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ANALYTICAL STUDY ON DEVELOPMENT OF LOCAL FAILURE CRITERIA OF RC PANELS COVERED WITH STEEL PLATE SUBJECT TO MISSILE IMPACT

Takaaki Tsukada[1], Ryosuke Imai[2], Ayaka Yokoyama[3], Yasuhiro Ohashi[4]

[1] Nuclear Projects Division, Shimizu Corporation, Kyobashi Chuo-ku, Tokyo, JAPAN
(t.tsukada@shimz.co.jp)
[2] Nuclear Projects Division, Shimizu Corporation, Kyobashi Chuo-ku, Tokyo, JAPAN
(r_imai@shimz.co.jp)
[3] Nuclear Projects Division, Shimizu Corporation, Kyobashi Chuo-ku, Tokyo, JAPAN
(a.yokoyama@shimz.co.jp)
[4] Nuclear Projects Division, Shimizu Corporation, Kyobashi Chuo-ku, Tokyo, JAPAN
(ohashi_y@shimz.co.jp)

ABSTRACT

The purpose of this study is to investigate the failure modes of half steel concrete (HSC) panels with large cross-section, assuming their application in nuclear-related buildings. Additionally, the perforation formula for HSCs proposed by Imai et al. (2024), which has been confirmed to be valid HSC panel thickness up to 300 mm, was validated for these large-section HSCs.

To increase the panel thickness compared to the previous studies [Tsukada et al. (2022) and Imai et al. (2024)], the analysis model for a large cross-sectional reinforced concrete (RC) panel was first validated through simulation analysis of an impact test on a 1600 mm-thick panel, considering that the non-linear behaviour of concrete is influenced by the mesh size.

Using the validated analysis modelling approach, a parametric study was conducted to validate the local failure criteria of HSCs and to identify the typical damage modes of their structural components. Specifically, the study evaluated the effectiveness of tie bars in preventing the spalling of steel plates from RC panels. When an adequate number of tie bars is installed, it was confirmed that the criteria of local failure of HSCs proposed by Imai et al. (2024) shows good agreement with the failure mode observed in analysis results. Furthermore, the energy absorbed by the concrete in the analysis was compared to show good agreement with that calculated using the proposed formula.

INTRODUCTION

The design of nuclear-related facilities, to withstand extreme conditions like accidental aircraft impact or unforeseen terrorist attacks, holds vital societal significance. In the context of these facilities, reinforced concrete panels are commonly used. Numerous studies have been conducted to evaluate the resistance of these reinforced concrete panels to missile impacts. In terms of localized damage to reinforced concrete panels, various formulas have been proposed to determine the necessary thickness of these panel to prevent perforation or scabbing on their rear surface [W. S. Chang (1981), NDRC (1946), P. Degen (1980)].

The HSC system is anticipated to offer effectiveness in preventing missiles from penetrating walls and containing the dispersion of crushed concrete. Consequently, adopting HSC provides a strong possibility for optimizing wall or roof thickness against missile impact, as well as reducing the construction period and environmental impact. This optimization directly correlates with material consumption and construction costs. However, these formulas for local damage criteria have not been implemented in the aircraft impact design involving HSCs.

Experimental research was conducted to assess the impact resistance performance of HSCs, as outlined in Figure 1 [Hashimoto et al. (2005)]. The effectiveness of enhanced impact resistance was verified. In the previous study, a formula was proposed to establish the local damage criteria for HSC design. This formula based on the results of impact tests that identified a critical bulging height of the steel plate at 53.8mm. However, this critical bulging height of 53.8mm was derived from the impact test case that resulted in failure through the splitting mode.

To establish a comprehensive design formula to prevent local failures in HSCs, it is necessary to attain a more universal representation of the critical state. An analytical investigation was undertaken by Tsukada et al. (2022) by simulating various impact test results, as conducted by Hashimoto et al. (8 impact tests for RCs and 16 for HSCs). The results of the analytical study revealed a significant correlation between the absorbed energy of concrete, E_c, and the impact velocity V_m. This V_m influences the pressure exerted on the concrete and enhances the concrete's strength through the strain rate effect. Tsukada et al. (2022) presented a prospective approach wherein the energy required by the steel plate to prevent perforation can be assessed through a comparison involving the difference between the residual kinematic energy of the missile and the E_c against the energy absorption capability of the steel plates, E_s. Based on this concept, Imai et al. (2024) proposed a formula for determining the required panel thickness and steel plate thickness to prevent perforation in HSCs. This formula provides structural designers with a cost-effective method to evaluate wall impact resistance, serving as a complementary tool to traditional FEM analysis particularly in the early design stages.

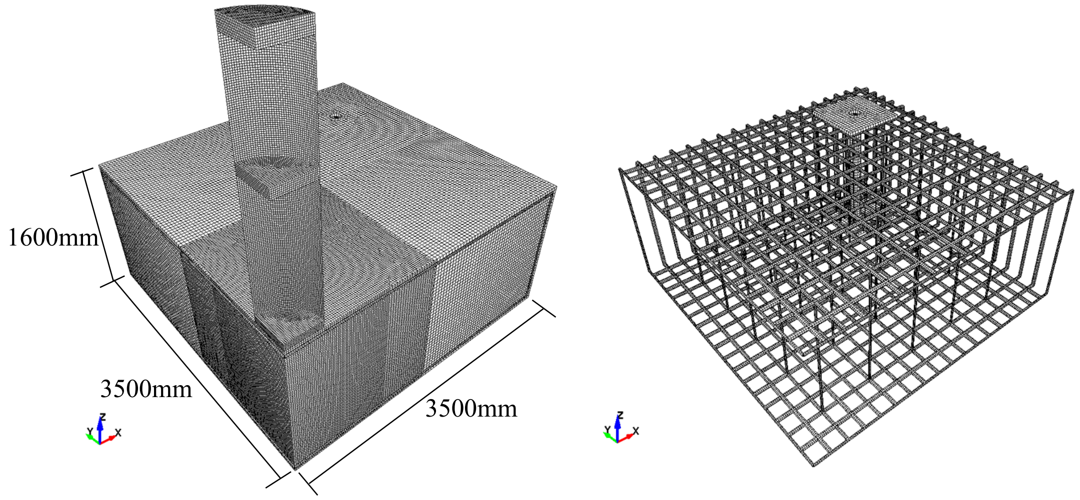
However, the proposed formula has only been validated for HSC panel thicknesses up to 300 mm based on impact tests, simulations of those tests, and supplemental analyses that considered impact parameters not addressed in the experiments. In this study, the failure modes of HSC panels with large cross-sections were investigated, assuming their application in nuclear-related buildings. Additionally, the perforation formula for HSCs proposed by Imai et al. was validated for these large-section HSCs.

VALIDATION OF ANALYSIS MODEL WITH LARGE SECTION

Since the non-linear behaviour of concrete is influenced by the mesh size, the analysis model for large cross-sectional reinforced concrete (RC) panels was first validated through simulation analysis. This validation was based on the impact test conducted by Muto et al. (1989), which involved a 1600 mm thick RC panel subjected to the impact of a deformable missile. The analysis model is shown in Figure 1. The analysis model is quarter model considering its symmetry. The RC panel is supported at four points on the diagonals. Concrete is modelled by solid elements to assess local damage due to the impact of deformable missile. The reinforcements are modelled by bar elements and share the nodes with concrete. The supporting plate and its stiffeners are modelled by solid, shell and beam element along its shape.

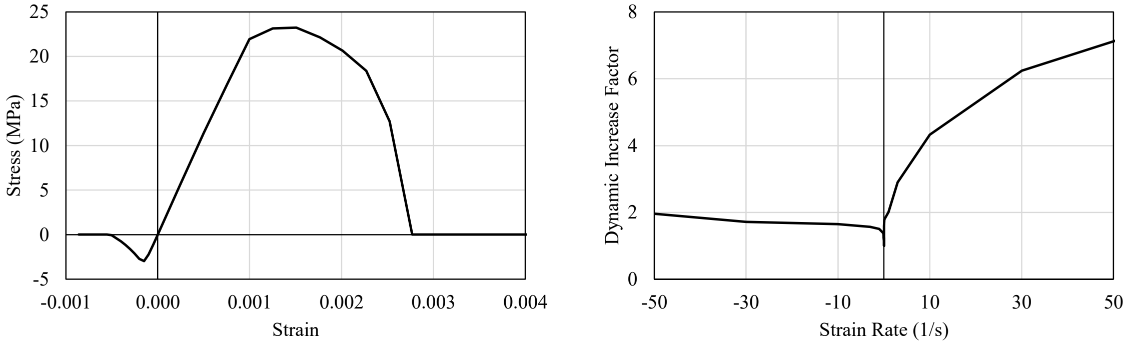
The compressive strength of concrete considered in the impact analysis is 23.5MPa in accordance with the impact test condition. Material model for concrete is the Karagozian & Case (K&C) concrete model verified in Crawford et al. (2011) which is already implemented in LS-DYNA. Based on the relationship between volumetric strain and hydrostatic pressure, the shear failure surface is defined by the yield failure surface, the maximum failure surface and the residual failure surface. The softening of concrete in compression and tension are modelled as shown in Figure 2 (a) based on the isotropic damage function depending on the effective plastic strain. As shown in Figure 2 (b), dynamic increase factors are considered as function of strain rate for compression by the approach of the CEB Model Code (2013) and for tension by the modified CEB formulation proposed in Malvar et al. (1998).

The distribution of the effective plastic strain obtained from the analysis is compared with the damage pattern of impact test as shown in Figure 3. The damage pattern in the test results and the analytical results is consistent both at front and rear surfaces. The comparisons of deformation of the RC panel and reaction force between impact test results and analysis results are shown in Figure 4. The overall behaviours of the RC panel and reaction force time history are consistent between impact test results and analysis results. Since the analysis results show good agreement with the impact test results, the modelling of the RC, such as mesh sizes and constitutive lows applied in the analysis, is validated for use in the parametric study for HSCs with large cross-section by installing steel plate at the rear surface.



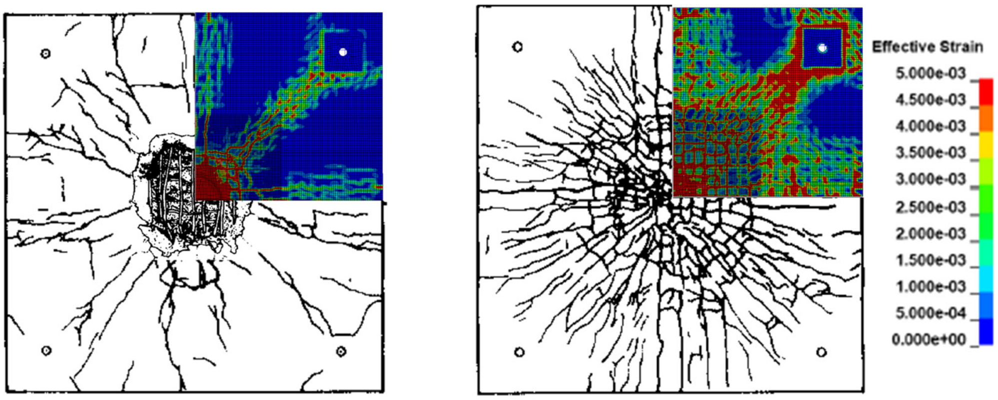
(a) Entire model *(b) Rebar, stirrup, and support*

Figure 1. Analysis model for simulation of impact test of Muto et al. (1989)



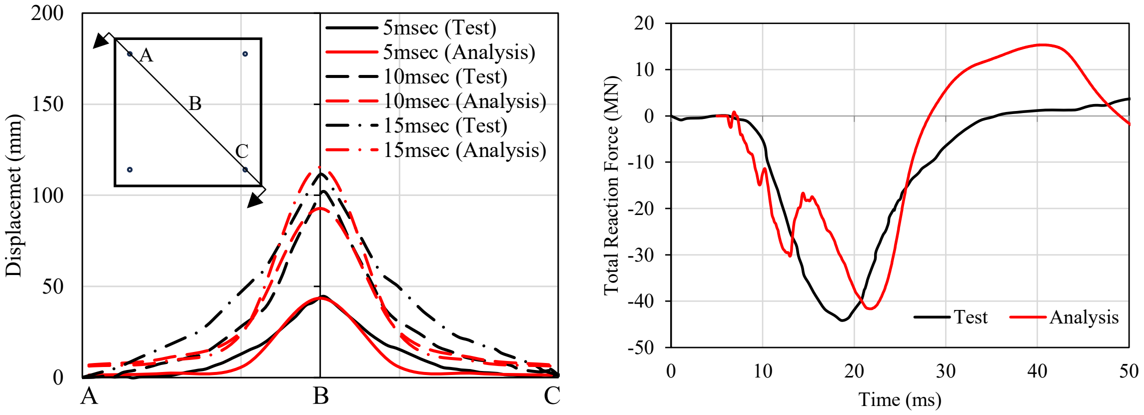
(a) Stress-strain relationship *(b) Dynamic increase factor-strain rate relationship*

Figure 2. Concrete model



(a) Front *(b) Rear*

Figure 3. Comparison of damage pattern between impact test by Muto et al. (1989) and analysis



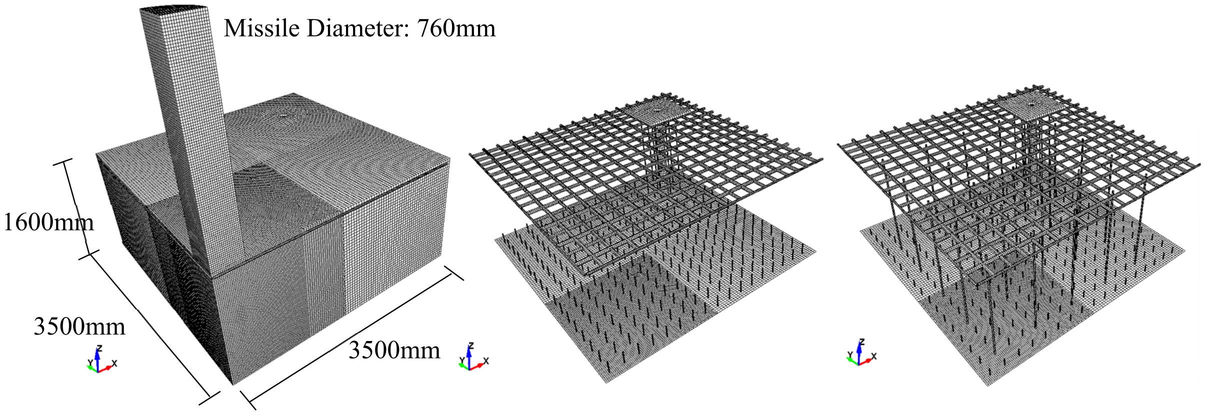
(a) Deflection between diagonally positioned support *(b) Total reaction time history*

Figure 4. Comparison of deformation and reaction force between
impact test by Muto et al. (1989) and analysis

LOCAL FAILURE CRITERIA ON HSCs WITH LARGE CROSS-SECTION

Analysis Model

By using the validated analysis modelling approach, the parametric study for the local failure criteria on the HSCs with large cross-section is conducted. The analysis models used for the study are shown in Figure 5. The reinforcement at the rear surface of RC panel and stirrup in the validation model were removed from the validation model and steel plate is installed with stud bolt. The nodes of steel plate, reinforcement, stud bolts and tie bars are shared with concrete. For some analysis cases, tie bar from the steel plate to the reinforcement at front side of the RC panel is installed as an analysis parameter. The mechanical properties of the steel plates, studs and tie bars are modelled according to the minimum requirement prescribed in Japanese Industrial Standard, JIS G 3101. The missile was modified for the study on local failure criteria of HSC from the deformable in the validation model to be rigid for simplification of the energy absorption mechanism so that the absorption of kinematic energy of missile is absorbed by the internal energy of crushed concrete and the deformation of the steel components of the HSC. The analysis parameters in this study is listed in Table 1 in Section '*Summary of Analysis Cases and Results.*'



(a) Entire model *(b) Inside panel (stud connect)* *(c) Inside panel (stud connect +tie bar)*

Figure 5. Analysis model for study on local failure criteria for HSC with large section

Summary of Analysis Cases and Results

The analysis cases and summary of the analysis results is shown in Table 1 with analysis parameters in this study. The typical damage modes listed in Table 1 are defined in Figure 9 in Section titled 'Failure Modes of HSC.'

Since the panel thickness of 1600 mm slightly exceeds the provisions of AISC N690-18 (2018) for SC walls, which limit the panel thickness to a maximum of 1500 mm, this study encompasses the scope of the existing design code for SC structures. The missile weights of 3.0 tons and 5.0 tons (0.75 tons and 1.25 tons for a quarter model in this study), which resemble the weighs of engines used in medium and large commercial aircraft, are assumed. The required RC panel thicknesses to prevent scabbing and perforation, based on the formulas proposed by Chang (1981) and Degen (1981), are shown in Figure 6. The impact velocities were determined such that the required RC panel thickness exceeds the analysis model (1600 mm) to prevent scabbing when no steel plate is installed on the rear surface. The required steel plate thicknesses to prevent local failure of HSCs are shown in Figure 7, following the criteria proposed by Imai et al. (2024).

The steel plate thicknesses in this study are varied to be relatively smaller and larger than the values required by the proposed formula. The steel plate thicknesses in this study, ranging from 12 mm to 25 mm, are within the provisions of AISC N690-18 (2018) for SC walls, which specify a steel plate thickness range of 6 mm to 32 mm and a reinforcement ratio by steel plate on one face ranging from 0.0075 to 0.025. The steel plate thickness of 12 mm in this study corresponds to a reinforcement ratio of 0.0075, which is the lowest limit specified in AISC N690-18 (2018). The length of stud bolt is changed from 120 mm to 300 mm to evaluate its effect on connectivity between the steel plate and concrete during the missile impact. The typical quantity of tie bars required for constructability of steel concrete (SC) structures is 0.05%. The shear reinforcement ratio, which considers the contribution of tie bars to the out-of-plane shear resistance, is set at 0.04%, 0.06% and 0.12% representing the minimum requirement and adequate cases.

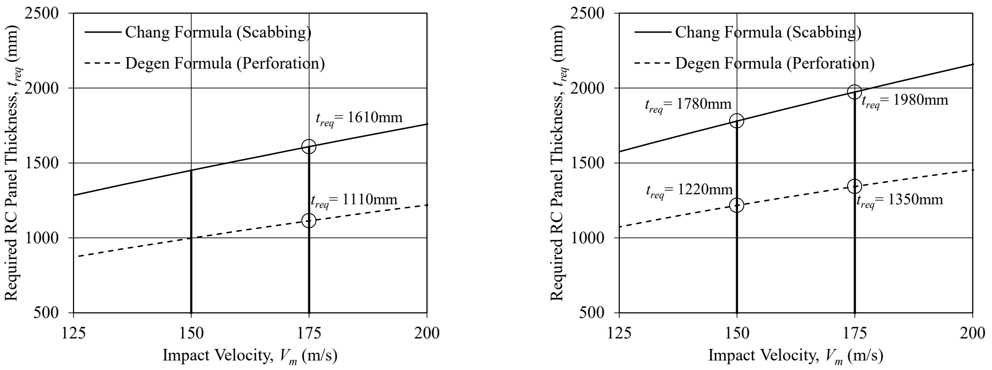
The method for determining whether local failure of the HSC occurred is shown in Figure 8. When local failure occurs, the concrete around the impact zone exhibits a higher out-of-plane velocity 50 msec after impact compared to the rest of the HSC, as shown in Figure 8 (a). Conversely, when local failure is prevented, the velocity of the impact zone converges to a lower value than that of the surrounding area, as shown in Figure 8 (b).

Table 1: Analysis Cases

Analysis Case	Missile Weight (ton)	Impact Velocity (m/s)	Steel Plate Thickness (mm)	Stud Length (mm)	Tie bar		Damage Mode*	Local Failure**
					Diameter (mm)	Ratio (%)		
1	3.0	175	12	120	-	-	Mode A	Perforation
2			12	180	-	-	Mode A	Perforation
3			12	300	-	-	Mode A	Perforation
4			12	120	13	0.04	Mode C	Bulging
5			12	120	22	0.12	Mode B	Bulging
6			16	120	-	-	Mode A	Perforation
7			16	120	22	0.12	Mode B	Bulging
8			19	120	-	-	Mode A	Perforation
9			19	120	22	0.12	-	Bulging
10	5.0	150	16	120	22	0.12	Mode B	Bulging
11			19	120	13	0.04	Mode C → A	Perforation
12			19	120	16	0.06	Mode C	Bulging
13			19	120	22	0.12	Mode B	Bulging
14			22	120	22	0.12	-	Bulging
15		175	12	120	22	0.12	Mode B → D	Perforation
16			19	120	22	0.12	Mode B → D	Perforation
17			25	120	22	0.12	-	Bulging

* The typical damage modes are shown in Figure 9. See Section titled ‘*Failure Modes of HSC.*’

** The failure modes are shown in Figure 8.



(a) Missile weight of 3.0ton *(b) Missile weight of 5.0ton*

Figure 6. Criteria on scabbing and perforation according to Chang (1981) and Degen (1981) formula

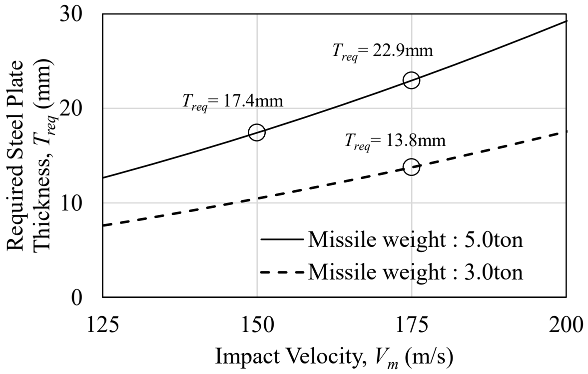
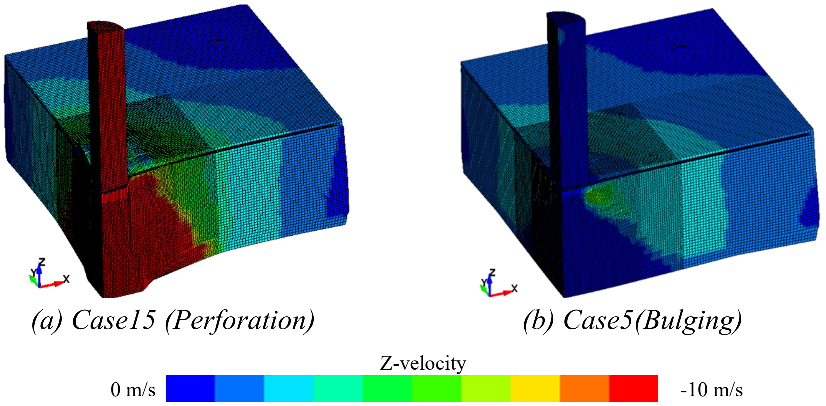


Figure 7. Criteria on perforation of steel plate according to Imai (2024) formula

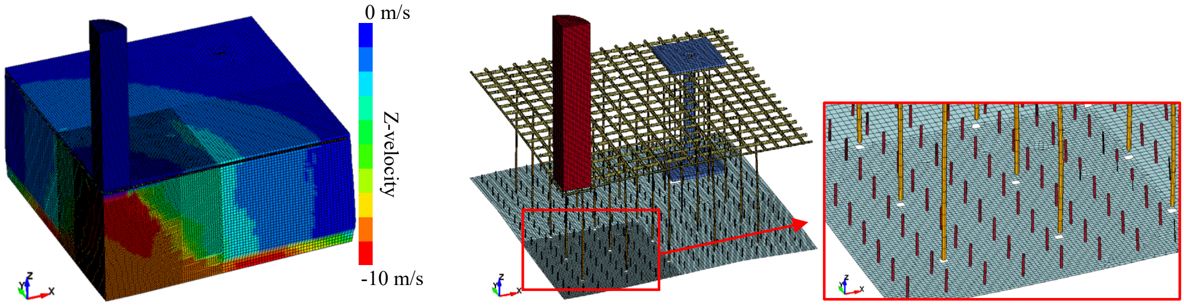


(a) Case15 (Perforation) *(b) Case5(Bulging)*

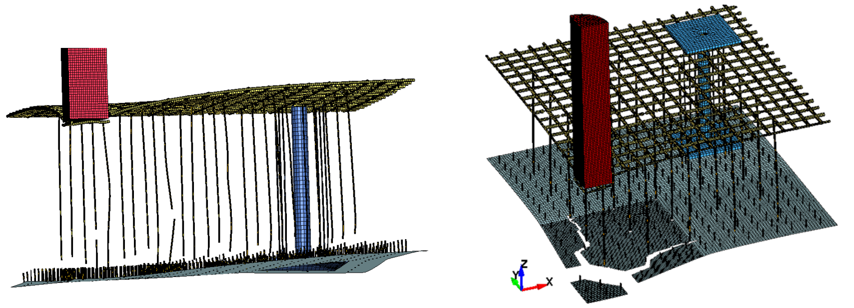
Figure 8. Determination of local failure of HSCs (50 msec after impact)

Failure Modes of HSC

The typical damage modes of the structural components in HSC are shown in Figure 9. Mode A refers to the spalling of the steel plate, where it detaches from the rear side of the RC panel. This spalling mode was not observed in prior impact tests or analytical simulations on HSCs [Hashimoto et al. (2005); Tsukada et al. (2022)], as the width of the HSCs (750 mm) was at least 6.25 times the panel thickness (60 mm to 120 mm), which was sufficient to prevent steel plate spalling. However, in this study, the HSC width (7000 mm) is only 4.375 times the panel thickness (1600 mm), resulting in all studs losing their connection to the concrete. Mode B describes the puncture of the steel plate at its connection with the tie bars. This failure mode occurred in analysis cases 5, 7, and 10, where the steel plate thickness was relatively thin compared to the tie bar diameters. Mode C refers to the failure of the tie bars connecting the steel plate to the reinforcement on the front surface of the HSC. Mode D involves the failure of the steel plate itself.



(a) Mode A: Spalling of steel plate *(b) Mode B: Puncture of steel plate*



(c) Mode C: Failure of tie bar *(d) Mode D: Perforation of steel plate*

Figure 9. Typical damage mode of structural components in HSC (concrete is hidden for *(b)* to *(d)*)

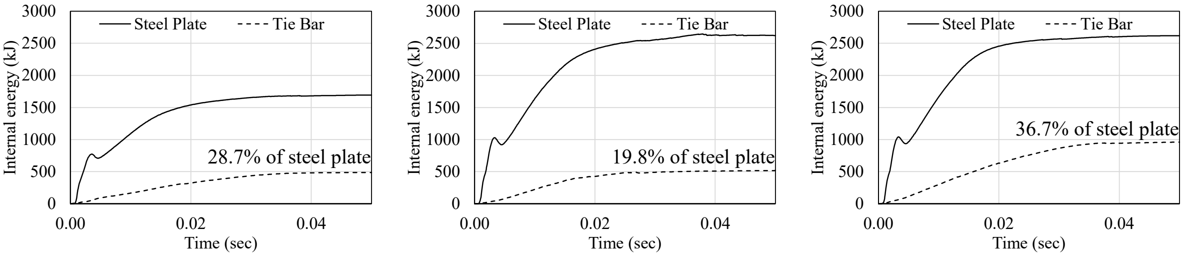
Validation of Perforation Criteria

Based on the analysis results shown in Table 1, the puncture of the steel plate (Mode B) and the failure of the tie bars (Mode C) do not directly lead to local failure of the HSC panel. However, the spalling of the steel plate (Mode A) and the failure of the steel plate (Mode D) do result in immediate local failure.

The spalling of the steel plate (Mode A) occurred with the steel plate larger than the required thickness evaluated by proposed formula in Imai et al. (2024) when the tie bars were not installed. The installation of tie bars is effective to prevent the spalling of steel plate (Mode A). The failure mode of the tie bars (Mode C) occurred in analysis cases 4, 11 and 12 where the shear reinforcement ratios of tie bars were less than 0.10%. Although the common quantity of tie bars required for constructability of steel concrete structure is 0.05%, increasing it to 0.1% could prevent in the failure of tie bars due to missile impact. The internal energy time histories of the steel plate and tie bars in analysis cases 4, 11, and 12, where failure of the tie bas is observed, are shown in Figure 10. In the local failure case (case 11), the energy absorbed by the tie bars was only 19.8% of the energy absorbed by the steel plate, compared to 28.7% and 36.7% in the non-local failure cases (cases 4 and 12, respectively). In analysis case 11, although the tie bar ratio was similar to that in case 4, the combination of a small tie bar diameter (φ13 mm), a relatively thick steel plate ($T = 19$ mm), and a heavy missile weight ($M_m = 5$ tons) resulted in the spalling of the steel plate after the tie bars failed, despite the steel plate thickness meeting the required value to prevent perforation. This indicates that the diameter of the tie bars should be determined in relation to the thickness of the steel plate to maintain an appropriate balance. Conversely, when enough tie bars are installed, they contribute to energy absorption through deformation, thereby reducing the required steel plate thickness. For example, in analysis case 4, the failure of the steel plate was prevented despite its smaller thickness ($T = 12$ mm) than required thickness ($T_{req} = 13.8$ mm) in Figure 7, due to the energy absorption contributed by the tie bars.

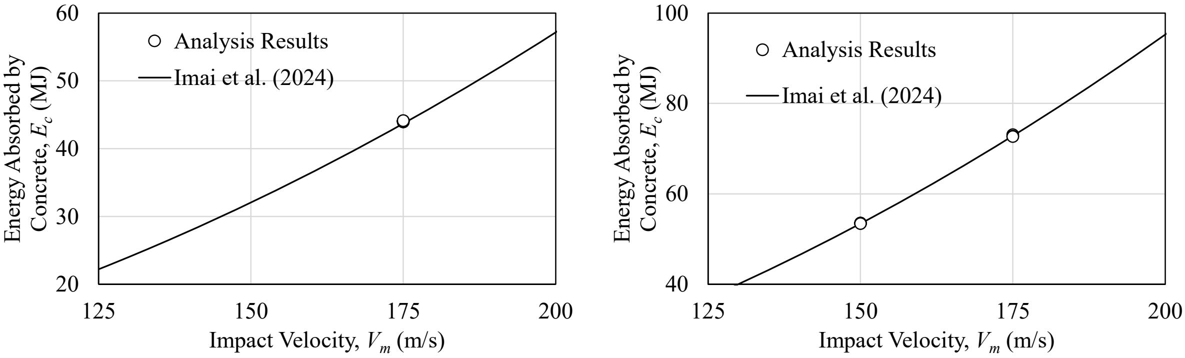
In analysis cases 15 through 17, the steel plate thickness was varied while maintaining enough tie bars. When an adequate number of tie bars (ratio of 0.12%) is installed, Mode D (failure of steel plate) becomes the dominant failure mode if the steel plate thickness is less than the required value specified by the criteria proposed by Imai et al. (2024). Therefore, if the spalling of the steel plate is prevented by installing tie bars, as observed in analysis cases 15 through 17, the criteria ($T_{req} = 22.9$ mm) proposed by Imai et al. (2024) shows good agreement with the failure modes observed in the analysis results. By installing the steel plate at rear surface of the RC panel, the panel thickness to prevent scattering of crushed concrete inside the building can be reduced from 1980mm (according to Chang formula) to at least 1600mm (analysis case 17).

Furthermore, the energy absorbed by the concrete in the analysis was compared with the values calculated using the formula proposed by Imai et al. (2024), as shown in Figure 11. Since the formula proposed by Imai et al. (2024) assumes 100% efficiency in the transformation of the missile's initial kinetic energy into the internal energy of the HSCs, the kinematic energies of the missile and HSCs 50 milliseconds after impact are accounted for as energy absorbed, as they do not contribute to the damage of the HSCs. The results demonstrate good agreement between the analysis and the proposed formula, validating the criteria presented by Imai et al. (2024) for HSCs with realistic dimensions of nuclear related facilities.



(a) Case 4 *(b) Case 11 (local failure case)* *(c) Case 12*

Figure 10. Comparison of internal energy of steel plate and tie bar



(a) Analysis cases 1 through 9 *(b) Analysis cases 10 through 17*

Figure 11. Comparison of energy absorbed by concrete between analysis results and formula proposed in Imai et al. (2024)

CONCLUSION

Since the non-linear behaviour of concrete is influenced by the mesh size, the analysis model for large cross-sectional reinforced concrete (RC) panels was first validated through simulation analysis. This validation was based on the impact test conducted by Muto et al. (1989), which involved a 1600 mm thick RC panel subjected to the impact of a deformable missile. Since the analysis results show good agreement with the impact test results, the modelling of the RC, such as mesh sizes and constitutive lows applied in the analysis, is validated for use in the parametric study for HSCs with large cross-section.

Using the validated analysis modelling approach, a parametric study was conducted to validate the local failure criteria of HSCs proposed in Imai et al (2024) and to identify the typical damage modes of their structural components. The study revealed several damage modes. Spalling of the steel plate, characterized by its detachment from the rear side of the RC panel, was observed when the tie bar was not installed. Additionally, puncture of the steel plate at its connection points with the tie bars occurred when the steel plate thickness was relatively thin compared to the tie bar diameters. Failures of the tie bars, which connected the steel plate to the reinforcement on the front surface of the HSC, as well as failures of the steel plate itself, were also observed.

Based on the analysis results, the puncture of the steel plate and the failure of the tie bars do not directly lead to local failure of the HSC. However, the spalling of the steel plate and the failure of the steel plate do result in immediate local failure. Especially, the spalling of the steel plate occurs with the steel plate larger than the required thickness evaluated by proposed formula in Imai et al. (2024) when tie bars are not installed. Conversely, when enough tie bars are installed, they contribute to energy absorption through deformation and the failure of the steel plate was prevented despite its smaller thickness than required thickness in Imai et al. (2024). When an adequate number of tie bars (tie bar ratio = 0.12%) is installed, the criteria of local failure of HSCs proposed by Imai et al. (2024) shows good agreement with the failure mode observed in analysis results. Furthermore, the energy absorbed by the concrete in the analysis was compared to show good agreement with that calculated using the formula proposed by Imai et al. (2024).

As a basis for the parameter settings in this study, the panel thickness of 1600 mm in this study slightly exceeds the provisions of AISC N690-18 (2018) for SC walls, which limit the panel thickness to a maximum of 1500 mm. Therefore, panel thickness in this study encompasses the scope of the existing design code for SC structures. The missile weights of 3.0 tons and 5.0 tons in this study are set to be close to the weighs of engines used in medium and large commercial aircraft. The impact velocities were determined such that the required RC panel thickness exceeds the analysis model to prevent scabbing when no steel plate is installed on the rear surface. The steel plate thicknesses in this study are varied to be relatively smaller and larger than the values required by the proposed formula. The steel plate thicknesses in this study, ranging within the provisions of AISC N690-18 (2018) for SC walls. The minimum steel plate thickness of 12 mm in this study corresponds to the lowest limit specified in AISC N690-18 (2018).

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