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RESISTANCE OF SC WALLS SUBJECTED TO MISSILE IMPACT: PART 3. SMALL-SCALE TESTS

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ABSTRACT

Reinforced concrete (RC) walls are commonly used for protective structures against blast or impact loads. Steel-plate composite (SC) walls – which consist of steel faceplates with a concrete infill, tie bars to connect the faceplates and steel-headed stud anchors for composite action – have demonstrated advantages over RC walls: easy to modularize, decreased construction time and excellent resistance for blast loads and missile impact. Recognizing these benefits, SC structures are being used in safety related facilities in the current generation of nuclear power plants. Although a variety of SC walls have been experimentally and numerically tested to evaluate their resistance to missile impact, the focus of previous tests was typically on understanding behavior rather than developing methods to design perforation resistant walls. Using the available database of previous tests, Bruhl et al. (2015) proposed a rational three-step design method to prevent perforation of SC walls for various missile threats. While this design method was validated using tests available in the literature, it has not been systematically evaluated and validated by an experimental program designed to quantify its inherent conservatism and refine the accuracy of the method. In this paper, results from an experimental program to meet this need is described. The program was designed to evaluate the three-step design method, confirm its accuracy and better quantify any inherent conservatism of the method. The test series included a variety of design parameters and projectile size and impact velocities. Post-test damage of the SC walls was quantified and observed damage modes and the extent of damage is described in this paper. Comparison of experimental results to the expected result based on the three-step method is presented and conservatism contained in the method is quantified and sources of this conservatism are discussed.

INTRODUCTION

Historically, reinforced concrete (RC) structures have been commonly used for protective structures. Experimentally and theoretically validated methods and equations to design RC walls to resist blast loads and projectile impact have been used for decades. Steel-plate composite (SC) walls are gaining much attention as a reasonable alternative and are being incorporated into the design of safety related nuclear facilities due to advantages over RC walls (Malushte and Varma, 2015). SC walls consist of steel faceplates, steel-headed shear stud anchors, tie bars and a concrete core. Steel faceplates form the exterior boundary of SC walls and supply flexural reinforcement just as reinforcing bars in the RC walls. SC structures are well-suited for modular construction and have been demonstrated to reduce construction time: the faceplates also serve as formwork and there are no reinforcing bar cages to construct (Schlaseman, 2004).

Also, the resistance of SC walls subjected to blast and impact loads has been shown to exceed that of RC walls of the same thickness (Bruhl and Varma, 2014; Tsubota, 1993).

Previous research on SC walls subjected to missile impact includes empirical methods to convert the steel plate thickness to equivalent concrete wall thickness, which is also applicable to perforation analysis of reinforced concrete barriers with a steel plate affixed to the back face (Walter and Wolde-Tinsae, 1984; Grisaro and Dancygier, 2014). As an aid to design SC walls, Mizuno et al. (2005) developed a curve of the required concrete thickness in terms of the missile velocity. This kind of curve is useful for designers, however there is a limitation in the application of it because the proposed method is applicable only for 12mm rear steel plate and 196kN missile. Bruhl et al. (2015) proposed a three-step design method of SC walls against impact load, specifically to design SC walls to prevent perforation by projectiles. Because this method was developed using existing design equations for steel and RC structures and was validated using a database of previous tests, its applicability is limited to the range of applicability of the original equations and previous tests. The method requires the engineer to select an initial concrete thickness based on design constraints or using 70% of the required thickness of an RC wall. Based on the projectile threat (missile diameter, weight, nose-shape and impact velocity) the method includes equations to calculate the required steel faceplate thickness to prevent perforation of the wall. While the method was validated using the existing database of tests, it has not been specifically evaluated and validated by an experimental program designed to confirm its accuracy, specifically to better quantify known conservatism within the method.

This paper presents results from an experimental program designed to evaluate and validate the three-step design method. This program included sixteen small-scale SC wall specimens; fourteen of which were tested under missile impact as of the time of this writing. The tests included projectiles of various diameter, weight, and impact velocity. A pressurized gas gun launched projectiles into specimens supported by a rigid frame. Test results presented include the damage mode, penetration depth and bulging depth.

EXPERIMENTAL PROGRAM

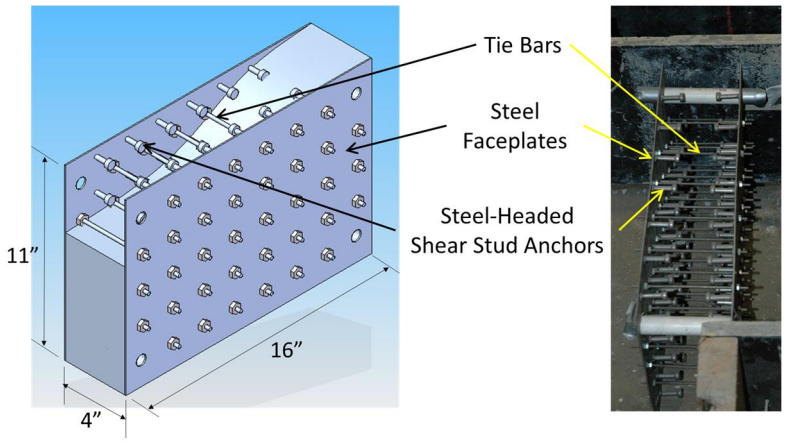
This experimental program was designed to evaluate the method to design SC walls to prevent perforation against missile impact. All specimens were designed in accordance with AISC N690s1-15, Appendix N9 (AISC, 2015) and tested using a variety of projectile parameters. The emphasis of this program was observation of local failure behaviour of these SC wall specimens. The test results will be used not only to verify performance of the design method but also to benchmark numerical models for further investigation of the failure behaviour of SC walls.

Specimen Design

Two different strengths of ASTM A1011 hot-rolled steel faceplates were used: Gr.50 and Gr.65. The flexural reinforcement ratio ($\rho = 2t_p/t_{sc}$) varied from 3.7% to 5.2%. Steel-headed shear stud anchors were welded to the interior of the steel faceplates and enable composite action between concrete core and steel faceplates. Stud anchors (0.25 in. diameter, 1.125 in. long) were spaced at 2 in. on each faceplate. Tie bars connect the exterior steel faceplates to maintain the wall thickness during construction and provide shear reinforcement when loaded. Threaded rods were used as tie bars and secured with hex nuts on both sides of the steel faceplates. Tie bar spacing varied between 2 and 4 in. Shear reinforcement ratio ($\rho_t = A_{tie}/S^2$) varied from 0.37% to 1.23% with tie bar diameter ranging from 0.138 to 0.3126 in. Normal weight concrete with 0.375 in. maximum aggregate diameter (pea gravel) was used as a concrete core.

The specimens were organized by groups as shown in Table 1. Group 1 and group 2 have a different flexural reinforcement ratio: 3.7% and 5.2%, respectively. Group 3 has a difference in the steel faceplate strength (65 ksi) from that of group 1 and group 2 (50 ksi). Measured yield strength and ultimate strength values of

the steel faceplate are 55.6 ksi and 67.9 ksi for group 1, 58.1 ksi and 66.5 ksi for group 2, and 72.7 ksi and 79.8 ksi for group 3 (Bruhl and Varma, 2016). Number 1 and 2 specimens of group 1 and number 3 and 4 specimens of group 2 were cast from one concrete batch and all other specimens were cast from a second concrete batch using the same mix design. Both concrete batches had a design strength of 5 ksi and measured concrete compressive strength at 28 days (f_c') was 5.31 ksi and 6.28 ksi, respectively. All the SC walls in the test matrix have the same global dimension: 16 in. by 11 in. by 4 in. Figure 1 illustrates the details of the specimen design.



(a) Illustration of SC wall specimen (b) Specimen before concrete cast

Figure 1 SC wall specimen design

Test Matrix

As shown in the test matrix (Table 1), three design parameters were varied: flexural reinforcement ratio (3.7% and 5.2%), shear reinforcement ratio (0.37% - 1.23%), and grade of the steel faceplates (50 ksi and 65 ksi). Projectile parameters also varied: diameter (1.0 and 1.5 in.), weight (1.3, 2.0 and 3.5 lbs), and impact velocity (350 - 770 ft/s). These varied parameters for each test were included in the specimen identifier from the test matrix which was comprised of 6 terms: the first three for the specimen parameters, and the next three for the projectile parameters.

In addition to using the three-step design method to determine required concrete and steel faceplate thickness to prevent perforation by a specific missile threat, it can also be used to calculate the projectile velocity which would be expected to perforate a given wall design: this calculated perforation velocity is considered as a design velocity of the SC walls. To determine the accuracy of the design velocity, the impact velocities selected for the test program included velocities above and below the design velocity. For cases in which perforation was expected the impact velocity was chosen to be 10% larger than the design velocity. On the other hand, the design velocity was decreased by 10% for cases when the projectile was expected to be stopped by the specimen. As seen in Table 1, at least one pair of test cases were selected for the same specimen design: one for each of these perforation and no-perforation cases.

Projectiles were cut from AISI 4340 steel round stock and heat treated with minimum 42-45 C Rockwell hardness to simulate nondeformable flat-nosed missiles. Material properties of the projectile were obtained from coupon tests and average values were 194 ksi yield strength and 206 ksi ultimate strength. Because there is a gap between the inside diameter of the gun barrel used for the tests and the projectile diameter, a

sabot was used to seal the gun barrel and ensure projectile flight remained level. Polypropylene was chosen for the sabot and designed and fabricated to fit the different projectiles in the test matrix. Compressive strength of this sabot material was 4.8 ksi.

Table 1 Missile impact test matrix on small-scale SC walls

Test group		Specimen identifier	SC wall					Projectile			Expected result
			ρ (%)	S/t_{sc}	ρ_t (%)	f'_c (ksi)	f_y (ksi)	Dia. (in)	Wt. (lb)	V_o (ft/s)	
Gr. 1	1	3-0.37-50-1.0-1.3-554	3.7	0.5	0.37	5	50	1.0	1.3	554	Stopped
	2	3-0.37-50-1.0-1.3-677	3.7	0.5	0.37	5	50	1.0	1.3	677	Perforated
	3	3-0.37-50-1.0-2.0-430	3.7	0.5	0.37	5	50	1.0	2.0	430	Stopped
	4	3-0.37-50-1.0-2.0-525	3.7	0.5	0.37	5	50	1.0	2.0	525	Perforated
	5	3-0.53-50-1.5-1.3-660	3.7	0.5	0.53	5	50	1.5	1.3	660	Stopped
	6	3-0.53-50-1.5-1.3-750	3.7	0.5	0.53	5	50	1.5	1.3	750	Perforated
	7	3-0.53-50-1.5-2.0-513	3.7	0.5	0.53	5	50	1.5	2.0	513	Stopped
	8	3-0.53-50-1.5-2.0-626	3.7	0.5	0.53	5	50	1.5	2.0	626	Perforated
	9	3-1.23-50-1.5-3.5-380	3.7	0.5	1.23	5	50	1.5	3.5	380	Stopped
	10	3-1.23-50-1.5-3.5-465	3.7	0.5	1.23	5	50	1.5	3.5	465	Perforated
Gr. 2	1	5-0.48-50-1.0-2.0-445	5.2	1.0	0.48	5	50	1.0	2.0	445	Stopped
	2	5-0.48-50-1.0-2.0-544	5.2	1.0	0.48	5	50	1.0	2.0	544	Perforated
	3	5-0.48-50-1.5-3.5-408	5.2	1.0	0.48	5	50	1.5	3.5	408	Stopped
	4	5-0.48-50-1.5-3.5-498	5.2	1.0	0.48	5	50	1.5	3.5	498	Perforated
Gr. 3	1	3-0.37-65-1.0-2.0-443	3.7	0.5	0.37	5	65	1.0	2.0	443	Stopped
	2	3-0.37-65-1.0-2.0-541	3.7	0.5	0.37	5	65	1.0	2.0	541	Perforated

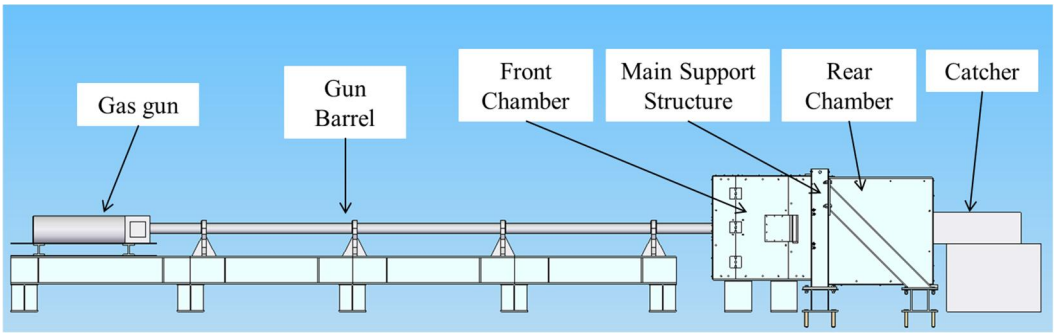


Figure 2 Schematic view of test setup

Test Setup

The tests were conducted at the Robert L. and Terry L. Bowen Laboratory at Purdue University. The test apparatus consisted of several parts as depicted in Figure 2: pressurized gas gun, gun barrel, front chamber, main support structure, rear chamber and catcher. For each test, the projectile was loaded at the front of the gun barrel and launched by pressurized nitrogen gas. The impact of the projectile on the SC wall occurs in the front chamber which is a protective shield to confine any possible hazardous pieces from the impact phenomenon in it. The specimen is fixed to the frames in the main support structure inside of the front

chamber. When the projectile perforates the specimen, debris generated from the concrete core and steel faceplates is collected in the rear chamber. The catcher is the very end of the protective shields to collect anything passing through the rear chamber including projectile and pieces from the test specimen.

High speed videography was used to record the projectile impact on the SC wall specimen and measure the impact velocity. Photron Fastcam APX PX model was used for the high-speed camera and images were recorded at 14,000 frames per second and 640 by 304 pixels' resolution. The high-speed images were recorded through a 9 in. square window on the front chamber which consisted of 2 in. thick transparent polycarbonate plate. A checker board with an attached scale was positioned inside the front chamber to enable calculation of projectile impact velocity and provide a level reference to confirm horizontal flight of the projectile. Figure 3 provides a photograph of the test setup in which the location of the high-speed camera and protective view portal are shown. Figure 4 shows a captured image of inside of the front chamber through the view portal by high speed camera. The projectile is right before impacting the specimen.

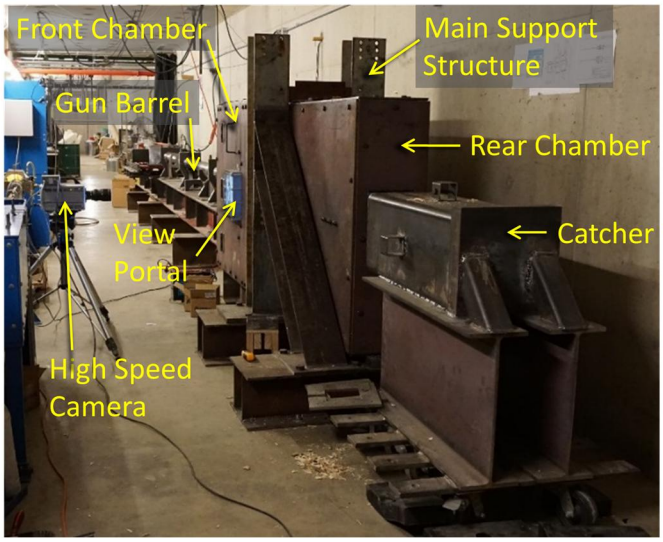


Figure 3 Photograph of test setup (after (Kim et al., 2017))

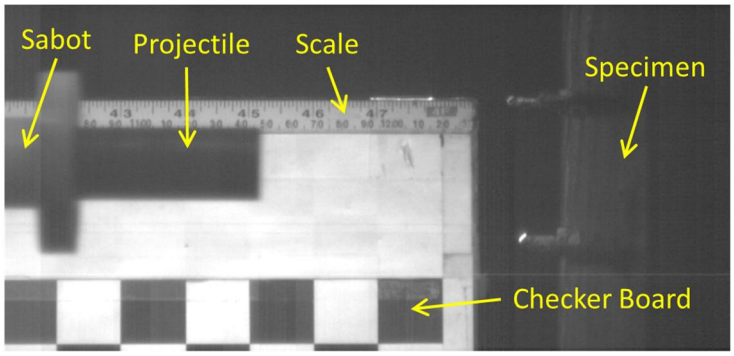


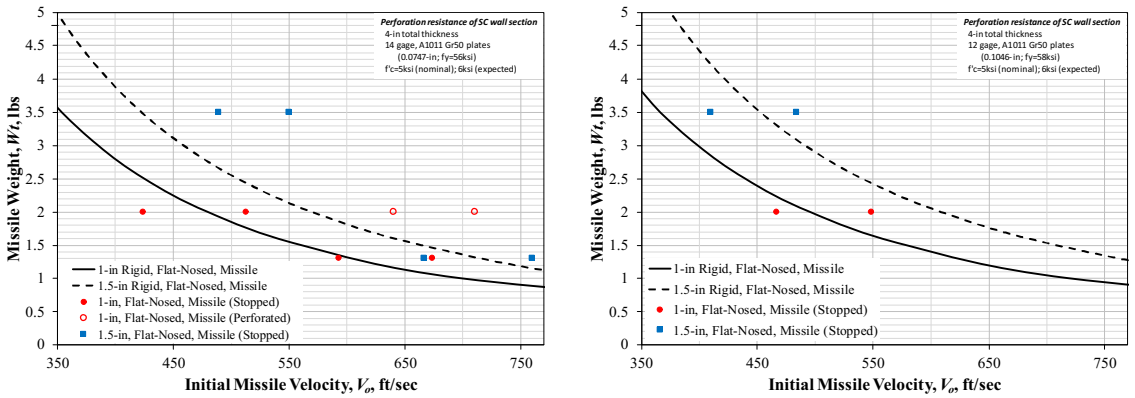
Figure 4 Captured image of inside of the front chamber by high speed camera

EXPERIMENTAL RESULTS

To date, 14 of the 16 tests were conducted and the results are summarized in Table 2. Results include: measured impact velocity, perforation check (test result), damage mode, penetration depth of the projectile and bulging depth of the rear steel faceplate. The test results are shown graphically in Figure 5 with each test plotted on the perforation resistance curves generated by the three-step design method. Of the 14 tests, two were completely perforated and the remaining twelve stopped the projectile with various magnitudes of penetration depth. All cases which fell on the left side of the impact resistance curves stopped the missiles as expected and measurable bulging deformation occurred on the rear steel plate (Figure 6(a) shows a representative result of bulging deformation). The cases which were positioned on the right side of the curves showed conservative results.

Table 2 Experimental tests results

Test group		*Test specimen*	Projectile			*Expected result*	*Test result*	*Damage mode*	V_{des} *(ft/s)*	V_{imp}/V_{des}	*Penetration depth (in)*	*Penetration depth / Wall thickness*	*Rear faceplate bulging (in)*
			Weight (lb)	*Diameter (Norminal, in)*	V_{imp} *(ft/s)*								
Gr. 1	1	3-0.37-50-1.0-1.3-554	1.316	1.0	593	Stopped	Stopped	Bulging	615	0.964	2.25	0.56	0.25
	2	3-0.37-50-1.0-1.3-677	1.301	1.0	674	Perforated	Stopped	Bulging	615	1.096	3.25	0.81	0.63
	3	3-0.37-50-1.0-2.0-430	1.991	1.0	424	Stopped	Stopped	Bulging	479	0.885	1.69	0.42	0.25
	4	3-0.37-50-1.0-2.0-525	2.000	1.0	513	Perforated	Stopped	Bulging	479	1.071	3.16	0.79	0.58
	5	3-0.53-50-1.5-1.3-660	1.303	1.5	667	Stopped	Stopped	Bulging	729	0.915	1.44	0.36	0.56
	6	3-0.53-50-1.5-1.3-750	1.301	1.5	760	Perforated	Stopped	Bulging	729	1.043	2.19	0.55	0.72
	7	3-0.53-50-1.0-2.0-513	2.000	1.0	640	Perforated	Perforated	Perforation	479	1.336	-	-	-
	8	3-0.53-50-1.0-2.0-626	1.991	1.0	710	Perforated	Perforated	Perforation	479	1.482	-	-	-
	9	3-1.23-50-1.5-3.5-380	3.521	1.5	550	Perforated	Stopped	Splitting	422	1.303	4.13	1.03	1.63
	10	3-1.23-50-1.5-3.5-465	3.541	1.5	489	Perforated	Stopped	Bulging	422	1.159	2.03	0.51	0.59
Gr. 2	1	5-0.48-50-1.0-2.0-445	1.997	1.0	467	Stopped	Stopped	Bulging	495	0.943	2.25	0.56	0.28
	2	5-0.48-50-1.0-2.0-544	1.997	1.0	549	Perforated	Stopped	Splitting	495	1.109	3.50	0.88	0.75
	3	5-0.48-50-1.5-3.5-408	3.512	1.5	410	Stopped	Stopped	Bulging	453	0.905	1.50	0.38	0.38
	4	5-0.48-50-1.5-3.5-498	3.534	1.5	484	Perforated	Stopped	Bulging	453	1.068	2.63	0.66	0.69



(a) Gr.1 test specimens (b) Gr.2 test specimens

Figure 5 Impact resistance curves of specimens

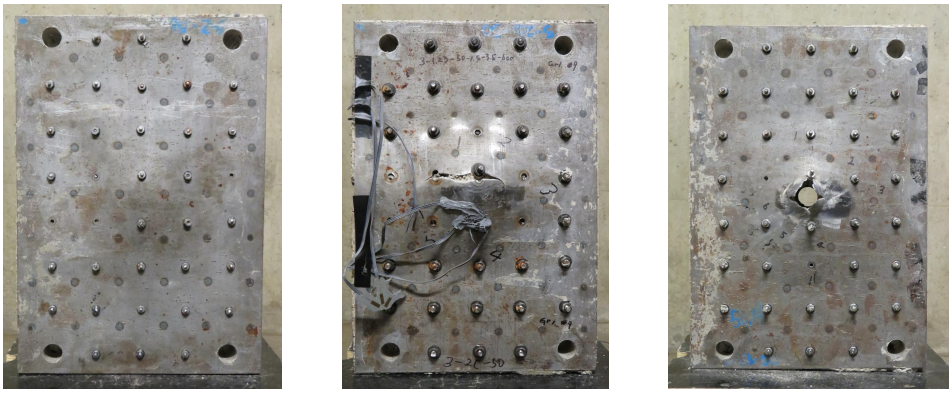
For group 1 test cases, the 1.0 in. diameter projectiles with 1.3 lbs weight which had increased velocity up to 7.6% lesser and 9.6% larger than design velocity did not perforate the specimens. For the 1.0 in., 2.0 lbs

projectile, when the velocity was increased up to at least 33.6% larger than the design velocity, the projectile perforated the specimen. The 1.5 in. diameter, 3.5 lbs projectile was still stopped by the specimen even when its velocity was increased up to 30.3% from the design velocity. For this test case, the rear faceplate was ruptured indicating splitting damage mode - the mode immediately preceding perforation (Figure 6(b) shows a representative result of splitting). For the projectile with same diameter and 1.3 lbs weight, the test results showed that the specimen stopped the projectile with an impact velocity 4.3% larger than the design velocity.

Tests 7 to 10 of group 1 were revised from the test matrix to quantify the actual perforation velocity. For tests 7 and 8, the projectile diameter was reduced from 1.5 in. to 1.0 in. and impact velocity was increased to 33.6% and 48.2%, respectively to attempt to ensure perforation occurred. Test 8 was conducted first to confirm that perforation would occur at the higher impact velocity. Perforation occurred and test 7 was conducted to further narrow the range of velocity which results in perforation (Figure 6(c) shows the perforation result from this test). Because test 7 resulted in perforation, the actual perforation velocity for the 1.0 in. diameter, 2.0 lbs, projectile lies between 7.1% and 33.6% larger than the design velocity calculated from the three-step design method for this specific wall configuration. For test 9 and 10 of group 1, only projectile velocities were changed to attempt to ensure perforation happened. Test 10 was conducted first at an increased velocity of 15.9% but resulted in bulging deformation on the rear steel faceplate without perforation. Next, test 9 was performed with an increased velocity of 30.3% and there was rupture on the rear steel faceplate with the projectile stopped by the specimen.

For the group 2 test cases, two test cases were on the right side of the impact resistance curve with impact velocities 6.8% and 10.9% larger than the calculated design velocity. The projectiles were stopped in both cases, which did not meet the expected results.

For test 9 in group 1 and test 2 from group 2, the rear steel faceplate split. As previously mentioned, tests 7 and 8 from group 1 resulted in perforation. All other test cases resulted in bulging deformation of the rear faceplate. Figure 6 depicts the three local damage modes of SC walls which occurred during this test program.



(a) Bulging (Gr.1 #2) (b) Splitting (Gr.1 #9) (c) Perforation (Gr.1 #7)

Figure 6 Local damage modes of the SC wall specimens presented in the test results

DISCUSSION AND CONCLUSIONS

Experimental tests to evaluate the three-step method to design SC walls to prevent projectile perforation were performed and a valuable set of test data was obtained. The experimental methodology including the test setup, specimen design, projectile and the sabot design was proved to be appropriate to carry out missile impact tests.

The test results can be categorized based on the expected behaviour and observed results as: (i) appropriate, (ii) conservative, or (iii) unconservative. Appropriate is when the observed behaviour (missile stopped or wall perforated) is in accordance with expected behaviour. Conservative is when the observed behaviour (missile stopped) is better than expected behaviour (wall perforated). Unconservative is when the observed behaviour (wall perforated) is worse than expected behaviour (missile stopped). The results from the test program were all either appropriate or conservative. There were no unconservative results. This provides confidence that the current (three-step) design method can be used to prevent perforation of SC walls due to missile impact. The test results also indicate that the design method has inherent conservatism, which is probably due to the use of a statistical variability parameter (β) in the design method by Bruhl et al. (2015).

For the tests on a specific SC cross-section design with a 1.0 in. diameter, 2.0 lbs weight, projectile, the perforation velocity was experimentally determined to be approximately in the range of 7.1 - 33.6% higher than the calculated design velocity by the three-step method. Generally, inherent conservatism in the design method is acceptable or even desirable for design purposes. However, it is important to better understand the failure mechanisms of SC walls subjected to projectile impact to improve the accuracy of the design method and ensure both efficient and effective designs.

The modified NDRC equations (ASCE, 1980) were adopted to estimate penetration depth in the design method. The penetration depth values from the test results (shown in Table 2) were compared with those calculated using the modified NDRC equations. Both the measured and calculated penetration depth values were normalized by wall thickness and compared graphically in Figure 7. The ratio of calculated penetration depth, x_{c_calc}, to total wall thickness, T_{sc}, is on the vertical axis and the ratio of measured penetration depth, x_{c_test}, to T_{sc}, is on the horizontal axis. Figure 7 shows that when the projectile penetrated the SC walls with depth ranging from approximately one-third to two-thirds of the wall thickness, the modified NDRC equations predicted it reasonably. However, if the penetration depth exceeded two-thirds of the wall

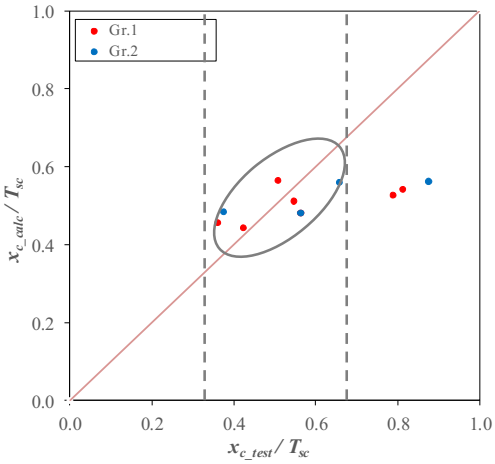


Figure 7 Graphical comparison of penetration depth between test results and calculation

thickness, then the penetration depth calculated using the modified NDRC equations did not agree well with test results as shown in the figure.

This may be attributed to the differences in the damage between traditional reinforced concrete (RC) walls and SC walls as shown in Figure 8: scabbing in RC walls and bulging in SC walls (Kim et al., 2015). For the RC walls subjected to missile impact, the scabbing from the rear face could be severe and lead to early perforation when the penetration depth exceeds about two-thirds of the wall thickness. On the other hand, SC wall has rear steel faceplate, which prevents scabbing from the rear surface of the wall. Therefore, the modified NDRC equations might not provide reasonable estimations of penetration depth when it exceeds two-thirds of the thickness of the SC wall.

(a) Scabbing in RC walls (b) Bulging in SC walls

Figure 8 Comparison of damage modes between RC and SC walls subjected to missile impact (after (Hashimoto et al., 2005))

FUTURE WORK

The purpose of this experimental research was to evaluate the accuracy of the estimated performance based on three-step design method. Additionally, these experiments provide a new set of test data to be compared with numerical analyses results. Numerical models will be developed and benchmarked with these test results to more thoroughly investigate local failure behaviour of SC walls subjected to missile impact. Parametric studies will be conducted using the developed numerical models to investigate the effect of design parameters including flexural reinforcement, shear reinforcement, and steel plate strength.

Results from this experimental program suggests that the three-step method includes inherent conservatism characterized by the statistical variation coefficient included in the method. Additional experimental and numerical investigations will inform modifications to the design method to generate more accurate estimation on the perforation of the SC walls with reduced conservatism.

Finally, large-scale experimental tests are scheduled to ensure the observations made in these small-scale tests are applicable at larger scales. These experiments are not expected to include as much variety as the small-scale test series, but will be critical to confirming the behaviour and applicability of findings to the impactive design of full-scale SC structures.

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