Transactions, SMiRT-23
Manchester, United Kingdom - August 10-14, 2015

Division III, Paper ID 115

Numerical impact simulation of aircraft into reinforced concrete wall

Kazuma Hirosaka[1], Motoki Nakane[2], Satoshi Saigo[3], and Norihide Tohyama[2]

[1] Simulation Engineer, Hitachi Research Laboratory, Hitachi, Ltd., Japan
[2] Senior Technical Staff Engineer, Hitachi-GE Nuclear Energy, Ltd., Japan
[3] Engineer, Hitachi-GE Nuclear Energy, Ltd., Japan

ABSTRACT

A safety assessment needs to be conducted to analyze the damage caused by an aircraft crashing into a concrete structure at a nuclear power plant. One of the analytical methods used for this is a numerical impact simulation conducted after the aircraft and reinforced concrete (RC) models have been determined. To determine these models, the results of impact simulations of an F4 Phantom fighter and its engines crashing into RC walls were compared with the results of a test conducted at Sandia National Laboratories (Muto 1989, Riesemann 1989). First, we conducted impact simulations of F4 Phantom engines (GE-J79) crashing into three different wall thicknesses of 900, 1150, and 1600 mm and then compared the damage to the wall in the simulation with the test results (Sugano 1993). Because these simulation results agree with the test results, the RC model was verified. Next, an impact simulation of an F4 Phantom crashing into an RC wall was conducted. The shape of the load function was the same as that of the test results, and most F4 frames broke into pieces on impact, which is also the same as the test results. These results validate the F4 model. Finally, an impact simulation of a large commercial aircraft crashing into an RC wall was conducted. We developed the aircraft model in the same way as we developed the F4 Phantom model. The shape of the load function in the impact simulation was the same as the shape of the estimated load function by Riera's method, which indicates that the methodology of modelling an aircraft and the established RC model can be used for impact simulations with any commercial aircraft crashing into an RC wall.

INTRODUCTION

A safety assessment needs to be conducted to analyze the damage caused by an aircraft crashing into the concrete structure at a nuclear power plant. The simulation model of the aircraft and the reinforced concrete (RC) used in the walls of the concrete structure should be established before impact simulation is conducted.

Many tests in which solid missiles are launched at RC targets have been conducted. By using these test data, several empirical formulae for predicting the penetration depth, scabbing thickness, and perforation thickness of the RC target have been proposed (NDRC 1946, Degen 1980, Chang 1981, UKAEA 1990). Impact tests using an actual aircraft engine were also conducted to take into consideration the effect of non-deformability of an aircraft engine on the destruction state of the RC target. These test results were used to estimate the reduction factors for each empirical prediction formula (Sugano 1993). With these formulae and reduction factors, the penetration depth, scabbing, and perforation thickness of an RC target after an aircraft engine impact can be predicted.

Impact tests using an actual aircraft are rarely conducted because a lot of preparation is needed for this kind of test. However, an impact test using a military aircraft (F4 Phantom fighter) crashing into an RC target was conducted in 1988. After this test, several impact simulations based on an F4 fighter were conducted, and their results were compared with the 1988 test results (Lee 2014). To establish an aircraft model for the impact simulation, it needs to be confirmed whether the results of the impact simulation based on an F4 Phantom model agree with the test results.

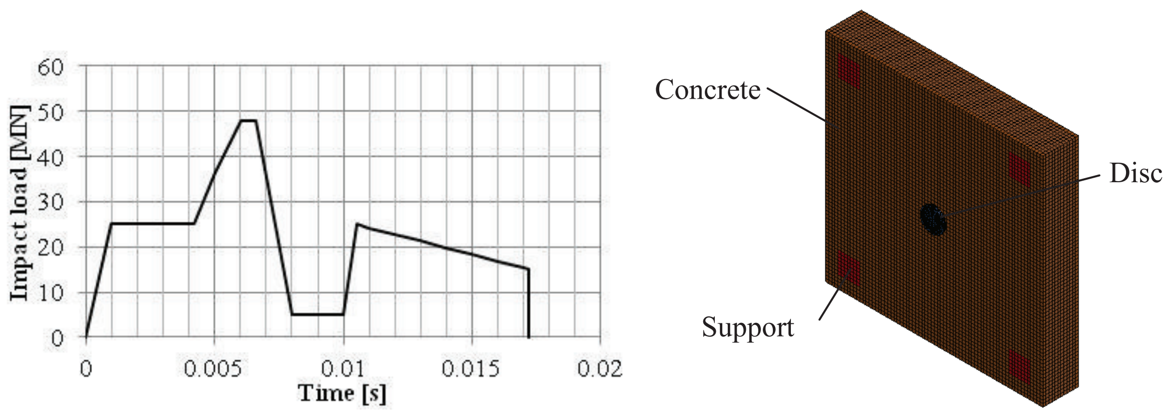
In this paper, the RC model was established first. Impact simulations of an aircraft engine missile crashing into the RC model were conducted and compared with the test results to check if the simulations with our RC model agree with them. Next, the F4 Phantom model was established. The results of the impact simulation based on the F4 Phantom crashing into the RC model were compared with the test results to check if our simulation reproduced the test results. These results include the load function, impulse caused by the impact, deceleration, and crash state of the F4 fighter. Finally, a large commercial aircraft model was established in the same way as the F4 Phantom fighter model. The impact simulation with the commercial aircraft model and an RC wall was conducted, and the impact load was compared with the load function obtained by Riera's method to check the validity of the aircraft model.
The dynamic finite element program LS-DYNA® was selected for running these numerical impact simulations because many impact simulations with an RC target using this program have been previously reported (Agardh 1999, Tai 2006), and this program is recognized as one of the best for simulating impacts.

REINFORCED CONCRETE MODEL

We need to establish an RC model for the aircraft impact simulation. We selected the Karagozian & Case concrete (KCC) model (MAT_72) from among the concrete models prepared with LS-DYNA® because it has appropriate concrete properties (Crawford 2011, Wu 2012). In this section, the impact simulation of an aircraft engine was conducted in the same way as the impact tests described in the paper (Sugano 1993) to check to see if the KCC model is applicable for an aircraft impact simulation. Table 1 specifies some of the impact test conditions described in that paper. It includes RC target conditions such as dimensions, properties of the concrete and rebar, and boundary. Three cases were selected for simulation from among the many that were conducted in the impact tests because the destruction state of the target differs among the tests of wall thicknesses of 1600, 1150, and 900 mm. The impact load used in the simulation is shown in Figure 1 (a). This load function was obtained from the test data (Sugano 1993). Figure 1 (b) shows the configuration of the simulation model. This model consisted of the concrete, rebar, support, and disc. The load function was applied to the disc, and the disc hit the concrete and rebar; thus, the disc represented a missile. The concrete, supports, and disc meshes were cubic solid, and the mesh sizes of the concrete and support were 100 × 100 mm. The rebar was modelled based on the beam and the 100 mm mesh. The properties of this simulation model had the same values as those of the test materials classified in Table 1. In our simulation, the destruction of the concrete was modelled by deleting the concrete meshes exhibiting maximum effective strain and maximum effective stress.
The test results, such as the destruction state of the RC target after impact, are described in the paper (Sugano 1993). These test data were compared with the impact simulation results. Figures 2 - 4 show the simulation results when the RC target thickness was 900, 1150, and 1600 mm, respectively. The perforation, scabbing, and penetration of the RC targets were observed for each target thickness. These simulation results are consistent with the test results (Sugano 1993). Table 2 compares the penetration depths on the front side and the displacements of the rebar or concrete on the back side of the RC target with the test results. These results show that the value differences between the test and simulations are within 30 mm, except the rebar displacement at 900 mm and the penetration depth at 1600 mm. The reasons for these exceptions are as follows. First, the size of the concrete mesh was 100 × 100 mm, and the penetration depth of 70 mm was not reproduced at 1600 mm. Second, there was no piece of concrete scabbed from the back side of the RC target after the scabbing in the simulation because the destruction was simulated by deleting these pieces of concrete. In the actual test of the 900-mm-thickness target, the scabbed pieces of concrete destroyed the rebar around the centre of the back side, and the displacement value of the test denoted in Table 2 is the value of the rebar that was not destroyed. The back-side rebar was not destroyed by concrete pieces in the simulation, so the displacement value in the simulation denoted in Table 1 is the value of the centre rebar. It was confirmed from the results denoted in Table 1 that the RC target using the KCC model is applicable for impact simulation of an aircraft engine.

Table 1 Impact test conditions

Item			Values
RC target			
	Concrete	Thickness	900, 1150, 1350, and 1600 mm
		Area	7000 × 7000 mm
		Strength	23.5 MPa
	Rebar	Diameter	32.1, 35.8 mm
		Yield strength	488.7, 466.5 MPa
		Ultimate strength	744.4, 732.9 MPa
		Number	35 × 35 (1 layer each at front and back sides)
	Boundary		Fixed at corners
Aircraft engine missile			
	Diameter		760 mm
	Mass		1760 kg
	Impact speed		215 m/s



(a) Impact load on disc (b) Configuration of simulation model

Fig. 1 Load function and configuration of simulation model

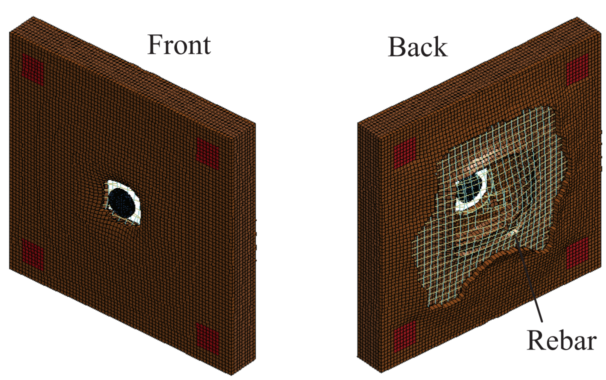


Fig. 2 Simulation and test results (900 mm)

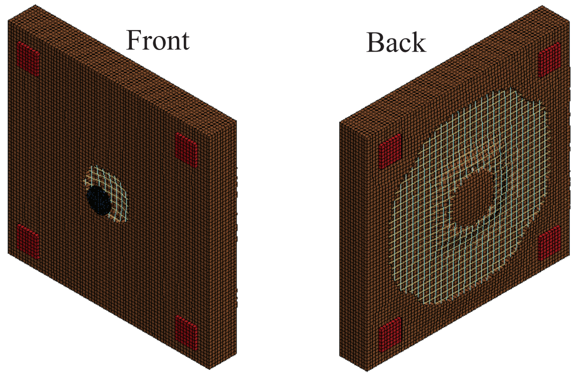


Fig. 3 Simulation and test results (1150 mm)

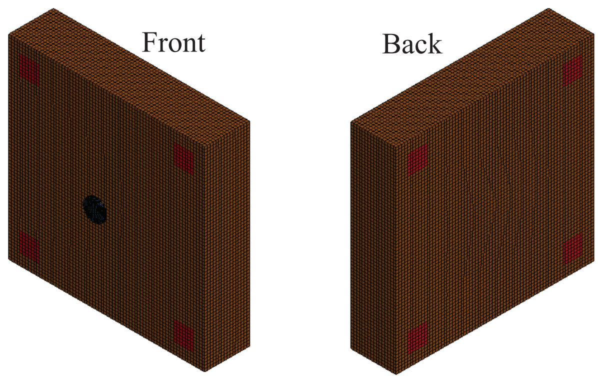


Fig. 4 Simulation and test results (1600 mm)

Table 2 Comparison of simulation and test results

Target thickness [mm]	Point	Measured item	Test result [mm]	Simulation results [mm]
900	Front	Destruction mode	Perforation	Perforation
	Back	Max displacement (non-destructed rebar)	600	782
1150	Front	Penetration depth	270	300
	Back	Max displacement (non-destructed rebar)	300	301
1600	Front	Penetration depth	70	0
	Back	Max displacement	35	26.8

AIRCRAFT MODEL

It was confirmed in the previous chapter that the KCC model is valid for reproducing the destruction state of an RC target due to the impact of an aircraft engine missile. In this chapter, the impact simulation of a small aircraft model is discussed.

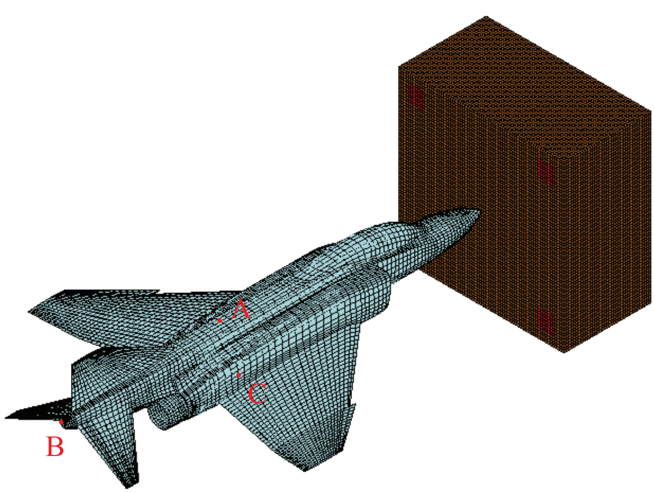
An impact test using military aircraft (F4 Phantom fighter) was conducted, and a lot of valuable data were obtained. The test conditions and results are summarized in the paper (Sugano 1993). Table 3 summarizes the configuration of the aircraft, and Figure 5 (a) shows the simulation model of this aircraft, which was established by using shell elements and smoothed particle hydrodynamics (SPH) elements. The nodal points A, B, and C are the middle point and end point of the aircraft and the middle point of the engine, respectively, and correspond to points J7, J12, and J13 in the test so that the speed data of these points can be compared with the test data (Sugano 1993). The mass distribution of the aircraft is shown in Figure 5 (b), where the solid line is the actual data and the dotted line is the input data for the simulation model. Aluminium alloy was assumed to be the material used in the aircraft model, and the fracture strain was also considered. The RC target model was almost the same as the one established in the previous chapter. Only its thickness was different at 3700 mm, which is close to the thickness of the target used in the impact test, which was 3660 mm.

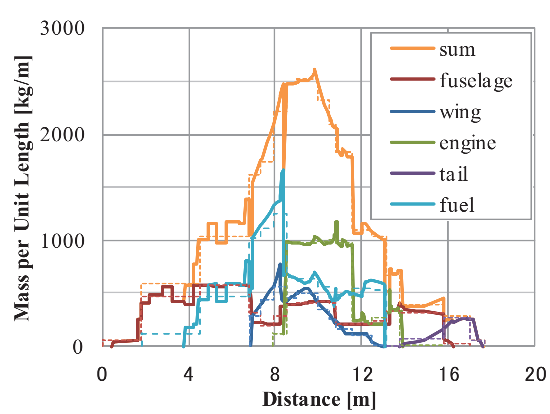
Figure 6 shows the impact simulation results. The whole aircraft body broke into pieces in the same way as in the test results. The small sphere represents the SPH elements, and it scattered after the impact. The destruction mode of the RC target was light penetration, and only part of the impact area on the first layer of the concrete was damaged, which is similar to the test results. Figure 7 shows the speed reductions at nodal points A, B, and C in the simulation and corresponding test data (J7, J12, and J13). The biggest difference in these reductions between the simulation and test results during the impact is about 20 [m/s] at point B at 0.05 [s], and the speed reductions in the simulation are generally larger than those in the test data by about 10-20 [m/s]. These differences are not so dominant compared with the impact speed of 215 [m/s] and only slightly affect the simulation results of, for example, load function and impulse. Figure 8 (a) shows the impact load function. This figure indicates that the shape of the simulation results, which were filtered at a low-pass of 1000 Hz to eliminate the simulation noise, is almost the same as that of the test results, and the difference in the maximum load between the simulation and test results is within 2%. Figure 8 (b) shows the impulse caused by the impact both in the simulation and test. This figure shows that the impulse after a crash in the simulation is 3.47 [MN･s], and the difference from the test results is within 8%.

Since the simulation results, such as the deformation state and deceleration of the F4 Phantom after the impact, and the impact load and impulse were reproduced in the simulation, we can see that our aircraft model is validated for an impact simulation that uses the KCC model as the RC concrete model.

Table 3 Configuration of F4 Phantom fighter

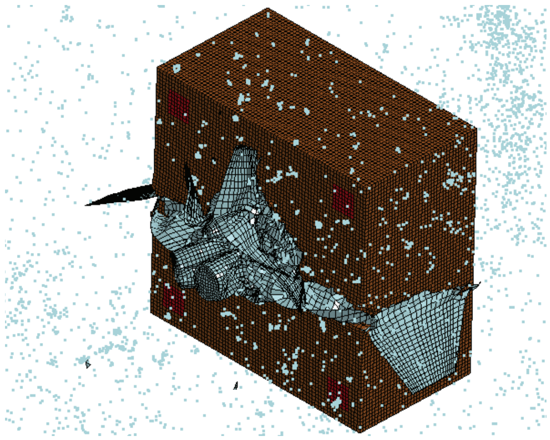
Item	Aircraft length	Wing span	Aircraft height	Weight	Impact speed
Values	17.74 m	11.77 m	5.02 m	17.5 tons	215 m/s

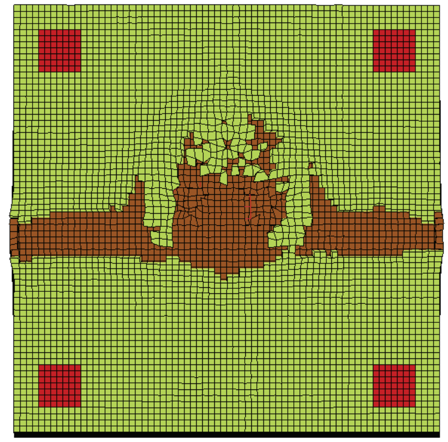




(a) Configuration of simulation model (b) Mass distribution of F4 Phantom

Fig. 5 F4 Phantom impact simulation model (3700 mm)





(a) State of aircraft body on impact (b) State of RC wall on impact

Fig. 6 F4 Phantom impact simulation results

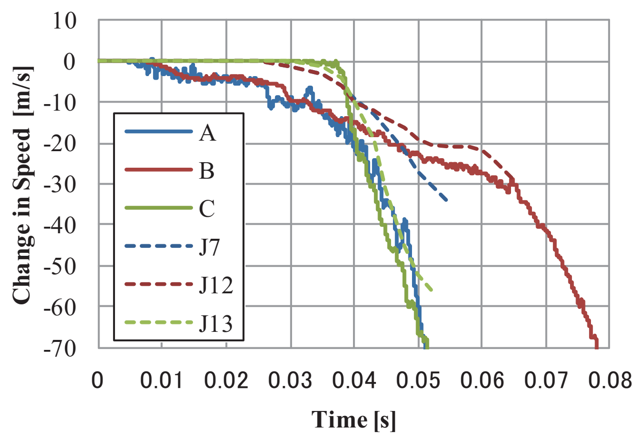
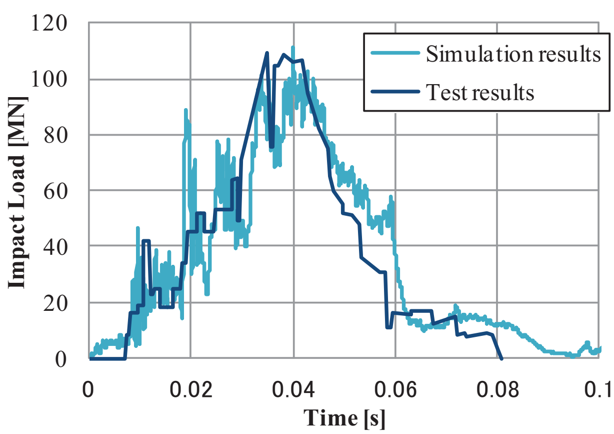
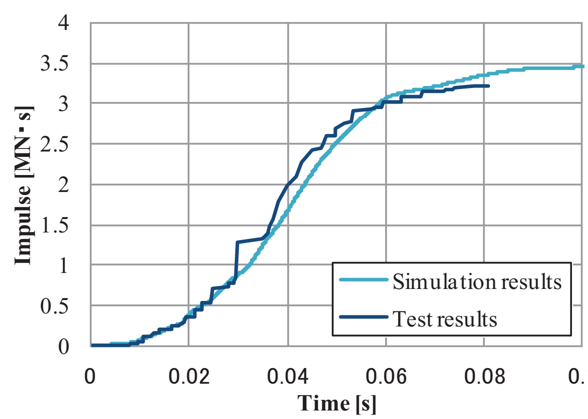


Fig. 7 Comparison of speed reduction





(a) Impact load function (b) Impulse on impact

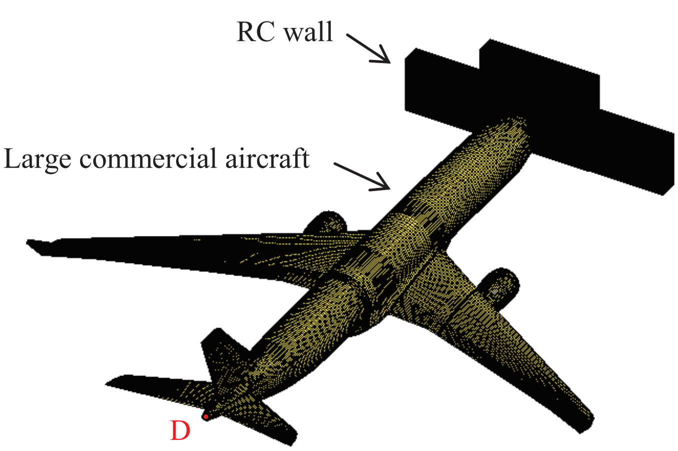
Fig. 8 Comparison of impact load and impulse between simulation and test

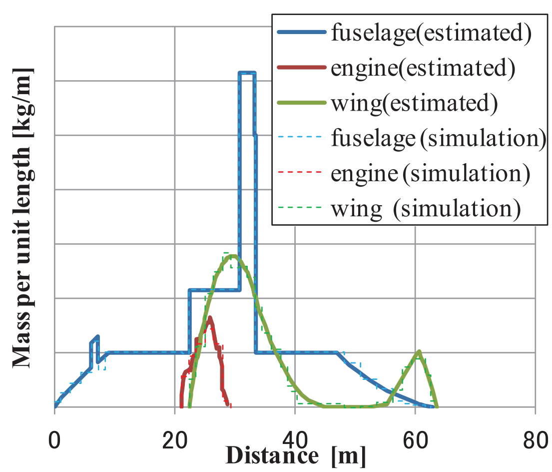
IMPACT SIMULATION OF LARGE COMMERCIAL AIRCRAFT MODEL

The impact simulation of an F4 Phantom fighter crashing into an RC wall was conducted in the previous chapter. The load function, destruction state of the aircraft body and RC target in the simulation agree with the test results. This indicates that the simulation model of an F4 Phantom fighter was valid. Next, development of a simulation model of a large commercial aircraft is discussed in this chapter. The validity of the model was confirmed when the load function on impact in the simulation was the same as the function derived by Riera's method.
Table 4 summarizes the specifications of the large commercial aircraft in this study. Figure 9 (a) shows the simulation model of this aircraft. The shell elements and SPH elements were used for the model, which was the same as the model of the F4 Phantom fighter. The shell elements consisted of fuselage, wing, and nacelle. The SPH elements consisted of fuel, engine, and weight on board, such as system equipment, undercarriage, and payload. Nodal point D is at the end point of the fuselage of the simulation model so that the reduction of speed on impact could be compared with the estimated speed reduction by Riera's method. The mass distribution of the aircraft is shown in Figure 9 (b), where the solid line is the one obtained from the mass estimation of each component of the large commercial aircraft and the dotted line is the input data for the simulation model. The material properties of the shell elements were assumed to be the same as those of the F4 Phantom fighter, and the material properties of aluminium alloy were applied. Figure 10 shows the RC target model. The thickness of the RC wall was 2000 mm. The reinforcement was installed vertically and horizontally at 200 mm intervals on both sides, and these reinforcements were buried 100 mm from the front and back surfaces. The support of the wall was installed at 10 locations, and the rear faces around these supports were fixed. Tie bars were also installed inside the RC wall to resist the impact load of large commercial aircraft. The intervals of these tie bars were also set to 200 mm.

Table 4 Configuration of large commercial aircraft

Item	Aircraft length	Wing span	Aircraft height	Weight	Impact speed
Values	17.74 m	11.77 m	5.02 m	17.5 tons	190 m/s





(a) Configuration of simulation model (b) Mass distribution of large commercial aircraft
Fig. 9 Impact simulation model of large commercial aircraft

Figure 11 shows the impact simulation results. The whole aircraft body broke into pieces. Figure 12 shows the destruction mode of the RC target. It was damaged but not perforated. This indicates that the specifications of the reinforcement and the tie bar were sufficient to protect the RC wall against the impact of the aircraft. Figure 13 shows the speed reductions at nodal point D in the simulation and the estimated speed reduction by Riera's method. The difference between them during the impact is within 40 [m/s] and is not so significant compared with the impact speed of 190 [m/s] and thus only slightly affects the simulation results of, for example, load function and impulse. Figure 14 (a) shows the impact load function. This figure indicates that the shape of the simulation results, which were filtered at a low-pass of 1000 Hz to eliminate the simulation noise, is almost the same as that of the estimated results, and the difference in the maximum load between the simulation and the estimated results is about 4.7 %. Figure 14 (b) shows the impulse after the impact both in the simulation and the estimation. This figure shows that the impulse in the simulation agrees with the estimated results and the difference from the estimation at around 400 [ms] is about 7 %.

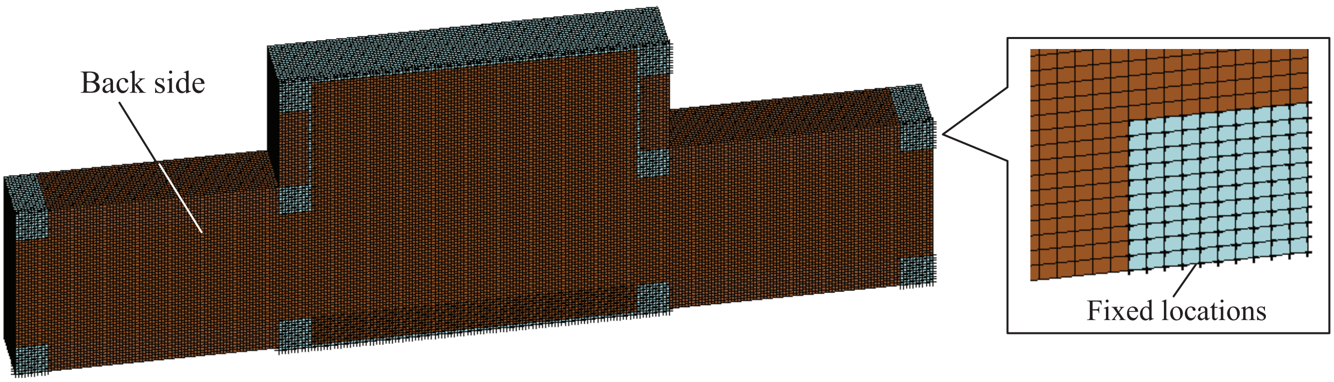
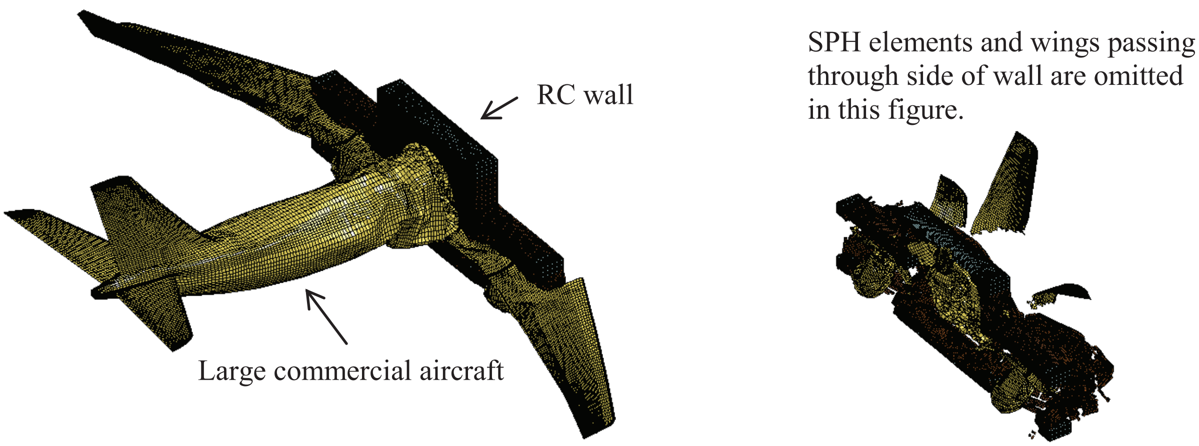


Fig. 10 RC wall model for impact simulation of large commercial aircraft



(a) t = 0.18 (s) after impact

(b) t = 0.36 (s) after impact

Fig. 11 State of large commercial aircraft on impact in simulation

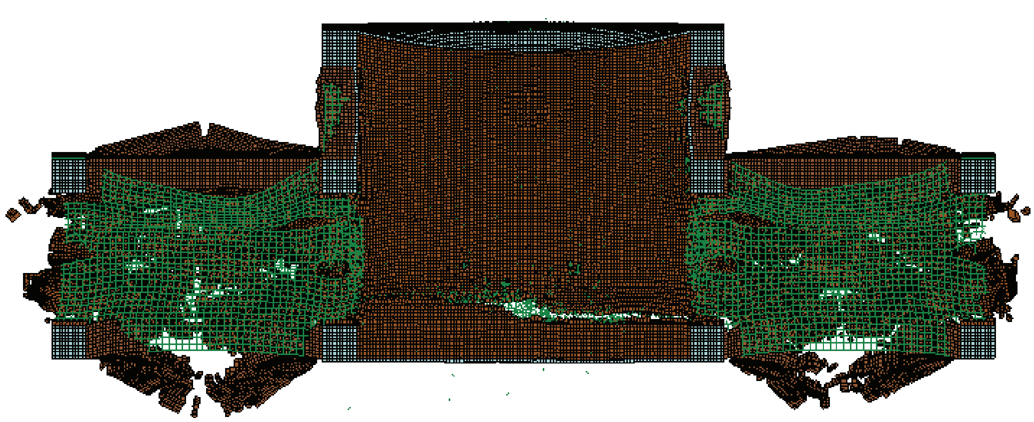


Fig. 12 State of RC wall on impact in simulation

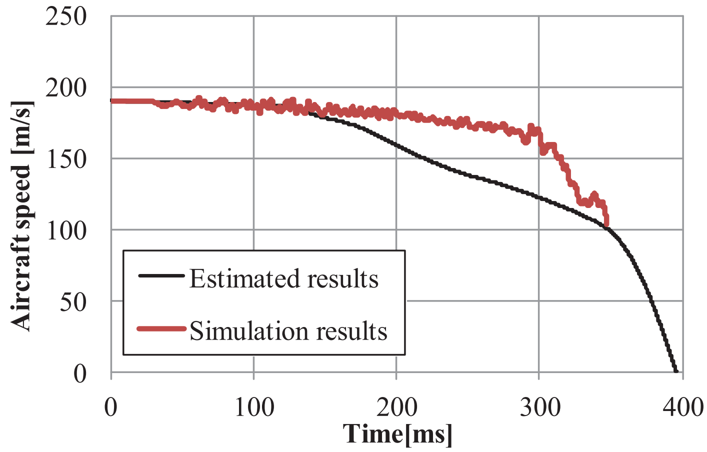
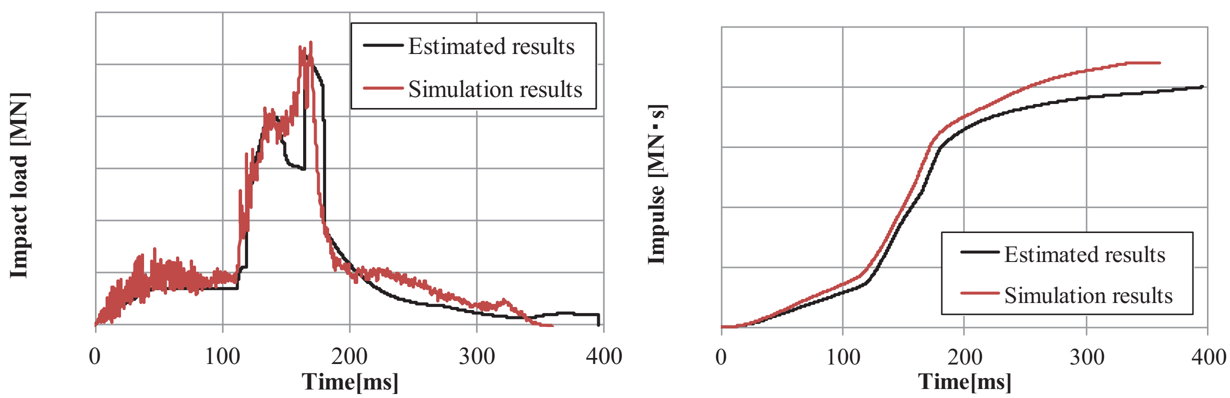


Fig. 13 Comparison of speed reductions between simulation and estimation



(a) Impact load function (b) Impulse on impact

Fig. 14 Comparison of impact load and impulse between simulation and estimation

CONCLUSION

We conducted impact simulations using aircraft engine missiles, an F4 Phantom fighter, and large commercial aircraft that were crashed into the RC target for this study.

・In the simulations representing the aircraft engine missile impacts, the KCC model could reproduce the test results, such as the destruction state of the target, penetration depth, and displacements of the rear face of the target.

・In the impact simulation using the F4 Phantom model, the impact test results such as the load function, impulse on impact, deformation of the aircraft, and destruction of the RC target were reproduced.

・In the impact simulation using the large commercial aircraft model, the simulation results such as the load function, impulse on impact, and the reduction in aircraft speed agree with the estimated results by Riera's method.

・Based on these simulation results, it is clear that the aircraft impact simulations using the KCC model as the RC target model and the aircraft model using shell and SPH elements are useful for aircraft impact analysis.

REFERENCES

Agardh, L. and Laine, L. (1999). "3D FE-simulation of high-velocity fragment perforation of reinforced concrete slabs", *International Journal Impact Engineering*, 22, 911-922.

Chang, W. S. (1981). "Impact of solid missiles on concrete barriers," *Journal of the Structural Division ASCE*, 107, ST2, 257-271.

Crawford, J. E., Wu, Y., Choi, H., Magallanes, J. M., and Lan, S. (2011). "Use and Validation of the Release III K & C Concrete Material Model in LS-DYNA," *TR-11 36-5*, Karagozian & Case, USA

Degen, P. O. (1980). "Perforation of reinforced concrete slabs by rigid missiles", *Journal of the Structural Division ASCE,* 106, ST7, 1623-1642.

Lee, K., Jung, J., and Hong, J. (2014). "Advanced aircraft analysis of an F-4 Phantom on a reinforced concrete building", *Nuclear Engineering and Design*, 273, 505-528.

Muto, K., Sugano, T., Tsubota, H., Nagamatsu, N., Koshima, N., Okano. M., Suzuki, K., Ohrui, S., Riesemann, W. A., Bickel, D. C., Parrish, R. L., and Tachau, R. D. M. (1989). "Experimental Studies on Local Damage of Reinforced Concrete Structures by the Impact of Deformable Missiles Part 3: Full-Scale Tests," *Trans. 10th International Conference on Structural Mechanics in Reactor Technology*, J, 271-278.

National Defence Research Committee. (1946). "Effects of impact and explosion," *Summary Technical Report of Division 2*, 1, USA.

Nuclear Energy Institute. (2011). "Methodology for Performing Aircraft Impact Assessments for New Plant Designs," *NEI 07-13 Revision 8*, USA

Riesemann, W. A., Parrish, R. L., Bickel, D. C., Heffelfiner, S.R., Muto, K., Sugano, T., Tsubota, H., Koshika, N., Suzuki, M., and Ohrui S. (1989). "Full-Scale Aircraft Impact Test for Evaluation of Impact Forces, Part 1: Test Plan, Test Method, and Test Results," *Trans. 10th International Conference on Structural Mechanics in Reactor Technology*, J, 285-299.

Sugano, T., Tsubota, H., Kasai, Y., Koshika, N., Orui, S., Riesemann, W. A., Bickel, D. C., and Parks, M. B. (1993). "Full-scale aircraft impact test for evaluation of impact force," *Nuclear Engineering and Design*, 140, 373-385.

Sugano, T., Tsubota, H., Kasai, Y., Koshika, N., Ohnuma, H., Riesemann, W. A., Bickel, D. C., and Parks, M. B. (1993). "Local damage to reinforced concrete structures caused by impact of aircraft engine missiles Part 1: Test program, method, and results", *Nuclear Engineering and Design*, 140, 387-405.

Sugano, T., Tsubota, H., Kasai, Y., Koshika, N., Itoh, C., Shirai, K., Riesemann, W. A., Bickel, D. C., and Parks, M. B. (1993). "Local damage to reinforced concrete structures caused by impact of aircraft engine missiles Part 2: Evaluation of test results", *Nuclear Engineering and Design*, 140, 407-423.

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

UK Atomic Energy Authority. (1990). *SRD R 436 Issue 3*, UK.

Wu, Y., Crawford, J. E., and Magallanes, J. M. (2012). "Performance of LS-DYNA® Concrete Constitutive Models", *12th International LS-DYNA Users Conference Constitutive Modelling (1)*, 1-14.