Internal Blast Test of a Reinforced Concrete Structure

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Abstract

Multiple tests were performed on a RC structure to measure performance of a wall with threaded rebar couplers and rebar with anchor plates compared to a baseline wall with conventional reinforcing lap splices and connection details. The tests were performed at the Hardened Internal Blast Structures (HIBS) facility at Tyndall Air Force Base. The test setup consisted of a detonation room with a roof slab, floor slab, and four walls that separated it from four witness rooms. One wall had a doorway size opening that allowed gaseous detonation products to vent out of the room. The first two tests used a single charge that was initiated in the center of the room, equidistant from each wall. The last test used two charges next to each wall being analyzed. The blast effects on the walls consisted of multiple shock reflections and quasi-static gas pressure. The results of the tests demonstrate the efficacy of new rebar technologies for use in protective structures subject to blast. This paper will summarize all of the tests completed, performance of new rebar technologies and discuss technology gaps and future work for implementation in current protective design criteria.

Introduction

Naval Facilities (NAVFAC) Engineering and Expeditionary Warfare Center (EXWC) and Air Force Civil Engineer Center (AFCEC) conducted three internal blast tests that were designed to demonstrate that RC walls with threaded mechanical couplers and rebar with end plates exhibit an equivalent response as a conventional RC wall design with lap splices and hooked rebar. The goal of the tests was to produce enough inelastic response in the walls to achieve a maximum support rotation greater than two degrees, where support rotation, θ, is defined as:

$$e = atan(\frac{2\Delta}{L}) \qquad \textbf{Equation 1}$$

where,

$$\Delta = Peak\ Displacement$$
$$L = Span$$

A value of e equal to two degrees is significant because that is the allowable limit on support rotation for RC walls providing personnel protection for Protection Category 1 as specified in Unified Facilities Criteria (UFC) 3-340-02 [1].

A schematic that displays how the rebar technologies are implemented into a wall section is shown in Figure 1. Protective construction designs may be exposed to external and/or internal blast loads where the former is generally characterized by a single pressure pulse and the latter consists of a short duration shock pressure with multiple reflections and a quasi-static gas pressure. The walls in this experiment were loaded by an internal blast load because the combination of shock pressures with multiple reflections and quasi-static gas pressure presents a worst-case load scenario that had not been previously tested.

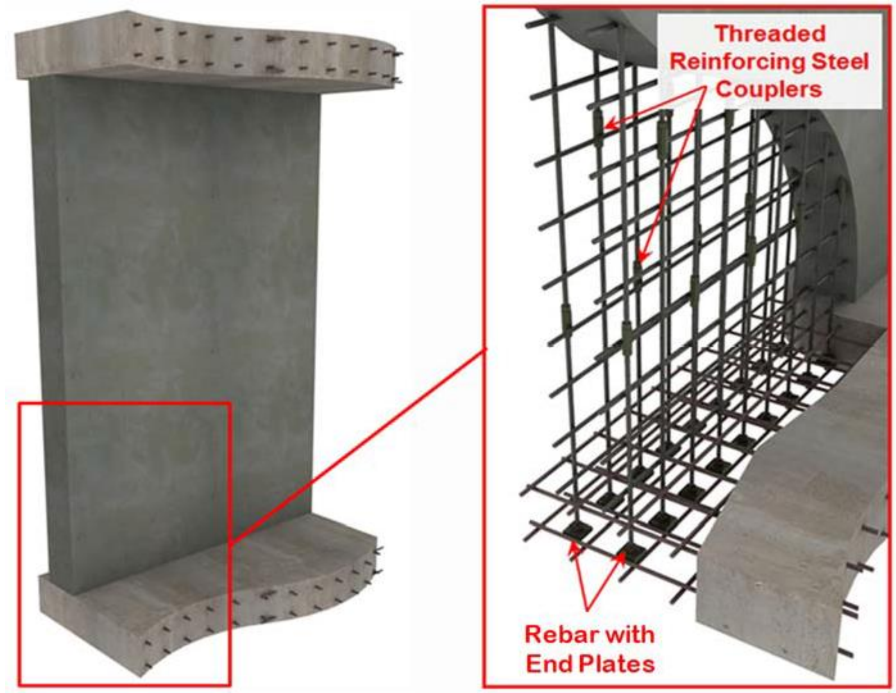


Figure 1. RC wall with threaded reinforcing steel couplers and rebar with end plates

Due to the quasi-static nature of the gas pressure load on the structure, the response of the walls and the roof are highly dependent on the peak pressure rather than the impulse, which typically is the important attribute of the shock pressure loading in the near field. The inelastic behavior of the walls and roof are typically modeled as elastic-perfectly plastic or elastic-perfectly plastic with tensile and/or compression membrane. The determination of a charge size that would produce two degrees of support rotation was challenging, because if the charge were too large, the gas pressure would overwhelm the resistance of the wall and, more importantly, the roof, which would result in a catastrophic failure that would fail to produce useful test data. Therefore, the planned approach was to increase the load gradually until the desired wall deformations were achieved.

The first test was performed with a cylindrical charge that was detonated in the center of the room at the floor. The second test also used a cylindrical charge with a weight equal to 1.65 times the charge in the first test as shown by the red diamond in Figure 3. The charge in the second was also detonated at the center of the room on the floor. The load generated in these confined blasts consists of a short duration shock pressure with multiple reflections and a quasi-static gas pressure. The magnitude and duration of the quasi-static gas pressure is dependent on the ratio of charge weight to room volume and the total area through which the built up pressure can vent. The third test was performed with two, simultaneously, detonated cylindrical charges, each with a weight equal to Test 1 charge resulting in a net explosive weight (NEW) of two times Test 1. Each charge from Test 3 was detonated against one of the test walls approximately 4 feet from the floor and 5 feet from the wall with an opening as shown in Figure 3 by the red stars.

Test Setup

The internal blast test was conducted at Tyndall Air Force Base in the Hardened Internal Blast Structure (HIBS). The HIBS is a modular test structure that currently can be configured to simulate a single, rectangular room of a building.

The HIBS structure was designed to observe the complex blast environment consisting of high-speed fragments, multiple shock reflections, and quasi-static gas pressure that are produced by the detonation of a cased charge in a confined space. HIBS consists of four culvert structures that are attached to a slab on grade and are configured to represent a four-wall room with ceiling and floor slab. An isometric cutaway schematic of the test setup is shown in Figure 2 and a plan view is displayed in Figure 3. Both figures show that the test consisted of a room that was 20 feet wide by 20 feet deep by 12 feet tall and that a charge was placed in the center of the room at the floor for the first and second test and two charges, one against the baseline wall and one against the test wall, were placed for the third test as shown in Figure 3 by the red stars. This resulted in a minimum standoff equal to 10 feet to the four walls and a minimum standoff slightly less than 12 feet to the roof for Test 1 and 2. The location of the two charges for the third test resulted in a zero standoff from the baseline and test walls, respectively, 5 feet standoff to the wall with an opening, and 8 feet standoff to the roof.

The room had one opening that was 3 feet wide by 7 feet tall on the South wall. This opening simulates a doorway that would likely be present in a typical structure and would provide venting of the gas products that result from the explosion. It was determined in the previous test that venting was required to prevent the confined blast from completely overwhelming the structure and producing a catastrophic failure. The level of venting was based on an estimate of a typical scenario where a door may fail, resulting in an opening; however, it should be noted that no door was included in the test.

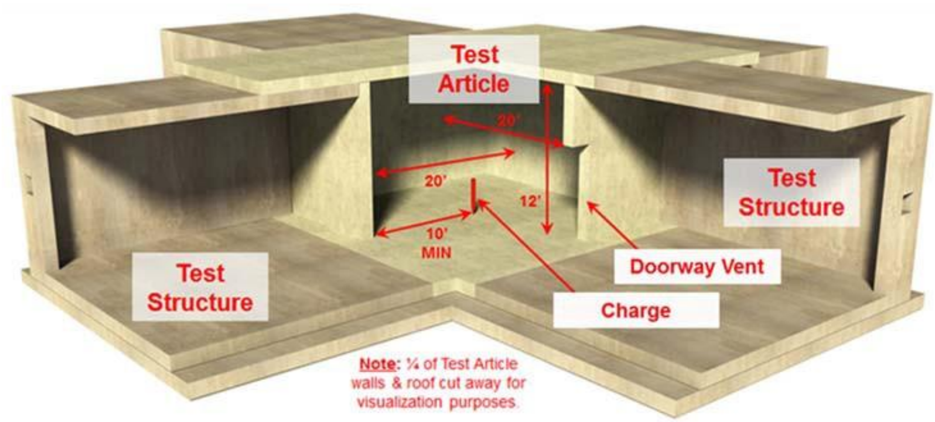


Figure 2. Isometric Cutaway View of HIBS Test Setup

The walls of the interior room in the test setup were designated as the test articles. The North wall labeled Composite Steel Stud Wall System (CSSWS) is a cold formed steel stud walls system. This wall was developed for an unrelated test series and is not critical to the overall objective of the tests discussed herein, except that the wall was required to resist the loads without failing, so that a desired internal gas pressure was generated in the blast.

The RC Baseline Wall was the control in the tests and was constructed with conventional lap splices and rebar hooks at joint locations. Each face of the wall was reinforced with 0.75-in. diameter A615 Grade 75 rebar spaced at 8 in. in the vertical and horizontal directions. The walls also had #4 single leg rebar spaced at 8 in. on-center with a 90-degree and a 135-degree hook on each end. The orientation of the stirrups were rotated by 180 degrees at each intersection with the vertical and horizontal rebar. The RC Test Wall (East wall) was nearly identical to the RC Baseline wall, except that it had threaded mechanical rebar couplers instead of lap splices and rebar with end plates at structural joints instead of hooked rebar. The end plates were 3 in. x 3 in. x ¾ in. thick A572 Grade 50 structural steel. Both the lap splices and rebar couplers were staggered 2 feet to adjacent connections. Each test article consisted of one complete wall and one-half adjacent segment as shown in Figure 3. The transition between the two wall types occurred at the centerline of the doorway. The boundary conditions for the two RC walls were fixed-fixed in the vertical direction, fixed at the corner, and free at the interface with the CSSWS. The boundary conditions at the top and bottom were provided by RC slabs serving as the roof and floor, respectively.

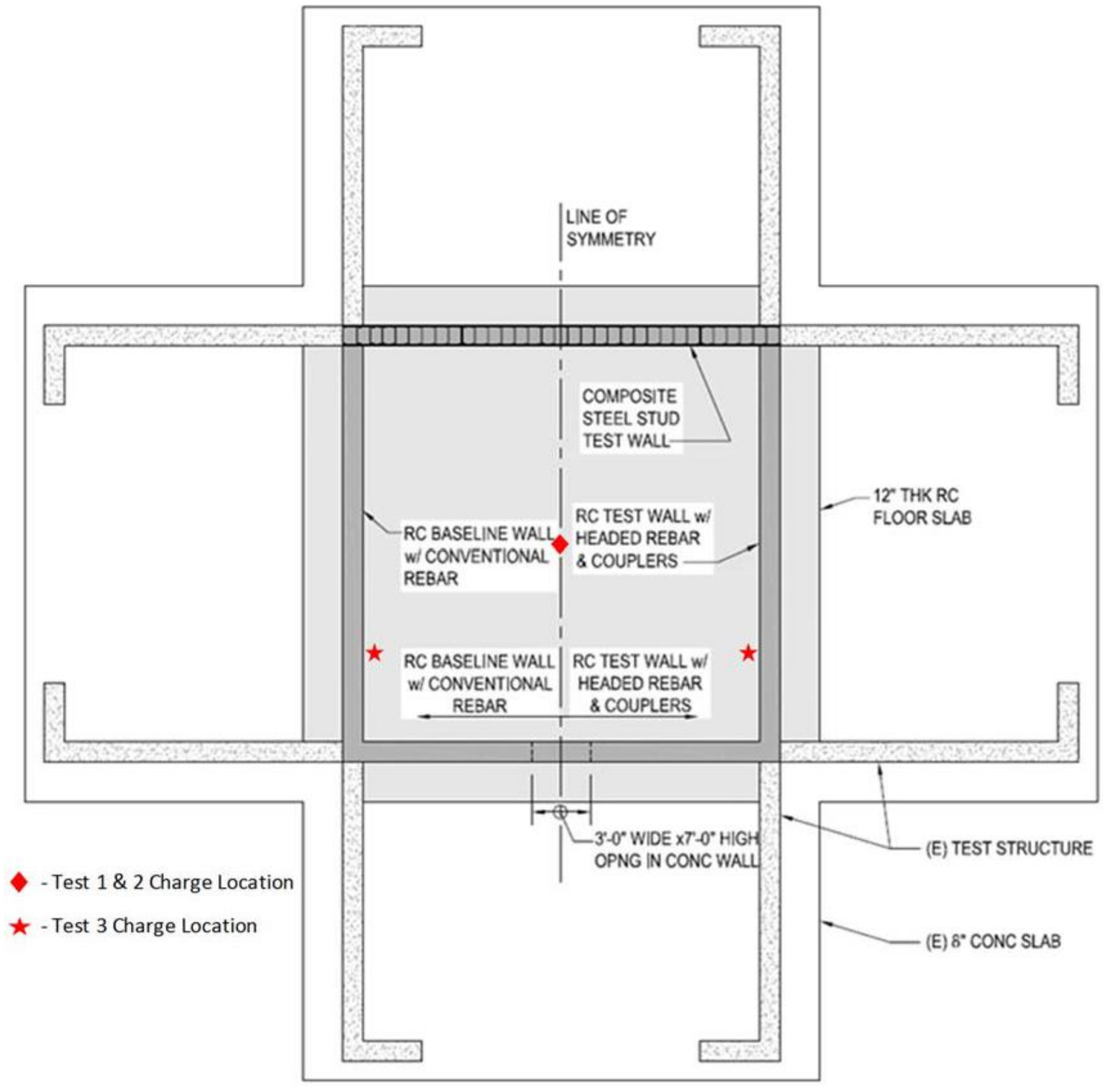


Figure 3. Plan view of HIBS test setup

Instrumentation

An array of instrumentation was used to measure pressure loads and structural performance during the internal blast tests. Incident and reflected blast pressures were measured inside and outside of the test structures with a combination of gauges. The general reflected pressure gauge layout is shown in Figure 4 for both the Baseline and Test Walls. In Test 1, incident pressure gauges were also placed in the detonation room, witness rooms, and in the free field. In Test 2, incident pressure gauges were placed in the witness rooms and a free field gauge was used, but no incident gauges were placed in the detonation room. In Test 3, the same instrumentation was used as in Test 2. The Baseline RC Wall and the Test RC Wall had nine displacement gauges for Test 1 and 2 and six displacement gauges each in patterns shown in Figure 5. The displacement gauges were attached to the exterior face of the concrete walls using concrete anchors and supported by a cantilever frame structure fixed at its base to the floor of the witness room. Displacement gauges were also used to measure the response of the roof slab at midspan and quarter span points along the centerline in the east-west direction. The pressures and displacements were recorded by a data acquisition at sampling frequency equal to 2 MHz. Video was also captured during the tests using seven high-speed cameras, and one high definition camera, recording in real time. Each wall of the test structure, except the wall with the doorway, was recorded by a high-speed camera that was located about 20 ft behind its exterior side. Four high-speed cameras were also positioned to provide a record of the overall test structure response during the test. The three high-speed cameras viewing the exterior side of the walls were recorded with a resolution of 1920 x 1200 pixels at a speed equal to 1300 frames/sec. The four high-speed cameras viewing the overall test structure response were recorded with a resolution of 1280 x 800 pixels at a speed that ranged from 1300 to 6200 frames/sec.

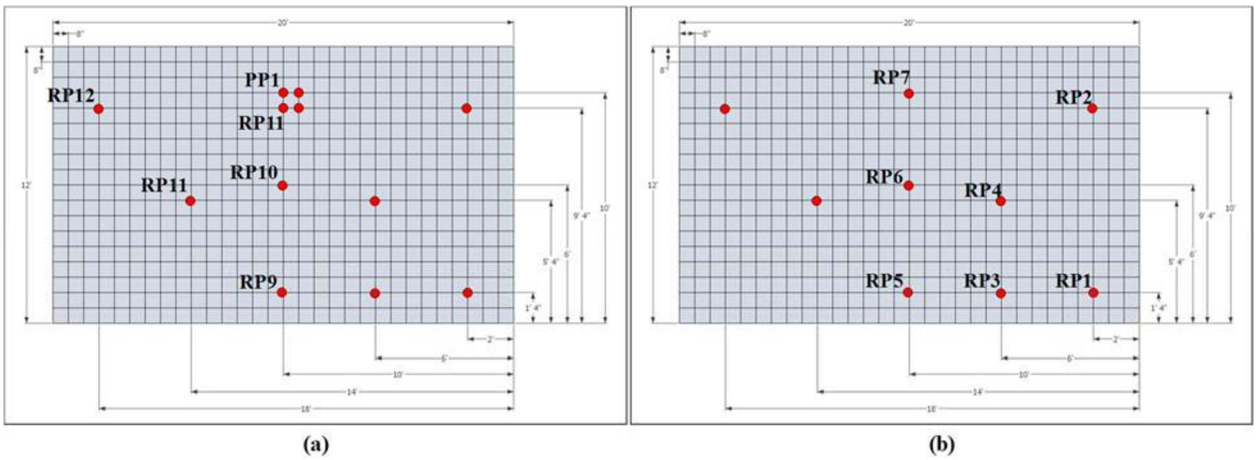


Figure 4. Interior view of reflected pressure gauges; (a) RC Test Wall – rebar couplers and rebar with end plates; (b) RC Baseline Wall –conventional reinforcement

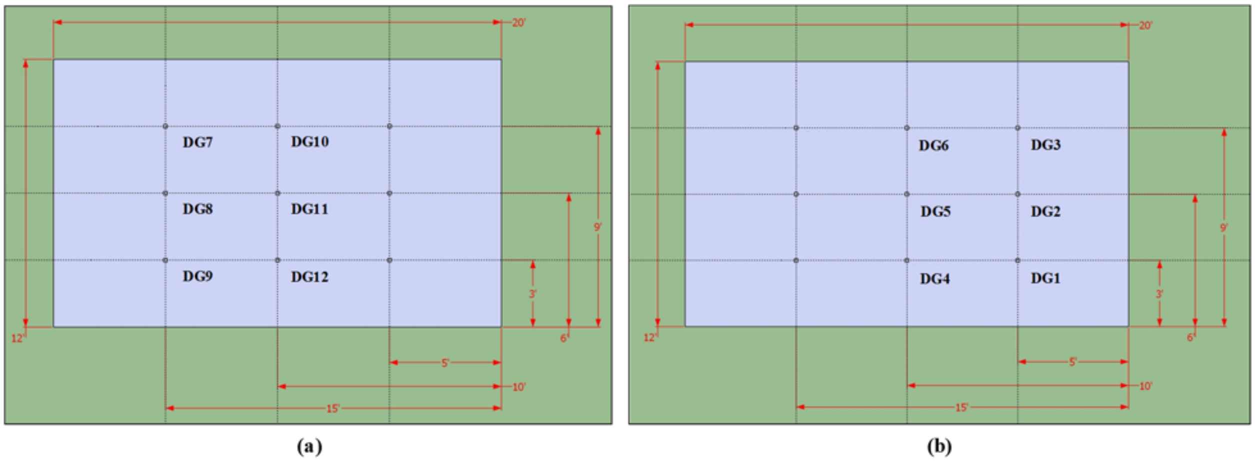


Figure 5. Interior view of deflection gauges; (a) RC Test Wall – rebar couplers and rebar with end plates; (b) RC Baseline Wall – conventional reinforcement

Results

The results of Test 1, 2 and 3 are summarized Table 1, which lists maximum displacement at the center of each wall and maximum support rotation. The maximum displacement and rotation of the roof from Test 3 is approximate because the roof deformed past the frame that was measuring the displacement. Therefore, the displacement was assumed to be the height of the frame measured from the top of the roof. Table 2 lists the residual displacement and support rotation from each test as well as the cumulative results. The cumulative results add the residual displacement and support rotation from the previous test to the maximum displacement and support rotation from the respective test. This is shown because it represents the total deformation that the walls and roof have seen in the three tests. The table shows that the maximum displacement in the baseline and test walls was 8.69 in. and 3.81 in., respectively. The maximum support rotation for the baseline wall was 6.88 degrees and for the test wall was 3.03 degrees.

Table 1. Summary of test results

Element	Test 1 Results		Test 2 Results		Test 3 Results	
	Max Displacement [in.]	Max Rotation [deg]	Max Displacement [in.]	Max Rotation [deg]	Max Displacement [in.]	Max Rotation [deg]
Baseline Wall	0.90	0.72	2.49	1.98	8.69	6.88
Test Wall	0.67	0.53	1.64	1.31	3.81	3.03
Roof	6.02	2.87	10.98	5.22	~ 48	~ 38

Table 2. Residual and cumulative results for test series

Test	Measurement	Element		
		Baseline Wall	**Test Wall**	**Roof**
Test 1	Residual Displacement [in.]	0.14	0.16	2.59
	Residual Rotation [deg]	0.13	0.12	1.23
Test 2	Residual Displacement [in.]	1.01	0.57	2.62
	Residual Rotation [deg]	0.80	0.45	1.25
Test 2 – Cumulative*	Max Displacement [in.]	2.64	1.81	13.6
	Max Rotation [deg]	2.11	1.43	6.45
Test 3	Residual Displacement [in.]	6.95	1.95	5.92
	Residual Rotation [deg]	5.51	1.55	2.82
Test 3 – Cumulative*	Max Displacement [in.]	9.7	4.38	~ 48
	Max Rotation [deg]	7.68	3.48	~ 38

*Cumulative includes maximums from respective test plus the residuals from the previous test

Photos of the non-loaded face of the baseline and test wall following Test 2 and 3 are shown in Figure 6. It can be observed that the damage in both walls is limited to cracking, which corresponds to locations where yield hinges are expected to form given that the walls had fixed supports top, bottom, and on one of the short sides with the other side free. The only significant damage observed following Test 2 was crushing of the concrete that occurred in the compression zone of the roof slab at the joint between it and the walls. Damage following Test 3 shows further development of yield hinges that are expected to form given the constraints. Both walls show concrete spalling at the location of the charge which was to be expected. Additional damage through concrete crushing and spalling is present along the yield lines in each wall.

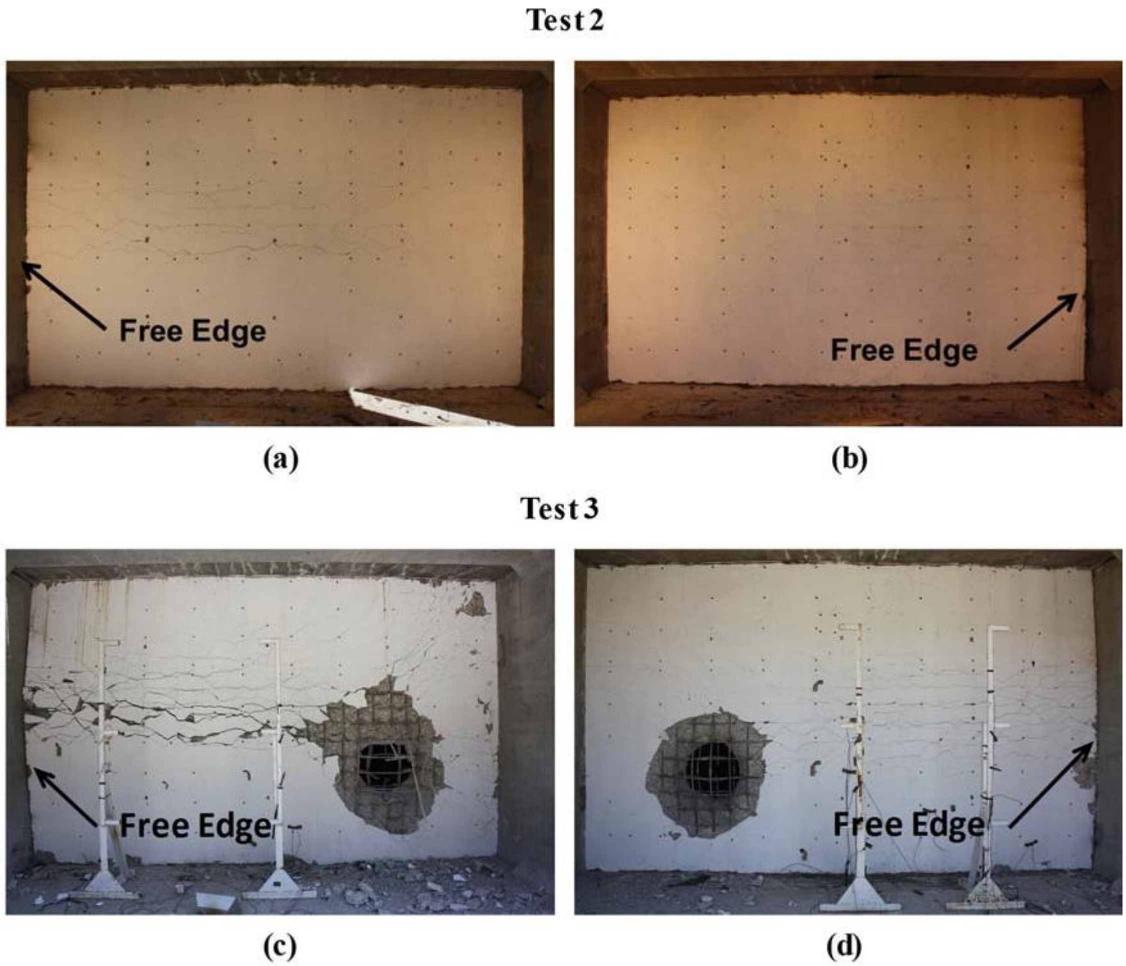


Figure 6. Post Test 2 and 3 photos of non-loaded faces of walls (a) RC Baseline Wall; (b) RC Test Wall; (c) RC Baseline Wall; and (d) RC Test Wall

Comparisons of the reflected pressure recorded at the center of the walls and the displacement time histories for Test 1, 2 and 3 are plotted in Figure 7, Figure 8 and Figure 9, respectively. It should be noted that the pressure time-histories have been normalized by the peak pressures and impulses. The plots demonstrate that the pressure loads were nearly equivalent on each wall, but the baseline wall experienced more deformation. It should be noted that the time-history shown in Figure 7 (b) indicates that the baseline wall vibrated at a higher frequency than the test wall; however, this vibration is due to the instrumentation frame shaking, not the wall. In Figure 7 (a) and Figure 8 (a), the baseline wall has an impulse that is about 5% higher than the test wall. It is unlikely that this additional impulse contributed significantly to the difference between the walls because the impulses do not diverge much until a significant portion of the load has been imparted on the structure. The baseline wall impulse in Figure 9 (a) for Test 3 is about 10% higher than the test wall and may have some contribution to the performance of the baseline wall compared to the test wall. The performance of the baseline wall compared to the test will be discussed in the subsequent section. In Figure 7 (b), Figure 8 (b) and Figure 9 (b) the evolution of damage is evident and the amount of the wall that remains in the elastic range is decreased with each test. The amount of elastic rebound decreases as the damage accumulates within each wall.

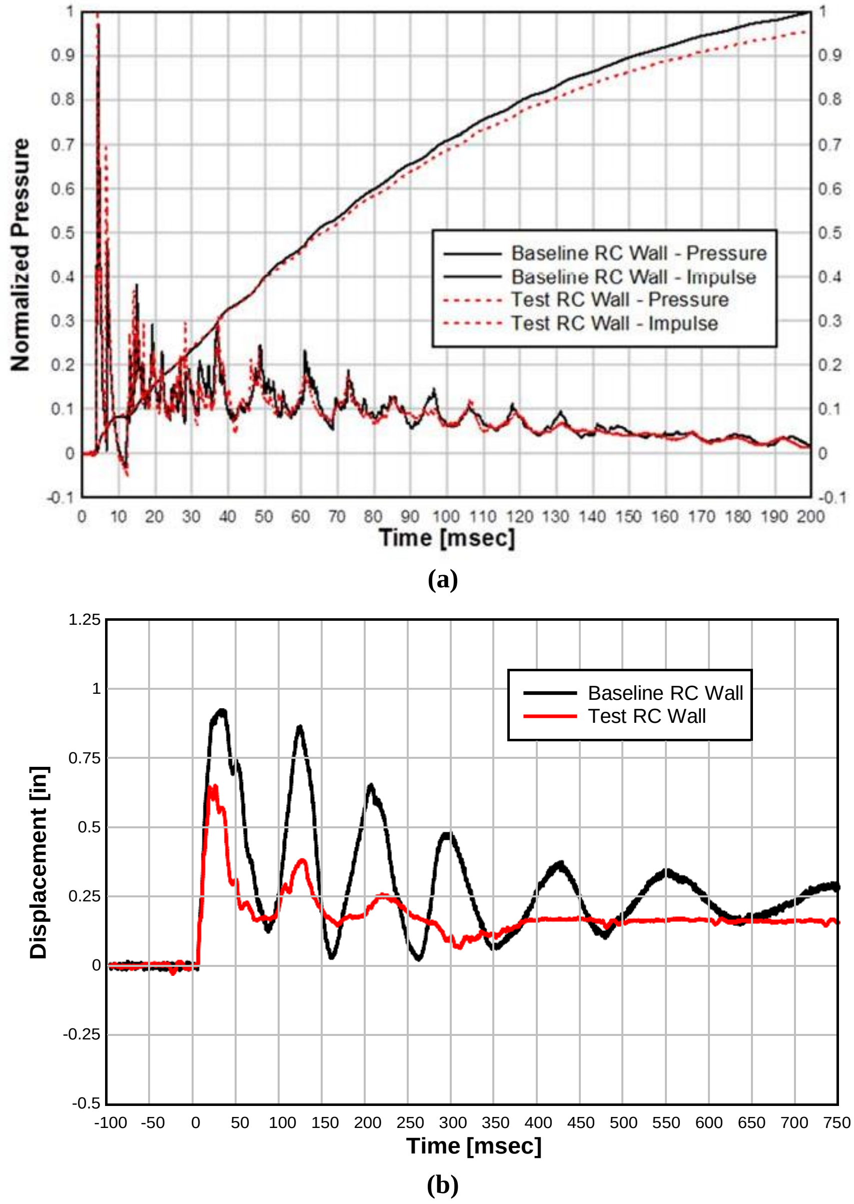
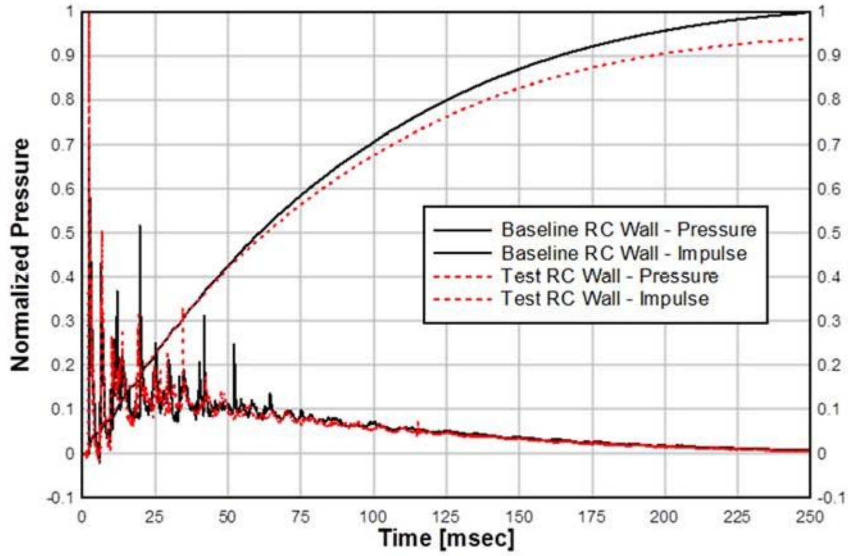
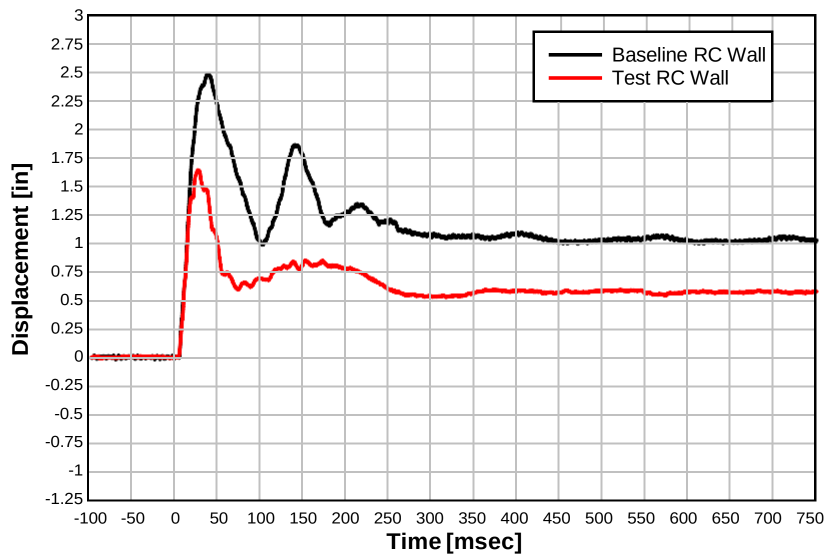


Figure 7. Test 1 results; (a) Reflected pressure and impulse; (b) Midspan displacement

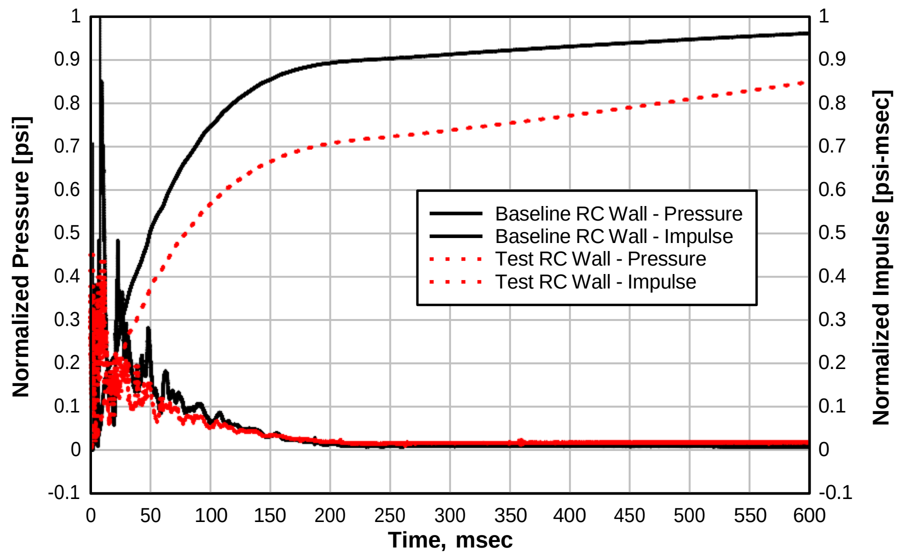


(a)

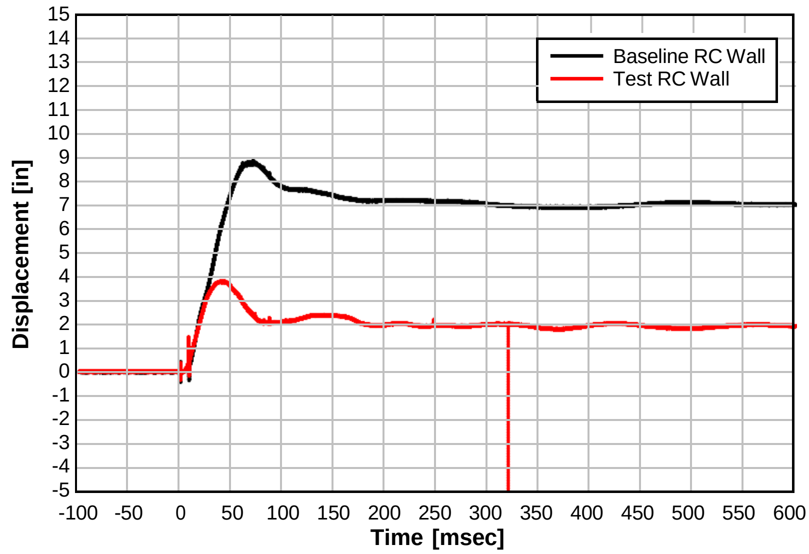


(b)

Figure 8. Test 2 results; (a) Reflected pressure and impulse; (b) Midspan displacement



(a)



(b)

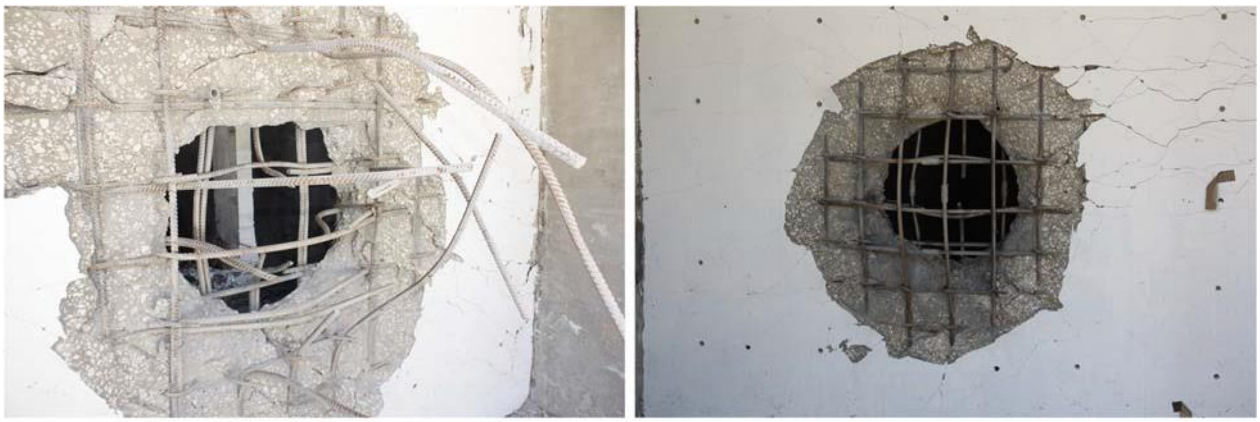
Figure 9. Test 3 results; (a) Reflected pressure and impulse; (b) Midspan displacement

Discussion of the Results

In the three tests, the cumulative deformation of the Baseline RC wall exceeded 2 degrees support rotation after Test 2 while the Test RC wall exceeded support rotation after Test 3 with an increased charge weight and reduced standoff. It is reasonable to assert that the RC wall with the rebar with end plates and threaded mechanical couplers will have equivalent or better performance than a RC wall with rebar details as specified in UFC 3-340-02 for multiple reasons.

Overall, the rebar with end plates deformed significantly less (approximately ½ the deformation of the Baseline wall) under similar loads, possibly due to better fixity at the supports. Figure 7, Figure 8, Figure 9 show the progression of midspan displacement for the Baseline and Test wall and as the damage level increases the Test wall performs significantly better than the Baseline wall.

Figure 10 compares the performance of the Baseline wall and Test wall that is in an area that undergoes extremely high strain rates. As expected, both walls did nothing to prevent breaching. However, the figure shows that only one coupler connection failed in the Test wall while 4 to 5 lap splice connections failed in the Baseline wall as a result of concrete spall. Failure of the one connection in the Test wall was fracture of the bar outside the coupler region. The significance from this result is that it indicates that couplers are still effective in areas of very high strain rates and have some benefits that relate to rebar continuity if spall occurs.



(a) (b)

Figure 10. Reinforcement details post Test 3; (a) Baseline RC wall; (b) Test RC wall

The overall deformation in the joint accounting for the roof displacement in the Baseline wall connection was equal to 15.2 degrees compared to 11 degrees in the Test wall connection. Figure 11 shows the roof performance for each wall after Test 3. Figure 11 (a) shows the roof connection to the Baseline wall and severe concrete spalling is evident. Also, the rebar hooks where pried open and the concrete was crushed and lost confinement near the connection of the walls to the roof. Figure 11 (b) shows the performance of the connection between the Test wall and the roof. There was no evident concrete spalling or failure of rebar anchor plates or stirrups. For large support rotations, the joint in the Test RC wall demonstrated sufficient detailing to achieve support rotations.

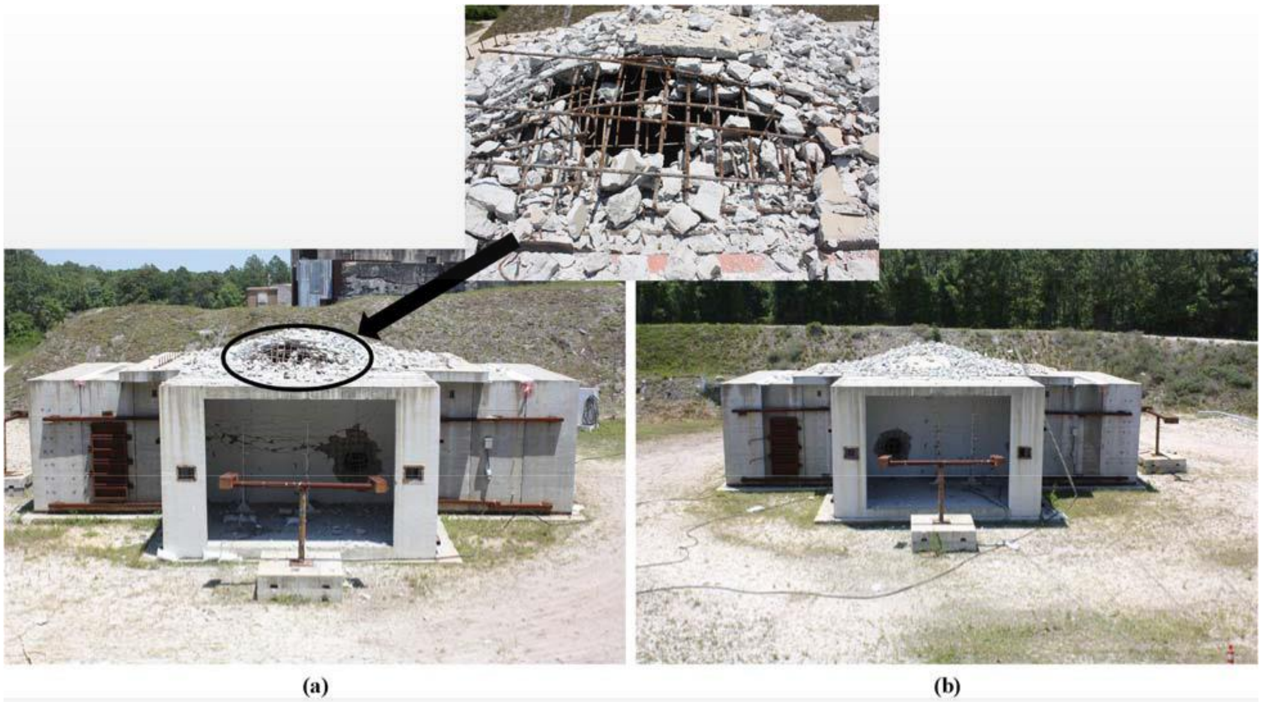


Figure 11. Performance of roof system post Test 3; (a) Roof-wall connection for Baseline RC wall with callout to roof damage; (b) Roof-wall connection for Test RC wall

There is a cost savings of approximately 5 to 10 percent using rebar with end plates and threaded mechanical couplers compared to traditional reinforcing details. This cost savings is due to reduced volumes of required steel, increased worker productivity during installation of rebar cages, and reduced likelihood of required repairs due to poor concrete consolidation stemming from rebar congestion. An additional benefit of the system promotes constructability, ensuring that the structure detailed in construction drawings is actually built to specifications.

Conclusions and Recommendations

Based on the results of the tests, it is concluded that the performance of the RC wall with threaded mechanical couplers and rebar with end plates exceeded the performance of a baseline wall with conventional rebar details using lap splices and hook ends. Rebar couplers are currently accepted for use in DoD protective construction and it is recommended that UFC 3-340-02 also allow the use of rebar with end plates in place of 90 degree hooks for longitudinal rebar at boundary conditions given that:

- Rebar with end plate system can develop stress-strain relation that is equivalent to a uniaxial stress-strain relation of a plain bar
- Rebar with end plate connection details are in accordance with ACI 318 [2]

Acknowledgements

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