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EXPERIMENTAL STUDY ON RESISTANCE OF STEEL PLATE REINFORCED CONCRETE AGAINST PROJECTILE IMPACT

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ABSTRACT

It is required to perform an assessment of effects on the facility of nuclear power plant against an intentional aircraft impact in the U.S., Europe, and Japan. There are nuclear power plants in the U.S. that adopt steel plate reinforced concrete (SC) structures with tie bars to a part of the reactor building as an external structure to reduce damage from aircraft impact. Although SC panels with tie bars may contribute to increased resistance to out-of-plane deformation of the overall dynamic response of target wall due to aircraft impact, there have been few experimental and analytical studies that have quantitatively evaluated the effectiveness of SC panels with tie bars against impact loads, and it is not clear how tie bars of SC panel works under aircraft impact load. The objective of this study is to clear the impact resistance of SC panels with tie bars against aircraft impact. Firstly, impact tests using 'hard' type projectiles were performed, and deformations and damages of the SC panels with tie bars were confirmed. Then, the numerical analysis method was verified through simulation analysis of the impact tests. Finally, numerical experiments using the verified method and 'hard' and 'soft' types of projectiles investigated the effectiveness of SC panels with tie bars in improving resistance to out-of-plane deformation. This study confirmed that tie bars of SC panels, which affect energy loss associated with local damage, affect energy input to the overall dynamic response of SC panels. In addition, it was confirmed that SC panels with tie bars have better resistance to out-of-plane deformation than reinforced concrete (RC) panels and are very effective in preventing the collapse of the entire wall due to aircraft impact.

INTRODUCTION

It is required in the U.S., Europe, and Japan to perform an assessment of effects on the facility of nuclear power plant against an intentional aircraft impact, to identify and incorporate design features and functional capabilities to meet the acceptance criteria. (Kennedy, R. P., (1976)) describes the relation between local damage and overall dynamic response under projectile impact. An aircraft impact on a building results in both local wall damage and the overall dynamic response of the target wall. Portions of the total kinetic energy of the impacting aircraft are converted to strain energy associated with deformability of the aircraft, energy losses associated with target penetration, and overall target response that includes flexural deformation of the walls. To improve the impact resistance of nuclear power plants to aircraft, it is important to design considering preventing excessive local damage and preventing the collapse of the wall resulting from its inability to withstand absorbed energy. Experimental and analytical studies of SC panels (Morikawa et al., (1997),-Mizuno et al., (2005)) show that a thin corrugated steel liner attached to the rear face of the concrete panel has a significant effect in preventing the scattering of scabbed concrete debris from the rear face of the panel. Through these studies, SC panels can be expected to reduce damage to important components of nuclear power plants more effectively than RC panels. The SC panels in this study are composed of steel plates, concrete, shear stud, and tie bar between opposite faceplates shown in Figure 1. Although SC panels with tie bars may contribute to increased resistance to out-of-plane deformation of the overall dynamic response of target wall due to aircraft impact, there have been few experimental and analytical studies that have quantitatively evaluated the effectiveness of SC panels with tie bars against impact loads and it is not clear how tie bars of SC panel works under aircraft impact load.

The objective of this study is to clear the impact resistance of SC panels with tie bars against aircraft impact. For the objectives, impact tests using 'hard' type projectiles were performed, and deformations and damages of RC and SC panels were confirmed. Then, the numerical analysis method was verified through simulation analysis of the impact tests. Finally, numerical experiments using the verified method and 'hard' and 'soft' types of projectiles investigated the effectiveness of SC panels with tie bars in improving resistance to out-of-plane deformation.

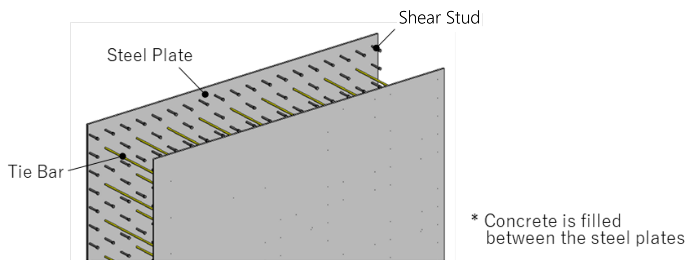


Figure 1. Arrangement of steel plates, tie bars, and shear studs for SC panel

IMPACT TEST

Test Conditions and Specimens

Test case and test conditions are shown in table 1. Models with a 1/8.3 scale were employed for both the RC and SC panel specimens. Two types of RC panels with different thicknesses and two types of SC panels with different shear stud and tie bar spacing were designed to analyze the failure mode and behavioral effects of impact. The projectile is shown in Figure 2, and the specimens are shown in Figure 3. The projectiles had a rigid front body with a flat impact surface and its diameter of 140 mm and aluminum skirt, and a target impact velocity of 150m/ s is applied. The direction of impact was assumed to be frontal, that is, perpendicular to the SC panel.

Table 1: Test cases and conditions

Test case	Type of panel	Thickness (mm)	Tie bar (mm)	Target velocity of projectile(m/s)
RC-1	RC	200	-	150
RC-2	RC	115	-	150
SC-1	SC	115 [2.3]*1	Φ3@45	150
SC-2	SC	115 [2.3]*1	Φ3@50	150

*1 [ ]: Thickness of steel plate

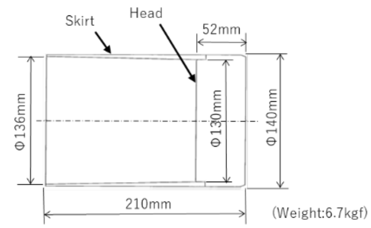
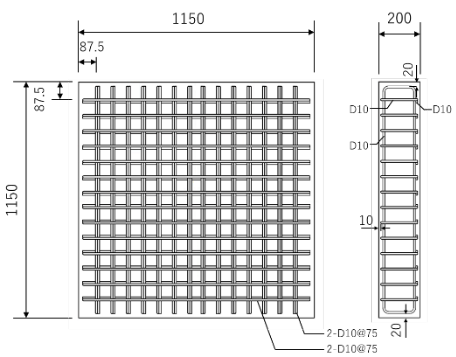
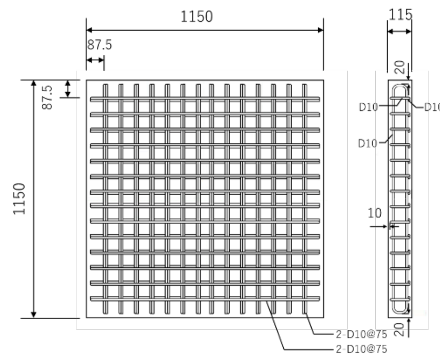


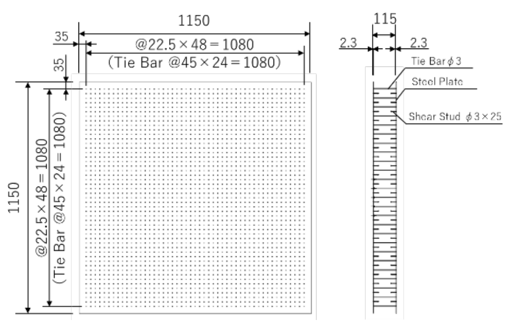
Figure 2 ‘hard’ type projectile



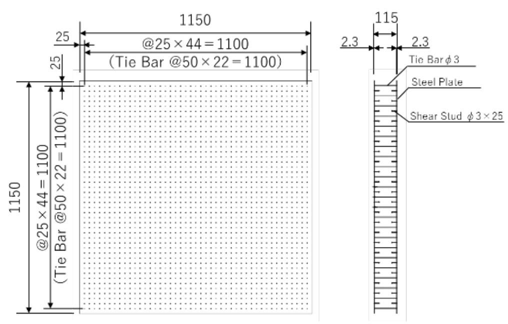
(a) RC-1



(b) RC-2



(c) SC-1



(d) SC-2

Figure 3. Detail of the specimens

Test Setup

The test setup is shown in Figure 4. As shown in Figure 4, the major components of the facility included an air tank, a flush valve, a barrel, a support stopper, a protect frame, hangers, and load cells. The projectile was fired from the barrel and was allowed to collide with the panel during free flight.

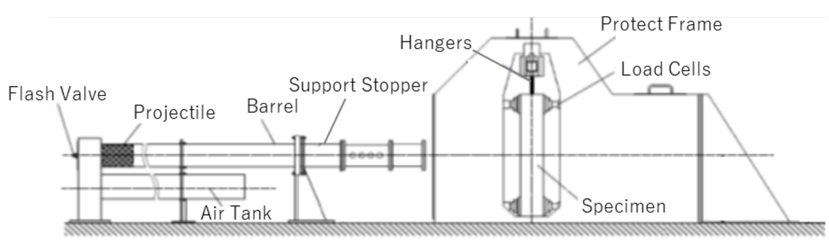


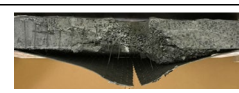
Figure 4 Test setup

Test Results

(1) Summary of Test Results

Table 2 shows the summary of the impact test results. Figure 5 shows the failure modes of the RC panel and SC panel (Hashimoto et al., (2005)). The failure mode of test RC-1 was classified as 'Scabbing', the failure mode of test RC-2 was classified as 'Perforation', the failure mode of test SC-1 was classified as 'Splitting', and the failure mode of test SC-2 was classified as 'Bulging'.

Table 2: Summary of test results

Test case	Type of panel	Velocity of projectile(m/s)	Failure mode	Panel damage
RC-1	RC	158	Scabbing	
RC-2	RC	156	Perforation	
SC-1	SC	157	Splitting	
SC-2	SC	150	Bulging	

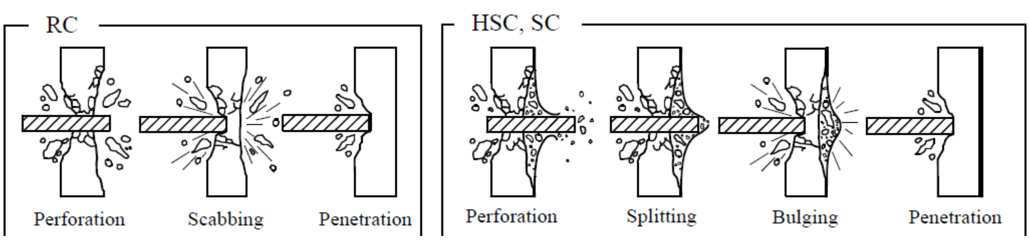
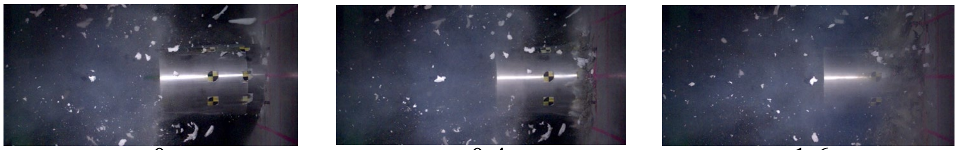


Figure 5. Failure mode (from Hashimoto et al., (2005))

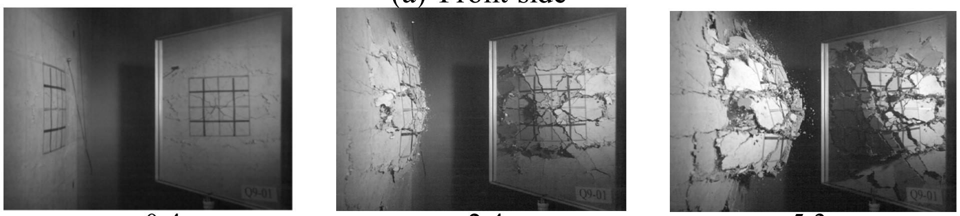
(2) Test Result of RC-1

Figure 6 shows the high-speed video camera sequence of the projectile's impact into the RC panel and the RC panel failure for test RC-1, and Figure 7 shows the damaged front and rear faces, and cross-section of the RC panel. The projectile velocity was 158 m / s while the target velocity is 150 m / s. From the high-speed camera sequence and the traces of the impact surface, it was confirmed that the projectile impacted with the plate almost perpendicularly without tilting. The failure mode of test RC-1 is classified as 'Scabbing'.



t=0 t=0.4ms t=1.6ms

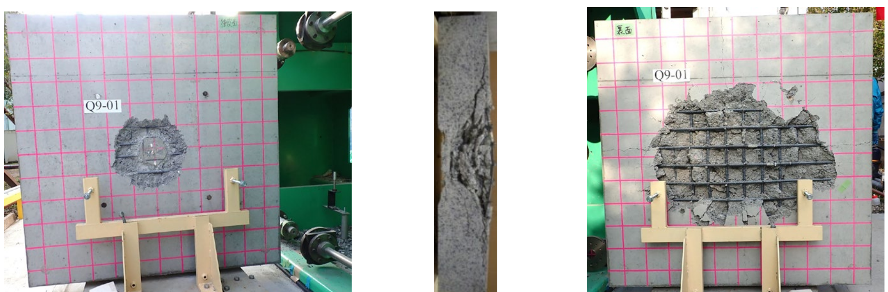
(a) Front side



t=0.4ms t=2.4ms t=5.3ms

(b) Rear side

Figure 6. High-speed video sequence of RC-1 panel failure



Front face Cross-section Rear face

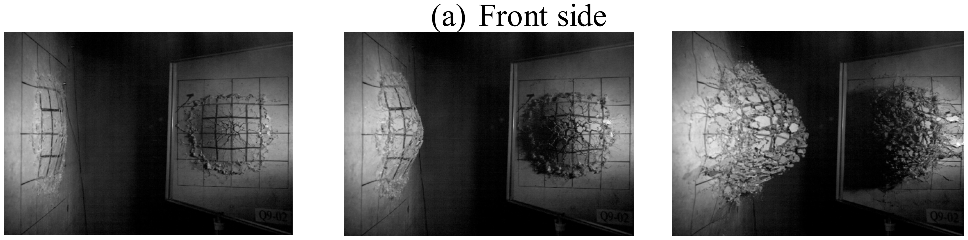
Figure 7. Damage to RC-1 panel after impact test

(3) Test Result of RC-2

Figure 8 shows the high-speed video camera sequence of the projectile's impact into the RC panel and the RC panel failure for test RC-2, and Figure 9 shows the damaged front and rear faces, and cross-section of the RC panel. The projectile velocity was 156 m / s while the target velocity is 150 m / s. The rebar on the impact surface side broke, but the rebar on the rear surface side did not break. The projectile did not penetrate, but a large amount of concrete debris was scattered from the rear face of the panel. The failure mode of test RC-2 is classified as 'Perforation'.

t=0 t=2.2ms t=3.0ms

(a) Front side



t=0.4ms t=1.6ms t=11.0ms

(b) Rear side

Figure 8. High-speed video sequence of RC-2 panel failure

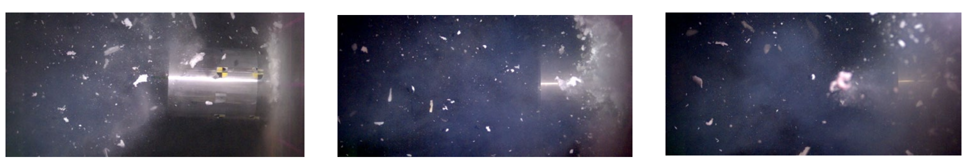
Front face Cross-section Rear face

Figure 9. Damage to RC-2 panel after impact test

(4) Test Result of SC-1

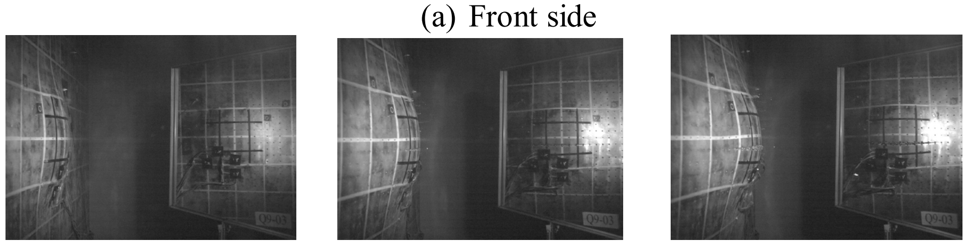
Figure10 shows the high-speed video camera sequence of the projectile's impact into the SC panel and the SC panel failure for test SC-1, and Figure 11 shows the damaged front and rear faces, and cross-section of the SC panel. The projectile velocity was 157 m / s while the target velocity is 150 m / s. The projectile stopped in the intrusive state and did not penetrate. The steel plate on the rear side was partially splitting, and a small amount of concrete debris was scattered. The failure mode of test SC-1 is classified as 'Splitting'.

The connections between the steel plates and the tie bars and studs were broken in a wide range, and a gap appeared between the steel plates and the concrete in a wide range. The split in the steel plate was a linear tear connecting the holes for connecting the studs and tie bars machined in the steel plate. It should be noted that the holes for the studs made in the plate are peculiar to the specimens made due to restrictions on the manufacture of the specimens, and do not exist in actual SC structure.

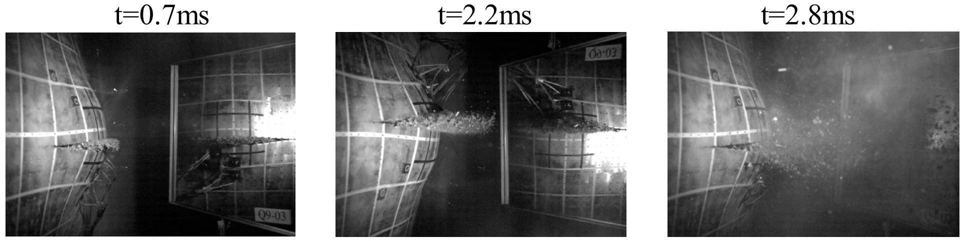


t=0 t=1.6ms t=4.6ms

(a) Front side



t=0.7ms t=2.2ms t=2.8ms



t=4.7ms t=8.3ms t=70ms

(b) Rear side

Figure 10. High-speed video sequence of SC-1 panel failure

Front face Cross-section Rear face

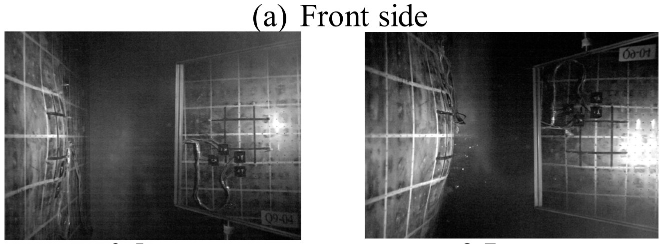
Figure 11. Damage to SC-1 panel after impact test

(5) Test Result of SC-2

Figure 12 shows the high-speed video camera sequence of the projectile's impact into the SC panel and the SC panel failure for test SC-2, and Figure 13 shows the damaged front and rear faces, and cross-section of the SC panel. The projectile velocity was 150 m / s while the target velocity is 150 m / s. The projectile stopped in the intrusive state and did not penetrate. The connections between the steel plate and the tie bars and studs were broken, and a gap appeared between the steel plate and the concrete in a wide range. The steel plate on the rear face side of the impact did not break, and the concrete debris did not scatter from the rear face. The damage mode of test SC-2 is classified as 'Bulging'.

t=0.2ms t=0.4ms t=1.0ms

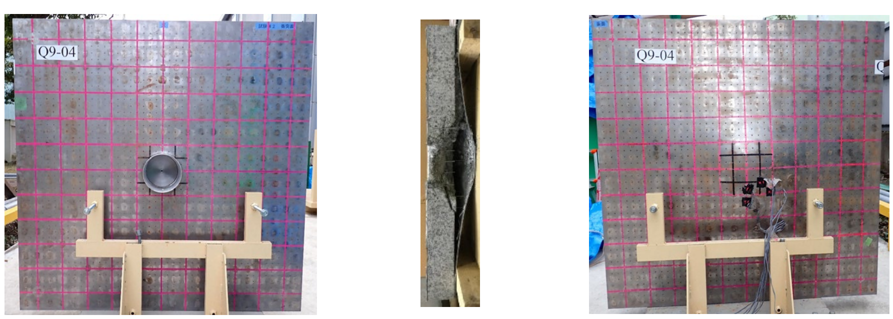
(a) Front side



t=0.5ms t=3.7ms

(b) Rear side

Figure12. High-speed video sequence of SC-2 panel failure



Front face Cross-section Rear face

Figure 13. Damage to SC-2 panel after impact test

ANALYTICAL INVESTIGATION FROM TEST RESULTS

Analytical Method

The analysis was performed using the commercial software LS-DYNA Ver.10.1.0. Figure 14 shows the models of the projectile and the test panels. Solid element was applied to the head of the projectile, the concrete for the panels, and the support structures. Shell element was applied to the skirt of the projectile and the plates for SC panels. Beam element was applied to the rebar for the RC panels and the tie bars and the studs for the SC panels. The material properties of concrete for the RC and the SC panels are shown in Table 3, and the material properties for the metal in the panels are shown in Table 4. The Karagozian & Case Concrete model (Malvar LJ., et al., (1996), Magallanes, J.M., et al., (2010)) is used as the material model for concrete and the kinematic hardening model is used as the material for metal. For the strain rate dependence, Dynamic Increase Factors (DIF) shown in Table 5 were used based on NEI 07-13 Guideline (ERIN Engineering & Research Inc., (2011)). For estimation of damage, the failure strain limits shown in Table 6 were used as structural failure criteria based on NEI 07-13 Guideline (ERIN Engineering & Research Inc. (2011)).

Figure 15 shows the relationship between strain rate and limit load obtained from the high-speed tensile test of the connection between steel plate and tie bar of the specimens and connection between steel plate and studs of the specimens. In the simulation analysis of test SC-1 and test SC-2, the limit load value of tie bars shown in Figure15 with a strain rate of 4 (1 / s) was applied as a limit load of each connection.

Table 3: Material properties for concrete

Parts	Maximum aggregate size(mm)	Compressive strength (MPa)	Splitting tensile strength (MPa)	Poison ratio
Concrete Panel	15	47	3.0	0.2

Table 4: Material properties for metal

Parts	Young's module	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Poison ratio
Rebar	1.739×105	371	560	20	0.3
Steel plate	1.980×105	299	437	25	0.3
Tie bar	2.017×105	725	782	17	0.3
Head of projectile	2.050×105	259	453	25	0.3
Skirt of projectile	0.683×105	138	274	35	0.3
Stud	2.020×105	482	-*1	20	0.3

*1: Tangent module of kinematic hardening model was defined as 1/200 of Young's module.

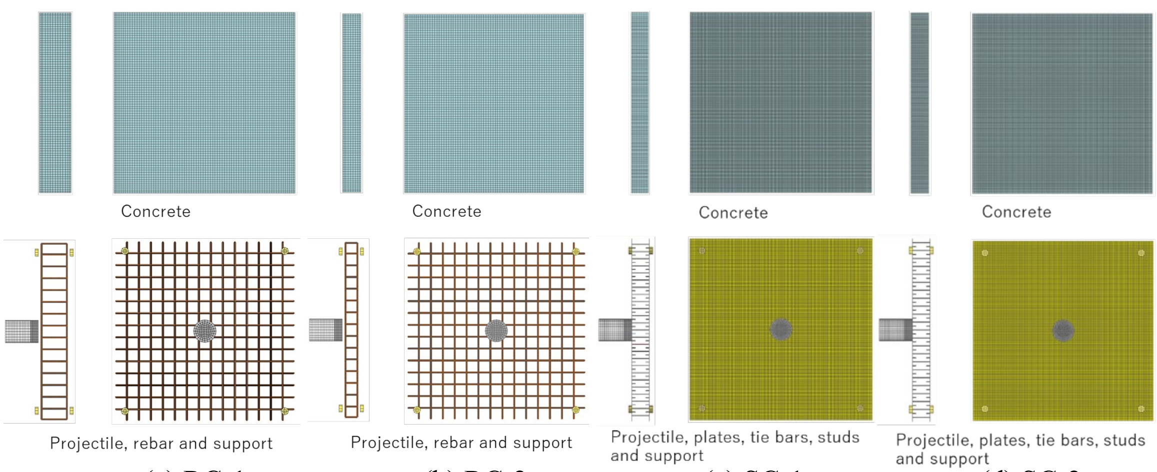
Table 5: Dynamic increase factors (DIF) for material dynamic strength increase

Parts	Material	DIF	
		Yield strength	Ultimate strength
Concrete panel	Concrete	-	1.25*1
Rebar	Reinforcing steel	1.20	1.05
Steel plate	Carbon steel	1.29	1.1
Tie bar	Carbon steel	1.29	1.1
Head of the projectile	Carbon steel	1.29	1.1
Stud	Carbon steel	1.29	1.1

*1: DIF for concrete compressive strength

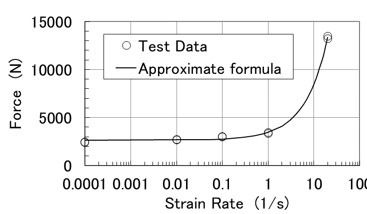
Table 6: Material failure strain limit

Parts	Strain measure	Limit value
Concrete panel	Shear strain	0.5%
Rebar	Tensile strain (Uniaxial)	5.0%
Steel plate	Membrane principal strain (Tensile)	5.0%

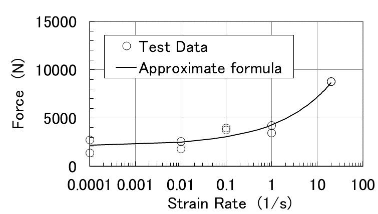


(a) RC-1 (b) RC-2 (c) SC-1 (d) SC-2

Figure 14. Analysis models



(a) Connection between stud and plate

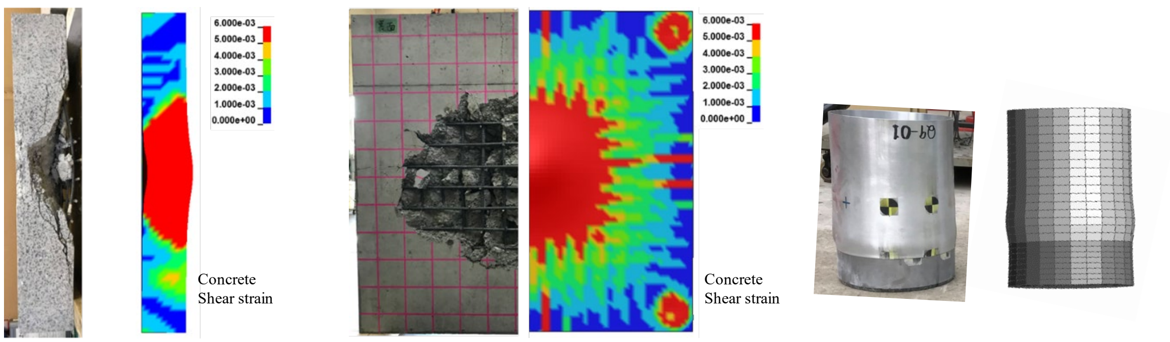


(b) Connection between tie bar and plate

Figure 15. Relation between dynamic limit load and strain rate

Analytical Results

Using the finite element method (FEM), calculated deformation and strain of the specimens were compared with the test results to verify that the modeling method is applicable. Figures 16 to 19 show comparisons of the RC panel's test results and the analysis results, and Figures 20 to 23 show comparisons of the SC panel's test results and the analysis results. The damage estimated based on the maximum shear strain distribution of concrete obtained by analysis of the RC panels was in good agreement with damage of the specimens, and it was confirmed that the concrete material model was appropriate. In analyses of the SC panels, the verified concrete material model was used, tie bars were modeled with beam elements, and connection strength between steel plate and tie bars was realistically modeled. By incorporating these modeling in the analysis models, it was confirmed that the damage of concrete and steel plate of the specimens were in good agreement.



Experiment Analysis
(a) Cross-section

Experiment Analysis
(b) Rear face

Experiment Analysis
(c) Projectile

Figure 16. RC-1 damage and strain distribution

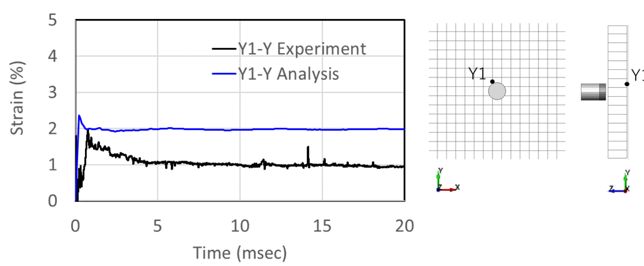
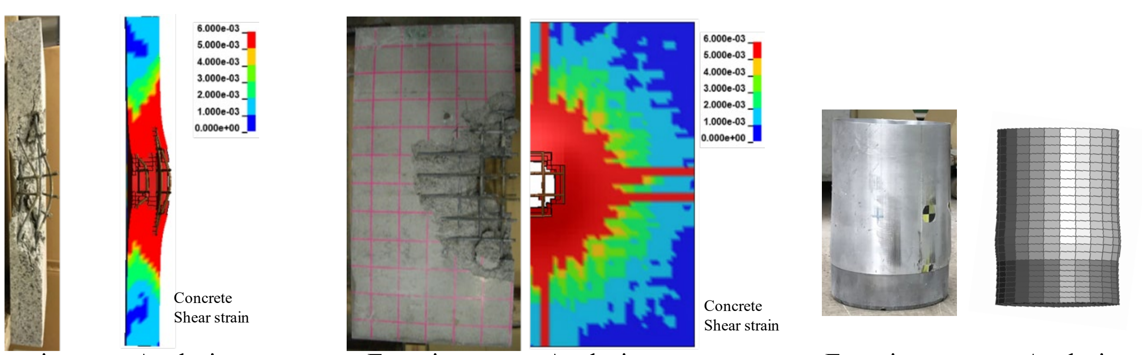


Figure 17. RC-1 Axial strain of rebar



Experiment Analysis
(a) Cross-section

Experiment Analysis
(b) Rear face

Experiment Analysis
(c) Projectile

Figure 18. RC-2 damage and strain distribution

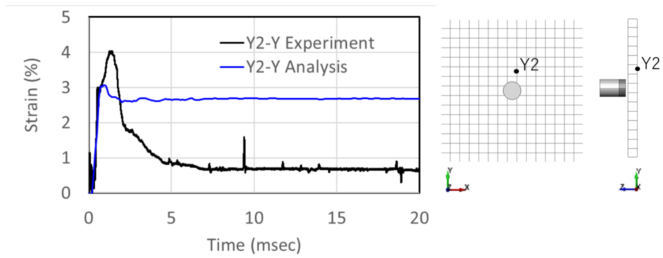
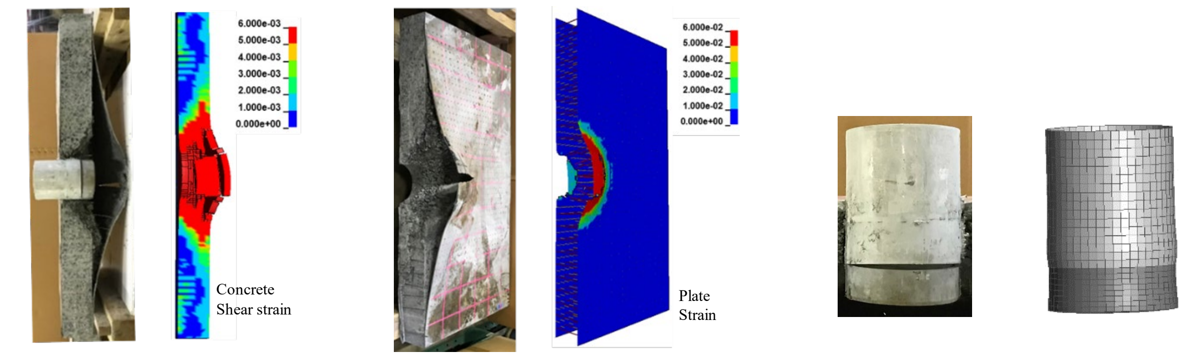


Figure 19. RC-2 Axial strain of rebar

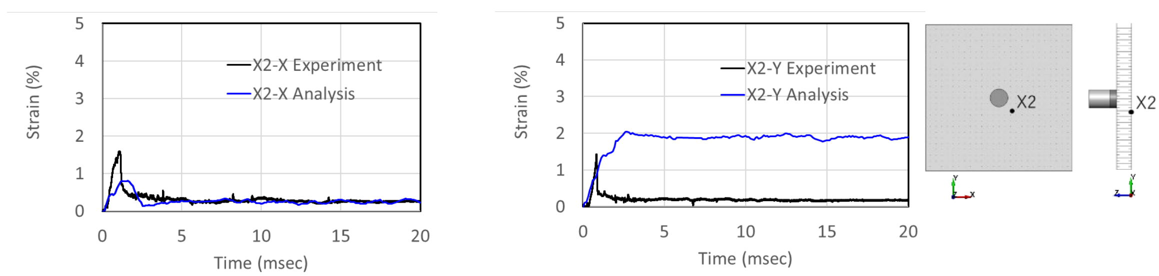


Experiment Analysis
(a) Cross-section

Experiment Analysis
(b) Oblique Perspective

Experiment Analysis
(c) Projectile

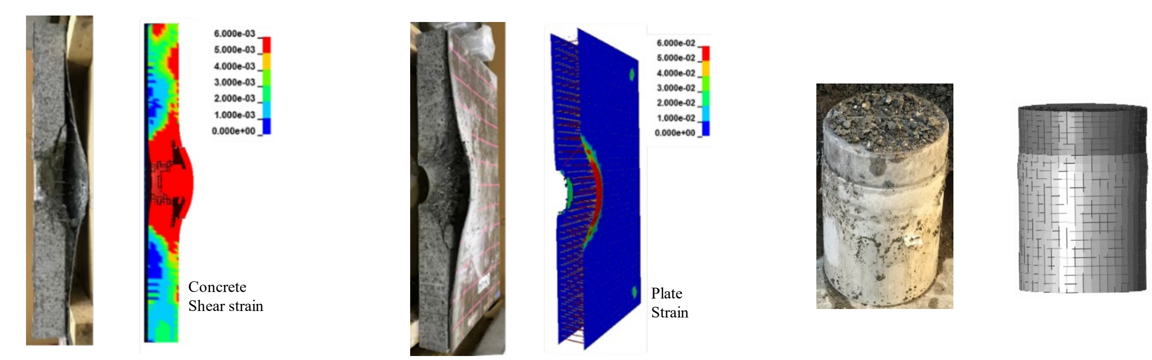
Figure 20. SC-1 damage and strain distribution



(a) X direction

(b) Y direction

Figure 21. SC-1 Strain on the rear plate

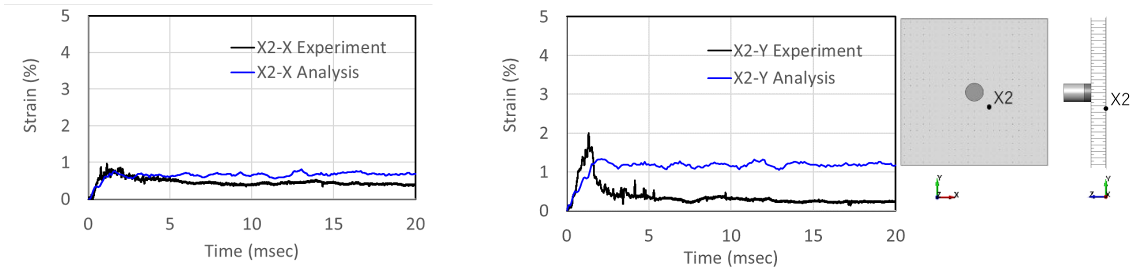


Experiment Analysis
(a) Cross-section

Experiment Analysis
(b) Oblique Perspective

Experiment Analysis
(c) Projectile

Figure 22. SC-2 damage and strain distribution



(a) X direction (b) Y direction

Figure 23. SC-2 Strain on the rear plate

NUMERICAL EXPERIMENT

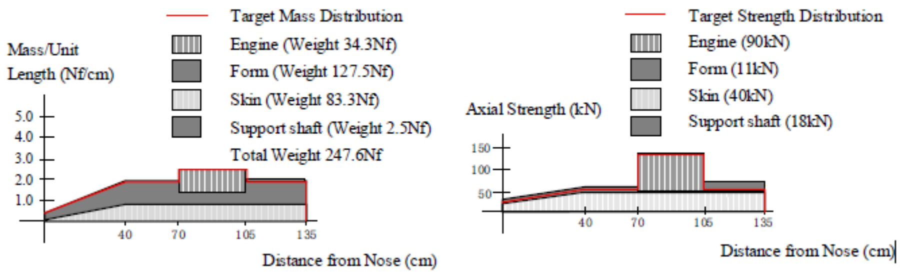
Method and Conditions

Numerical experiments using verified methods and verified models of the specimens were planned to confirm the effect of improving the resistance of SC panels with tie bars to out-of-plane deformation. Table 7 shows the cases and conditions of numerical experiments. In the numerical experiment, the analysis models of RC-2, SC-1, and SC-2 verified in the previous chapter are used. The connection between steel plate and tie bars and the connection between steel plate and studs in the analysis model of the SC panels were modified to have the same material strength as the tie bars and the studs. The impact speed of a projectile was 150 m / s in all cases. For 'hard' type projectile, the model verified in the previous chapter was used. For 'soft' type projectile, the FEM model re-modeled for this study, with a 1 / 7.5 scale of the aircraft used in Mizuno's study (Mizuno, J., (2005b).) was used. Figure 24 shows mass and strength distribution of 'soft' type projectile and Figure 25 shows the analysis model of 'soft' type projectile.

Table 7: Analysis cases and conditions for the numerical experiment

Analysis case	Type of panel	Thickness (mm)	Tie bar (mm)	Type of projectile	Velocity of projectile(m/s)
RC-2H	RC	115	-	'hard'	150
SC-1H	SC	115 [2.3]*1	Φ3@45	'hard'	150
SC-2H	SC	115 [2.3]*1	Φ3@50	'hard'	150
RC-2S	RC	115	-	'soft'	150
SC-1S	SC	115 [2.3]*1	Φ3@45	'soft'	150
SC-2S	SC	115 [2.3]*1	Φ3@50	'soft'	150

*1 [ ]: Thickness of steel plate



(a) Mass Distribution *(b) Strength Distribution*

Figure 24. Mass and strength distribution of 'soft' type projectile (from Mizuno et al., (2005b))

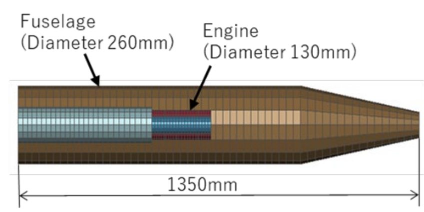


Figure 25. Analysis model of 'soft' type projectile

Analytical Results

The summary of the analysis results is shown in Table 8. Table 8 shows crater size on the front surface of the panels and displacement of out-of-plane deformation on the rear surface obtained by analysis. For crater size on the front face, the width of the area where the shear strain of concrete is equal to or greater than the failure strain limit value of 0.5% was measured. Displacement of the rear face is a value at the central position of the panels. Figure 26 shows results of impact analysis using 'hard' type projectile, and Figure 27 shows results of impact analysis using 'soft' type projectile.

The results of comparing displacement on the front face and damaged area of the SC panels and RC panel shows that SC panels with tie bar have a great effect of improving resistance to out-of-plane deformation. In the 'hard' type analysis results, local damage occurred markedly. In the 'soft' type analysis results, both local damage and damage due to out-of-plane deformation of the entire concrete of the SC panels occurred, but the strain of the steel plates was smaller than the damaged strain limit value of 5.0%.

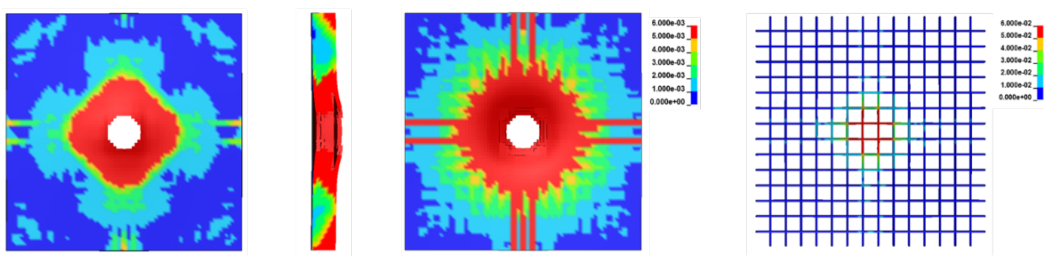
In the "soft" type impact case, the crater size of the SC panel with wide tie bar spacing was 6% larger than the crater size of the SC panel with small tie bar spacing. Also, in the "soft" type impact case, displacement of out-of-plane deformation of the SC panel with wide tie bar spacing was 15% smaller than the displacement of out-of-plane deformation of the SC panel with small tie bar spacing. Furthermore, from the calculated strain distribution of concrete, it can be confirmed that the area of local damage of the SC panel with wide tie bar spacing is larger than the area of local damage of its with small tie bar spacing.

From these, it is presumed that widening spacing of tie bars has the effect of increasing energy loss associated with local damage to the concrete of SC panels and reducing energy input for the overall dynamic response of SC panels.

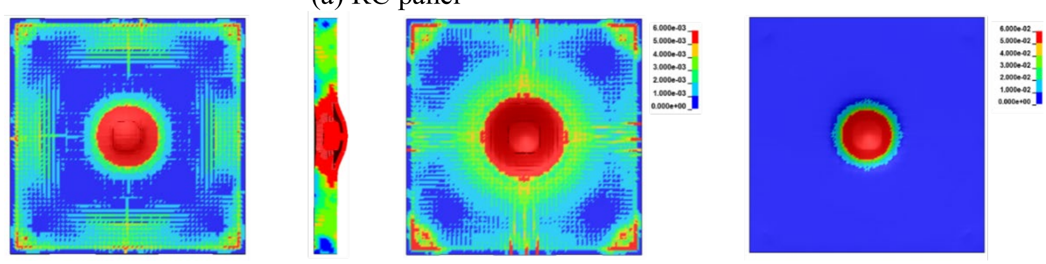
Table 8: Summary of analysis results

Analysis case	Type of panel	Tie bar (mm)	Type of projectile	Size of the crater on front face*2 (mm)	Displacement of the rear face (mm)
RC-2H	RC	-	'hard'	524	-*1
SC-1H	SC	Φ3@45	'hard'	285	58
SC-2H	SC	Φ3@50	'hard'	300	53
RC-2S	RC	-	'soft'	-*3	101
SC-1S	SC	Φ3@45	'soft'	330	27
SC-2S	SC	Φ3@50	'soft'	350	23

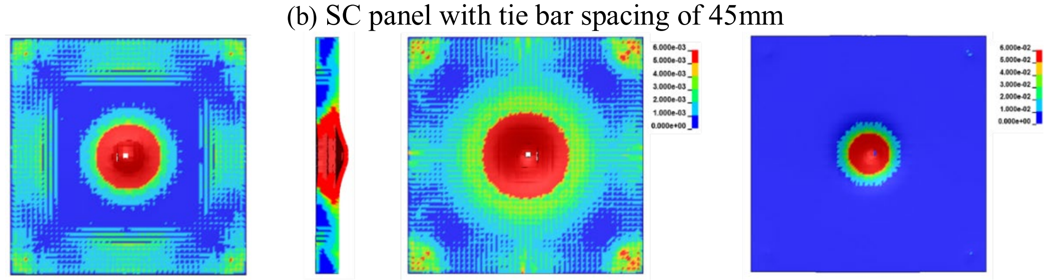
* 1: The displacement could not be measured due to the scattering of concrete by penetration.
* 2: The size of the area where shear strain is 0.5% or more was measured.
* 3: The size of the crater could not be measured due to the shear strain caused by out-of-plane deformation.



Front face Cross-Section Rear face Rebar
Concrete shear strain Rebar axial strain
(a) RC panel



Front face Cross-Section Rear face Rear plate
Concrete shear strain Plate strain
(b) SC panel with tie bar spacing of 45mm



Front face Cross-Section Rear face Rear plate
Concrete shear strain Plate strain
(c) SC panel with tie bar spacing of 50mm

Figure 26. Impact analysis results by 'hard' type projectile

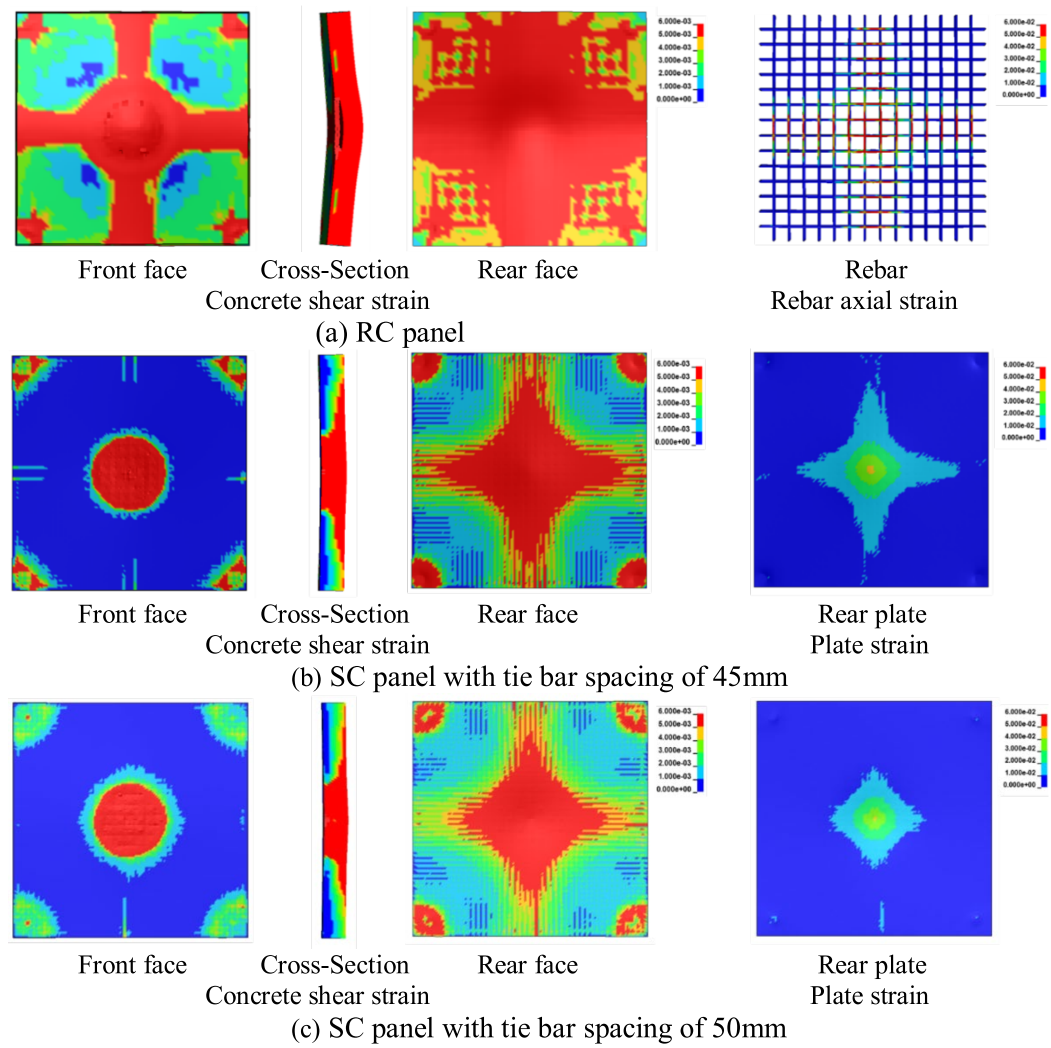


Figure 27. Impact analysis results by 'soft' type projectile

DESIGN RECOMMENDATION

It has become clear that tie bars of SC panels affect the local damaged area of concrete at the impact zone and elegy loss consumed there, as well as energy input related to the overall dynamic response of SC panels. It also became clear that the local damage state of the SC panel can be accurately estimated by appropriately considering the dynamic material properties of SC panel components, and that strength properties of the connection between the tie bar and the steel plate have a significant effect on the damage of SC panel.

In evaluating SC structures with tie bars for aircraft impact protection design, it is recommended that dynamic strength of the tie bar to plate connection be verified in advance to be greater than that of the base metal, or that dynamic strength characteristics of the tie bar to plate connection be considered in the evaluation.

CONCLUSION

Impact tests were conducted on 1/8.3 scale models of RC panels and SC panels with tie bars using hard type projectiles to obtain data on their deformation and damage conditions and to verify numerical analysis methods for SC structures against aircraft impacts. The results of the impact test showed that even in the case of severe localized damage where a projectile penetrates the panels, the rear plate has a significant effect in preventing scattering of concrete debris from the rear face of the panel, and the excellent protective performance of SC panels with tie bars was confirmed.

The numerical analysis method using the finite element method was verified by conducting a simulation analysis of impact tests on RC and SC panels. First, simulations of the RC panels were used to verify that the concrete material model functioned properly, and simulations of the SC panels were used to verify that the tie bars modeled by the beams functioned properly. The results confirmed that the numerical methods applied were able to simulate the damage conditions in the tests well.

By numerical experiments using the verified numerical analysis method with 'hard' and 'soft' types of projectiles, it was confirmed that tie bars of SC panel, which affect energy loss associated with local damage, affects energy input to the overall dynamic response of SC panels. In addition, it was confirmed that SC panels with tie bars have better resistance to out-of-plane deformation than RC panels and are very effective in preventing the collapse of the entire wall due to aircraft impact.

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