Static Resistance Function of Octaform Wall Panels for Blast Response Prediction

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Abstract – Concrete-filled PVC forms supplied by Octaform were evaluated under simulated uniform pressure to develop their static resistance functions for blast response predictions. The added strength and ductility provided by the PVC faces and containment of the concrete enhanced the energy-absorption capability of the panels. This in return improved the blast resistance of the wall systems. The dynamic response of the Octaform panels was predicted under a hypothetical explosion threat, and the results indicate that their response was greatly improved compared to the control samples of the same design. Therefore, the Octaform wall panels are expected to provide added blast resistance and are recommended for further evaluation under live explosion tests.

1.0 Introduction

Experimental evaluation of Octaform wall panels has previously been performed by the University of British Columbia and Seattle University to demonstrate the improvement in flexure and ductility due to the PVC encasement. Such improved bending behavior is desirable for blast protection. To be able to develop an engineering level analysis and design prediction tool, it is necessary to determine the static response of the wall panels under uniform loading, or the static resistance function. The previous testing performed on these panels was done using axial compression and three point bending tests, but to develop a resistance function a uniform loading is necessary.

Recently, similar concrete filled PVC forming systems have been tested for blast mitigation, which have been proven to be effective in providing enhanced blast protection. However, there is currently no engineering level methodology to analyze and design the Octaform wall system for blast design. Therefore, it is necessary to evaluate their bending behavior to failure under distributed load. This resistance function is the key property that can be used to develop a dynamic model under blast loads.

To develop the resistance function for Octaform wall panels, the following tasks were realized:

1. Construct full-scale wall samples
2. Evaluate these samples experimentally using simulated uniform pressure
3. Develop the resistance function of the samples
4. Develop a simple dynamic model to predict dynamic response
5. Provide a summary and recommendation for field evaluation using live explosives

2.0 Test Samples and Construction of Tests

2.1 Test Matrix

The test samples selected for this project were designed in collaboration with Octaform. Four variations of sample thicknesses were tested, all being 18 inches wide. For each thickness four samples were built; two without rebar and two reinforced with rebar. All specimens were cast 18 inches wide and 144 inches long to allow for a support-to-support span of 120 inches during testing. Four reinforced concrete control specimens were cast and tested; two were 6 inches thick and the others were 8 inches thick. The samples and controls tested and details of the reinforcement in each are provided in Table 1 below.

The construction of the samples followed the ACI 318-05 Section 14 for selecting vertical reinforcement requirements as suggested by Octaform. A minimum reinforcement ratio of $\rho = 0.0012$ for vertical steel was used to select the size of rebar for each sample. Since the maximum allowable spacing is 3 times the wall thickness, not to exceed 18", a single #4 rebar was placed in the middle of the cross section for the 6-inch and 8-inch thick samples. Also, a single #5 rebar was placed in the middle of the cross section of the 10 inches thick samples. Since for walls more than 10" thick, two layers of steel are required, and thus two #4 rebars were used for the 12-inch thick samples placed 1½ inches from each face.

Table 1 – Octaform Test Matrix

Sample Name	Thickness (in)	Reinforcement
OF1	6	None
OF2	6	None
OF3	6	one #4 placed in the center of cross section
OF4	6	one #4 placed in the center of cross section
OF5	8	None
OF6	8	None
0F7	8	one #4 placed in the center of cross section
OF8	8	one #4 placed in the center of cross section
0F9	10	None
OF10	10	None
OF11	10	one #5 placed in the center of cross section
0F12	10	one #5 placed in the center of cross section
OF13	12	None
OF14	12	None
OF15	12	two #4's, both placed 1.5" from either face.
OF16	12	two #4's, both placed 1.5" from either face.
C1	6	one #4 placed in the center of cross section
C2	6	one #4 placed in the center of cross section
C3	8	one #4 placed in the center of cross section
C4	8	one #4 placed in the center of cross section

2.2 Construction

Since the samples were being cast in early January and outdoor temperatures were near freezing, the samples were cast indoors. The test samples were cast vertically to closely represent the field construction method, requiring the samples to be secured in an upright position. This can be seen in Figure 1, which also shows how samples were restrained at approximately the one-third points to prevent blowout caused by hydrostatic pressure during concrete pouring.

To maintain the full 18” width, vertical samples were grouped together using the 1½” connectors, into which 2” nominal lumber was inserted with a thin steel sheet on each side (Figures 2 & 3). These steel sheets are used to allow samples to be easily removed from the group and handled individually after curing in preparation for testing.

Figure 1 – Samples secured and restrained vertically

In addition to producing uniform samples, it was also important to hold the reinforcing steel in the desired location. This was achieved by welding a steel “loop” made of 1/8-inch steel rod to the reinforcement, which stretched diagonally across the gap to hold steel in place when dropped into samples from above (Figure 4).

Octaform 45-degree diagonal pieces were not inserted in the 6-inch and 8-inch samples. This was done based on the recommendation of an Octaform Field Service Operator, since in the field these pieces are normally not used on smaller samples because of the difficulty and time involved to insert these diagonal pieces.

As illustrated in Figure 5, the control samples were cast flat, as it was not considered important to the test for them to be cast in an upright position. Control forms were lined with plastic to prevent significant bonding with wooden forms, and reinforcing steel was held at proper depth using rebar chairs (Figure 5).


Figure 2 – Inserting steel sheet into separator


Figure 3 – Grouping with sample separators in place

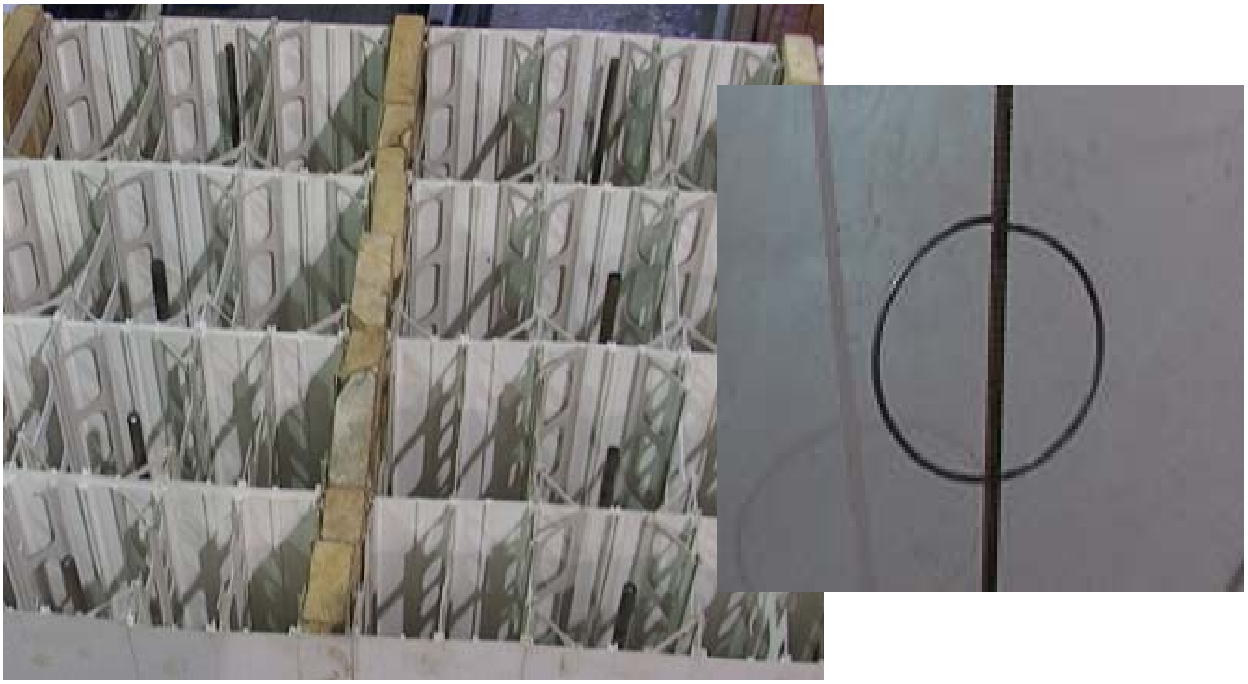

Figure 4 – Placement of rebars in center of cell using welded rings

Figure 5 – Control with plastic and reinforcement in place

2.3 Casting

The design mix used was 4,000 psi (six bag mix) with 3/8" pea gravel and a five inch slump. Field slump tests were done as per ASTM C143, and the results matched those of the design.

Samples were cast using a combination of two techniques. The first was to use a small grout pump and the second involved a hopper that could be raised and lowered with the overhead crane (Figures 6 and 7). Various limitations necessitated both techniques throughout the pour, one of which was maintaining a rather low pour rate (approximately 3 feet of depth per hour). Throughout the pour the samples were vibrated or tapped around the edges with a rubber mallet as needed to promote consolidation while avoiding concrete segregation. The control samples were cast horizontally as shown in Figure 8.

Figure 6 – Crane and 3" hose from grout pump to place concrete

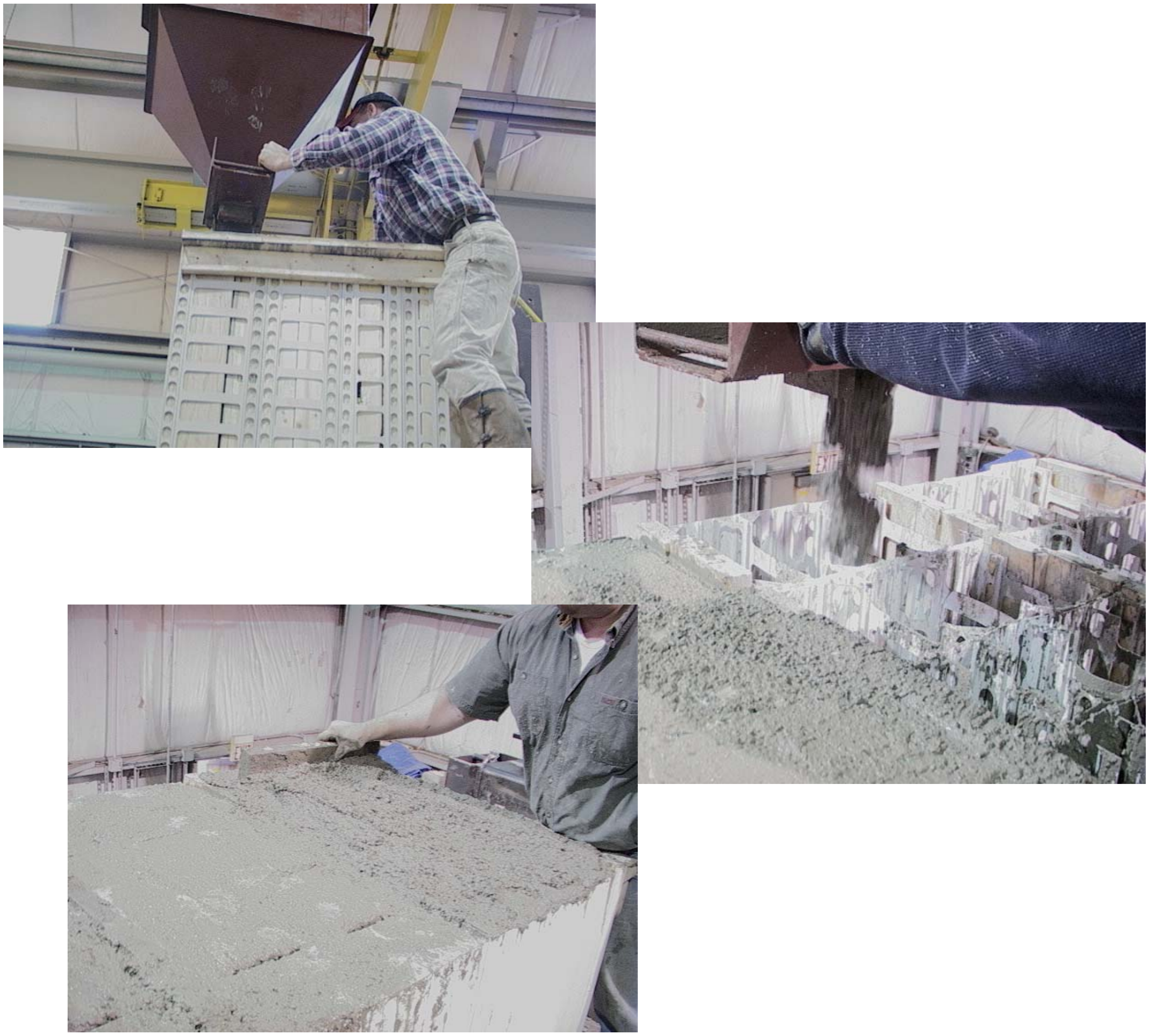

Figure 7 – Crane and hopper used for casting of Octaform samples

Figure 8 – Casting of control samples

2.4 Samples Preparation for Testing

As mentioned above the Octaform samples were cast together upright, so it was necessary to develop a method to carefully break the samples apart and lay them down in preparation for installation into the loading tree. The method involved the fabrication of a supporting frame that was strapped around the sample while still vertical, followed by slowly leaning the sample and frame to a horizontal position using the overhead crane. The sample was then placed on specially designed casters to roll the sample in place in the loading tree.

3.0 Experimental Evaluation

3.1 Cylinders

Concrete cylinders were prepared during casting in accordance with ASTM C192. Standard test method, ASTM C39, was used to determine the compressive strength of the concrete cylinders at various days of age. The results are summarized in Table 1 and Figure 9, which shows an average 28-day compressive strength of 3,635 psi.

Table 1 – Results of Cylinder Tests

days	load (lbs)	stress (psi)
7	53040	1876
7	69810	2469
7	81345	2877
7	78600	2780
14	70755	2502
14	73920	2614
14	83300	2946
22	102555	3627
22	105165	3719
28	99650	3524
28	97305	3441
28	105795	3742
28	108405	3834
106	131715	4658
119	130965	4632

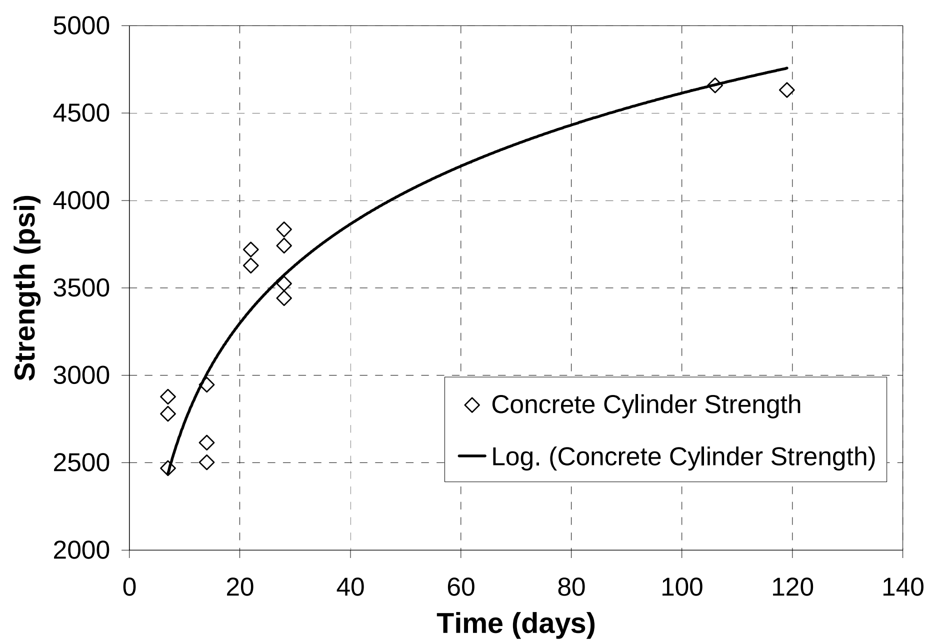

Figure 9 – Compressive strength of concrete samples

3.2 Tree Testing

The blast loading considered for this application can generally be assumed uniform across the face of the wall. Therefore, to develop the dynamic model, the static resistance of the wall under uniform loading is necessary. This was achieved by loading the samples using the 16-point Load Tree (Figure 10), which nearly resembles a uniform loading. These tests were performed 120 to 130 days after casting of the samples.

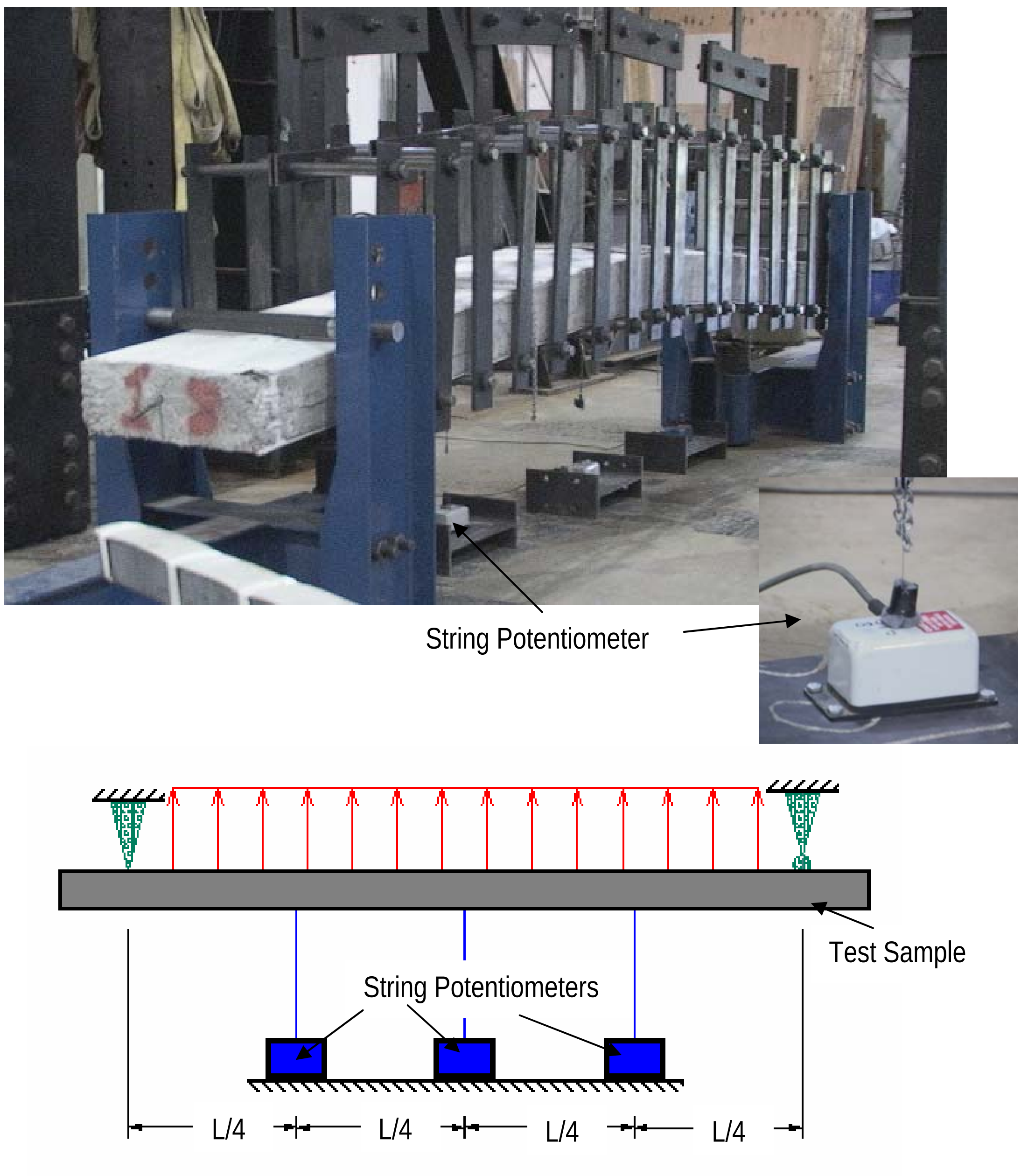

Figure 10 – Sample being tested with Load Tree showing loading mechanism and deflection measurement devices and locations

During the tests, the applied load was measured using a load cell, and the deflections were measured at three locations along the length of the sample using string potentiometers (Figure 10). The end supports of the sample were considered to be simply-supported, with no membrane forces developing, allowing the sample to move freely along its length. Any longitudinal forces that may have developed due to friction at the supports were neglected. The load-deflection response of the wall was recorded to failure, from which the static resistance functions for the samples were calculated. The results for each of the sample groups are represented graphically along with the control samples results in Figures 11 through 18. Table 2 shows the performance of each sample; the 6- and 8-inch samples are compared to the average of the two control samples of each thickness.

Table 2 – Static Performance Comparison

	Sample	Reinforcement	Static Energy SE (psi-in)	SE_{OF} / $SE_{Control}$	Max Pressure (psi)	Max Deflection (in)
6-in. Samples	OF1	None	20.48	1.03	2.23	13.27
	OF2	None	20.46	1.03	2.30	11.73
	OF3	one #4 bar	53.27	2.67	3.34	25.66
	OF4	one #4 bar	59.68	2.99	3.32	26.31
	Controls	one #4 bar	19.93	1.00	2.02	11.42
8-in. Samples	OF5	None	18.24	0.97	3.18	8.62
	OF6	None	19.28	1.03	3.29	10.74
	OF7	one #4 bar	47.00	2.51	5.13	11.08
	OF8	one #4 bar	44.87	2.39	4.94	11.45
	Controls	one #4 bar	18.76	1.00	2.52	8.36
10-in. Samples	OF9	None	7.50	NA	4.32	5.23
	OF10	None	8.04	NA	4.65	6.26
	OF11	one #5 bar	39.56	NA	8.30	11.15
	OF12	one #5 bar	33.59	NA	8.33	10.40
12-in. Samples	OF13	None	17.11	NA	5.08	10.99
	OF14	None	10.21	NA	5.90	7.29
	OF15	two #4 bars	32.65	NA	10.14	6.76
	OF16	two #4 bars	42.99	NA	11.85	7.92

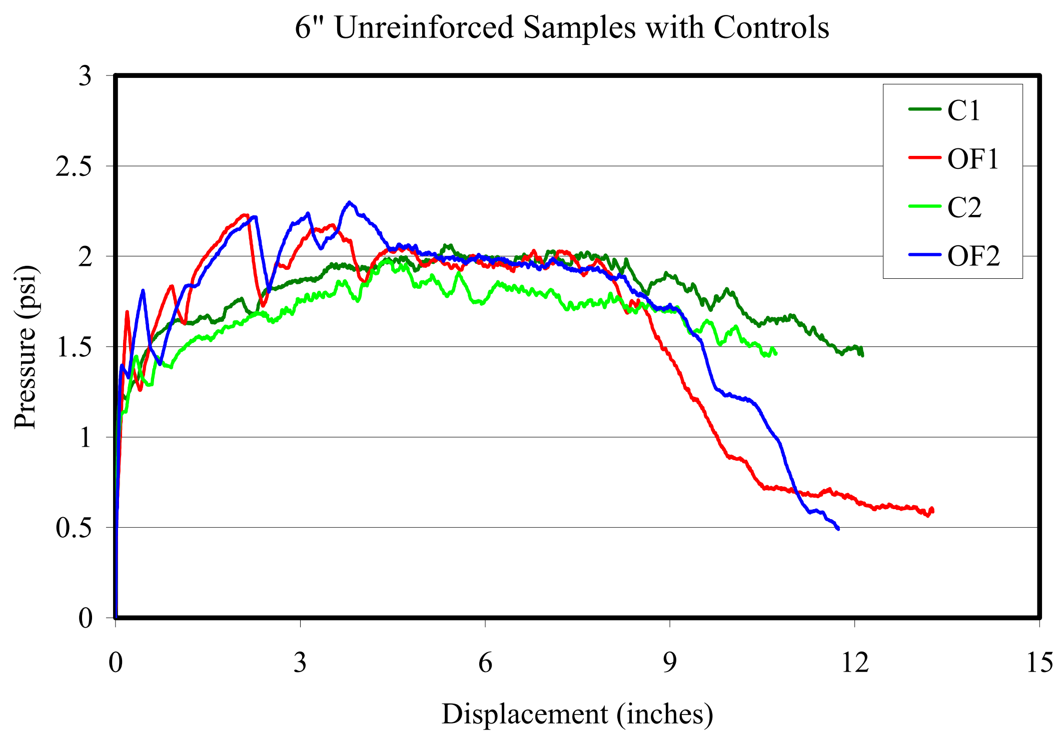

Figure 11 – Static Resistance Function for the 6-inch Unreinforced Octaform Samples and Reinforced Control Samples

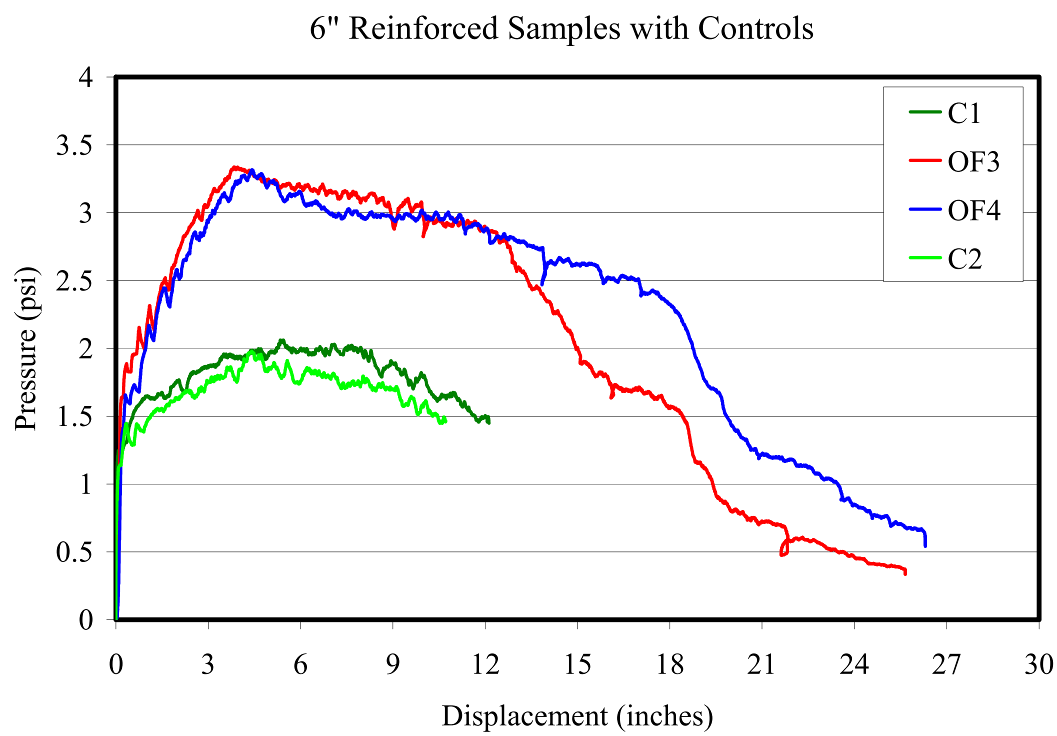

Figure 12 – Static Resistance Function for the 6-inch Reinforced Octaform Samples and Reinforced Control Samples

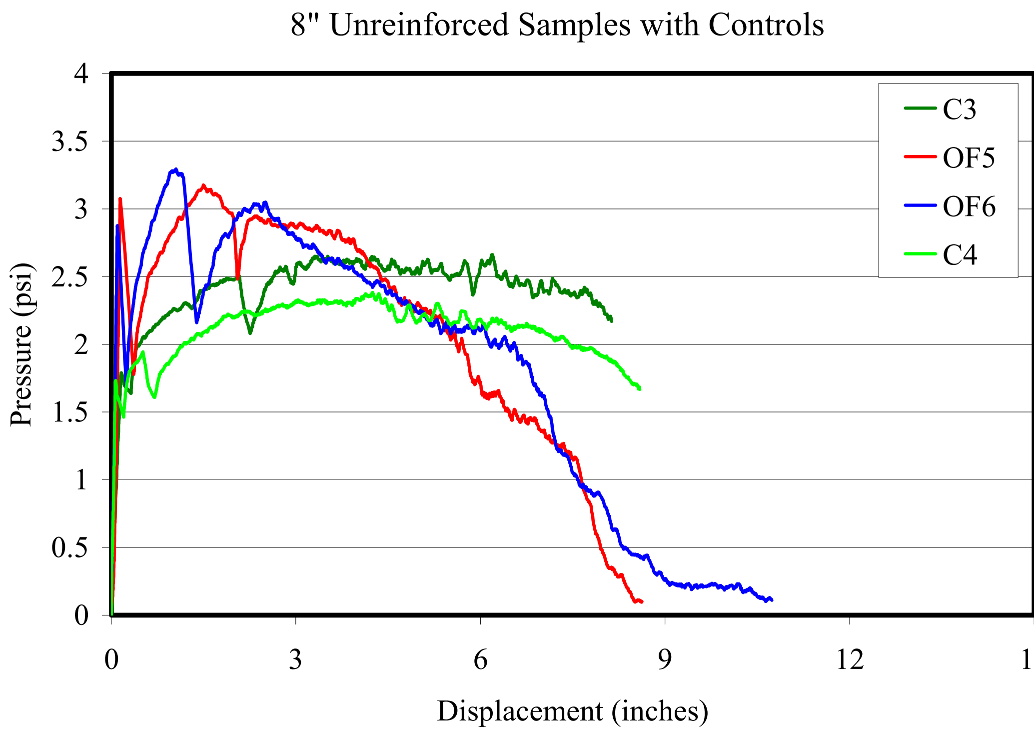

Figure 13 – Static Resistance Function for the 8-inch Unreinforced Octaform Samples and Reinforced Control Samples

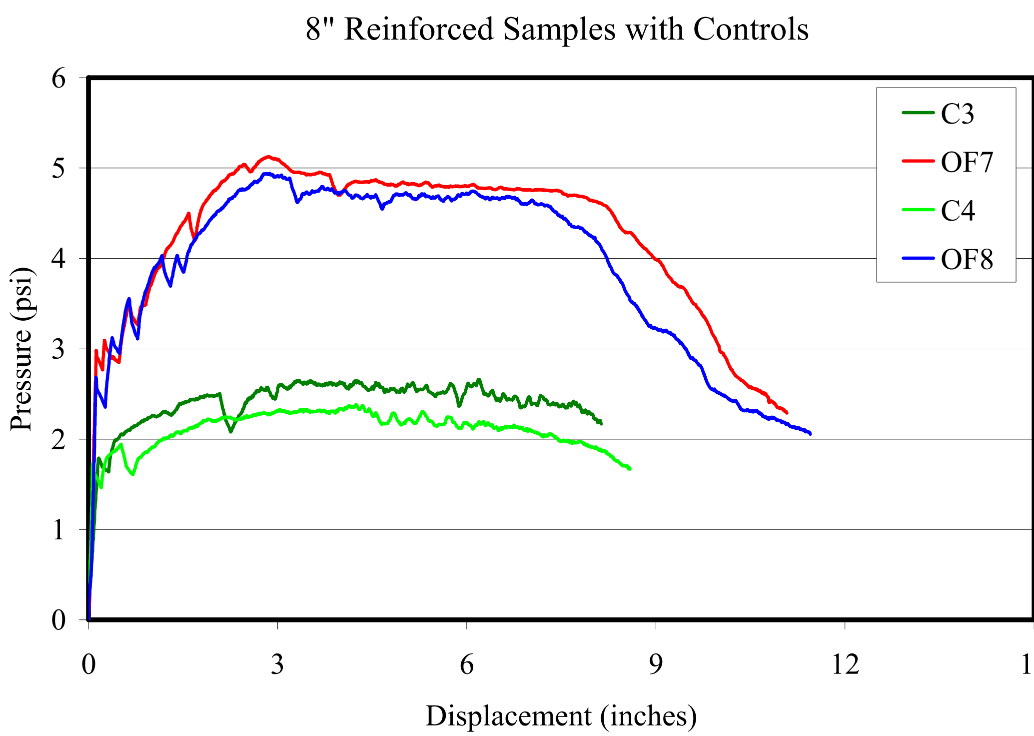

Figure 14 – Static Resistance Function for the 8-inch Reinforced Octaform Samples and Reinforced Control Samples

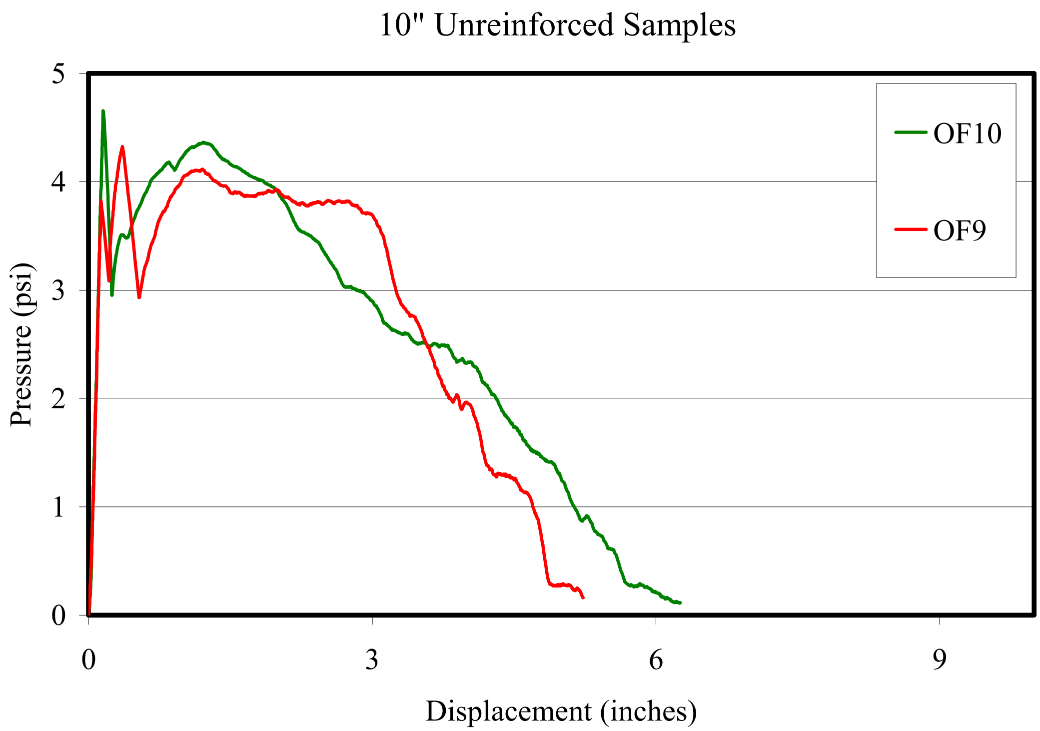

Figure 15 – Static Resistance Function for the 10-inch Unreinforced Octaform Samples

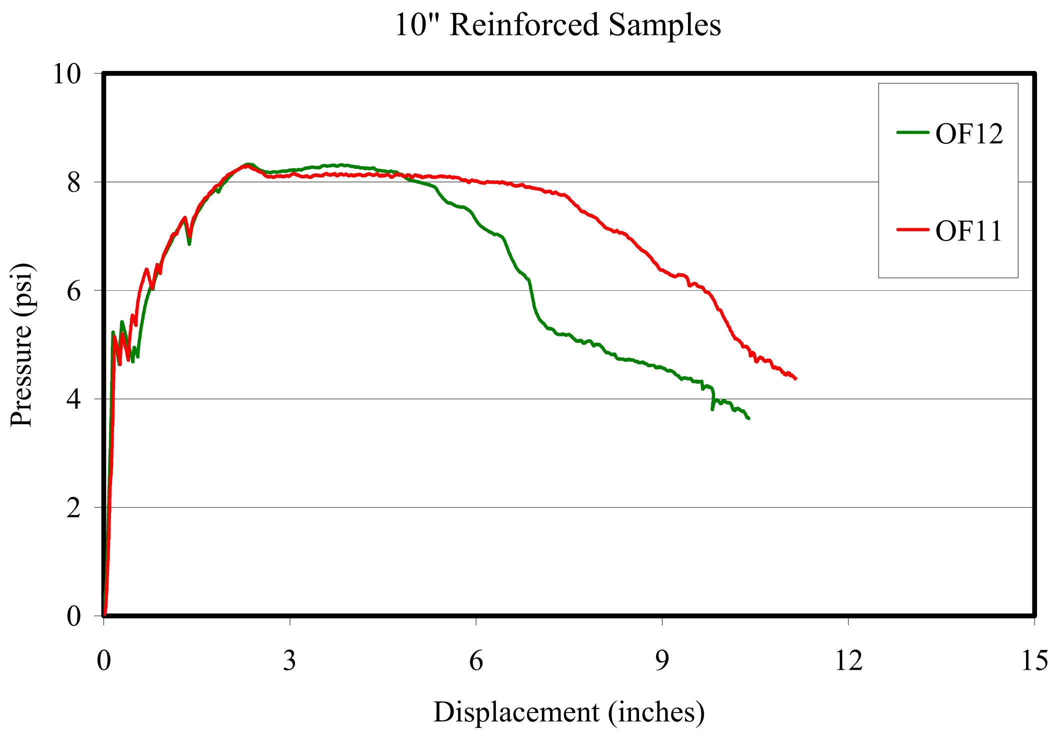

Figure 16 – Static Resistance Function for the 10-inch Reinforced Octaform Samples

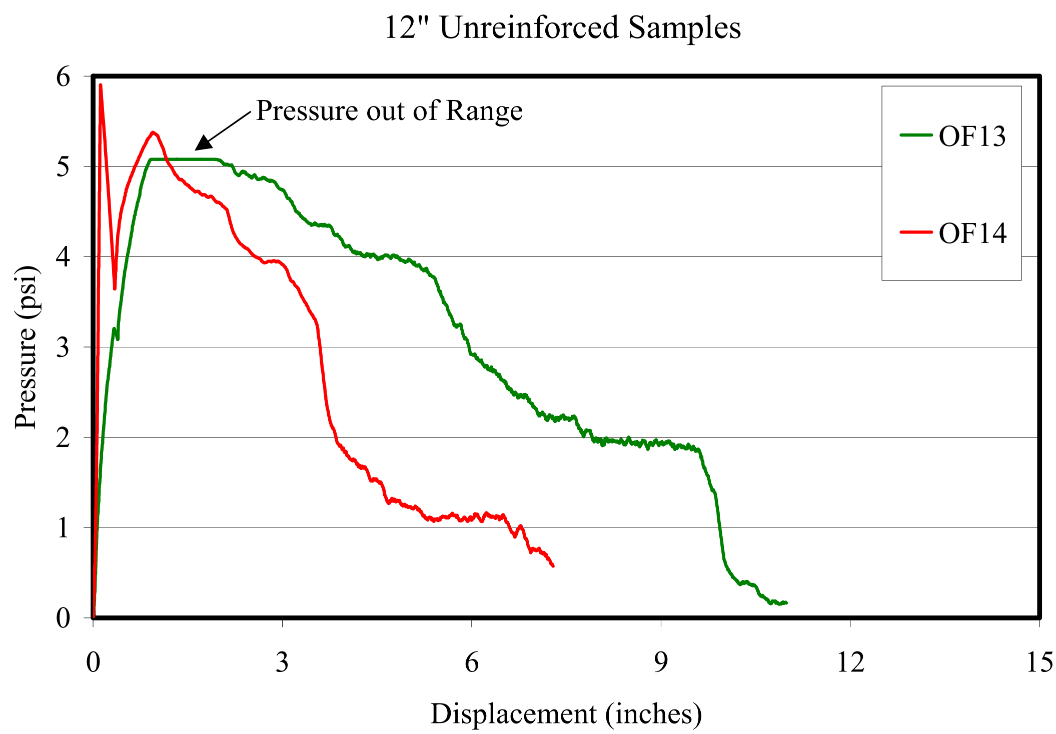

Figure 17 – Static Resistance Function for the 12-inch Unreinforced Octaform Samples

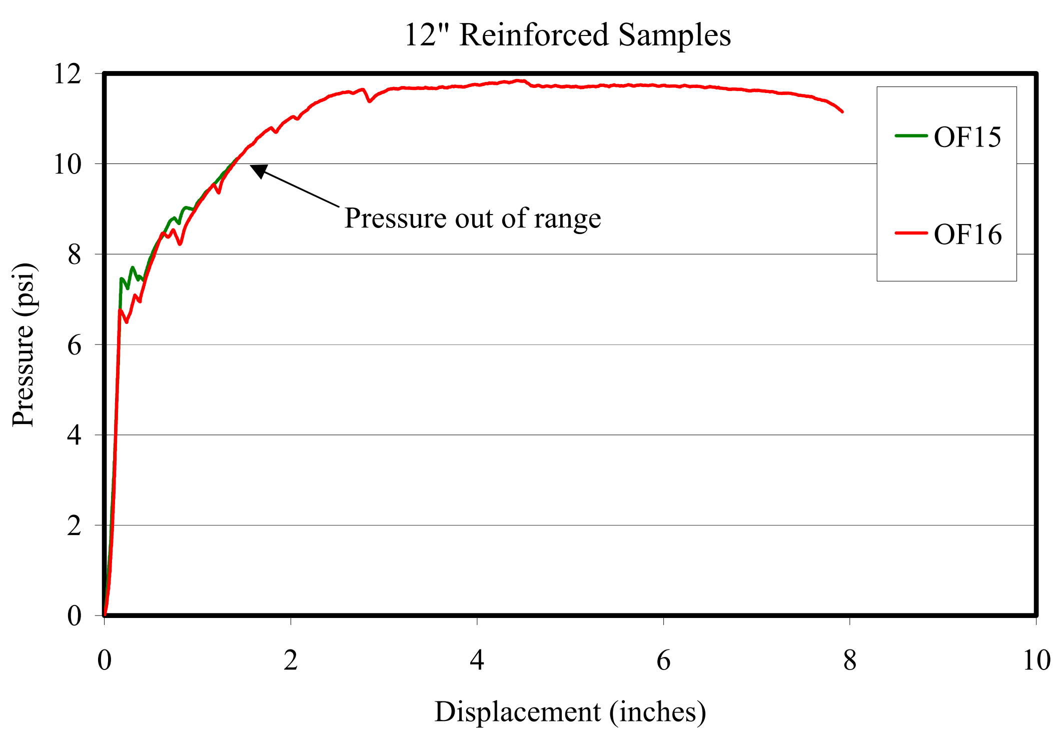

Figure 18 – Static Resistance Function for the 10-inch Reinforced Octaform Samples

3.3 Observations

In general, the failure of the Octaform samples was started with necking of the PVC followed by tearing as shown in Figures 19 – 22. In all of the steel reinforced samples the rebars failed after the PVC failing, except for samples OF3 and OF4. For these samples, the maximum available travel of the loading tree was reached before the steel reinforcement failed. It was also observed that for OF3 and OF4 samples the PVC on the tension face failed and the available resistance was nearing zero. For samples OF15 and OF16 the steel reinforcement was in two layers, and only the tension steel failed. This was considered to be failure of the samples as the applied pressure neared zero also.

In larger samples, 10- and 12-inch samples, it was observed that the failure of the PVC was premature when compared to the 6-inch and 8-inch samples. It is suggested that designer should consider determining the optimal concrete to polymer thickness ratio to better utilize the polymer in larger samples. It was also noted that failure of larger samples was much more brittle in nature Figure 21 shows the PVC suddenly tearing followed by collapse of samples.

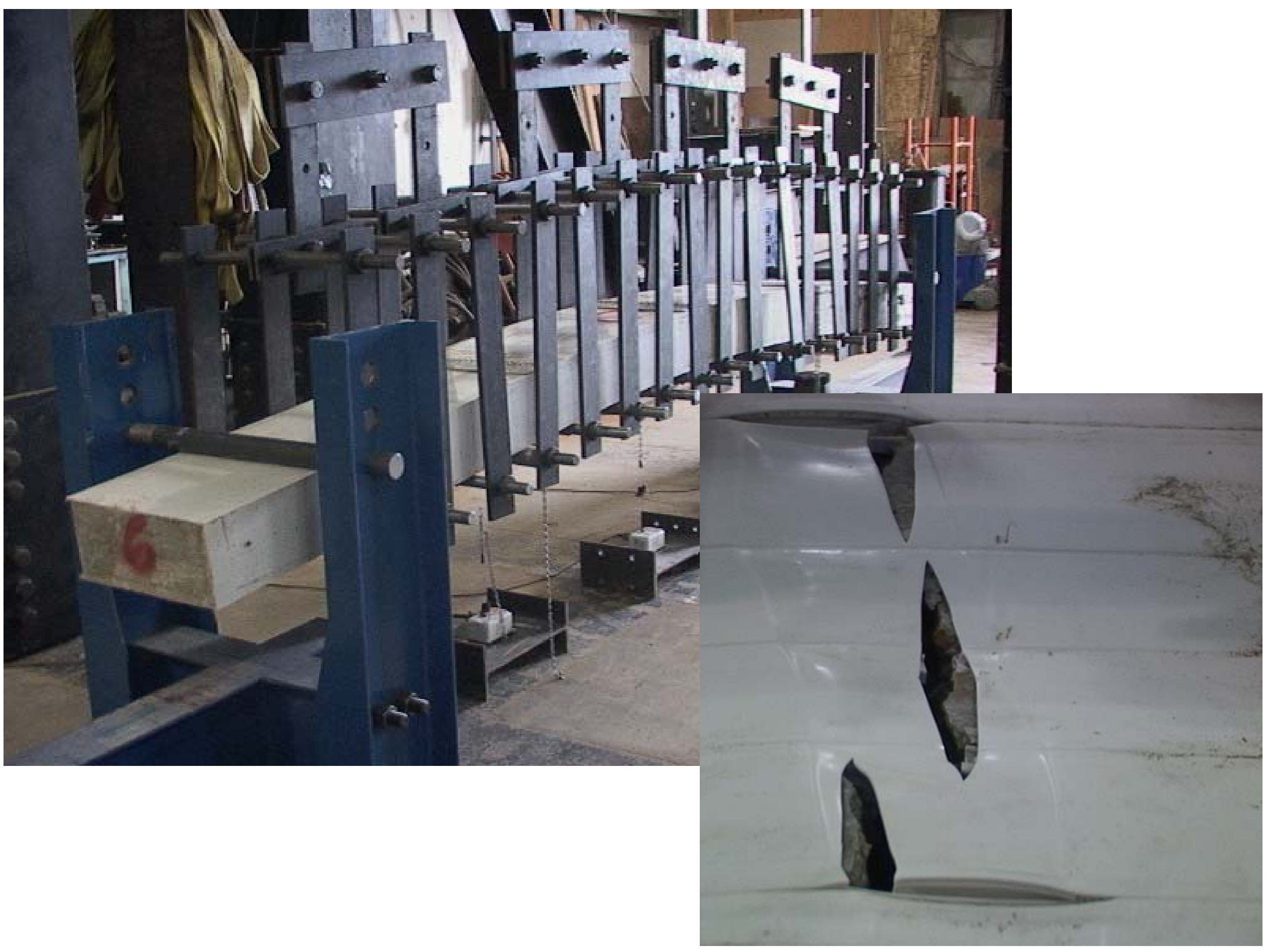

Figure 19 – Initial cracking of concrete and tearing of PVC

Figure 20 – Typical ductile behavior of samples signified by parabolic deformed shape for thinner Octaform samples

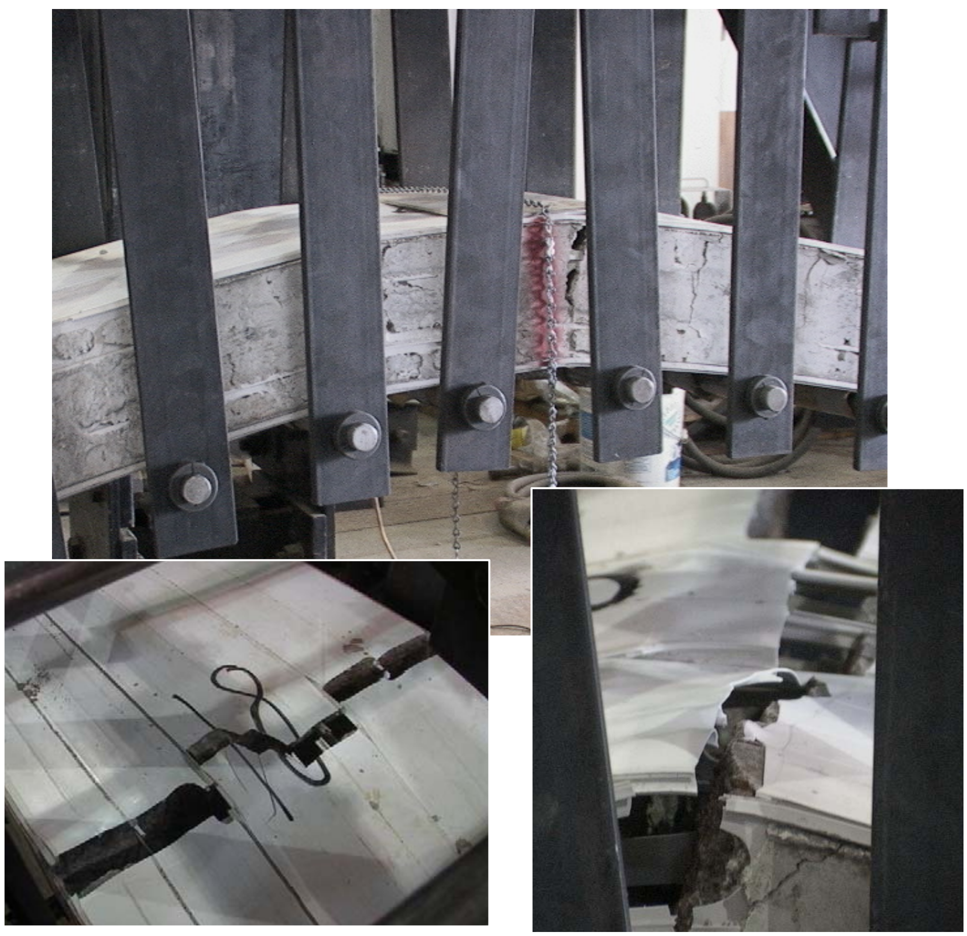

Figure 21 – Typical response of 10-inch and 12-inch thick samples

Figure 22 – Failure sequence of PVC: thinning followed by tearing

4.0 Dynamic Response Predictions

The experimental static resistance functions developed in this project are used to predict the dynamic response of the wall panels under blast loading. The dynamic response of a wall panel under blast is approximated by the following single degree of freedom (SDOF) equation of motion:

$$M_e \ddot{y}(t) + R_e = F_e(t) \qquad (1)$$

Where M_e is the equivalent mass of the wall, R_e is the equivalent static resistance of the wall, F_e is the equivalent blast loading on the wall, and t is time. The equivalent quantities, M_e, R_e, and F_e, are calculated using the actual quantities and appropriate mass and load factors (Biggs 1964).

The exact solution to Equation 1 can be obtained using a detailed step-by-step numerical integration, but in this report an approximate solution is obtained using energy equivalence. This is done by comparing the stored strain energy of the wall to the kinetic energy of the wall resulting from the momentum of the wall induced by the impulse of the blast.

The wall systems tested in this report are evaluated using two hypothetical explosion threats. The first threat evaluated is 1000 lbs of TNT at 75 feet, which produces a reflected pressure of 49 psi and a reflected impulse of 252.5 psi-msec (TM5-1300). The results of the approximate dynamic analysis are given in Table 3.

Table 3 – Approximate Dynamic Response Predictions for 1000 lb of TNT @ 75 ft

Sample	Static Energy SE (psi-in)	Kinetic Energy KE (psi-in)	Dynamic Deflection (in)	SE / KE	Status
C1 Reinf.	13.96	19.35	NC	0.72	NOT SAFE
C1 Unreinf.	0.25	19.35	NC	0.01	NOT SAFE
C2 Reinf.	11.55	19.35	NC	0.60	NOT SAFE
C2 Unreinf.	0.32	19.35	NC	0.02	NOT SAFE
C3 Reinf.	12.48	14.51	NC	0.86	NOT SAFE
C3 Unreinf.	0.25	14.51	NC	0.02	NOT SAFE
C4 Reinf.	11.53	14.51	NC	0.79	NOT SAFE
C4 Unreinf.	0.16	14.51	NC	0.01	NOT SAFE
OF1	13.11	19.35	NC	0.68	NOT SAFE
OF2	13.09	19.35	NC	0.68	NOT SAFE
OF3	34.09	19.35	6.84	1.76	SAFE
OF4	38.19	19.35	7.11	1.97	SAFE
OF5	11.68	14.51	NC	0.80	NOT SAFE
OF6	12.34	14.51	NC	0.85	NOT SAFE
OF7	30.08	14.51	3.46	2.07	SAFE
OF8	28.72	14.51	3.59	1.98	SAFE
OF9	7.50	10.74	NC	0.70	NOT SAFE
OF10	8.04	10.74	NC	0.75	NOT SAFE
OF11	39.56	10.74	1.77	3.68	SAFE
OF12	33.59	10.74	1.78	3.13	SAFE
OF13	17.11	8.95	2.06	1.91	SAFE
OF14	10.21	8.95	1.89	1.14	SAFE
OF15	32.65	8.95	1.18	3.65	SAFE
OF16	42.99	8.95	1.21	4.81	SAFE

The second threat evaluated is 450 lbs of TNT at 75 feet, which produces a reflected pressure of 25.1 psi and a reflected impulse of 142 psi-msec (TM5-1300). The results of the approximate dynamic analysis are given in Table 4.

Table 4 – Approximate Dynamic Response Predictions for 450 lb of TNT @ 75 ft

Sample	Static Energy SE (psi-in)	Kinetic Energy KE (psi-in)	Dynamic Deflection (in)	SE / KE	Status
C1 Reinf.	13.96	6.12	3.65	2.28	SAFE
C1 Unreinf.	0.25	6.12	NC	0.04	NOT SAFE
C2 Reinf.	11.55	6.12	3.88	1.89	SAFE
C2 Unreinf.	0.32	6.12	NC	0.05	NOT SAFE
C3 Reinf.	12.48	4.59	2.15	2.72	SAFE
C3 Unreinf.	0.25	4.59	NC	0.06	NOT SAFE
C4 Reinf.	11.53	4.59	2.36	2.51	SAFE
C4 Unreinf.	0.16	4.59	NC	0.04	NOT SAFE
OF1	13.11	6.12	3.33	2.14	SAFE
OF2	13.09	6.12	3.28	2.14	SAFE
OF3	34.09	6.12	2.69	5.57	SAFE
OF4	38.19	6.12	2.85	6.24	SAFE
OF5	11.68	4.59	1.75	2.54	SAFE
OF6	12.34	4.59	1.75	2.69	SAFE
OF7	30.08	4.59	1.40	6.55	SAFE
OF8	28.72	4.59	1.44	6.26	SAFE
OF9	7.50	3.67	1.07	2.04	SAFE
OF10	8.04	3.67	1.02	2.19	SAFE
OF11	39.56	3.67	0.78	10.77	SAFE
OF12	33.59	3.67	0.79	9.15	SAFE
OF13	17.11	3.06	0.91	5.59	SAFE
OF14	10.21	3.06	0.71	3.34	SAFE
OF15	32.65	3.06	0.51	10.67	SAFE
OF16	42.99	3.06	0.54	14.05	SAFE

5.0 Summary

The static resistance and mass are most important quantities for resisting a blast. The PVC layers provided additional strength and ductility to the concrete samples. The added energy-absorption capability provided by the PVC forms enhanced the blast resistance of the wall systems. The static energy of the thinner samples was in some cases larger than the ones for the thicker samples. Therefore, it is recommended that additional work is necessary to optimize the thickness of the faces of the PVC form to better utilize their contribution to the overall static resistance of the system.

For the dynamic field tests, it is suggested that 6-inch or 8-inch Octaform samples be tested. Reinforced and unreinforced samples can be tested in the field using live explosions. The size of the explosion threat and standoff distance can be determined in collaboration with Octaform and the Air Force Research Laboratory.

6.0 References

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