front and back sides) |
| Interval of rebar         | Vertical: 200 mm Horizontal: 200 mm |

Solid: measured data (Sugano et al., 1993)
Dotted: model input data
2.3 Simulation results

The impact simulations in each condition shown in Table 4 were conducted. Figure 4 shows the impact simulation results in case No.1-1. The whole aircraft body broke completely into pieces just as in the test results. The wings broke off after impact and most of the wing material passed alongside the ends of the target, which was also the same behavior as seen in the test results. The small spheres are the SPH elements and they were widely distributed after the impact. The destruction mode of the RC target was slight penetration and the first layer of the concrete was only damaged to the extent shown in Figure 5, which was similar to the test results where the maximum depth of penetration was 60 mm (Sugano et al., 1993).

Nodal points A, B, and C on the aircraft model in Figure 1 were selected as points where the velocity were compared between simulations and tests. Nodal points A, B, and C were the middle point and end point of the aircraft, and the middle point of the right engine, respectively. They corresponded to points J7, J12, and J13 in the test so that the velocity data of these points be compared with the test data (Sugano et al., 1993). Figure 6 shows the change in velocities at the impact at nodal points A, B, and C in case No. 1-1 and corresponding test data (J7, J12, and J13). The horizontal axis indicates the time after the impact and 0 means the moment of the impact. The changes in velocities at points A and C were larger than those in the test data and the change in velocity at point B was smaller than that in the test data. The biggest difference in these changes between the simulation and test results during the impact was about 20 [m/s] at point A at 0.05 [s]. These differences were not so dominant compared with the impact velocity 215 [m/s] and only slightly affected the simulation results, such as impact load history and impulse.

Figure 7 shows the impact load history in case No. 1-1. This figure indicated that the shape of the impact load history, which was the direct data and not low-pass-filtered, was almost the same as that of the test results. Figure 8 shows the impulse due to the impact in both case No. 1-1 simulation and test. Figure 8 shows that the impulse after the crash in the simulation was 3.5 [MN·s] and the difference from the test results, about 3.25 [MN·s], was within 10%. Initial momentum of the aircraft was 3.76 [MN·s] and then more momentum was transferred toward the RC target in the simulation. Figure 9 shows the velocity of the RC wall which measured on one side of the wall in both test and simulation in case No. 1-1 after the impact. The velocity obtained by the simulation model was in good agreement with the test result. Since the simulation results such as the deformation state and deceleration of the aircraft after the impact and the impact load history and impulse were reproduced in the simulation, it was confirmed that the numerical simulation based on case No. 1-1 shown in Table 2 reproduced the test results.

Next, the simulations were conducted using the different thicknesses and failure strains for the shell elements as shown in Table 4. Figure 10 shows the destruction mode of the aircraft by the impact in case No. 1-2. The wings were not separated from the body. As mentioned previously, the wings broke off, passing alongside the RC wall after the impact in the test, and these simulation results differed from the test results. The reason for this difference was that the failure strain of the wings in case No. 1-2 was 1.8 and the connections between the body and wings were modelled more strongly than the actual aircraft. Failure strain of 1.8 for the fuselage did not adversely affect the aircraft destruction mode because the shape of the fuselage of the aircraft was tubular and it was crushed with buckling during the impact.

Figure 11 shows the destruction mode of the target after the impact in case No. 1-3. The surface was extensively destroyed in case No. 1-3 compared to the case No. 1-1 where the failure strain of 1.8 was used for the fuselage. Figure 12 shows the impact load between the aircraft and the target. The impact load in case No. 1-3 had more high-frequency vibration than in the case No. 1-1 in Table 4. The reason for this was that the failure strain of the shell elements of the fuselage in case No. 1-3 was smaller than the value in case No. 1-1 and it became easier to be deleted, which led to the contact between the shell elements of the fuselage and the target to have a bigger tendency to be off-and-on. It was considered that the target surface was damaged more in case No. 1-3 than in the case No. 1-1 because the impact load contained more high-frequency vibration and instantaneous load was larger in case No. 1-3. The fact that more high-frequency vibration were produced in case No. 1-3 might be resolved when the mesh size of the shell elements for the fuselage became smaller and then the contact between the shell elements and the target had less tendency to be off-and-on. But decreasing the mesh size contributes increasing simulation time, then the failure strains of case No.1-3 were determined to be inappropriate in our study.

Figure 13 shows the changes in velocity at nodal points A, B, and C in the simulation of case No. 1-4. The changes were noted to be larger than in the case No. 1-1 and the difference from the test results became larger. These simulation results were reasonable because the reduction in velocity became larger as the shell thickness became larger. From these
results, the value of 1 mm thickness for the shell elements of the fuselage and wings was appropriate for the aircraft model in our study.

From these simulation results, it was revealed that the thickness and failure strain of the shell elements denoted in case No. 1-1 were the most reliable for the aircraft model to reproduce the impact test results.

Table 4 Thickness and failure strain of shell elements

| Case No. | Failure strain | Thickness |
|----------|----------------|-----------|
|          | Fuselage | Wings |         |
| 1-1      | 1.8      | 0.1    | 1 mm    |
| 1-2      | 1.8      | 1.8    |         |
| 1-3      | 0.1      | 0.1    |         |
| 1-4      | 1.8      | 0.1    | 2.5 mm  |

Fig. 4 Aircraft impact simulation results in case No. 1-1 (0.1 seconds after the impact)

Fig. 5 Destruction state of RC wall in case No. 1-1

Concrete destroyed.

RC wall fix plate

1st layer: light green
2nd layer: light blue
3rd layer and so on: brown

Fig. 6 Comparison of change in velocities in case No. 1-1

Fig. 7 Impact load in case No. 1-1

Fig. 8 Impulse from simulation in case No. 1-1 and test results
Fig. 9 Velocity of RC target after impact in case No. 1-1

Fig. 10 Destruction state of aircraft in case No. 1-2
(0.1 seconds after the impact)

Fig. 11 Destruction state of RC wall in case No. 1-3

Fig. 12 Impact load in case No. 1-3

Fig. 13 Comparison of change in velocities in case No. 1-4
In the previous chapter, the aircraft model was established. The impact simulation of the aircraft into the RC target was conducted and then the impact test results was reproduced. When a small aircrafts impacts into a RC wall, both the aircraft and the RC wall are damaged and the aircraft is decelerated even if it perforates the wall. When an aircraft impacts into a RC building and goes inside the building, it hits several inner RC walls which decelerate it and it ends up stopped somewhere inside the building. It is necessary to evaluate how far an aircraft goes inside the building and how large an area inside the building is damaged. One of the evaluation methods is a numerical simulation but it takes long time especially when several RC walls need to be modeled.

Another evaluation method uses theoretical and empirical equations. When an aircraft impacts into a RC wall, the aircraft receives the impact load from the wall and is decelerated. Because the velocities of the aircraft before or after the perforation are same at any point of the aircraft, these two velocities are denoted as follows;

\[ (m v + \sum_{i} m_i v_i') - m_0 v_0 = F \cdot \Delta t \quad (1) \]
\[ \Delta t = \frac{2L}{(v + v_0)} \quad (2) \]

Here \( m \) and \( v \) are the aircraft mass and the residual velocity of the aircraft in the impact direction after the perforation. \( m_0 \) and \( v_0 \) are the initial aircraft mass and the initial velocity of the aircraft. \( m_i' \) and \( v_i' \) are the mass and the velocity in the impact direction of \( i \)-th portion of the scattered debris and fuel after the perforation. \( F \) is the average of the impact load during \( \Delta t \), \( \Delta t \) is the duration of the impact and \( L \) is the summation of the RC wall thickness and the representative length of an aircraft such as the length of fuselage. Substituting Equation (2) into Equation (1) under the condition that \( |m_0 v| >> \sum_{i} m_i v_i' \), equation (3) is derived. This condition is correct when little debris and fuel are scattered, or the velocities of the scattered objects are much smaller, or both.

\[ m v = F \cdot \frac{2L}{(v + v_0)} + m_0 v_0 \quad (3) \]

When above condition is met and \( F \) is estimated, \( v \) can be calculated by equation (3). By conducting this calculation one after another for each impact during sequential impacts into several inner RC walls inside a RC building, how many inner walls are perforated before the aircraft stops is evaluated. The average of the impact load \( F \) which an aircraft receives from a RC wall during the perforation is equal to the dynamic punching strength \( F_p \) [N] of the RC wall. The dynamic punching strength is estimated by following equations reported by the UKAEA (United Kingdom Atomic Energy, 1990)

\[ F_p = 8170 \left( R f_{cu}\right)^{1/3} \pi D(T+2.5T) \quad (4) \]
\[ R = \left( \frac{n_i a_i}{l} + \frac{n_w a_w}{w} \right)^{50} T^{-1} \quad (5) \]

Here, \( R \) is the effective reinforcement quantity [%], \( n_i \) and \( a_i \) are the numbers of rebar in length and width directions, \( a_i \) and \( a_w \) the rebar cross section areas [m²], \( l \) and \( w \) are the wall length and the width[m], \( f_{cu} \) is concrete compressive strength[Pa], \( D \) is the aircraft mean cross section diameter[m], \( T \) is the concrete effective thickness[m], which is the concrete thickness minus its cover thickness, and 8170 is the constant [N^{2/3}·m^{4/3}].

The formula (4) estimates the dynamic punching strength most accurately, when the impact load duration exceeds the time needed to reach the maximum plate deflection. The UKAEA also reports that the equations may make reliable predictions of all levels of target damage and may be used confidently over the following ranges;

\[ 0.07 < T < 0.90 \quad (6) \]
\[ 0.66 < D/T < 1.30 \quad (7) \]
\[ 0.22 < R < 1.26 \quad (8) \]

Wall thicknesses of a reactor building is often over 1000 mm, especially at an outer wall. In addition, for example, the F4 Phantom fighter impact area at the impact test was about 10 m² (Sugano et al., 1993), and the aircraft mean cross section diameter \( D \) is estimated to be about 3.57 m when \( D \) of the aircraft is assumed to be same as the mean diameter of the impact area at the test. And then \( D \) over \( T \) is 1.428, which is out of range of equation (7) even if the thickness of RC wall is 2.5 m, which is categorized as a thick RC wall in a RC building. Therefore, when the aircraft impact by a small aircraft is considered, the estimated dynamic punching strength by the UKAEA equation may include some errors.
When a residual velocity of an aircraft after its perforating a RC wall is estimated by equation (3), it is expected to calculate the dynamic punching strength of the RC wall with small errors. Then, the possible causes of the error in equation (4) should be investigated especially when the UKAEA equation is applied out of ranges of equations (6) to (8). One of the causes of the error in the UKAEA equation might be selecting aircraft mean cross section diameter \( D \) as a coefficient related to an affected area on the RC wall at impact, especially when the RC wall bends severely and then the diameter of the perforated area on the RC wall is larger than the aircraft mean cross section diameter. Figure 14 shows the schematic drawing of this situation. Because the diameter of the perforated area is larger than the aircraft mean cross section diameter as illustrated in Figure 14, we assumed that a diameter of the perforated area \( D' \) appeared after the perforation of a RC wall might be a better choice for the coefficient related to an affected area in the UKAEA equation.

In order to check this assumption, we conducted several impact simulations with different RC wall thicknesses by the aircraft established in the previous chapter. These impact simulations were used to obtain the impact loads which the aircraft received from the RC wall with different thicknesses. Then, these impact loads were compared with the dynamic punching strengths estimated by the UKAEA equation. First, the aircraft mean cross section diameter \( D = 3.57 \) m was used for the estimation. Next, the diameter of the perforated area \( D' \) appeared after the impact in each simulation with different RC wall thicknesses were measured. And then the impact loads in simulations were compared with the dynamic punching strengths estimated by the UKAEA equation using \( D' \).

### 3.2 Model configurations

Figure 15 shows the simulation model of the aircraft and RC wall. We utilized the aircraft model established in the previous chapter for these simulations. Table 5 shows the specifications of the RC wall. The concrete of the RC wall was modelled by solid elements and the rebar was modelled by beam elements. The material properties of the concrete and the rebar were summarized in Table 6 and Table 7. Figure 16 shows the dimensions of the RC wall and boundary conditions. The height was 30 m, about the height of a three-story RC building, and the width was 60 m. When a dynamic punching strength of a RC wall at impact is considered, RC wall is usually supported around corners or edges of the wall and projectile hits into the middle of the wall. Because comparing the dynamic punching strength estimated by the UKAEA equation with the impact load obtained in simulations was the main purpose in this chapter, bending failure of the RC wall had to occur in simulations. In order to cause bending failure on the RC wall easily, columns which are usually employed in wide RC walls, were not employed inside the RC wall. The dotted line of the 60 m-wide RC wall in figure 16 indicates that a floor and a ceiling existed behind the wall, and the boundary condition on these 2 lines was x-direction-displacement constraint. The solid line of the RC wall indicates that side walls, floor and ceiling existed behind the wall and the boundary conditions on these 4 lines were assumed as the displacement constraint condition. Grids of rebars were installed on both sides of the wall. Impact velocity of the aircraft was fixed at 215 m/s, which was the same as the impact test velocity.
### Table 5 Specifications of RC wall

| Case No. | Thickness (mm) | Diameter of rebar (mm) |
|----------|----------------|------------------------|
| 2-1      | 250            | φ13                    |
| 2-2      | 450            | φ16                    |
| 2-3      | 600            | φ19                    |
| 2-4      | 800            | φ29                    |
| 2-5      | 1000           | φ35                    |
| 2-6      | 1400           | φ35                    |
| 2-7      | 1800           | φ35                    |

### Table 6 Material properties of concrete

|                       |                |
|-----------------------|----------------|
| Density               | 2500 kg/m³     |
| Poisson ratio         | 0.19           |
| Young modulus         | 27 GPa         |
| Compressive strength  | 33 MPa         |
| Erosion criterion     | Max principal strain: 20% |

### Table 7 Material properties of rebar

| Property                          | Value                        |
|-----------------------------------|------------------------------|
| Diameter                          | Noted in Table 5             |
| Density                           | 7850 kg/m³                  |
| Poisson ratio                     | 0.3                          |
| Young modulus                     | 206 GPa                     |
| Yield strength                    | 345 MPa                      |
| Ultimate strength                 | 495 MPa                      |
| Failure strain                    | Effective strain: 6%         |
| Amount of rebar                   | Vertical×Horizontal: 300×150 (1 layer each at front and back sides) |
| Interval of rebar                 | Vertical: 200 mm             |
|                                   | Horizontal: 200 mm           |

![Fig. 16 Size of RC wall model for impact simulation](image_url)

**3.3 Simulation results**

Figure 17 and Figure 18 show the destruction states of the simulation models in case No. 2-1 and No. 2-7 in Table 5. In both cases, the RC wall was perforated. In No. 2-1, most components passed through the wall and the aircraft was not severely damaged. In contrast, in case No. 2-7, most of the components were remained in front of the RC wall and the aircraft body was totally crushed. The damage to the aircraft was smaller in Figure 17 than in Figure 18. This result was plausible because the thicker the RC wall is, the more severe the damage to the aircraft becomes.

Figure 19 shows the damage states of the RC wall in each simulation in Table 5. When the wall thickness was between 250 mm and 600 mm, the shape of the perforated area indicated two types of areas, one was the area the fuselage perforated and the other was the area the wings perforated. When the wall thickness was over 600 mm, the shape of the perforated area was more like ellipse and the perforated area was not separated by areas where the fuselage and the wings went through. When the perforated area was separated into two areas, the diameter of perforated area $D'$ also needed to...
be evaluated separately by fuselage and wings. The main purpose in this chapter was to check the assumption that using a diameter of perforated area $D'$ as a substitute of coefficient $D$ in the UKAEA equation would estimate a dynamic punching strength better when a bending failure of an RC wall occurred. Thus, we did not take into consideration the complex situations where different $D'$ must be investigated for fuselage and wings separately at impacts. In figure 19, the diameters of the perforated areas $D'$ were measured and denoted in each figure.

Figure 20 shows the impact loads from case No. 2-4 to case No. 2-7. In each figure, the average of the impact loads were indicated. The duration of the impact for calculating average of the impact load was set between the beginning and the end of the impact in each simulation. The thicker the RC wall became, the larger the average of the impact load became as shown in Figure 20.

The dynamic punching strength was estimated with the UKAEA equation using $D$ as a coefficient in the first place. In this estimation, $D = 3.57 \text{ [m]}$ mentioned in section 3.1 was used. Figure 21 compares the impact loads in the simulations with the estimated dynamic punching strengths. From this figure, it was found that the dynamic punching strengths did not match with the impact loads in the simulations. When the thickness was smaller than around 1600 mm, the impact loads in simulations were larger than the dynamic punching strengths. On the other hand, the impact loads in simulations were smaller than the dynamic punching strengths when the thickness was over around 1600 mm.

Figure 22 summarizes the diameters of the perforated areas $D'$ of the RC walls in each simulation with different RC wall thicknesses, which were indicated in Figure 19. It was found that the diameter was larger than the value 3.57 m when the thickness was smaller than around 1600 mm. The diameter was smaller than the value 3.57 m when the thickness was larger than 1600 mm. Figure 23 compares the impact loads in simulations with the estimated dynamic punching strength under the conditions that $D'$ was used as a coefficient. The dynamic punching strengths were in good agreement with the simulation results in Figure 23.

From the results in Figure 21 and Figure 23, it was revealed that the dynamic punching strength was estimated more accurately when the diameter of the perforated area $D'$ was used as a coefficient in the UKAEA equation rather than the aircraft mean cross section diameter $D$. This was because $D'$ on the RC wall was larger than $D$ when the RC wall thickness was thin and then it bent a lot at the aircraft impact. On the other hand, $D'$ on the RC wall became smaller than $D$ when the RC wall thickness was thick and it bent a little, therefore only the middle of the affected area on the RC wall was perforated at the aircraft impact.
(a) Dispersion state after the impact
(b) Destruction state of the aircraft (shell elements only)

Fig. 18 Destruction state of whole simulation model by the impact into 1500-mm-thick RC wall in case No. 2-7
(0.2 seconds after the impact)

(a) 250-mm-thick RC wall  (b) 450-mm-thick RC wall
(c) 600-mm-thick RC wall  (d) 800-mm-thick RC wall
(e) 1000-mm-thick RC wall  (f) 1400-mm-thick RC wall
(g) 1800-mm-thick RC wall

Fig. 19 Destruction state of RC wall due to the impact (destruction of concrete is modelled by erosion of elements)
Fig. 20 Impact load at each RC wall thickness

(a) 800-mm-thick RC wall
- Impact load: 41.1 MN

(b) 1000-mm-thick RC wall
- Impact load: 50.1 MN

(c) 1400-mm-thick RC wall
- Impact load: 58.3 MN

(d) 1800-mm-thick RC wall
- Impact load: 63.5 MN
Fig. 21 Relationship between impact loads in simulations and estimated dynamic punching strengths with $D = 3.57$ m

Fig. 22 Relationship between measured diameter of the perforated area and RC wall thickness

Fig. 23 Relationship between impact loads in simulations and dynamic punching strengths by UKAEA equation using the measured diameter of the perforated area $D'$

Table 8 Calculation results by UKAEA equation

| No. | Thickness | $T^\text{a}$ | $D$ | $D'$ | $F_p$ | Note                  |
|-----|-----------|--------------|-----|------|-------|-----------------------|
| 1   | 800 mm    | 700 mm       |     |      | 19.0 MN |                       |
| 2   | 1000 mm   | 900 mm       |     |      | 33.8 MN | Plotted in Figure 21 |
| 3   | 1400 mm   | 1300 mm      | 3.57 m |      | 51.1 MN |                       |
| 4   | 1800 mm   | 1700 mm      |     |      | 70.5 MN |                       |
| 5   | 800 mm    | 700 mm       |     | 8.0 m | 34.8 MN | Plotted in Figure 23 |
| 6   | 1000 mm   | 900 mm       |     | 6.9 m | 53.1 MN |                       |
| 7   | 1400 mm   | 1300 mm      |     | 4.4 m | 57.3 MN |                       |
| 8   | 1800 mm   | 1700 mm      |     | 3.2 m | 67.2 MN |                       |

*a concrete effective thickness = concrete thickness – concrete cover thickness, 100 mm
4. Conclusion

Impact simulations into RC walls by the aircraft model were conducted in this study. The findings in this study are summarized as follows;

- In the impact simulation using the aircraft model whose mass distribution was the same as the aircraft used in the test, the impact test results such as the impact load history, the impulse by impact, the deformation of the aircraft, and the destruction state of the RC target were reproduced. Although the structure of the aircraft model did not reproduce the design information in detail such as the shape of stringers inside the aircraft body, the simulation results were in good agreement with test results. It was found that the detailed design information of the aircraft was not so important for analysis of aircraft impacting into RC buildings.

- In the aircraft impact simulations, a parameter study for the shell elements of the aircraft body was conducted. The appropriate failure strain for the fuselage and the wing shell elements were 1.8 and 0.1, respectively. The appropriate thickness of these shell elements was 1 mm. From these sensitive analysis results, it was found that the thickness and the failure strain of the shell elements affected the simulation results such as destruction states of the RC walls.

- It was revealed that the dynamic punching load of the RC wall was estimated more correctly by the UKAEA equation when a diameter of a perforated area $D'$ on the RC wall was used as a coefficient in the equation. The diameter of the perforated area on the RC wall can be measured from an impact simulation result.

- When a aircraft mean cross section diameter $D$ was used for the coefficient in the UKAEA equation under the condition that the RC wall thickness was thin, dynamic punching strength was estimated less than the actual value. This was because the thin RC wall bended a lot at the aircraft impact and the diameter of the perforated area on the wall was often larger than the aircraft mean cross section diameter.

References

Agardh, L., Laine, L., 3D FE-simulation of high-velocity fragment perforation of reinforced concrete slabs, Int. J. Impact Engrg., Vol. 22, (1999), pp 911-922.

Iwasaki, K., Miyaki, H., Shoji, H., Minegishi, M., Data Base for High Velocity Strain- Rate Properties Data of Aircraft Aluminum Alloys, JAXA-RM-12-010, JAXA Research and Development Memorandum, (2013). (in Japanese)

Lee, K., Jung, J-W., Hong, J-W., Advanced aircraft analysis of an F-4 Phantom on a reinforced concrete building, Nucl. Engrg. Des., Vol. 273, (2014), pp. 505-528.

Nuclear Energy Institute ed., Methodology for Performing Aircraft Impact Assessments for New Plant Designs ,NEI 07-13 Revision 8P, Nuclear energy institute, (2011).

Sugano, T., Tsubota H., Kasai, Y., Koshika, N., Orui, S., Riesemann, W.A., Bickel, D.C., Parks, M.B., Full-scale aircraft impact test for evaluation of impact force, Nucl. Engrg. Des., Vol. 140, (1993c), pp. 373-385.

Tai, Y-S., Tang, C-C., Numerical simulation: The dynamic behavior of reinforced concrete plates under normal impact, Theoretical and Applied Fracture Mechanics, Vol. 45, (2006), pp. 117-127.

United Kingdom Atomic Energy Authority ed., Guidelines for the design and assessment of concrete structures subjected to impact, SRD R 436 Issue 3, (1990), UK Atomic Energy Authority.