Development of High Performance Concrete Panels for Curtain Wall Systems

L.K. Stewart[1], K.B. Morrill[2], K. Natesaiyer[3]

[1]Karagozian & Case, 2550 N. Hollywood Way, Suite 500 Burbank, CA 91505; PH (818) 240-1919; FAX (818) 240-4966; email: stewart@kcse.com
[2]Karagozian & Case, 2550 N. Hollywood Way, Suite 500 Burbank, CA 91505; PH (818) 240-1919; FAX (818) 240-4966; email: morrill@kcse.com
[3]USG Corporation, 550 W. Adams St. Chicago, IL 60661; PH (312) 436-6760; FAX (312) -672-6760; email:KNatesaiyer@usg.com

ABSTRACT

There has been an increasing interest in the use of advanced materials in the design of curtain wall systems to resist blast loading. This paper summarizes a series of tests on high performance concrete (HPC) and ultra high performance (UHPC) panels to characterize the panel strength in flexure and shear for several panel types under dynamic loading conditions.

The tests were performing using three types of FORTOCRETE™ panels supplied by USG. One set of HPC panels was lightweight concrete fiber-reinforced FORTOCRETE™ structural panels developed by USG. Another set of UHPC panels consisted of FORTOCRETE™ Armor panels that use ultra high strength fiber-reinforced concrete with and without E-glass face sheets.

The testing was conducted at the University of California San Diego (UCSD) Blast Simulator Test Facility. A series of 20 panel tests were performed using the three panel types. Each panel was instrumented to provide experimental data to characterize the response of the panels that are suitable for developing and validating analytical models for the various configurations of FORTOCRETE™ panels. The instrumentation consisted of three types of measurements: 1) load measurements of the dynamic panel reactions, 2) strain measurements of the dynamic flexural strains in the panels, 3) velocity measurements of the overall panel deflection histories, and 4) dynamic reactions.

Each panel type was tested at different levels of blast loading to achieve a range of panel damage responses ranging from light to failure. The experimental data was used to develop material property data, validate analytical response models and to generalize the panel results into PI response diagrams.

Based on these results, several blast curtain wall concepts were developed for GSA Level C blast loads and above and were validated in full-scale wall experiments with the UCSD Blast Simulator.

INTRODUCTION

This paper presents results from a series of tests on high performance concrete (HPC) and ultra high performance (UHPC) panels to characterize the panel strength in flexure and shear for several panel types under dynamic loading conditions using the UCSD Blast Simulator.

The Blast Simulator Facility (Hegemier, 2006) is located at the Robert and Natalie Englekirk Structural Engineering Center (ESEC) at UC San Diego. The UCSD Blast Simulator, shown in Figure 1, is a one of a kind blast mitigation and impact characterization device that simulates the effects of conventional high-explosive events. The energy deposition on the target is adjustable to less than 1 ms, which is accomplished with ultra-fast, computer controlled hydraulic actuators with a combined hydraulic/high pressure nitrogen energy source called Blast Generators, shown in Figure 1. The actuators are used conjunction with appropriate loading media (i.e. urethane pads, foam, felt), which attached to the variable masses assist in the appropriate loading conditions for various desired shock responses.

Figure 1. UCSD Blast Simulator (left) and Blast Generator (right).

EXPERIMENT DESCRIPTION

The test series included twenty panel experiments (Stewart, 2010) using the three panel types. Each specimen was impacted with various flyer mass and velocity combinations to achieve a range of impulses. The tests utilized one Blast Generator to launch a 15 in × 14.25 in × 1.625 in impacting (flyer) mass, shown in Figure 2, consisting of a urethane pad mounted on a 1⁄2 in aluminum backing at the FORTOCRETE^{TM} Panel target. Custom phenolic mounts were used to hold the impacting mass to the Blast Simulator guide rails and the impacting mass was pushed by a 16 in × 16 in × 3⁄4 in pusher plate that was attached to the actuator piston rod. Photos of the actuator/pusher plate/impacting mass assembly can also be seen in Figure 2.

Figure 2: Test setup (left) and actuator/pusher/flyer assembly (right).

The testing fixtures and loading protocol for this test series were designed to allow the panels to exhibit response and damage in flexure and shear and therefore, two test setups were used. This paper will focus solely on the flexure experiments. Two load cells were mounted to a concrete block, to which a 36 in × 30 in × 2 in steel plate was attached. Steel supports were fabricated and bolted to the steel plate. The test specimens were then placed on the rounded steel supports to simulate simply supported (roller) boundary conditions. The clear span between the supports was 31 in. Urethane pads mounted on a 1⁄2 in aluminum backing were clamped to the specimen to hold the specimen flush against the roller supports. This connection, also seen in Figure 3, prevented rebounding at the supports and promoted flexural response by allowing additional rotation.

Figure 3: Boundary conditions for flexural experiments.

USG provided three types of panels, shown in Figure 4, for testing with the dimensions of 18 in wide by 36 in tall. The first panel type was the UHPC FORTOCRETE^{TM} Armor, which consisted of the 150 pcf core only. These panels were approximately 0.34 in thick and weighed approximately 34 lbs each. The second type of panel was a lighter-weight FORTOCRETE^{TM} Structural Panel which was 75 pcf. These panels, although lighter, came with a 0.90 in thickness, which was thicker than the 150 pcf core and weighed approximately 29 lbs each. Laminated panels were also provided. These panels consisted of the 150 pcf FORTOCRETE^{TM} Armor with E-glass facesheets applied to the front and back of the panels. The laminated panels weighed approximately 34 lbs each.

FORTOCRETE^{TM} Armor core (150 pcf) FORTOCRETE^{TM} Structural (75 pcf) Laminated FORTOCRETE^{TM} Armor

Figure 4: FORTOCRETE^{TM} panel types.

Each panel was instrumented to provide experimental data to characterize the response of the panels that was suitable for developing and validating analytical models for the various configurations of FORTOCRETE^{TM} panels. The instrumentation consisted of three types of measurements: 1) load measurements of the dynamic panel reactions, 2) strain measurements of the dynamic flexural strains in the panels, and 3) velocity measurements of the overall panel deflection histories.

Two Interface 1220 load cells were used to measure the total reaction force in each test. Each load cell had a capacity of 50 kips. The load cells were mounted to the concrete reaction block via thread rods and separated from the steel plate by a 1⁄2 in washer and 1 in bearing plate. Two TML, type PL-60-11-7LT, 60 mm strain gages were placed at the center line on the back of the specimens, at 1/3 and 2/3 points along the width. These locations were maintained for all the tests. Each gage was bonded to the surface of the panels on either the FORTOCRETE^{TM} core or the laminate, depending on the panel type. Additionally, two phantom cameras were used to record each test. Phantom Camera #1 recorded in monochrome, while Phantom Camera #2 recorded in color. Both were equipped with zoom lenses. Phantom Camera #1 was placed head on directly in front of the specimen. Phantom Camera #2 was placed off to the side and gave an angled view of the back-side of the specimens. Displacements and velocities were then determined using the tracking software, *TEMA*.

EXPERIMENTAL RESULTS

From the twenty tests conducted, this paper will highlight the results of the three flexure tests (Tests 6, 7 and 14) conducted on the FORTOCRETE^{TM} Structural panels. A summary of the test results is given in Table 1 and the specimen results are described in additional detail for each test.

FORTOCRETE^{TM} Test 6 was the first in the series of 75 pcf experiments utilizing the flexure test setup. The target impact velocity for this test was 5 m/s (197 in/s) and a 26 lb flyer mass was used. Flyer mass velocities were then calculated from the target displacements. An average impact velocity of 5.6 m/s (220.4 in/s) was measured for the flyer. Figure 5 shows the response of the Test 6 specimen recorded with the high-speed cameras. The first frame shows the flyer in free flight while the second shows the initial impact of the panel. The frame on the right shows the maximum displaced shape of the specimen before returning to the original, undeformed position.

Table 1. Summary of results of FORTOCRETE^{TM} Structural panel tests.

Test #	Target Velocity	Recorded Flyer Velocity (m/s)	Recorded Panel Velocity (m/s)	Calculated Impulse (psi-ms)	Maximum Midspan Displacement (in)	Comments
6	5 m/s	5.5	6.7	39.1	1.49	Specimen remained elastic
7	10 m/s	9.2	14	50.5	2.69	Complete failure at midspan
14	7.5 m/s	8.0	12.5	44.9	2.40	Tension crack and some residual deformation

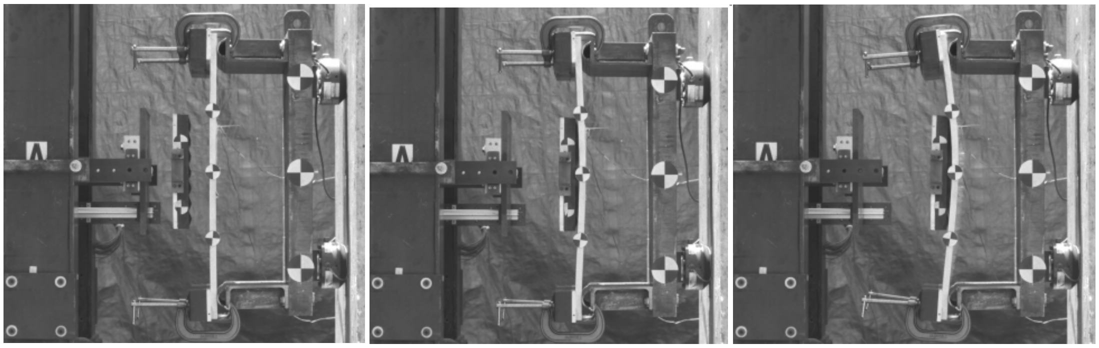

Figure 5: Test 6 specimen response from high-speed cameras.

FORTOCRETE^{TM} Test 7 was the second flexural test and had a target impact velocity of 10 m/s (393 in/s) as compared with the 5 m/s velocity in Test 6. The setup was identical to Test 6 with a clear span of the specimen was 31 in and targets to measure displacement placed and the midspan and quarter points. Flyer mass velocities were calculated by differentiating the target displacements. An impact velocity of 9.2 m/s (361.9 in/s) was measured. Figure 6 shows photos from the high-speed cameras. From the three frames, the progression of damage can be observed. The specimen post-test, from the side and the back of the damaged panel are given in Figure 7, which a photo of the back of the specimen showing the fracture of the concrete on the back face. Damage at the bottom connection is shown in Figure 8.

FORTOCRETE^{TM} Test 14 was an additional test in the flexure test series. It had a target impact velocity for this test of 7.5 m/s (295 in/s). This test was conducted to describe the behavior between Test 6 (5 m/s), which remained elastic, and Test 7 (10 m/s) which had a full failure at midspan. Figure 9 shows the response of the specimen from the high-speed cameras. The first frame shows the initial specimen impact. The middle frame shows the maximum deformed shape of the specimen and the last frame show the maximum rebound. Figure 10 shows the specimen posttest and shows slight, noticeable residual deformation in the panel. The panel also exhibited some slight tension cracking on the non-impact side, which is pointed out with arrows.

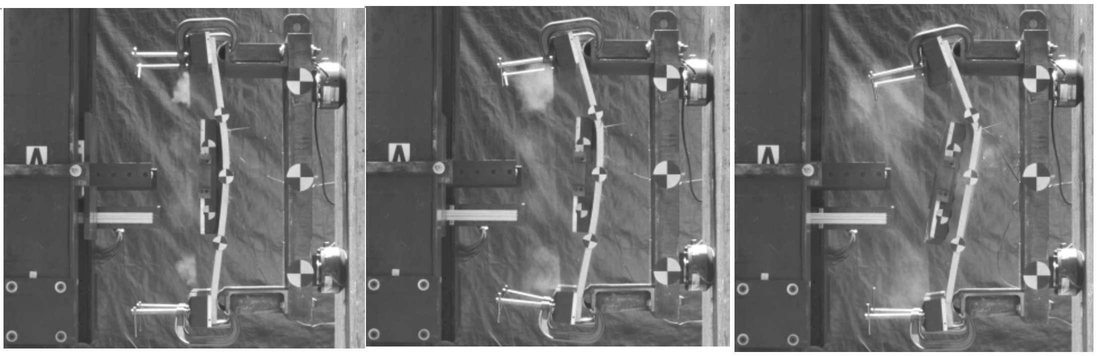

Figure 6: Test 7 specimen response from high-speed cameras.

Figure 7: Test 7 posttest damage from side (left) and back (right).

Figure 8: Test 7 posttest bottom connection damage.

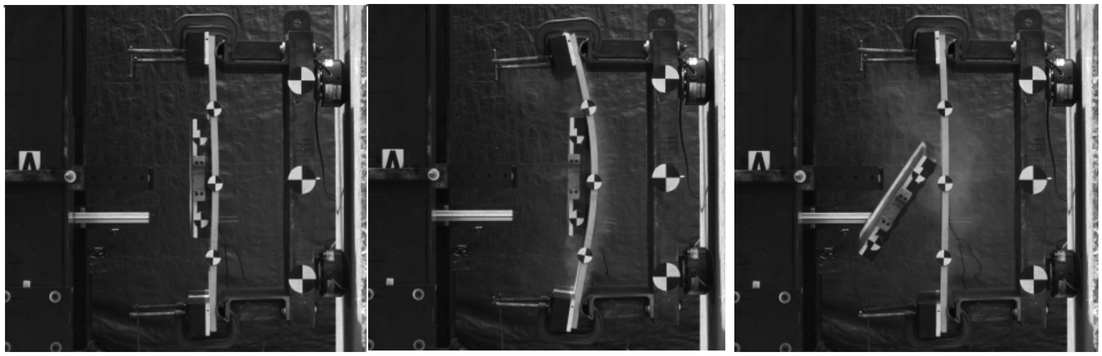

Figure 9: Test 14 specimen response from high-speed cameras.

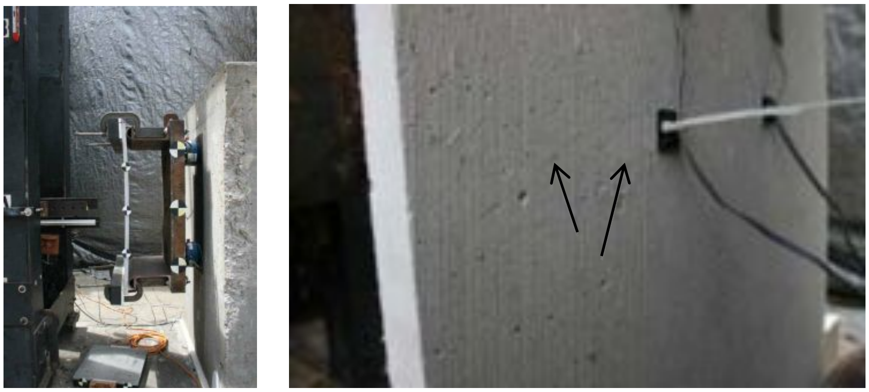

Figure 10: Test 14 posttest damage from side (left) and back (right).

METHODOLOGY FOR DEVELOPMENT OF P-I CURVES

As a prelude to Blast Simulator testing of FORTOCRETE^{TM} panels, a series of tests using 1⁄4 in thick steel plate specimens was conducted to develop the methodology to be used in the subsequent FORTOCRETE^{TM} panel tests. The basic test setup for the steel plate test is identical to that described in the previous section for the FORTOCRETE^{TM} tests. A flyer mass was launched at the plate with a prescribed velocity and resulting response recorded on high-speed video. The velocity of the flyer was obtained from the cameras from the initial constant velocity stage through impact and rebound with the steel plate target. The bending of the plate causes the loading on the plate to act essentially as two point loads during most of the impact/contact as indicated in Figure 11. In relating the response of this test to a uniform airblast, this difference in loading has to be taken into account in developing the analysis model.

The steel plate displacement history was used to develop a simple single degree of freedom (SDOF) model of the plate response. The SBEDS program was used to develop this model. The resistance function for the 1⁄4 in steel plate is shown in Figure 12. The plate was assumed to be simply supported at both ends with an effective span of 31 in. As mentioned above, the plate acts as two point loads so this was included in the model. The response of the plate to this “third point” loading is compared to a similar uniform load of the same total load is also shown in Figure 12.

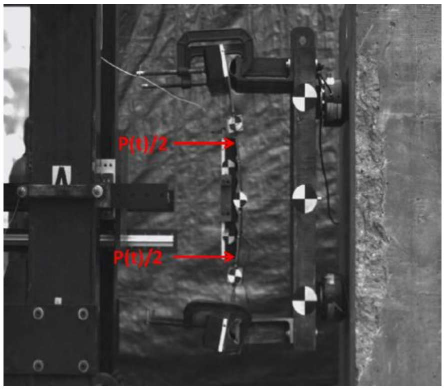

Figure 11: Loading of steel plate.

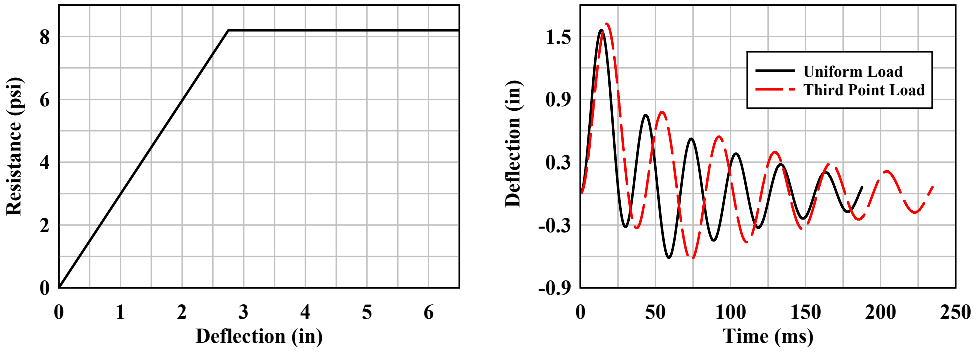

Figure 12: Resistance function (left) and displacement comparison (right).

To develop the relationship between the simulator response and the equivalent airblast loading, a pressure-impulse (P-I) curve was generated for the specific maximum displacement achieved in a particular test. For example, for Test S08, a peak defection of 1.66 in was obtained. The corresponding P-I curve is shown in Figure 13. This curve represents the combinations of applied peak reflected pressure and peak reflected impulse (using an assumed triangular load) that results in a peak plate deflection of 1.66 in. To obtain a corresponding deflection history, a specific point on the curve was selected. Using a peak pressure of 3.4 psi and an impulse of 100 psi-ms results, the SDOF response is compared to the Test S08 results in Figure 13. Excellent agreement between test and analysis was obtained. Thus, this methodology provides a convenient way to relate the Blast Simulator tests to an equivalent range of airblast pressures.

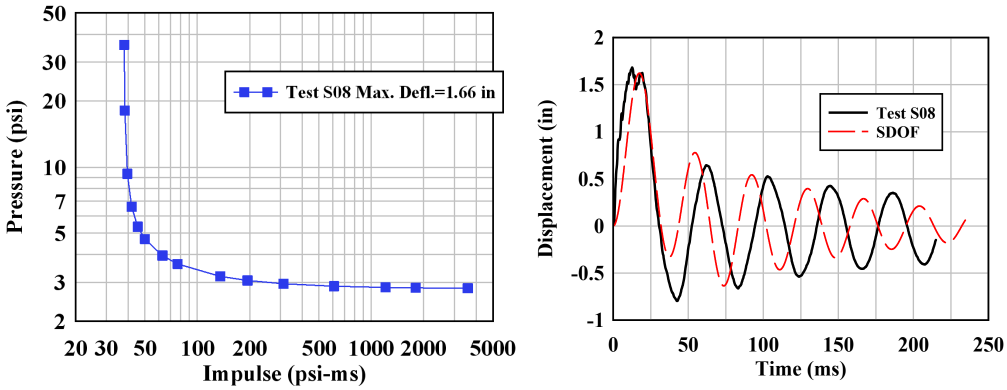

Figure 13: P-I curve (left) and displacement comparison (right).

RESISTANCE OF FORTOCRETE PANELS TO AIRBLAST LOADING

As part of a development effort to design a blast wall system using FORTOCRETE^{TM} structural panels, the methodology described was used to determine the blast capacity of the panels in terms of peak pressure and impulse. The focus was on developing a wall system to resist at least a GSA Level “C” blast load requirement.

To obtain the single degree of freedom (SDOF) response a resistance function was developed base on quasi-static third point loading tests conducted by USG and validated using the Blast Simulator test data. Using this resistance function and idealizing the FORTOCRETE^{TM} panel as a homogeneous elasto-plastic section, an SDOF analysis was performed using SBEDS. P-I curves for each of the tests are presented in Figure 14. In order to compare the response histories with the tests, the P-I curve for Test 14 was used to define a specific P-I combination that results in a peak deflection of 2.4 in. A comparison of the SDOF results with the corresponding test results is shown in Figure 14. The loading phase compares very well but the SDOF response shows more residual displacement than the test. This is due to elasto-plastic idealization used in the SDOF model. The panel material response appears to have more elastic rebound stiffness. It should be noted that the impulse based on a purely impulsive loading (i.e., v = I/m) recorded for Test 14 is 44.9 psi-ms, which has a corresponding peak pressure of 0.9 psi.

This validated SDOF model was then used to determine a span that would satisfy the GSA Level “C” loads. Referring to Figure 14, it is seen that the 31 in span used in the test does not meet the requirement. As a result, a reduced span of 16 in was used in the SDOF model. A set of P-I curves was developed and shown in Figure 15. The upper bound curve represents the estimated failure displacement of the panel. The GSA Level “C” is indicated on the figure at the 4 psi, 28 psi ms level. This value is well below the predicted failure curve indicating that the 16 in span satisfies the GSA requirement.

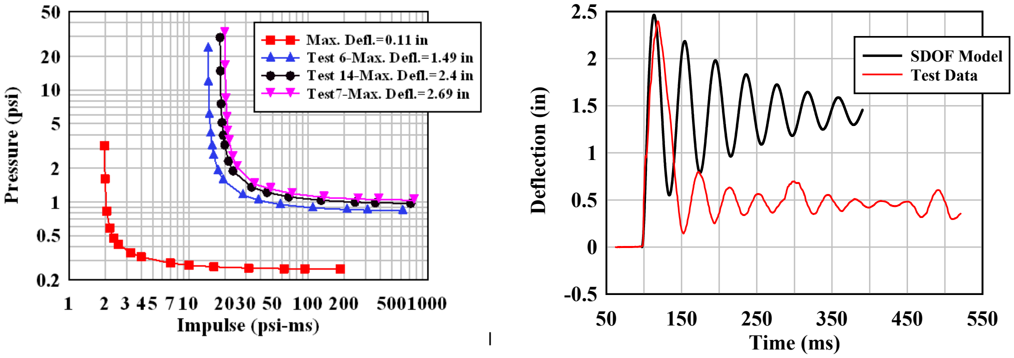

Figure 14: FORTOCRETE^{TM} P-I curve and displacement comparison.

The 16 in span was chosen to represent a blast wall consisting of steel studs spaced at 16 in on center with FORTOCRETE^{TM} panels spanning horizontally and fastened to the blast side of the studs using screws. This type of wall system can be used as an infill type wall or an exterior curtain wall that meet the GSA Level “C” blast requirement.

A preliminary design of the FORTOCRETE^{TM}/Steel Stud blast was analyzed using SBEDS. In developing the model, a conservative assumption of no composite action was assumed between the panels and the studs. Figure 16 shows four P-I curves corresponding to DoD definitions of levels of protection (LOP) ranging from High (HLOP) Med (MLOP) low (LLOP) and Very low (VLOP) for non-structural walls. These different levels are associated with ductility limits that determine the allowable deflections. The LLOP corresponds to moderate damage at the GSA Level

"C" loads. The curves were generated assuming a 10-ft high wall with 6 in steel studs at 16" oc. The top and bottom connection would have to be designed to resist the shear loads using something like a structural steel angle rather than a conventional track. As can be seen in the figure the GSA Level "C" load produces a LLOP or moderate damage for this wall design.

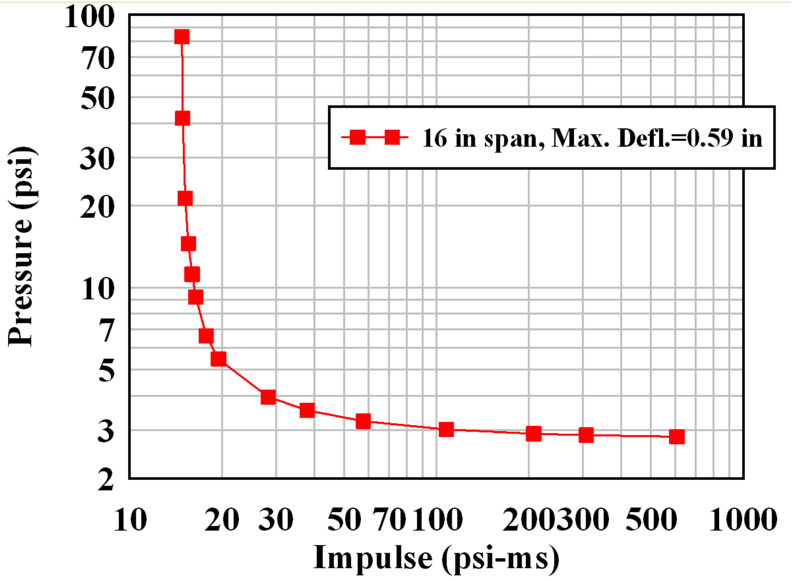

Figure 15: P-I curve for 16 inch stud spacing.

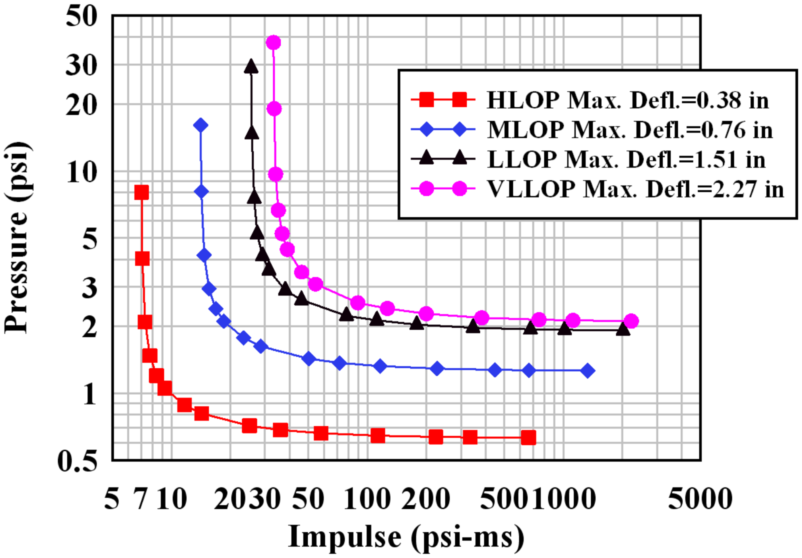

Figure 16: P-I curves for FORTOCRETE/Stud wall at levels of protection.

FULL-SCALE CURTAIN WALL SIMULATOR EXPERIMENTS

Based on the result of the above tests, a blast resistant panel design was developed. The goal was the development of an economical, light-weight system that could be used as in an exterior blast resistant curtain wall. The proposed design consisted of 6 in x 1.625 16 gage (.06 in) steel studs with FORTOCRETE™ panels. The studs were attached to the panels using Grattan #8, 1.5 in self-drilling screws spaced at approximately 3.5 in at the top and bottom and 6 in at all other locations. A drawing of the test specimen is shown in Figure 17.

In order to validate the design proposed for the system above, a full-scale test was conducted on a 10 ft wall with the UCSD Blast Simulator. The test setup is shown in Figure 18. The wall was placed on a 2 ft footer and reacted against a 6 in concrete slab header held up by steel angles and steel tube supports. The top reaction angle (Figure 18) was connected to the header using 10 in long, 5/8 in high strength steel bolts. The bottom (Figure 18) of the specimen reacted against a steel angle, which was secured to the footer using 4 in long, 5/8 in high strength bolts. Shot pins were used to secure the bottom steel track of the wall system to the concrete footer. A 48 in x 30 in x 1.625 in urethane pad mounted on a 1 in aluminum backing plate was used as the impacting mass attached to the actuator piston rod.

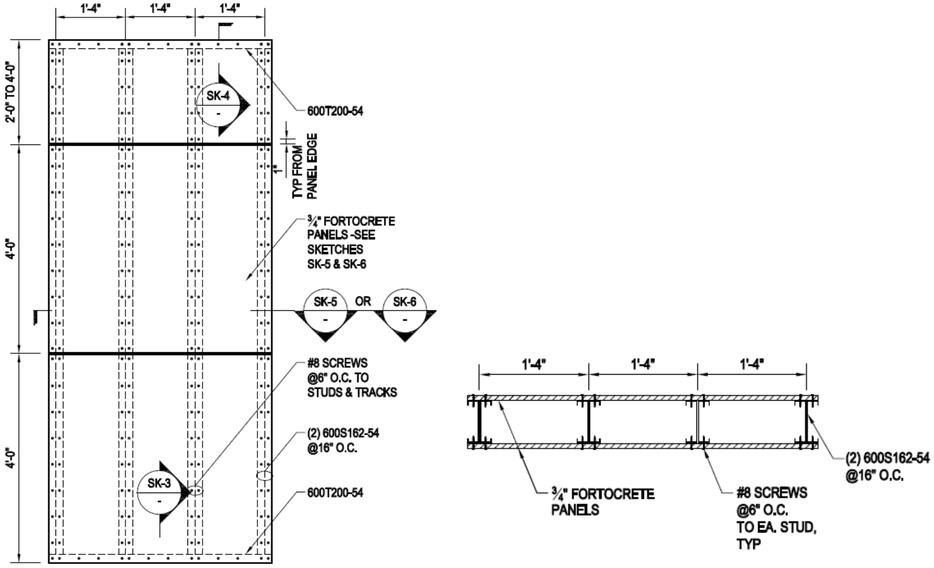

Figure 17: FORTOCRETE™ wall specimen detail.

Figure 18: Test setup (left) with upper (middle) and bottom (right) connection.

The system was tested initially at a Level "C" load and then was increased until reasonable amounts of damage were noted. The results from the last impact are given. The impacting mass accelerated and came into contact with the wall at 490.6 in/s

(12.4 m/s). The impulse on the wall was calculated to be 220 psi-ms with a maximum displacement of 7.2 in. The progression of damage from the high-speed cameras is shown in Figure 19. The residual displacement at midspan was measured to be 5.6 in. Photos of the wall's connections, posttest, are given in Figure 20. The response of the wall system fails well within the Level "C" and "D" criteria.

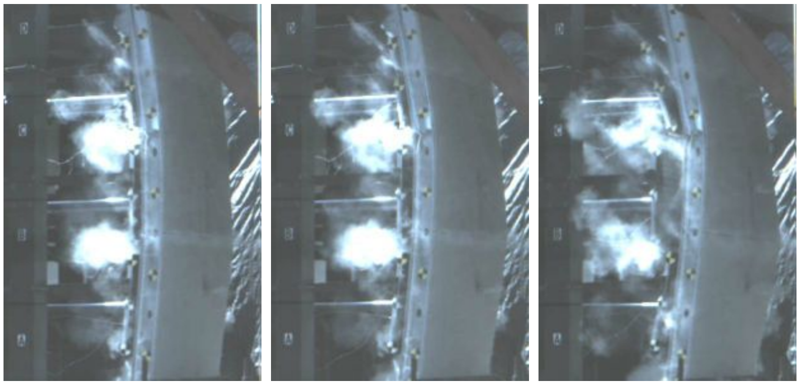

Figure 19: Full-scale wall tests progression of damage from high-speed cameras.

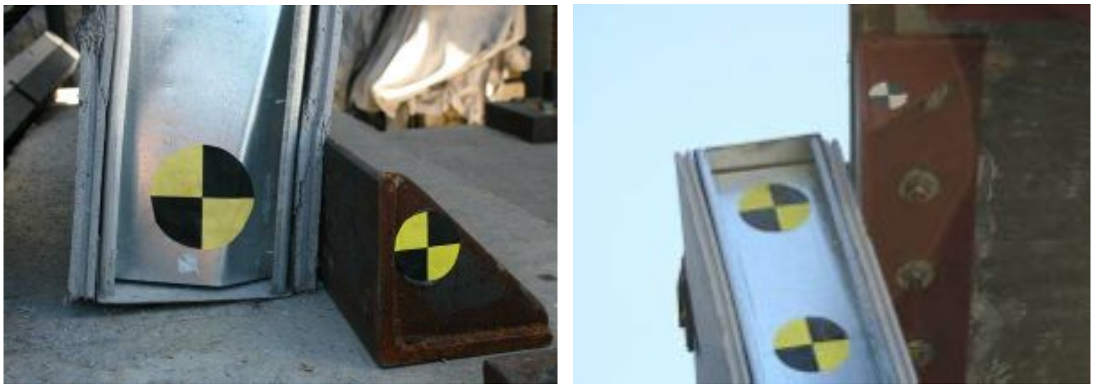

Figure 20: Wall test connection behavior.

CONCLUSIONS

Using the UCSD Blast Simulator, dynamic tests were conducted to characterize panel strength and behavior for panels of various types of FORTOCRETE^{TM} panels. The test results were utilized to design a FORTOCRETE^{TM} /steel stud wall system to withstand various levels of GSA blast loads. Such designs were successfully validated with full-scale tests also using the Blast Simulator.

REFERENCES

Hegemier, G., Seible, F., Arnett, K., Rodriguez-Nikl, T., Oesterle, M., Wolfson, J. Gram, M. and Clark, A. (2006). "The UCSD Blast Simulator." *77th Shock and Vibration Symposium. Monterey*, CA.

Stewart, L.K., Morrill, K.B., (2010). "Blast Simulator Tests of USG Fortocrete Panels."