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INVESTIGATION ON IMPACT RESISTANCE OF STEEL PLATE REINFORCED CONCRETE BARRIERS AGAINST AIRCRAFT IMPACT PART 1: TEST PROGRAM AND RESULTS

Jun Mizuno
Kobori Research Complex Inc.

Norihide Koshika
Kobori Research Complex Inc.

Yoshikazu Sawamoto
Kobori *Research* Complex Inc.

Nobuyuki Niwa
Kobori Research Complex Inc.

Toshio Yamashita
The Tokyo Electric Power Company
Nuclear Power Engineering,
Quality & Safety Management
Department

Atsushi Suzuki (*)
Kobori Research Complex Inc.
6-5-30, Akasaka, Minato-ku, Tokyo, 107-8502
Japan
Phone:+81-3-6229-6847
Fax:+81-3-5561-2345
E-mail: a-suzuki@kajima.com

ABSTRACT

Steel plate reinforced concrete (SC) structures composed of concrete and steel plates with headed studs are considered to be more effective than RC structures against aircraft impact. This is due to the effects of the steel plates, especially the rear-face steel plates. Thus, their application to outer walls and roofs of risk-sensitive structures such as nuclear-related structures is expected to mitigate damage to critical components. However, few data have been available to understand and evaluate the complex behavior and damage process of SC panels against an aircraft impact.

The objective of this study was to obtain valuable experimental and analytical data essential to investigate and establish a protection design method for SC structures against an aircraft impact. As a first step, impact tests using 1/7.5-scale models were carried out to clarify the damage phenomena caused by an aircraft crash into steel plate reinforced concrete (SC) panels. The results indicated that the steel plate, especially the rear-face plate, has a significant effect in preventing scattering of scabbed concrete debris. It was confirmed that SC panels have much better impact resistant performance than conventional reinforced concrete panels, enabling the thickness of protection panels to be reduced by approximately 30%.

Keywords: Steel Plate Reinforced Concrete Structure, protective capability against aircraft impact, impact test

1. INTRODUCTION

Steel plate reinforced concrete (SC) structures (Takeuchi et al. 1998) are useful and effective for walls and floors of large-scale buildings such as nuclear related structures, and can replace conventional reinforced concrete (RC) structures. As shown in Figure 1, the wall and floor members of SC panels are composed of concrete and steel plates with headed studs.

Extensive experimental and analytical studies (Sugano el al. 1993a, Sugano el al. 1993b, Sugano el al. 1993c,Tsubota et al. 1993, Sawamoto et al. 1998, Tsubota et al. 1999, Morikawa el al. 1999, Mizuno et al. 1999) have been carried out to establish a rational structural design method for nuclear related structures against aircraft impact. Through these studies, several techniques for improving the impact resistance of conventional RC structures have been proposed, and attaching a thin steel plate to the rear-face of a RC panel is considered to be one of the most effective. Sugano et al. (Sugano et al. 1993a) carried out full-scale impact tests using actual aircraft engines and reported that a thin corrugated steel liner attached to the rear-face of the concrete panel has a significant effect in preventing scattering of scabbed concrete debris from the rear face of the panel. Furthermore, experimental studies on impact resistance of RC panels with steel plates subjected to rigid missiles were conducted by the authors (Tsubota et al. 1993) and the effect of the steel plates was quantitatively evaluated. UKAEA (Barr 1987) reported that a steel plate attached to a RC slab improves its perforation and scabbing resistance, and Walter et al. (Walter 1984) proposed a formula for predicting the equivalent thickness of a slab with a steel plate is attached. Morikawa (Morikawa 1997) also proposed a formula for determining the perforation thickness of an RC panel with a steel plate.

These past studies have shown that SC structures are more effective than RC structures against aircraft impact. This is due to the effects of the steel plates, especially the rear-face steel plates. Thus, their application to outer walls and roofs of risk-sensitive structures such as nuclear-related structures is expected to mitigate damage to critical components. However, these past studies have focused on local damage such as perforation and scabbing under rigid or relatively hard missiles. Few data have been available to understand and evaluate the complex behaviors and damage processes of SC panels against soft and/or deformable missile impact such as aircraft impact.

Thus, the objective of this study was to obtain valuable experimental and analytical data essential to investigate and establish a protection design method for SC structures against an aircraft impact. As a first step, impact tests using 1/7.5-scale models were carried out to clarify the damage phenomena caused by an aircraft crash into a steel plate reinforced concrete (SC) panel. Next, simulation analyses of the tests were carried out to verify an analytical method using a Discrete Element Method (DEM) developed by the authors (Sawamoto et al. 1998). Finally, numerical predictions on the protective capability of SC walls and roofs against a full-scale aircraft impact were conducted. This paper presents the detailed plan and test results of scale model impact tests on SC panels.

2. TEST PLAN

2.1 Test Conditions

In order to quantitatively evaluate the effectiveness of SC panels against aircraft impact in comparison with that of conventional RC panels, the same test conditions of reduced scale, impact velocity, aircraft model and size of specimens, used in the scale-model impact tests on RC panels conducted by the authors (Tsubota et al. 1999) were employed.

1/7.5 scale models were employed for both the SC panel specimens and the aircraft model. An impact velocity of 150m/s corresponding to the design condition of the Rokkasho reprocessing plant in Japan was employed for the test. The impact orientation was assumed to be head-on, i.e., normal to the SC panel.

The impact tests were planned to evaluate the following phenomena.

(1) Damage to SC panel
(2) Damage to aircraft model
(3) Deceleration characteristics during aircraft collision into SC panel and residual aircraft velocity after perforation.
(4) Strain and deformation of rear-face steel plate of SC panel

2.2 Test Cases

The test cases are shown in Table 1. Two types of SC panels were designed: full SC and half SC. The full SC type had steel plates on both faces of the panel and is applied to external walls, and the half SC had a steel plate on the rear-face only and rebars on the front side as a conventional RC panel and is applied to roof slabs.

2.3 Specimens

(1) SC Panels

The SC panels were 1.7m square with a parameter of panel thicknesses of 6, 8, and 12cm. The panel thicknesses were determined from preliminary analyses by a discrete element method (DEM) (Sawamoto et al. 1998), to obtain test data of typical failure modes such as perforation and non-perforation. The thickness of the steel plate was about 1/70 to 1/100 of the panel thickness, decided in accordance with the thickness of the SC panel. In the tests, the SC panels were mounted on a reaction frame at their four corners by tensioned bolts. In order to avoid unexpected damage near the support points, thick support beams were placed around the SC panel.

Figure 2 shows the details of the SC panel for test HSC-80 as a typical example. The results of material tests on the concrete, steel plates and reinforcing bars are summarized in Table 2.

(2) Aircraft Model

The aircraft model was designed with reference to the damage process of an actual aircraft observed in the full-scale aircraft impact test (Sugano et al. 1993c) to represent the mass and axial strength distribution along the impact direction of the engine and fuselage. The collision response of the projectile was characterized as follows: (i) the axial strength of the fuselage was relatively small, and only the colliding portion fractured in a brittle manner; and (ii) the axial strength of the engine was much higher than that of the fuselage, and it buckled from the front end. An overall schematic view of the aircraft model is shown in Figure 3. The fuselage consisted of a 2mm-thick fiberglass cylinder and a high-density low-strength foam filler, and the engine consisted of a 0.127mm-thick steel outer shell, a Hexcel honeycomb core, a lead tape attached to the outside and two 1.6mm-thick steel end plates. The mass distribution and the axial strength distribution of the manufactured projectile are shown in Figure 4.

2.4 Launcher Facility

The gas propelled launcher facility (Tsubota et al. 1999) located at an experimental site of SRI International was used to gradually accelerate the aircraft model to its impact velocity of 150m/s. As shown in Figure 5, the major components of the facility included an acceleration cart, a two-rail support track, a high-strength tow rope, a piston, a gas reservoir, a piston acceleration tube and a piston catcher tank. The aircraft model was attached to an acceleration cart, which in turn was mounted on 16.8m-long rail guides in the support track. A high-strength tow rope was attached to the cart at one end and to a piston at the other end. The piston was accelerated to the right using a reservoir of gas pressure while the cart was accelerated to the left. When the aircraft model reached the desired velocity, the cart was separated from the aircraft model, which was then allowed to collide with the SC panel in free flight. Photo 1 shows the aircraft model and the SC panel (FSC-80) set on the launcher facility.

2.5 Measurement

To evaluate the aircraft model's deceleration, one accelerometer was mounted on the fuselage and one on the engine, as shown in Figure 6. The SC panels of FSC-80 and HSC-120 were instrumented with displacement transducers and strain gauges on the rear-face steel plate, with the layout shown in Figure 6. Furthermore, high-speed video cameras were placed perpendicular to the flight trajectory on the front face of the SC panel to record the projectile's impact into the SC panel. Another high-speed video camera was placed on the back face of the SC panel to observe the failure mode on back surface, such as initiation of perforation and debris scattering after perforation.

3. IMPACT TEST RESULTS

3.1 Test Results of SC Panel

(1) Summary of Test Results

The results of the impact tests are summarized in Table 3. Figure 7 shows the high-speed video camera sequence of the projectile's impact into the SC panel for test FSC-60. The high-speed video sequences of the SC panel failure of FSC-60, FSC-80 and HSC-80 are shown in Figure 8. Furthermore, the damaged front and rear-faces of the SC panels are shown in Figure 9, and the damaged fuselage and engine of test FSC-80 are shown in Figure 10.

The damage mode of the conventional RC panels are classified into three types: perforation, scabbing and penetration. However, for SC panels, the scabbing mode was prevented by the rear face steel plate, and the damage modes are classified into only two types: perforation and non-perforation. These modes are shown in Table 3. From the results it can be concluded that the required SC panel thickness for preventing perforation is between 6cm and 8cm.

(2) Damage to Aircraft Model

A typical example of a sequence of the impacting process, as photographed by a high-speed video camera, is shown in Figure 7. This figure shows the aircraft model colliding with the center of the SC panel at a perfectly normal orientation, showing that the collided portion of the projectile fractured successively. This failure process corresponds closely with the results of the full-scale aircraft impact test (Sugano et al. 1993c).

Figure 10 shows photos of the fuselage and the engine damaged during the impact test of FSC-80, as a typical example. It shows that the aircraft model was almost completely destroyed during the impact test, most of the fuselage turning into powder while only a small aft section on which the accelerometers were attached remaining intact. The engine was seriously deformed, with 15cm of the front section being crushed. The test results indicate that damage to the aircraft model increases with the thickness of the SC panels.

(3) Damage to SC Panel

As shown in Figure 8(a) of test FSC-60, swelling deformation of the rear-face steel plate began within 2ms after impact. It then continued to develop and after about 8ms tearing cracks appeared on the rear-face steel plate. As the cracks extended, debris from the internal concrete scattered. The projectile perforated the SC panel.

As shown in Figures 8(b) and 8(c) of tests FSC-80 and HSC-80, global bending deformation due to the collision of the aircraft models was observed on the rear-face steel plate. However, no tearing cracks were observed on the rear-face steel plates and no scattering of internal concrete.

As shown in Figure 9(a) of test FSC-60, the SC panel was severely damaged. A shear cone was formed in the concrete of the perforated SC panel and debris from the internal concrete scattered backward. Most of the rear-face steel plate did not scatter but curled up.

However, for test FSC-80, the front face of the steel plate was locally deformed with a 3cm depression forming at the center of the SC panel, but no cracks were observed on the front-face steel plate. The rear-face steel plate of the SC panel was globally deformed and about 3cm residual deformation occurred, but no cracks were observed on the rear-face steel plate.

As shown in Figure 9(c) of test HSC-80, the front-face concrete suffered severe damage. Aircraft model penetration formed a shear cone in the SC panel with a 6.5cm depression at the center. The diameter of the damaged area on the front-face was about 45cm. The aircraft fuselage penetrated the damaged part into the internal concrete. The engine rebounded to front of the SC panel. No cracks were observed on the rear-face steel plate of the SC panel and no debris scattered backward.

As shown in Figure 9(d) of test HSC-120, damage to the front-face of the SC panel was limited to slight cracking, almost no visible damage. There was no residual deformation of the front-face or the rear-face. No cracks and or scattered debris were observed on the rear-face steel plate.

As shown in Table 3, the measured maximum strains of the rear-face steel plate for the non-perforated panels were fairly small compared with its tensile rupture strain.

(4) Deceleration and Residual Velocity of Aircraft Model

Deceleration curves of FSC-60 and FSC-80 are shown in Figure 11. The velocity time histories of the engine were obtained from on-board accelerometers, while those of the fuselage were obtained from on-board accelerometers and a high-speed video camera that showed the motion of the aft portion of the aircraft model. The time 0ms on the time axis denotes the instant at which the projectile's nose touched the SC panel. According to the results, the decelerations of the fuselage and the engine were relatively gradual in both test cases until the collision of the front end of the engine. The velocity changes for the engines and fuselages were about 20m/s in the first 5ms. Thereafter, the engines decelerated more quickly, being separate from the fuselages. The velocity change for the engine of FSC-60 was about 90m/s over the following 5ms.

For FSC-60, the deceleration curves of the engine and fuselage where perforation occurred show that the change of speed becomes smaller, and after about 8ms cracks appeared on the rear-face steel plate of the SC panel. However, for FSC-80, where no perforation occurred, the engine kept decelerating and rapidly approached zero velocity.

3.2 Comparison of Test Results for SC and RC Panels

Figures 12(a) and (b) compare the protection performance against aircraft impacts for each test result, showing (a) residual velocities of engines that caused perforation, (b) velocities of scattered debris on the rear face and (c) residual deformations of the rear-face steel plate. They also include the results of impact tests on RC specimens with the same test conditions conducted by the authors (Tsubota et al. 1999).

(1) Residual Velocity of Engine

The results show that the residual velocity of the engine for HSC-60 was about 40m/s compared to about 22m/s for FSC-60. This means that the residual velocity of the full SC was lower than that of the half SC for the same panel thickness.

The residual velocity of the engine for the RC specimens (MP-6-47) with thickness 60mm (reinforcement ratio 0.47%) was 80m/s (Tsubota et al, 1999). It was confirmed that the residual velocities for both HSC-60 and FSC-60 were 50% and 28% lower than that of the RC panel with the same thickness as an SC panel. This means that the SC panel provides better protection performance against aircraft impacts than the RC panel.

(2) Velocity of Scattered Debris

The velocity of the scattered debris from the rear-face was 53m/s and 58m/s for HSC-60 and FSC-60, respectively. This difference was small compared with that for the residual velocity of the engine. The velocity of the scattered debris of the rear-face for MP-6-47 was 80m/s. It was confirmed that the velocities of the scattered debris for both HSC-60 and FSC-60 were 66% and 73% lower than that of the RC panel with the same thickness.

The velocities of scattered debris of FSC-80 and HSC-80 80mm thick were zero. This means no scattered debris was observed. However, the RC panel (MP-8-47) with 80mm-thick did perforate with velocity of scattered debris of 60m/s.

(3) Residual Deformation

The residual deformation of the rear-face of the SC panels where the damage mode showed no perforation were compared with the RC panel as shown in Figure 12(c). Residual deformations of the rear-face of HSC-80 and FSC-80 were 7cm and 3cm, respectively, at the center of rear-face. However, that of the RC panel (MP-10-47) was 8cm. These results show that the deformations of the Half SC panel and the Full SC panel of 80mm thickness were less than that of the RC panels of 100mm-thickness.

(4) Damage Mode and Decrease in Required Panel Thickness

As can be seen from the rear-face failure modes shown in Figure 13, while the 8cm-thick RC panel showed perforation, the SC panels, both half and full SC, of the same thickness showed no perforation. Furthermore, even when RC panel did not show perforation, scattered debris was observed. In comparison, the SC panels did not show scattered debris if cracks did not appear in the rear-face steel plate of the SC panels, as shown by the results for HSC-80 and FSC-80. Thus, the tests showed improved protection performance with SC panels.

As a result, the limit panel thickness for preventing the perforation mode, which is the important requirement for protection design, is between 6cm and 8cm for the SC panel and nearly 10cm for the RC panel. This decrease in limit thickness of the SC panel to that of the RC panel is regarded as the effect of the steel plate, and it can be concluded that the limit thickness of SC protection panels can be reduced by approximately 30% from that of RC panels.

4. CONCLUSION

Using 1/7.5 scale models of aircraft, impact tests were conducted on SC panels, and valuable data essential to investigate and establish a protection design method for SC structures against an aircraft impact were successfully obtained. The results indicated that the steel plate, especially the rear-face plate, has a significant effect in preventing scattering of scabbed concrete debris from the rear face of the panel and excellent protection performance of SC panels was clarified. It was also found that perforation limit thickness could be greatly decreased compared with that of RC panels under the same conditions. It was thus verified that the SC panel should be very effective for protection of structures that contain critical equipment such as nuclear facilities, etc.

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Table 1 Test Cases

Test No.	Test name *1	Type of SC Panel	Thickness of SC panel	Thickness of steel plate	Expected Failure mode
1	HSC-60	Half SC	6cm	0.8mm	Perforation
2	FSC-60	Full SC	6cm	0.8mm	Perforation
3	FSC-80	Full SC	8cm	1.2mm	Not-Perforation
4	HSC-80	Half SC	8cm	1.2mm	around perforation limit
5	HSC-120	Half SC	12cm	1.6mm	Not-Perforation

*1 Test name: HSC-60
Type of SC panel: **HSC**: Half SC, **FSC**: Full SC
Thickness of SC panel (mm)

Table 2 Results of Material Tests

Material	Size	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Material	Case	Compressive strength (N/mm^2)
Rebar	D3	350	412	47	Concrete	FSC-60	37.7
	D6	361	544	24		FSC-80	39.6
Steel Plate	PL-0.8	355	476	33		HSC-80	38.1
	PL-1.2	346	496	33		HSC-120	40.9
	PL-1.6	302	473	34		HSC-60	36.4

Table 3 Summary of Test Results

Test Name	Impact Velocity (m/s)	Residual Velocity of Engine (m/s)	Velocity of Scattered Debris (m/s)	Maximum Deformation of Rear-face Steel Plate (cm)	Residual Deformation of Rear-face Steel Plate (cm)	Maximum tensile strain of Rear-face Steel Plate (μ)	Damage of SC Panel
HSC-60	149	40	53	-	-	-	Perforation
FSC-60	152	22	58	(16.1)*1	-	-	Perforation
FSC-80	146	0	0	4.3	3	8970	No Perforation
HSC-80	149	0	0	7.8	7	-	No Perforation
HSC-120	146	0	0	0.5	0	813	No Perforation (a few cracks on the front-face)

*1 The Deformation when a crack on the rear-face steel plate was initiated

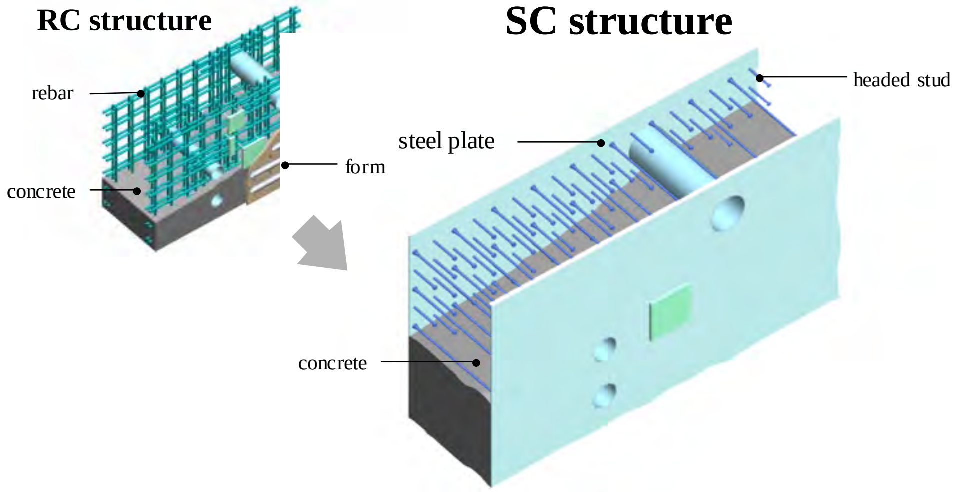


Fig.1 Structural Concept of SC Structure

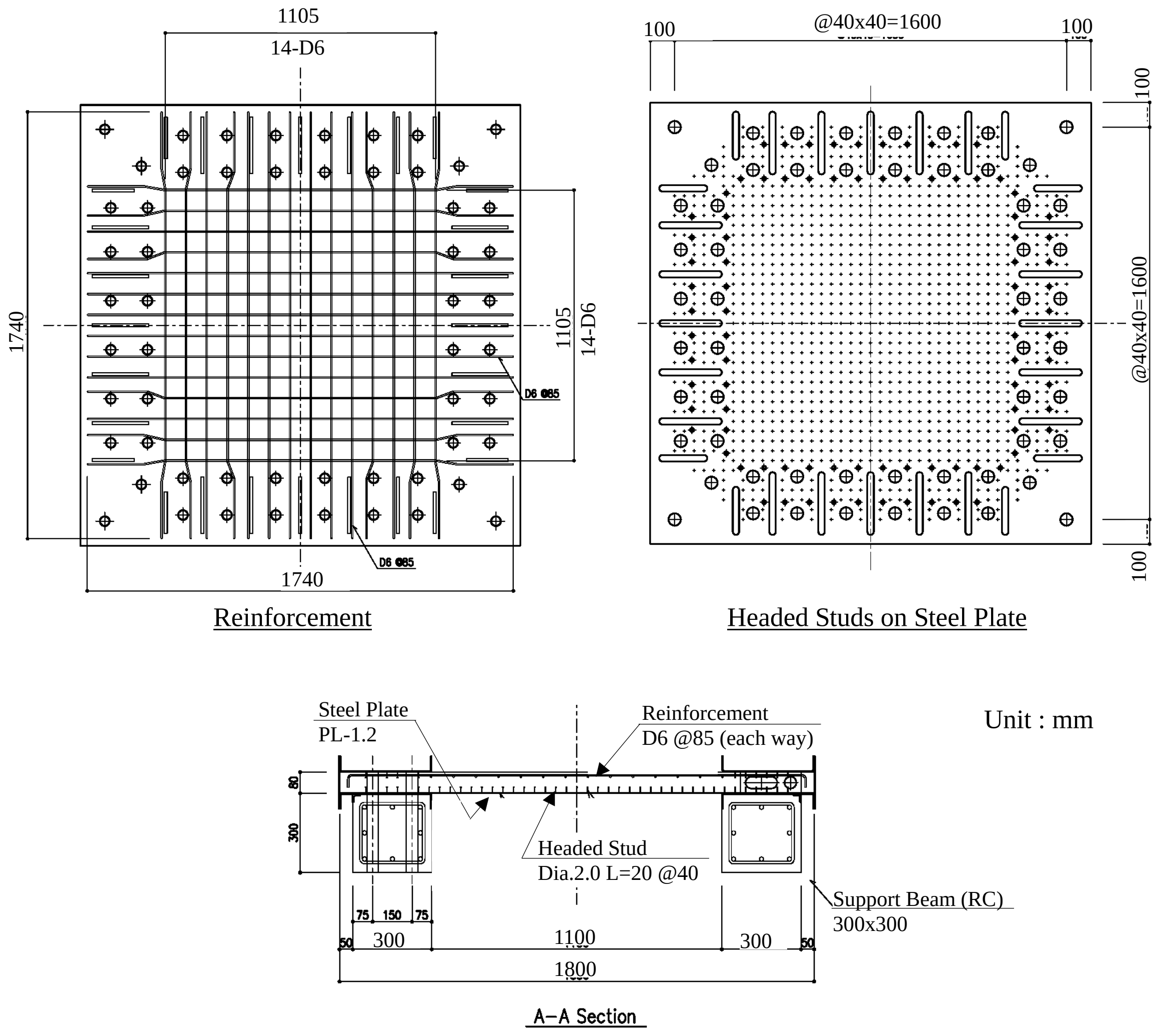
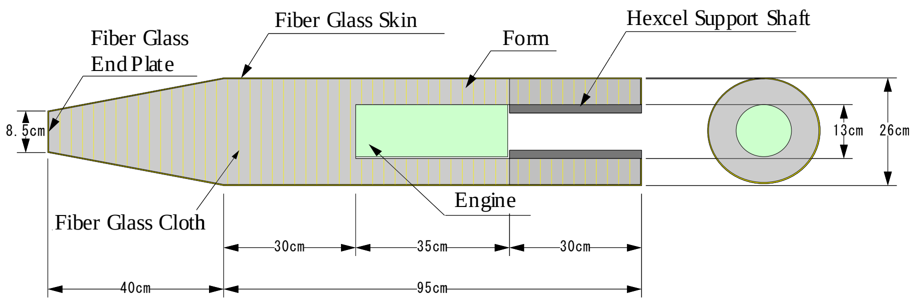
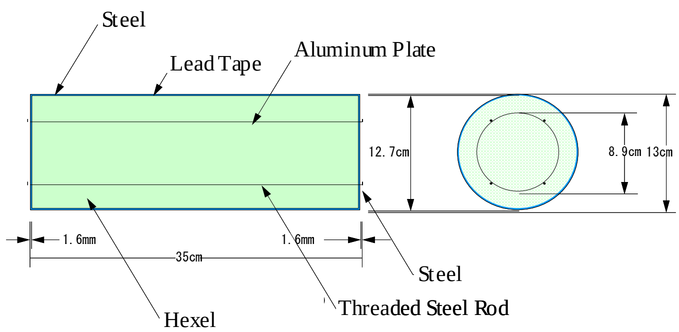


Fig.2 SC Panel (HSC-80)



Fuselage



Engine

Fig.3 Schematic View of Aircraft Model

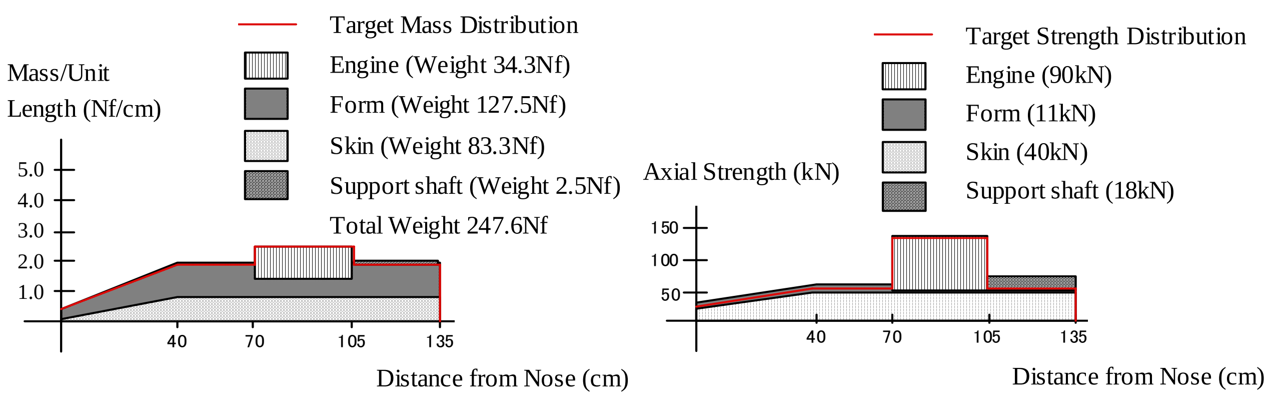


Fig.4 Mass and Strength Distribution

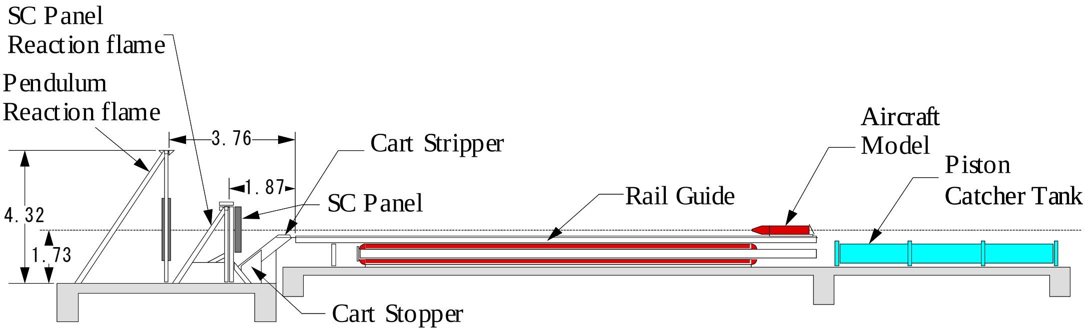
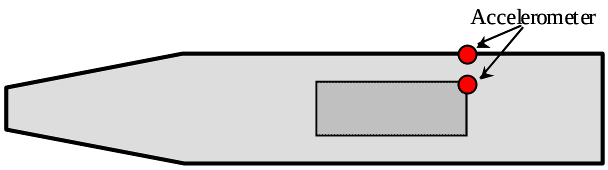
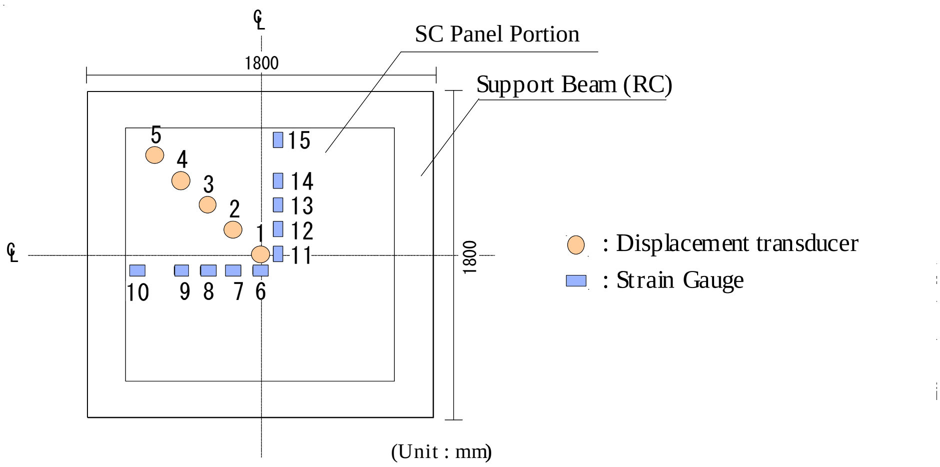


Fig.5 Gas Propelled Launcher Facility

Photo.1 Setting of Aircraft Model and SC Panel on Launcher Facility



(a) Deceleration Measurement of the Aircraft model



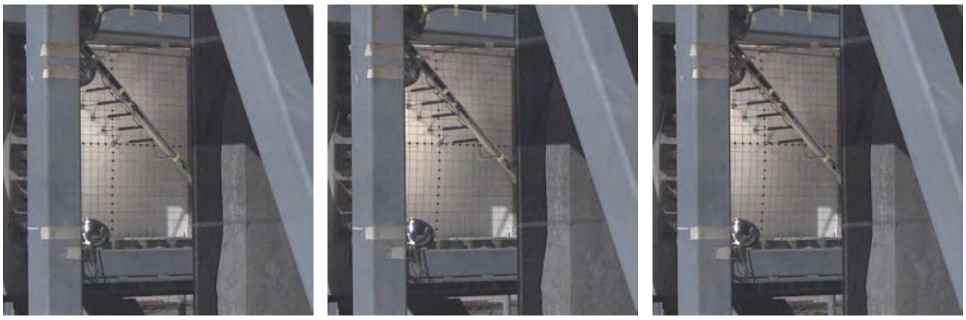
(b) Displacement and Strain Measurement of FSC-80 and HSC-120
Fig.6 Measurement Plan

0ms 2ms 5ms

Fig.7 High-speed Video Sequence of FSC-60 Impact

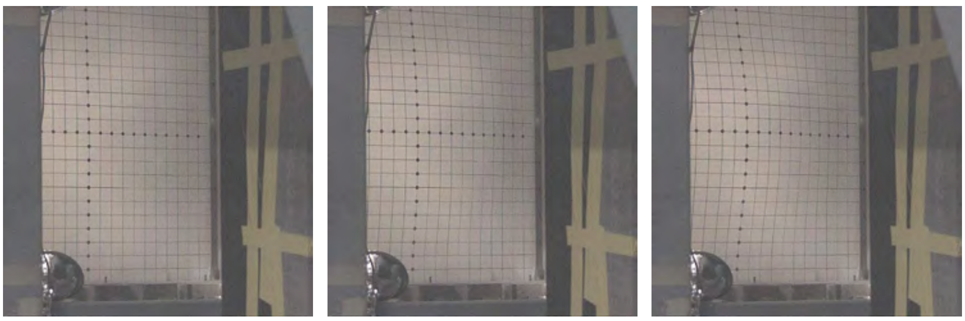
2ms 8ms 12ms

(a) Rear-face of FSC-60 panel



2ms 8ms 12ms

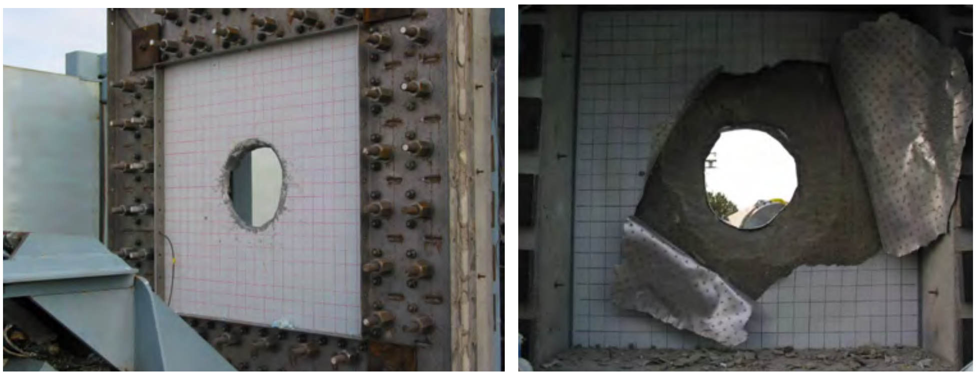
(b) Rear-face of FSC-80 panel



2ms 8ms 12ms

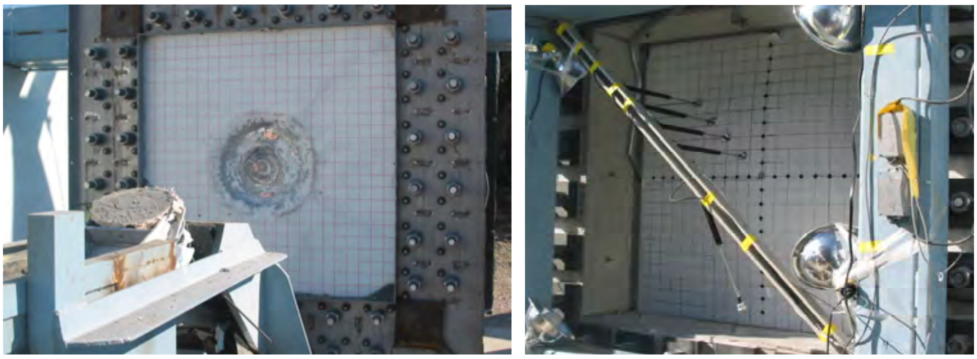
(c) Rear-face of HSC-80 panel

Fig.8 High-speed Video Sequence of Panel Failure



Front-face *Rear-face*

(a) FSC-60 panel

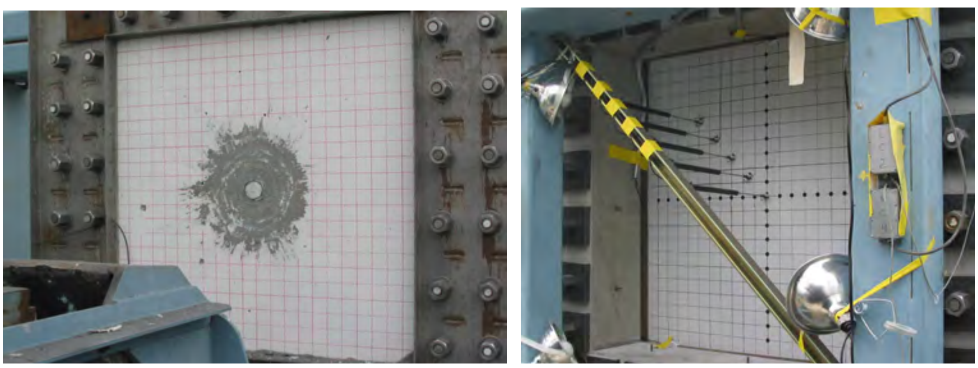


Front-face *Rear-face*

(b) FSC-80 panel

Front-face *Rear-face*

(b) HSC-80 panel



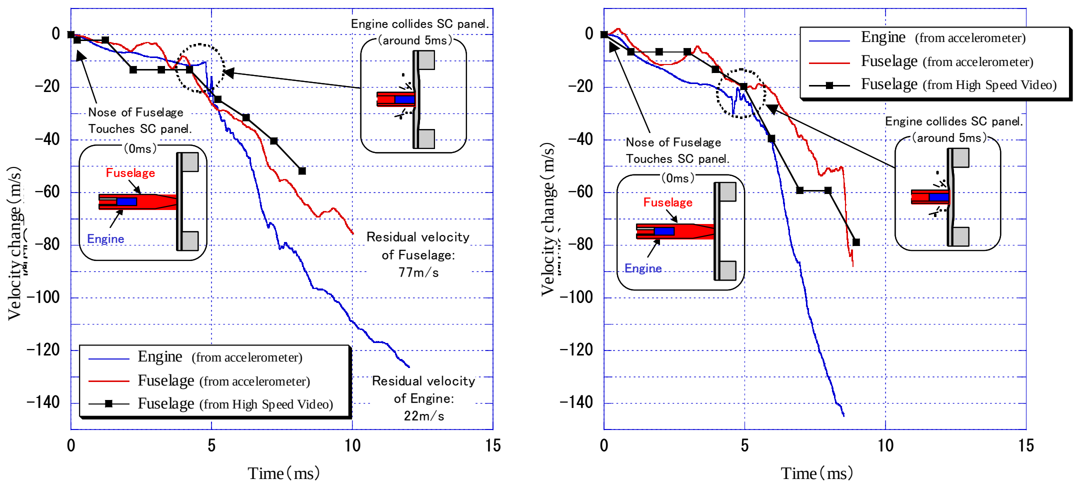
Front-face *Rear-face*

(d) HSC-120 panel

Fig.9 Damage to SC panel after Impact Test

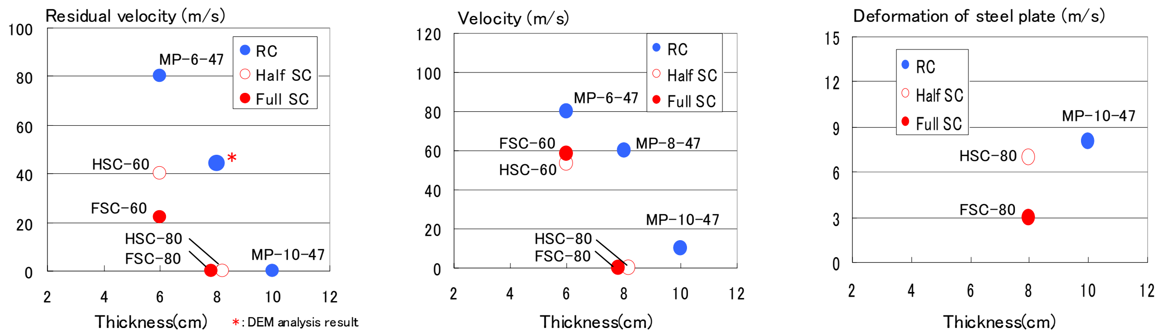
Fuselage *Engine*

Fig.10 Damage to FSC-80 Aircraft Model



(FSC-60; perforated) *(FSC-80, not perforated)*

Fig.11 Deceleration Curves of Fuselage and Engine



(a) Residual velocity of engine *(b) Velocity of scattered debris on the rear-face* *(c) Residual deformation of the rear-face steel plate*

Fig.12 Comparison of Test Results for SC Panels and RC Panels

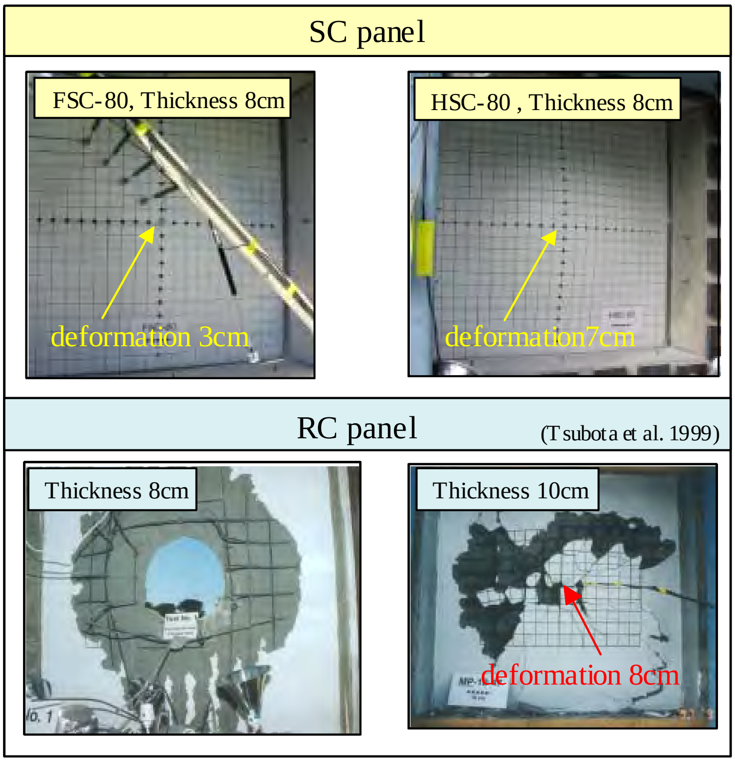


Fig.13 Comparison of Failure Modes for SC Panels and RC Panels