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Division V

EFFECT OF PROJECTILE MATERIAL ON LOCAL DAMAGES OF REINFORCED CONCRETE PANELS SUBJECTED TO IMPACT LOADING

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ABSTRACT

The impact resistance of reinforced concrete (RC) panels has been extensively investigated through impact tests, and hard impact tests have been especially performed to observe local damages. However, in practice, projectiles are not rigid bodies, so the accurate evaluation of the local damages requires consideration of the material properties of projectiles. In this study, an experimental study was performed to investigate the effect of projectile material on the local damages of RC panels subjected to impact loading. The impact tests for RC panels were performed with projectiles made of two different materials: mild steel and tough pitch copper. The failure mode, damage area, penetration depth, reduced length of soft projectiles, and residual velocity were obtained as test results. The test results indicated that the impact behavior of RC panels as well as projectiles were remarkably dependent on the material of the projectile. The local damages became more severe as the strength of the projectile increased.

INTRODUCTION

The safety of nuclear power plant (NPP) structures is one of the most important considerations in the construction due to potential hazard of radioactive contamination when collapsed. Therefore, design codes and guidelines require discrete impact-resistant design against extreme event, such as an aircraft collision, as well as conventional structural design. Accordingly, the impact resistance of reinforced concrete (RC) panels has been extensively investigated through hard impact tests (Dancygier et al. (2007), Orbovic et al. (2015), Lee et al. (2021)), and various predictive formulae of local damages have been developed for the design of RC panels subjected to hard impact (Fullard et al. (1991), Li et al. (2005), Wen and Xian (2015), Deng et al. (2021)). However, most predictive formulae have focused on hard impact (Li et al. (2005)), whereas projectiles may be deformable in actual situations. Therefore, accurate assessment of local damages requires consideration of the material properties of the projectile.

In this study, a series of high-velocity impact test was carried out to investigate the effect of projectile materials on the local damages of RC panels considering projectile material and impact velocity as main variables. In all, 6 RC panel specimens were designed to simulate NPP structure (APR1400), and the flat-nosed projectiles were made of two types of material: mild steel (SS275) and tough pitch copper (C1100-BD-O). The impact velocity was determined considering the collision velocity of the commercial aircraft. As test results, the failure mode, damage area, penetration depth, reduced length of soft projectiles, and residual velocity were obtained, and the effects of projectile material on the local damages were investigated.

IMPACT TEST FOR RC PANELS

Test Variables

This study carried out impact tests for RC panels with impact velocity and projectile material as variables. The impact velocity was ranged in 100–200 m/s considering aircraft collision velocity (Fang and Wu (2017)). Moreover, the SS275 steel and C1100-BD-O copper were selected as projectile materials to represent the hard and soft projectiles, respectively. Table 1 shows the impact test cases and their designations. Here, the hard impact tests are a part of the authors' previous study (Lee et al. (2021)).

Table 1: Impact test cases.

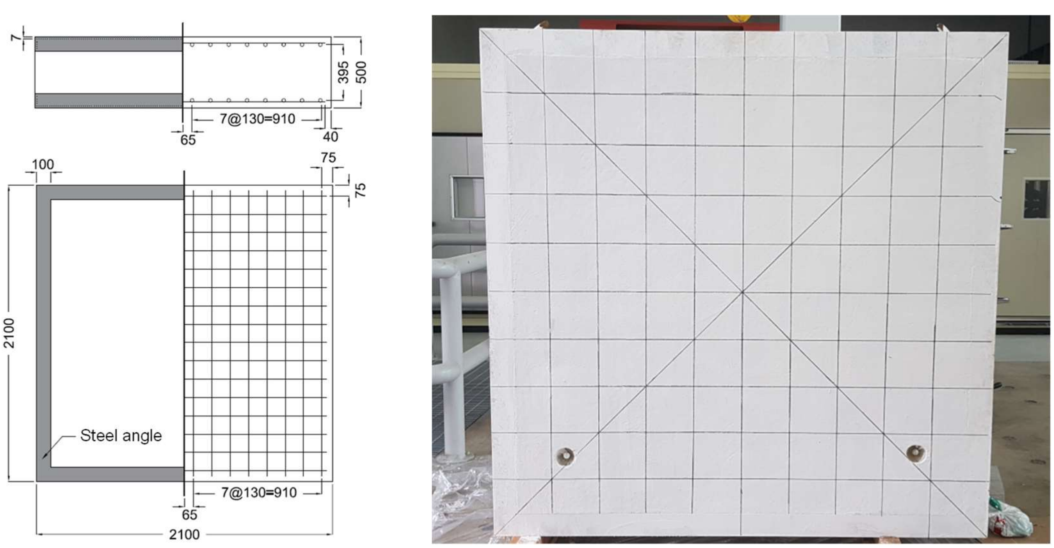
Designation	H-V100	H-V150	H-V200	S-V100	S-V150	S-V200
Projectile material	SS275 steel (hard)			C1100-BD-O copper (soft)		
Impact velocity, m/s	100	150	200	100	150	200

RC Panel Design

Figure 1 and Table 2 show the details of the RC panels. A Korean NPP structure was scaled down to a geometry similarity ratio of 1:2.4 to design RC panels. The size of the RC panels was determined to be 2.1×2.1 m, which was large enough to include the expected scabbing area. L-shaped steel angles were attached to the edges of the RC panels to prevent local failure at the supports.

Table 2: Details of RC panels.

Dimension, m	Concrete compressive strength, MPa	Rebar yield strength, MPa	Rebar diameter, mm	Rebar spacing, mm
2.1×2.1×0.5	49.4	484	25.4	130



(a) (b)

(c)

Figure 1. RC panel; (a) Drawing (unit: mm); (b) Fabricated RC panel;
(c) RC panel clamped by target frame.

Projectile Design

Figure 2 shows the manufactured projectiles. The hard projectiles were designed as solid cylinders of SS275 steel to represent an aircraft engine shaft, and the soft projectiles were designed to have the same mass as the hard projectiles. The size and material properties of the projectiles are listed in Table 3, and Figure 3 shows the results of the static tensile tests of the projectile materials.

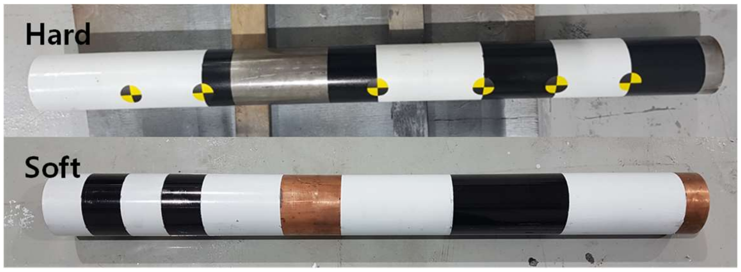


Figure 2. Manufactured projectiles.

Table 3: Details of projectiles.

Type	Dimension, mm	Mass, kg	Elastic modulus, GPa	0.2% offset yield strength, MPa	Ultimate tensile strength, MPa
Hard	D85×L980	43.65	205	526	633
Soft	D85×L860	43.63	115	307	311

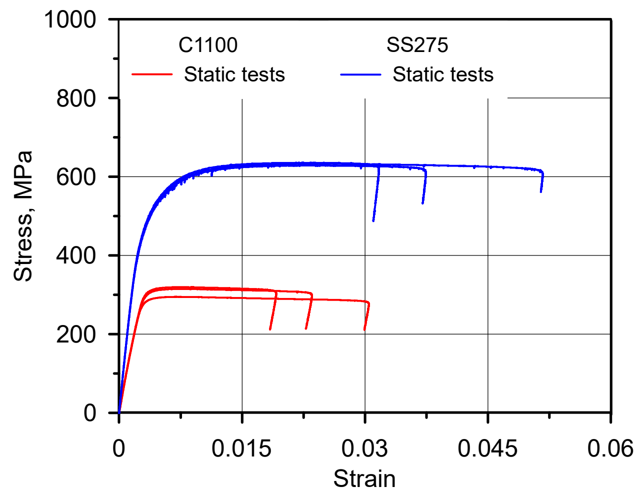


Figure 3. Engineering stress-strain curves of projectile materials.

Impact Test Procedure

A 254-mm caliber single-stage gas gun was employed for impact tests of the RC panels. The RC panel was placed in the target tank and clamped on four sides with a span length of 2×2 m, as shown in Figure 1 (c). Then, the projectile was accelerated using compressed air up to the target impact velocity.

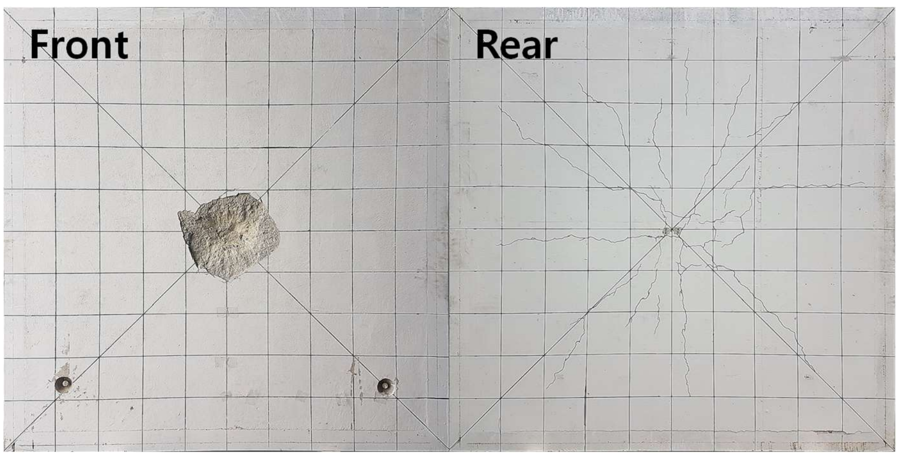
Impact velocity and residual velocity were measured using a laser interrupt system and high-speed camera, respectively. After the tests were completed, the failure mode, penetration depth, and reduced length of soft projectiles were observed, and the damaged area, such as spalling and scabbing area, was obtained through image processing.

IMPACT TEST RESULTS AND DISCUSSION

Figure 4 shows the damaged RC panels after the impact tests, and Table 4 shows the impact test results. Hard impact test results were referred from Lee et al. (2021). In Table 4, x_p, v_i, v_r, and l_r denote the penetration depth, impact velocity, residual velocity, and reduced length of the soft projectile.

Table 4 indicated that the impact behaviors of RC panels and projectiles strongly depended on the projectile material. At an impact velocity of 200 m/s, the soft impact test showed scabbing as the failure mode, whereas the hard impact test showed perforation. The penetration depth and scabbing area of the hard impact tests were significantly different from those of the soft impact tests at similar impact velocities.

(a)



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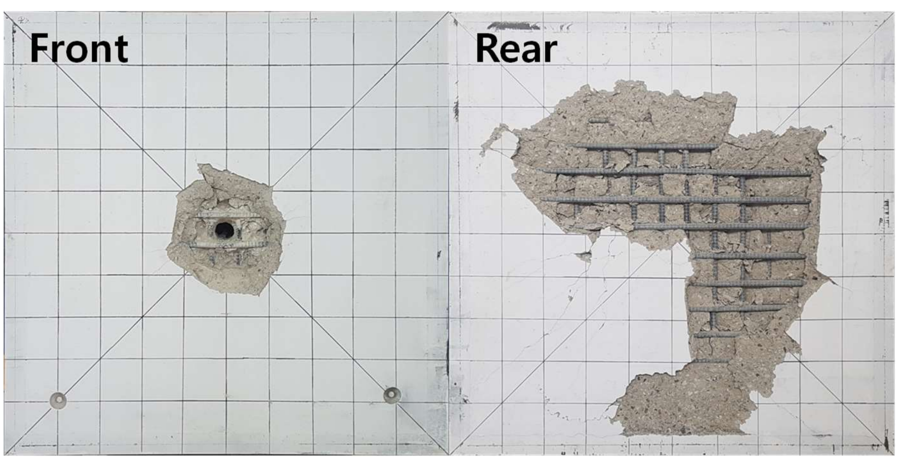
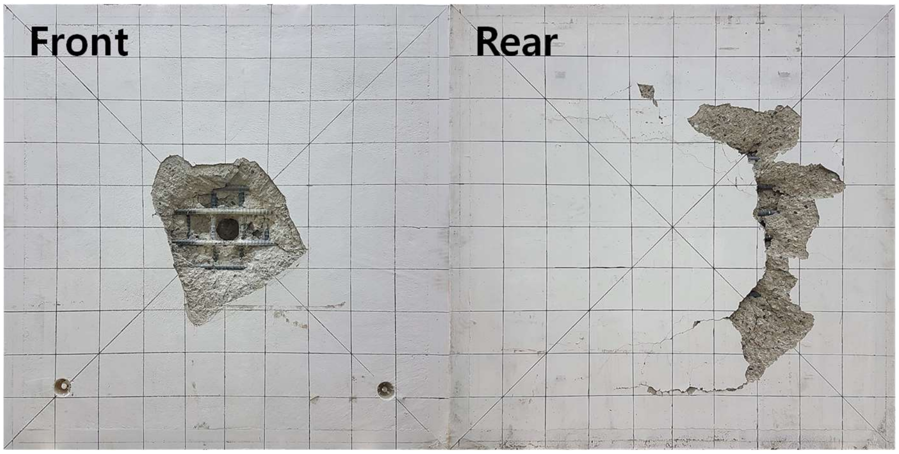


(c)



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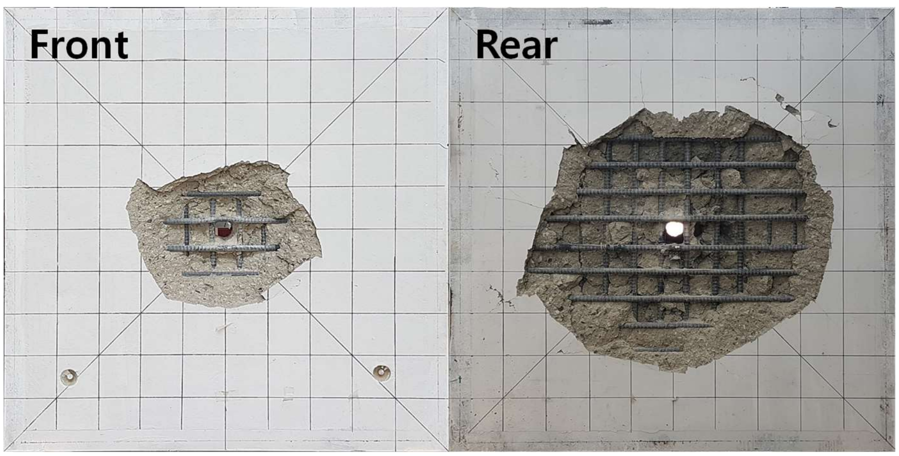
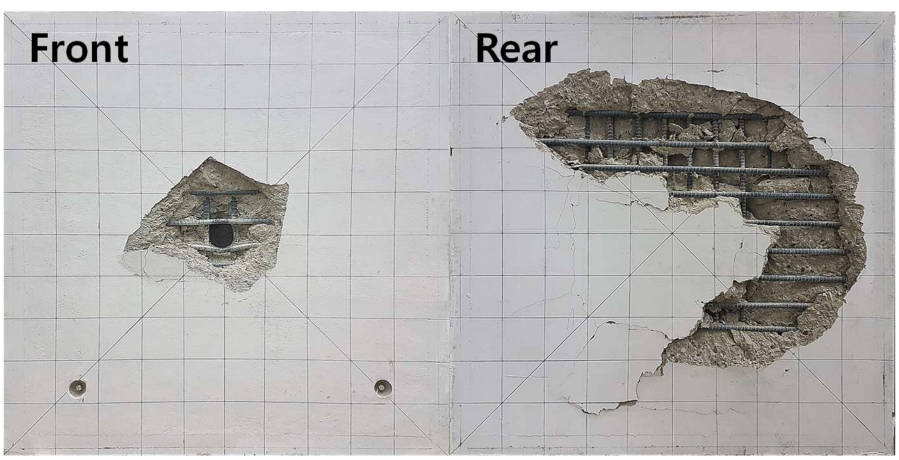


(e)



(f)

Figure 4. RC panels after tests; (a) H-V100; (b) S-V100; (c) H-V150; (d) S-V150; (e) H-V200; (f) S-V200 (hard impact tests referred from Lee et al. (2021)).

Table 4: Impact test results.

Designation	v_i , m/s	Failure mode	Spalling area, m^2	Scabbing area, m^2	l_r , mm	x_p , mm	v_r , m/s
H-V100	104.1	Penetration	0.25	-	-	137	-
H-V150	151.6	Scabbing	0.25	1.40	-	391	-
H-V200	199.6	Perforation	0.45	1.36	-	-	97.2
S-V100	104.3	Penetration	0.14	-	55	84	-
S-V150	151.0	Scabbing	0.37	0.36	83	197	-
S-V200	198.3	Scabbing	0.30	1.11	163	240	-

Table 5 summarizes the ratio of the soft impact test results to hard impact test results to further examine the influence of the projectile materials. The impact velocities of the hard and soft impact tests were almost identical and had differences of less than 1%, which means that the difference in impact behaviors of RC panels and projectiles was due to the projectile materials. At impact velocities of 100 and 200 m/s, the damages on the front face of the hard impact tests were greater than those of soft impact tests, showing greater spalling areas. However, the spalling area of S-V150 was larger as much as 48% than that of H-V150, and this result means that the spalling area was relatively independent of the projectile materials. As for the damages of the rear face, all hard impact test cases showed severe damages. As shown in Figure 4 (a) and (b), much less crack in S-V100 was visible than in H-V100, and the scabbing areas of S-V150 and S-V200 were smaller as much as 74% and 18% than H-V150 and H-V200, respectively. The penetration depth showed a similar tendency to the scabbing area. The penetration depth was 40-50% smaller for the soft impact tests at 100 and 150 m/s than for the hard impact tests. Furthermore, the soft projectile with 200 m/s impact velocity penetrated the RC panel up to 240 mm, while the hard projectile perforated the RC panel with residual velocity of 97.2 m/s.

In summary, the test results such as failure mode, scabbing area, and penetration depth indicated that the hard projectiles caused more critical damage on the RC panels than the soft projectiles although the spalling area was relatively independent of the projectile materials. In other words, the local damages became more severe as the strength of the projectile was stronger.

Table 5: The ratios of soft impact test results to hard impact test results.

Nominal impact velocity	The ratio of soft impact test result to hard impact test result ([soft impact test]/[hard impact test])			
	v_i	Spalling area	Scabbing area	x_p
V100	1.00	0.56	-	0.61
V150	1.00	1.48	0.26	0.50
V200	0.99	0.67	0.82	-

This phenomenon is caused by the energy dissipation of projectiles. Part of the kinetic energy of the projectiles was dissipated by plastic deformation of the projectiles, as shown in Figure 5. If the rate effect and strain-hardening of copper can be neglected, the behavior of projectiles can be simplified from an average point of view using Figure 6. Here, σ_y, F_y, and ε_r denote the yield strength, the force at yield point, and the residual strain, respectively. Then, the average dissipated energy can be calculated, which is listed in Table 6. Here, E_k and E_d denote the kinetic energy and the dissipated energy of projectiles, respectively. As shown in Table 6, the dissipated energy was in the range of 30–40% of the initial kinetic energy of projectiles. In other words, 30–40% less energy was transferred to RC panels in the soft impact tests than in the hard impact tests, resulting in less damage to RC panels in the soft impact tests. Consequently, the strength of the projectiles was found to have a significant effect on the damage of RC panels subjected to impact loadings.

Figure 5. Soft projectiles before and after the tests.

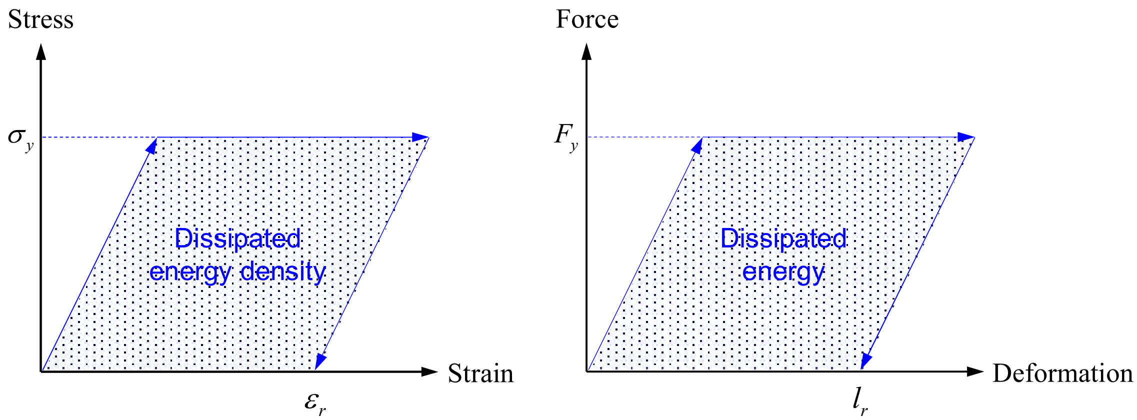


Figure 6. Assumed behaviour of soft projectiles.

Table 6: The ratio of dissipated energy to kinetic energy of soft projectiles.

Designation	v_i, m/s	E_k, kJ **(A)**	l_r, mm	F_y, kN	E_d, kJ **(B)**	**(B)/(A)**
S-V100	104.3	237	55	1742	96	40.4%
S-V150	151.0	497	83		145	29.1%
S-V200	198.3	858	163		284	33.1%

CONCLUSION

In this study, the impact tests for RC panels were conducted with hard and soft projectiles made of steel and copper, respectively, to investigate the effect of projectile materials on the local damages of RC panels subjected to impact loading. The experimental results support the following conclusions.

1. The spalling area was relatively independent of the projectile materials. However, the scabbing area was larger in the soft impact test cases than in the hard impact test cases, and the penetration depth showed the same trend as the scabbing area. Moreover, a critical failure mode was observed in the hard impact test with 200 m/s impact velocity compared with the soft impact test with the same velocity.

2. The test results indicated that the projectile materials significantly affected the impact behavior of RC panels and projectiles, and it was found that the stronger the projectile strengths were, the more severe damages were generated. This phenomenon can be explained by the energy dissipation of projectiles. Copper projectiles dissipated 30–40% of kinetic energy, causing milder damage compared to steel projectiles.

As revealed in this study, the projectile materials remarkably affect the impact behaviors of RC panels. Therefore, the projectile material properties need to be considered for the evaluation of the local damages of RC panels subjected to impact loadings, and relevant further research should be conducted.

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