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INVESTIGATION ON IMPACT RESISTANTCE OF STEEL PLATE REINFORCED CONRETE BARRIERS AGAINST AIRCRAFT IMPACT PART 3: ANALYSES OF FULL-SCALE AIRCRAFT IMPACT

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ABSTRACT

Steel plate reinforced concrete (SC) walls and slabs are structural members in which the rebars of reinforced concrete are replaced by steel plates. Steel plate reinforced concrete structures are more attractive structural design alternatives to reinforced concrete structures, especially with thick, heavily reinforced walls and slabs such as nuclear structures, because they enable a much shorter construction period, greater earthquake resistant and more cost effectiveness.

Experimental and analytical studies performed by the authors have also shown that SC structures are much more effective in mitigating damage against scaled aircraft models , as described in Parts 1 and 2 of this study.

The objective of Part 3 was to determine the protective capability of SC walls and roofs against a full-scale aircraft impact by conducting numerical experiments to investigate the fracture behaviors and limit thicknesses of SC panels and to examine the effectiveness of SC panels in detail under design conditions. Furthermore, a simplified method is proposed for evaluating the localized damage induced by a full-scale engine impact.

Keywords: Steel Plate Reinforced Concrete Structure, protective capability against aircraft impact, discrete element method, simplified design method

1. INTRODUCTION

Steel plate reinforced concrete (SC) walls and slabs are structural members in which the rebars of reinforced concrete are replaced by steel plates, as shown in Fig.1. A design method has been developed to achieve a much shorter construction period, greater earthquake resistant capability and more cost effectiveness than conventional reinforced structures, especially for those with thick, heavily reinforced walls and slabs (Takeuchi et al 1998, Ozaki et al 2001, Akita et al 2001).

Although significant advances have been made in the area of protective design of reinforced concrete structures against aircraft impact loads (Sugano et al 1993a, Sugano et al 1993b, Sugano et al 1993c, Tsubota et al 1999, Morikawa et al 1999, Mizuno et al 1999a, Mizuno et al 1999b, Tsubota et al 1998a, Tsubota et al 1998b), there have been few experimental and analytical studies that have quantitatively evaluated the effectiveness of SC panels against impact loads, especially soft missile impacts such as aircraft impacts.

Part 1 of this study (Mizuno et al 2005a) presented valuable test results on the effectiveness of SC panels against aircraft impacts based on 1/7.5 scale impact tests, in which simplified aircraft models with similar crush characteristics to both the fuselage and engine of an actual jet fighter were impacted against SC panel specimens of various thicknesses. It was found that SC panels are much more effective against aircraft impacts than conventional reinforced concrete (RC) panels. Furthermore, simulation analyses of impact tests on SC panels presented in Part 2 of this study (Mizuno et al 2005b) confirmed that a discrete element (DE) code developed by the authors (Sawamoto et al 1998, Morikawa et al 1999) simulates the highly complex fracture processes and failure modes of both SC panels and aircraft models up to perforation phenomena remarkably well.

The objective of Part 3 of this study is to determine the protective capability of SC walls and roofs against a full-scale aircraft impact by investigating the fracture behaviors and limit thicknesses of SC panels in detail under the design basis conditions of a typical reprocessing plant in Japan. Furthermore, a simplified method is proposed for evaluating localized damage induced by a full-scale engine impact.

2. ANALYTICAL INVESTIGATION OF FULL-SCALE AIRCRAFT IMPACT ON SC PANELS

2.1 Outline

Full-scale aircraft impacts on SC protective walls and roofs were investigated through DE analyses. A hypothetical jet fighter based on an F-16 with a total weight of 20tf (196KN), whose impact load was taken into account in the design of a typical reprocessing plant in Japan, was modeled as a axi-symmetric DE model. The aircraft's mass and axial strength distribution are shown in Fig.2. The impact velocity was assumed to be 150m/s.

Harf SC panels for roof slabs and full SC panels for outer walls were selected as examples of SC structure barriers, as shown in Fig.1. The thicknesses of the SC panels are 0.6m, 0.9m and 1.0m for half SC with 12mm steel plate, and 0.9m and 1.0m for full SC with 9mm steel plates, as shown in Table 1.

All axi-symmetric SC panels of radius 10m were applied with fixed boundary conditions considering the effects of the continuous condition of 10m square panels. For the roof slab, in which a half SC structure is normally employed, the reinforcement ratio was assumed to be 0.47% on the impact side.

DEM idealizes the concrete medium of SC panels as an assemblage of particles, each of which satisfies equations of motion, and expresses equilibrium conditons of the whole body by forces transferred between particles in contact. The steel plates of the SC panels are modeled as elasto-plastic multi-axial springs with flexural stiffnesses connecting to concrete particles. The fuselage, engine and wings of the aircraft model are also modeled as an assemblage of circular elements. The mass distribution of the DE model is evaluated from the mass distribution of the aircraft model for design. The details of the DE model parameters of the full-scale aircraft are given in reference (Mizuno et al 1999a).

The DE model of the full-scale aircraft and the 1.0m-thick Half SC panel are shown in Fig. 3. The material characteristics for the full-scale aircraft and the SC panels are shown in Fig. 4 and Tables 2-3.

2. 2 Analytical Results

(1) Fracture Processes of SC Panels

Fig. 5- Fig. 9 show the final fracture processes of the full-scale aircraft and SC panels with the elapsed times after the initial impact of the projectile. The 100cm thick panels of both full and half SC, i.e. FSC100 and HSC100, respectively, showed only minor damage under the impact of the jet fighter with an initial impact velocity of 150 m/s, as shown in Fig. 5 and Fig. 6. The maximum panel deformations were 15.7cm and 21.9cm, respectively.

More noticeable damage was observed in the 90cm thick panels, i.e. FSC90 and HSC90, as shown in Fig. 7 and Fig. 8, than in the 100cm thick panels. In particular, HSC90 showed a pronounced crater in the front-side concrete due to the penetration of the projectile, and a deeper dent in the rear panel with a maximum deformation of 89.5cm, whereas FSC90 showed much lighter damage with a maximum deformation of

31.7cm. For rigid missile impacts, Tsubota et al studied the effects of steel liner plates attached to only the rear faces and to both faces of reinforced concrete panels based on small scale impacts tests (Tsubota et al 1993, Koshika et al 1993), and reported that the front face steel liner has little effect on prevention of perforation of a rigid missile. However, against relatively soft missile impacts such as those of an aircraft fuselage, a front side steel plate does reduce panel damage and deformation more than a half SC panel with only a rear side steel plate. This is due to the higher strength of the front face steel plate and stronger confinement effects on concrete inside the full SC panel.

To investigate the limit thickness of SC panels under the conditions given, a 60cm thick half SC panel (HSC60) was selected for one of the DE analyses, and the fracture processes are shown in Fig. 9. The half SC panel barely escaped the perforation of the projectile with a maximum deformation of 165cm, but the concrete portion impacted by the fuselage and wings were severely fractured almost up to the rear steel plate. Thus, the 60cm thick half SC panel may be close to the perforation limit, while the perforation limit for a full SC panel is expected to be thinner than 60cm.

Fig. 11 compares the damage mode of 130cm thick reinforced concrete panel with the same concrete properties as the SC panels with a reinforcement ratio of 0.47% each face and each direction with those of the SC panels at 150ms, when the entire projectile had crushed into the panel. The 130cm thick RC panel showed relatively minor damage, similar to that of 100cm thick half and full SC panels. However, the 100cm thick RC panel was evaluated as the perforation mode while the 60cm thick half SC panel was not, and showed no scabbed concrete debris from the rear face of the panel. Thus, a significant improvement of protective capability against an aircraft impact can be achieved by SC panels for outer walls and roofs in risk-sensitive structures.

(2) Deceleration Curves of Fuselage and Engine

Fig. 10 shows the velocity time histories, or deceleration curves, of the aft portion of the engines and fuselages for the full and half SC panels, respectively. The decelerations of the fuselages are more gradual, reflecting the relatively low strength and rigidity, while the decelerations of the engines are more rapid, reflecting the relatively high rigidity. In spite of the large differences in the degrees of damage and the maximum deformation among the SC panels, there are no significant differences between their deceleration curves. Thus, it can be said that even the significant deformation of a heavily damaged panel has a relatively small effect on the deceleration of the fuselage and the engine unless the SC panel is not perforated.

(3) Tensile Strain Distribution of Rear Steel Plate

As shown by the damage to the SC panels due to the impact of a full-scale jet fighter evaluated by the detailed DE analyses, and the results of 1/7.5 scale impact tests on the SC panels, the rear steel plates play the most critical role in preventing damage to important facilities inside structures. In Fig. 12, the maximum tensile distributions of the rear steal plates are plotted for the full and half SC panels. The strains of all SC panels are locally concentrated as a result of engine impact, which is a relatively hard portion of the aircraft. The strains of the full SC panels are smaller than those of the half SC panels due to the constraint effects of the front face steel plates.

3. EVALUATION OF LOCAL DAMAGE DUE TO ENGINE IMPACT

3.1 DE analyses of Local Damage Due to Engine Impact

The impact of an full-scale engine, which has much higher rigidity and a smaller diameter than the fuselage, tends to cause much more localized damage to protective panels than that of the fuselage. For design of reinforced concrete protective panels against an engine impact, Sugano et al conducted extensive engine impacts tests including four actual F-4 jet fighter engine impact tests, and proposed an empirical formula for the perforation limit and scabbing limits for RC panels taking into account the deformability of the engine in the empirical formula derived for rigid missiles (Sugano et al 1993b, Sugano et al 1993c).

In this study, detailed DE analyses for full-scale engine impacts on SC panels were performed as numerical experiments. Analysis cases are listed in Table 4, in which the initial impact velocities were varied from 150m/s to 250m/s, and the thickness of the SC panels were varied from 60cm to 100cm. The engine model was the same as that shown in Fig. 3. The thicknesses of the panels and the impact velocities of the engines were varied to explore the limit thicknesses of the SC panels due to the engine's impact. Only the half SC panels were selected for the evaluation, since a front steel plate was found to be less effective against hard missile impacts than a rear steel plate.

Fig. 13 shows the final fracture patters of the half SC panels against the engine impacts, evaluated by DE analyses. There is no perforated panel even at an impact velocity of 250m/s, but two cases show tearing of the rear steel plate, i.e. the 60cm and 80cm thick half SC, at engine impact velocities of 200m/s and 250m/s, respectively.

3.2 Simplified Formula for Evaluation of Local Damage due to Engine Impact

Morikawa proposed an empirical formula for predicting the perforation limit thickness of reinforced concrete panels with rear steel plates for protection against rigid missiles (Morikawa 1997). In this study, the effect of engine deformability is taken into account into Morikawa's formula for the evaluation of the tearing limit of the rear steel plate of SC panels against an engine impact for design purposes. Following Morikawa's approach, the evaluation procedure is shown in Fig. 14. The procedure consist of three steps: evaluation by the Mutoh-Degen formula of residual velocity, Vr, of an engine after perforating the concrete of a SC panel, considering the reduction factor for the deformability of engine (Sugano et al 1993c); evaluation by Kar's formula (Kar 1979) of limit impact velocity, Vps, to just perforate the rear steel plate, assuming that the engine becomes rigid after the perforation of the concrete; and confirmation that Vr ≦Vps.

In Fig. 15, the curves of tearing limit thickness of the SC panels with 12mm thick rear steel plate, evaluated by the proposed procedures, are plotted with the results of DE analyses. The proposed simplified method gives conservative estimates compared to the results of DE analyses. Also plotted are the curves for the perforation and scabbing limits of RC panels. Compared to the scabbing limit thickness of RC panels (Sugano et al 1993c), the tearing limit thickness of SC panels gives approximately 30% lower thickness.

4. CONCLUSION

A new structural design with significantly improved protective capability against an aircraft impact is proposed, utilizing steel reinforced concrete (SC) panels for outer walls and roofs. This design was originally proposed to significantly shorten the construction period, to achieve higher earthquake resistant capability, and to improve cost effectiveness for relatively heavily reinforced structures such as nuclear structures.

Firstly, impact tests were performed on SC panels to experimentally examine their protective capability against a realistic scaled aircraft model (Part 1 of this study). In Part 2 of this study, the applicability and reliability of a discrete element (DE) code were thoroughly examined through simulation analyses of the experiments.

The effectiveness of SC protective panels under actual design conditions against a full-scale aircraft impact is extensively investigated in Part 3 of this study by means of DE analyses. It may be concluded that an SC panel with approximately 30% less thickness than a reinforced concrete panel provides similar or higher protective capability. Furthermore, a simplified evaluation method is proposed to evaluate the localized damage induced by an full-scale engine impact.

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Table 1 Analysis Cases for Full-scale Aircraft Impact

Case Name	Type of SC Panel	Thickness of SC Panel	Thickness of Steel Plate	Compressive Strength (N/mm^2)	Impact Velocity of Aircraft Model (m/s)
FSC-100	Full SC	100cm	9mm	29.4	150
HSC-100	Half SC	100cm	12mm	29.4	150
FSC-90	Full SC	90cm	9mm	29.4	150
HSC-90	Half SC	90cm	12mm	29.4	150
HSC-60	Half SC	60cm	12mm	29.4	150

Table 2 Model Parameters of Aircraft

	Engine	Fuselage	Wings
Yield Strength (N/mm^2)	412	206	206
Young's Modulus (N/mm^2)	$2.06x10^5$	$6.86x10^4$	$6.86x10^4$
Poisson's Ratio	0.3	0.3	0.3
Tensile Fracture Strain (%)	20	3.0	3.0
Diameter (cm)	98	194	495

Table 3 Model Parameters of SC Panel

(a) Concrete and Rebar

Concrete		Rebar for Half SC	
Compressive Strength (N/mm^2)	29.4	Yield Strength (N/mm^2)	378
Tensile Strength (N/mm^2)	2.94	Young's Modulus (N/mm^2)	$2.06x10^5$
Shear Strength (N/mm^2)	4.38	Mass per Unit Volume (kN/m^3)	78.5
Young's Modulus (N/mm^2)	$2.53x10^4$	Poisson's Ratio	0.3
Mass per Unit Volume (kN/m^3)	23	Tensile Fracture Strain (%)	26
Poisson's Ratio	0.2	Rebar Ratio (%)	0.47
Coefficient of Friction	0.2	Spacing (cm)	20

(b) Steel Plate and Stud

Steel Plate		Stud	
Yield Strength (N/mm^2)	356	Yield Strength (N/mm^2)	259
Young's Modulus (N/mm^2)	$2.06x10^5$	Young's Modulus (N/mm^2)	$2.06x10^5$
Mass per Unit Volume (kN/m^3)	76.9	Mass per Unit Volume (kN/m^3)	76.9
Poisson's Ratio	0.3	Poisson's Ratio	0.3
Tensile Fracture Strain (%)	26	Tensile Fracture Strain (%)	26
		Diameter (mm)	22
		Spacing (cm)	20

Table 4 Analysis Cases for Full-scale Engine Impact

Case No.	Type of SC Panel	Thickness of SC Panel	Thickness of Steel Plate	Compressive Strength (N/mm^2)	Impact Velocity of Engine Model (m/s)
1	Half SC	60cm	12mm	29.4	150
2	Half SC	60cm	12mm	29.4	200
3	Half SC	80cm	12mm	29.4	200
4	Half SC	80cm	12mm	29.4	250
5	Half SC	100cm	12mm	29.4	250

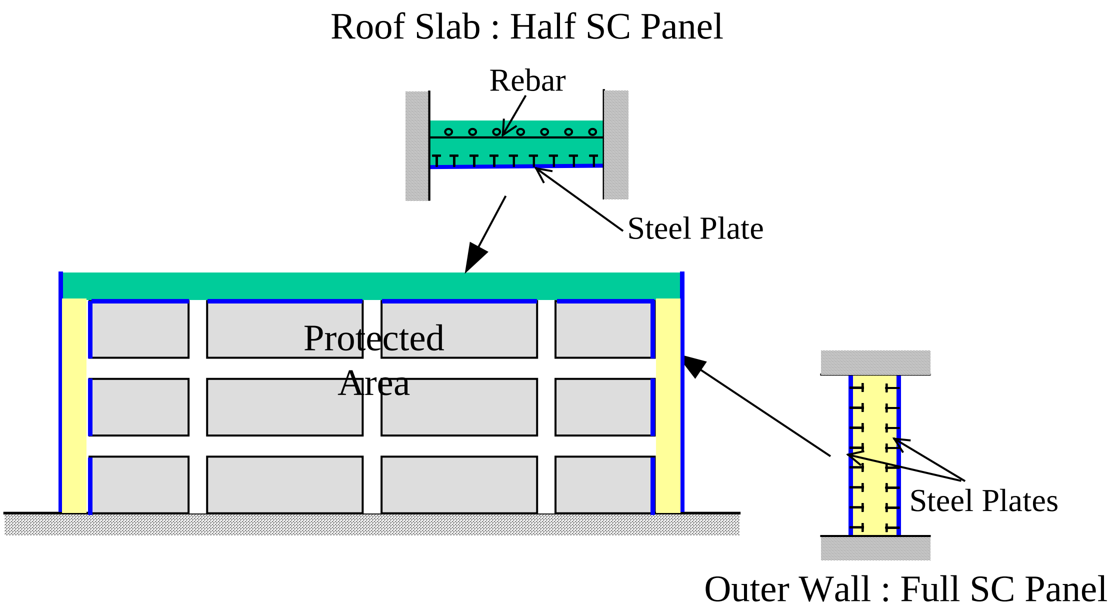
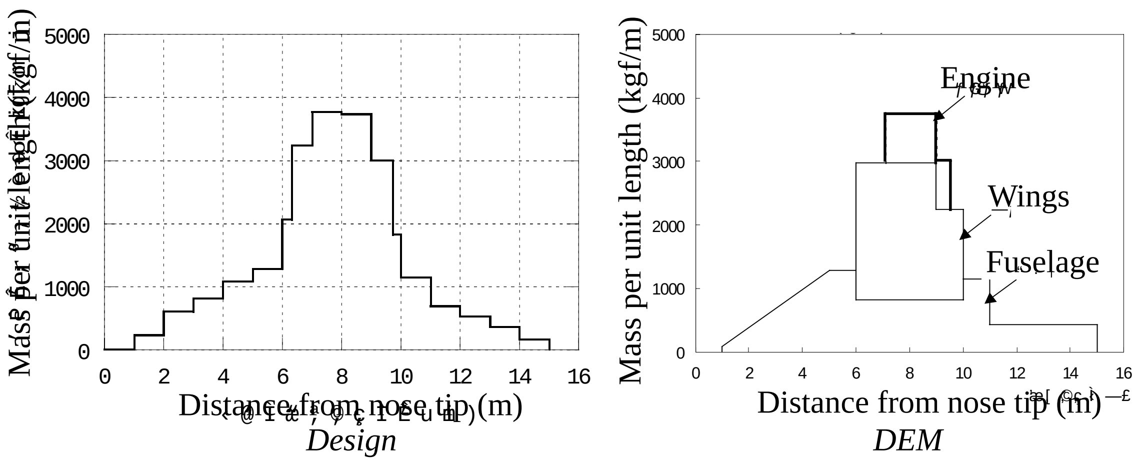
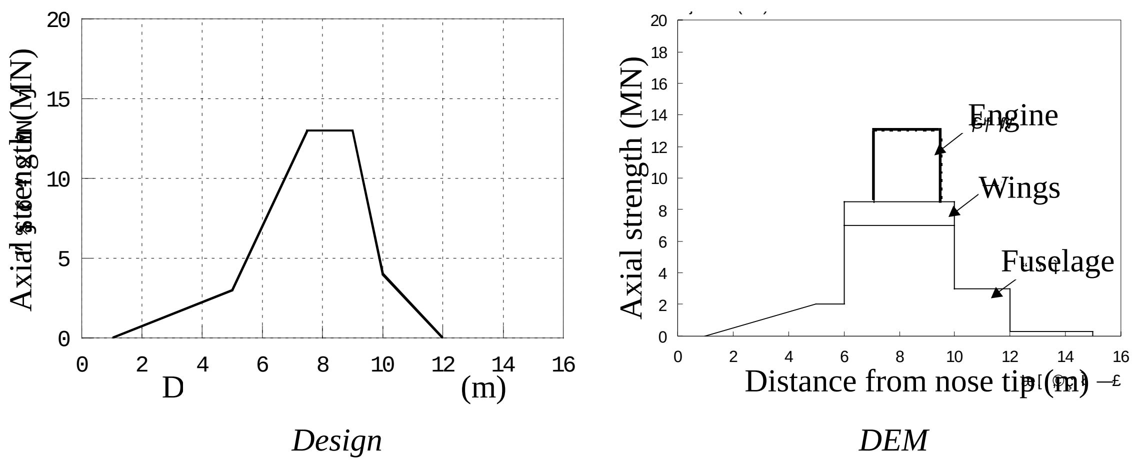


Fig. 1 Schematic Illustration of Full SC Wall and Half SC Slab



(a) Mass Distribution



(b) Axial Strength Distribution

Fig. 2 Distribution of Mass and Axial Strength of an Aircraft Model

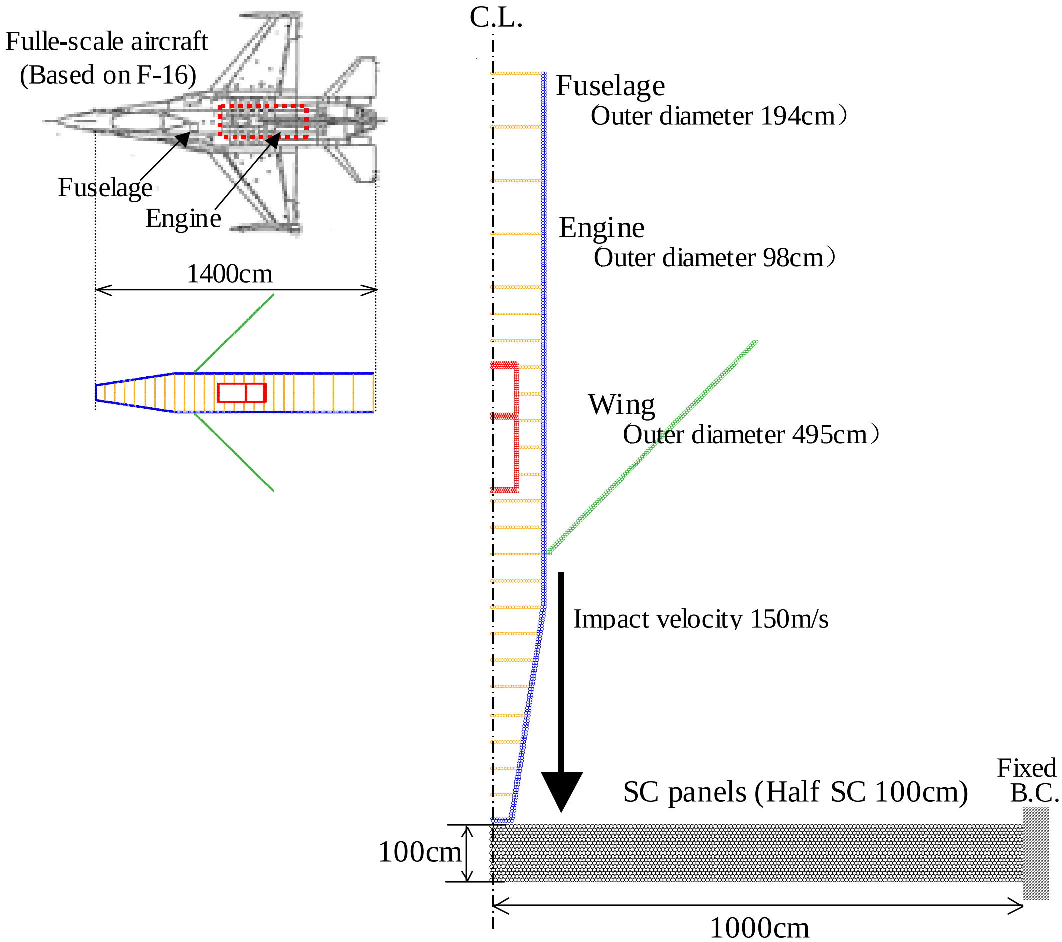


Fig. 3 DE Model of the Full-scale Aircraft and a Half SC Panel

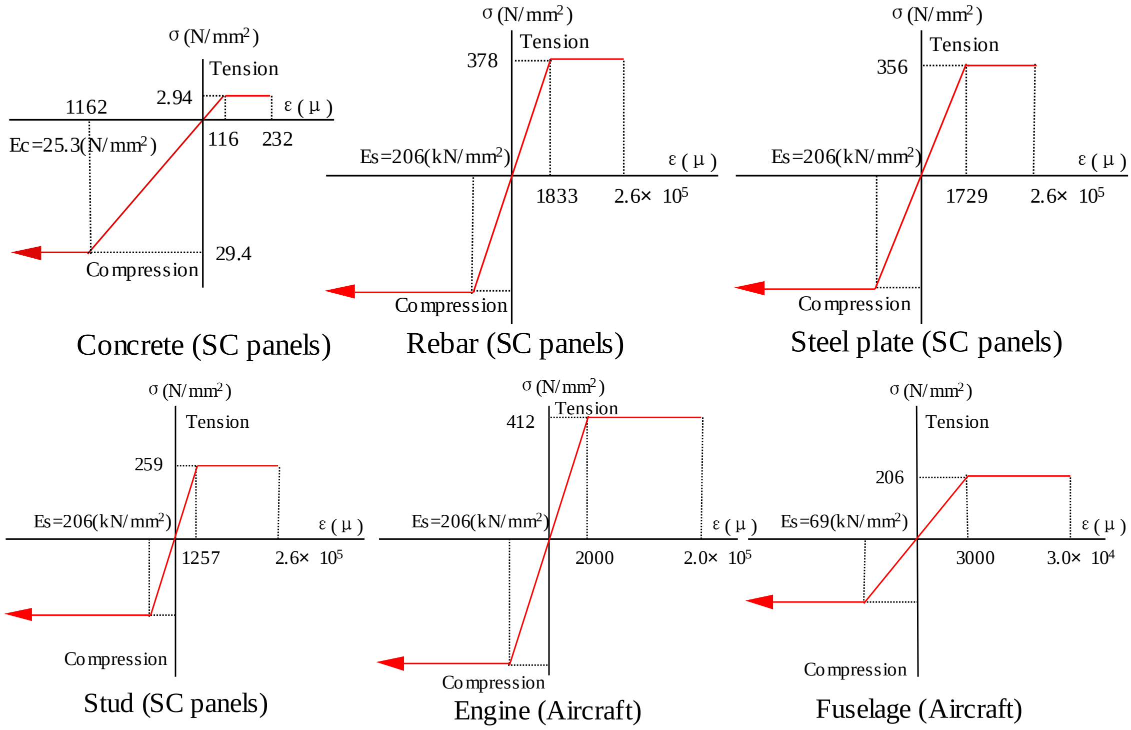


Fig. 4 Material Characteristics for the Full-scale Aircraft and the SC Panels

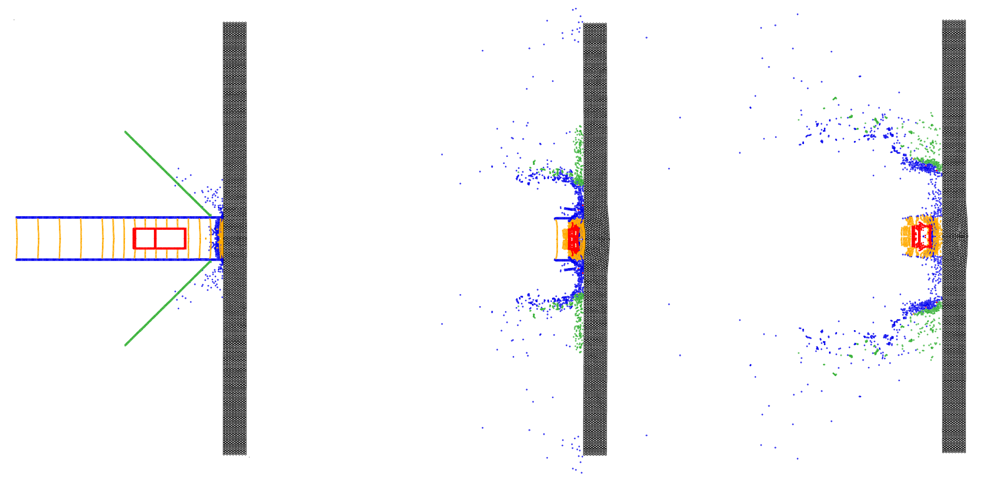


Fig. 5 Fracture Process of FSC-100

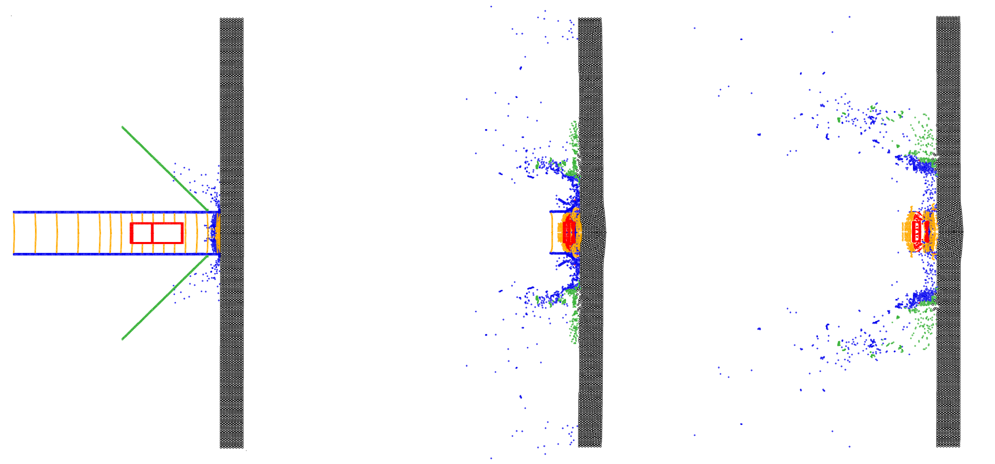


Fig. 6 Fracture Process of HSC-100

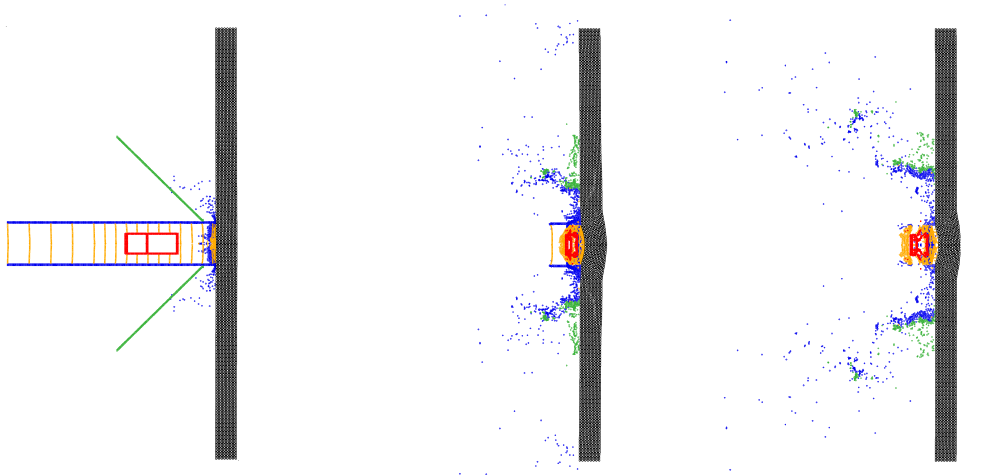


Fig. 7 Fracture Process of FSC-90

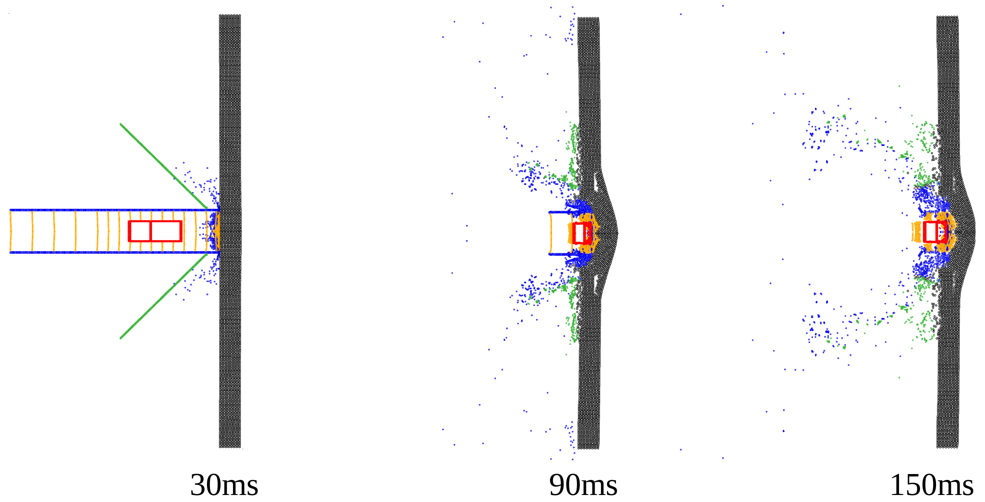


Fig. 8 Fracture Process of HSC-90

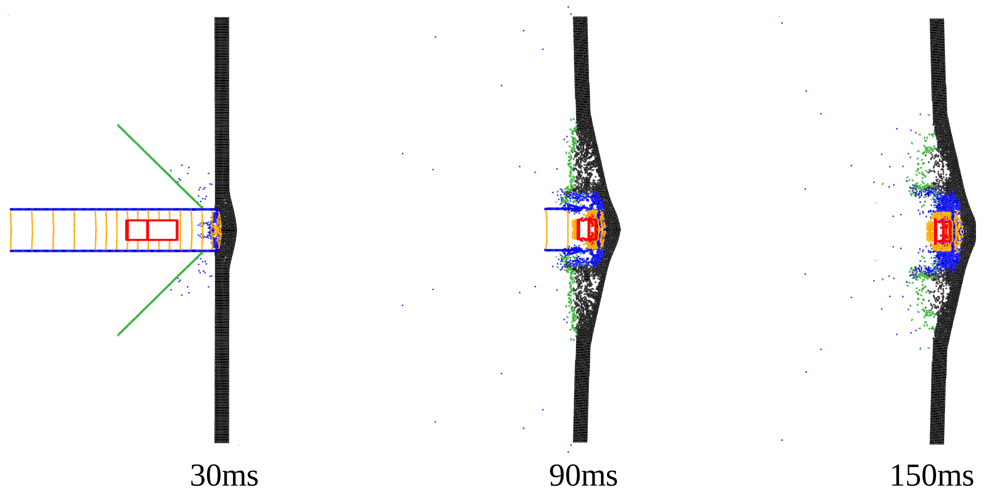


Fig. 9 Fracture Process of HSC-60

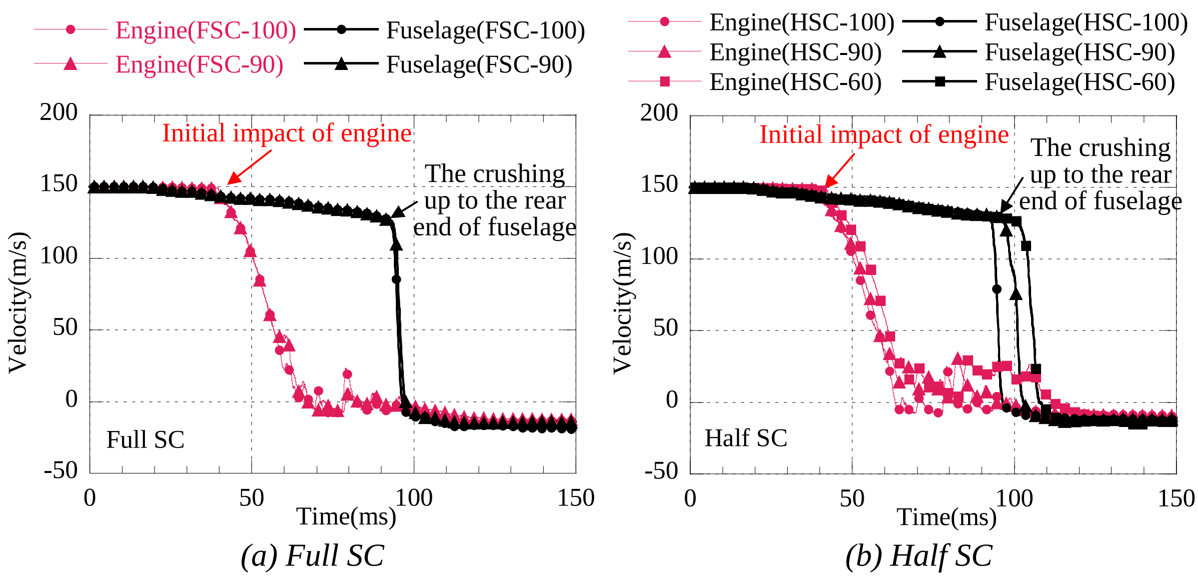


Fig. 10 Velocity Time History of Fuselage and Engine after Impact against SC Panels

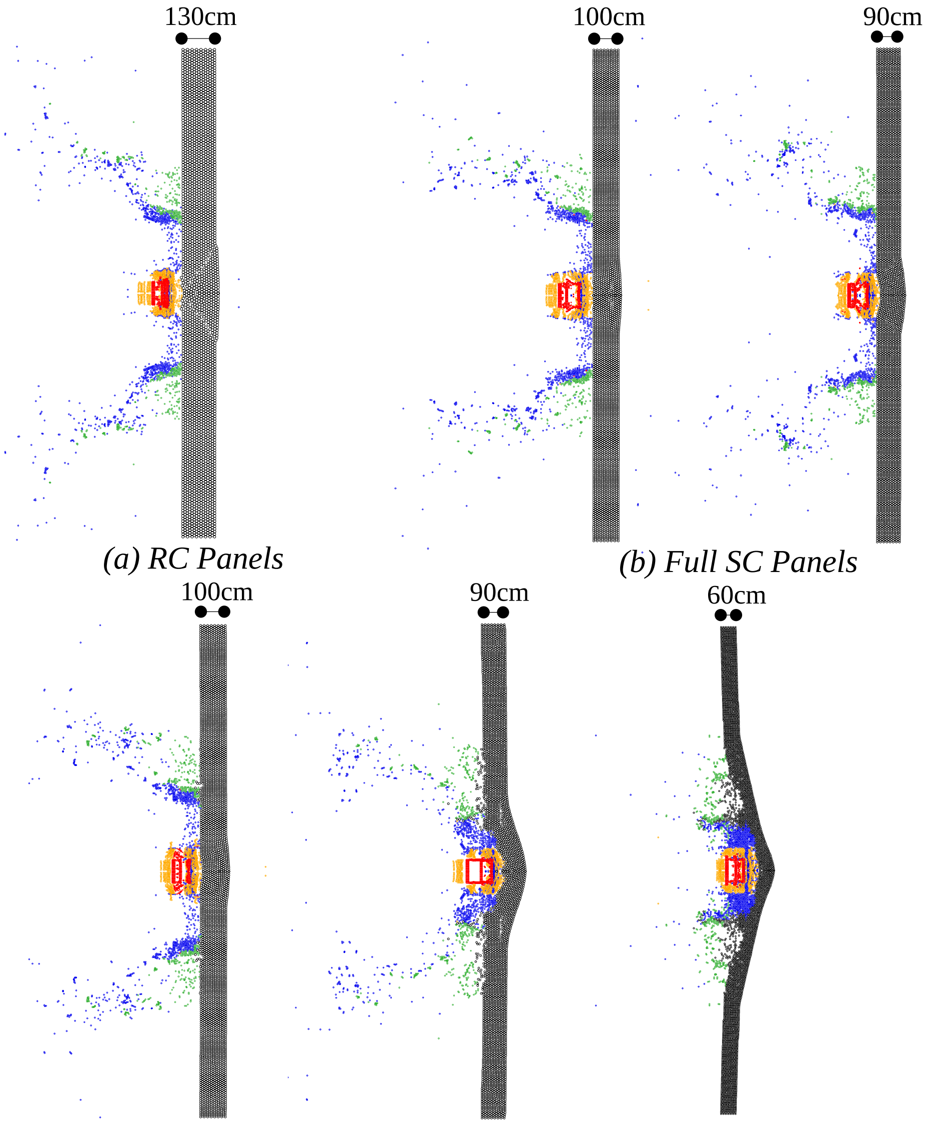


Fig. 11 Final Fracture Patterns of RC and SC panels at 150ms

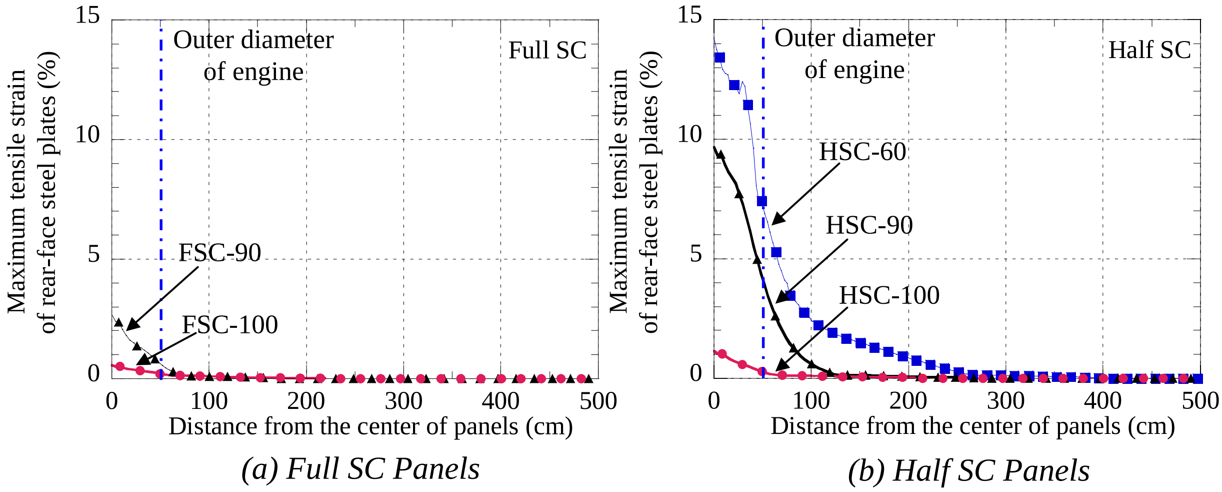


Fig. 12 Maximum Tensile Strain Distribution on the Rear-face Steel Plates of SC Panels

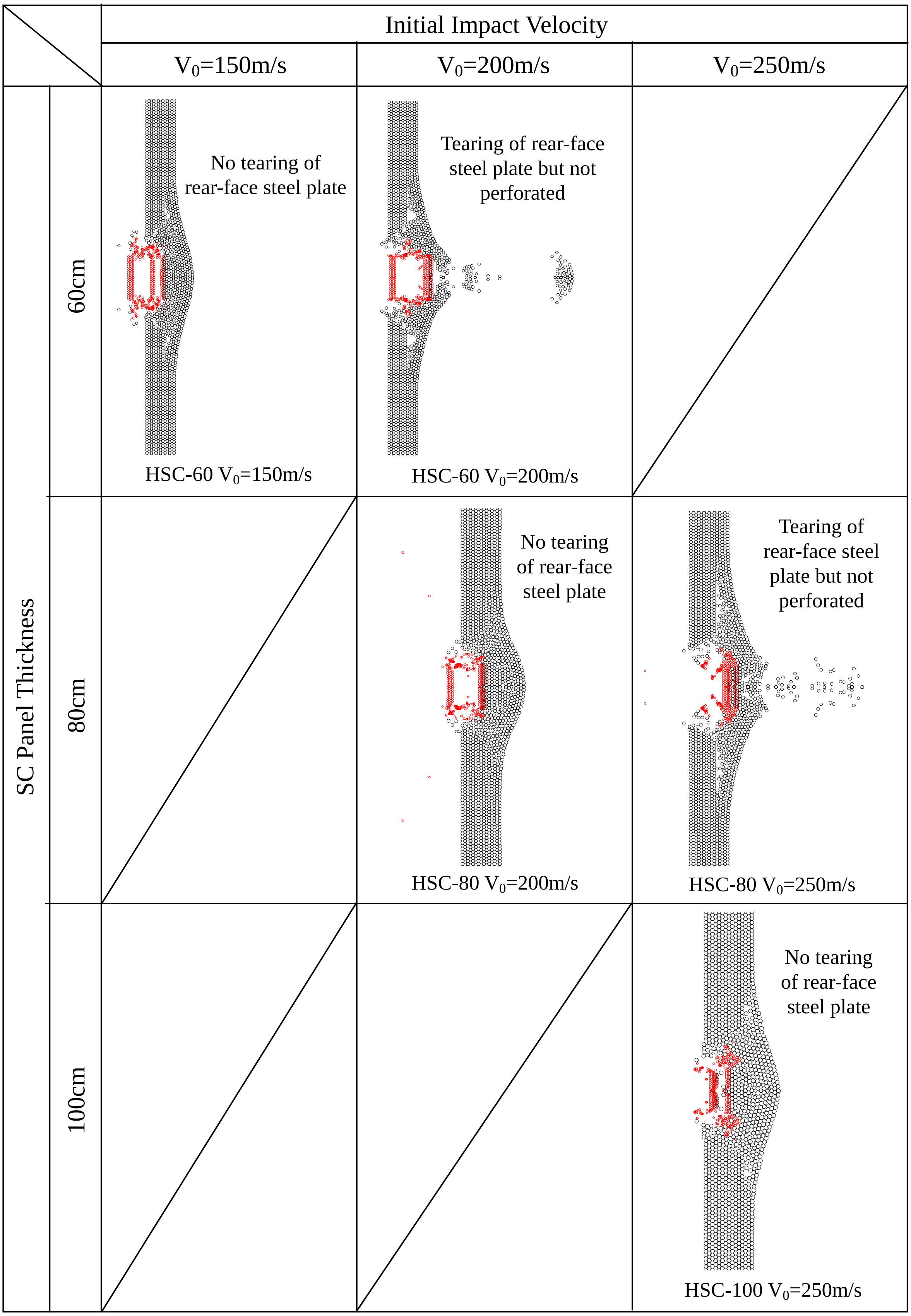


Fig. 13 Final Fracture Patterns against Engine Impact at 80ms

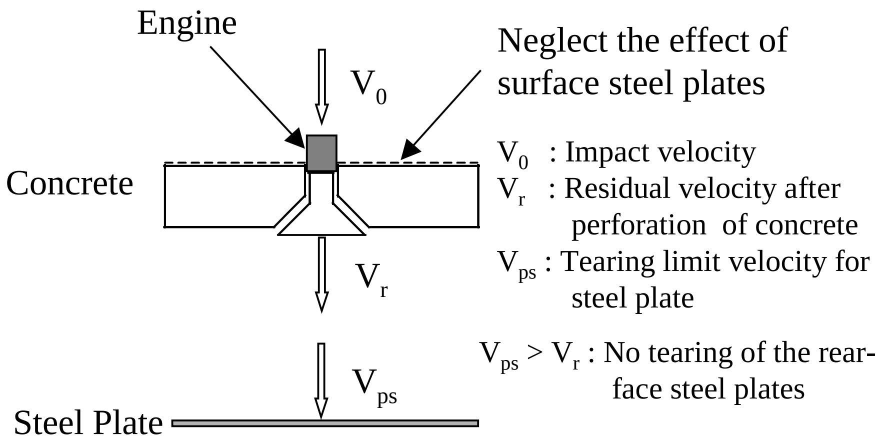


Fig. 14 Evaluation Procedures for the Tearing of SC panels against an Engine Impact

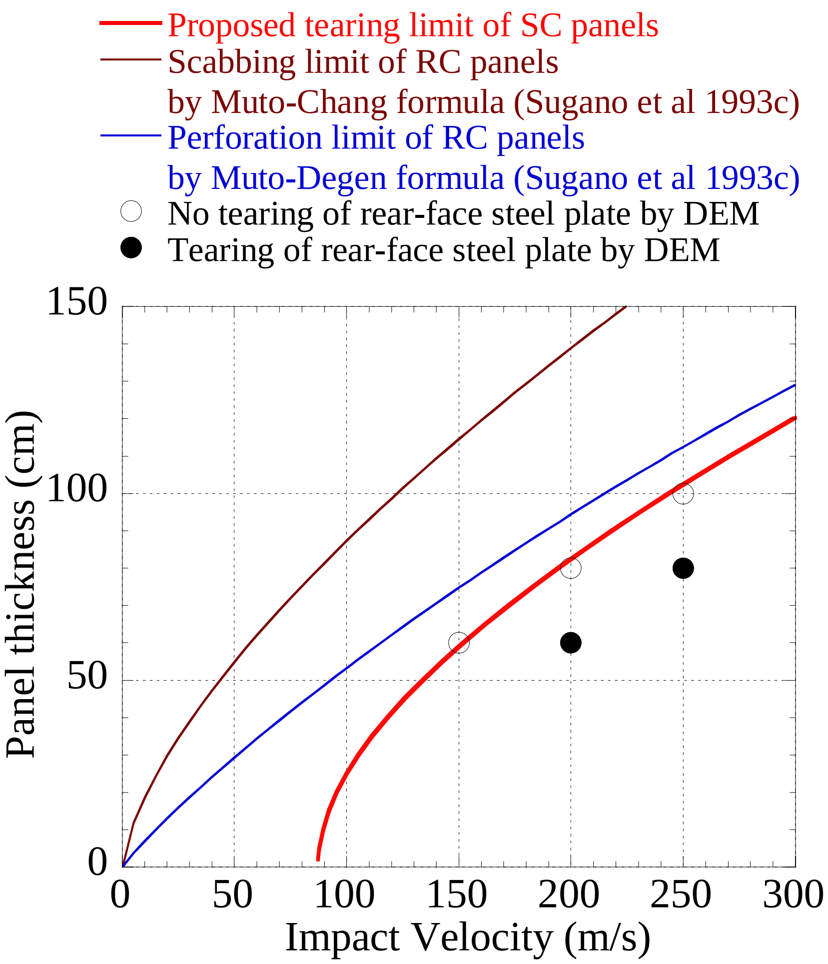


Fig. 15 Proposed Tearing Limit of SC Panels against an Engine Impact