Blast Testing of Helix Fibre Reinforced Concrete Panels

Created By: Martin Walker
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Explora Foundation
Unit-9 Talina Centre, Bagleys Lane,
London SW6 2BW. United Kingdom
T:0207 736 3420 F:0207 736 0321
info@theexplorafoundation.org
www.theexplorafoundation.org

Executive Summary

Explora Research performed a blast test series the week of April 15th, 2013 to investigate the feasibility of using Helix fibre reinforcement to improve the blast resistance of concrete panels. The tests took place at the Pecos Research and Testing Centre located near Pecos, Texas, USA. Breaching (near-field) tests were performed on 4' x 4' x 6" concrete panels with a range of Helix fibre and traditional reinforcement configurations.

The breaching tests showed that the addition of Helix fibre reinforcement can result in a significant improvement to breach and spall resistance. However, to obtain this benefit, Helix fibre reinforcement must be combined with at least minimal traditional reinforcement. The improvement provided by including Helix reinforcing fibre can be seen by comparing the results of the tests on Panels 4 and 10. Both panels had the same traditional reinforcement (#3 @ 5¾") and were subjected to the same charge and standoff distance (10lb of C4 at 15"). Increasing the Helix dosage from 30 lb/yd^3 to 50 lb/yd^3 reduced the spall area and volume by 91%.

This test series demonstrated the benefits of using Helix fibre reinforcement in order to improve the breach and spall resistance of concrete panels. A more extensive series of tests is required in order to quantify the benefits of using Helix fibre reinforcement to improve the resistance to breach and spall and develop design guidance.

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1. Introduction

1.1. Explora Research

1.1.1. Explora Research is a limited liability not-for-profit company that is wholly owned by the Explora Foundation. The sole object of the company is to carry out primary research dedicated to resilience and whole physical protection systems and any related matters. Explora Research is led by a Chief Scientist, who advises the Board of Directors and a team of corresponding associates, each a respected expert in his/her field. The company is competing for research funds to conduct in-house and collaborative projects. All proceeds from such projects are used to fund further research.

1.2. Helix

1.2.1. Helix is high performance, optimized steel for use in the reinforcement of concrete. Helix is short, twisted and polygonal shaped wires that are added to concrete during mixing. The shape and the twist maximize both the frictional and mechanical bonds between Helix and a cement based matrix. The twist drives the failure mechanism from frictional pullout to a torsional, or untwisting, mode.

2. Blast Testing

2.1. Overview

2.1.1. Blast testing was conducted at the Pecos Research and Testing centre located near Pecos, Texas, USA. This facility provides the capability to conduct fully instrumented explosive tests using over 9000lbs of TNT. The test arena location is shown in Figure 1.

Figure 1 View from test arena

2.1.2. The test series was performed over the week of April 15, 2013.

2.1.3. The explosive used to test the concrete panels was C4, a common plastic explosive with a TNT equivalency of approximately 1.3.

3. Panel Construction

3.1. All of the test specimens had the same external dimensions. They measured 4'x4' with a thickness of 6". Three control panels were manufactured using only traditional reinforcement. In order to test the effect of Helix fibres on the blast resistance of concrete panels, seven additional panels were manufactured with different quantities of traditional reinforcement replaced with Helix fibres. The panels ranged from 100% traditional reinforcement and no Helix, to 0% traditional reinforcement and 100 lb/yd of Helix. An overview of the test panels is provided in Table 1.

Table 1 Test panel matrix

Specimen	Rebar Spacing (inches)	Helix Dosage (lb/yd)
1 (control)	4	0
2 (control)	4	0
3 (control)	4	0
4	5¾	30
5	7½	30
6	7½	50
7	7½	70
8	15⅓	70
9	None	100
10	5¾	50

3.2. All panels used #3 rebar (0.11 in^2) as the traditional reinforcement and used a design concrete strength of 4500 psi. The panels were manufactured by Lee's precast based in Aberdeen, Mississippi. Photos of the manufacturing process are included in Appendix A. Compressive cylinder tests were conducted after 7 days curing time. A summary of the results is provided in Table 2.

Table 2 Panel concrete compressive strength

Panel	Compressive Strength (psi)
1,2,3	6014
4,5	5663
6	6096
7,8	6006
9	6344
10	6764

3.3. All of the panels were transported to the test site by road.

4. Breach Testing

4.1. Test Setup

4.1.1. The concrete panels were supported in all four corners by cylindrical concrete drums.

Figure 2 Breach testing panel support

4.1.2. A spherical C4 charge was mounted on a stack of polystyrene sheets in order to provide a standoff distance of 15" without affecting the loading, as shown in Figure 4. The charge weight was varied from 7 lb to 10 lb.

Figure 3 Charge placement

4.2. Control Tests

4.2.1. Three control tests were carried out using the traditionally reinforced panels. In order to determine an appropriate charge size for the tests. Spherical C4 charges of 10lb, 7lb and 8lb were used on panels 3, 2 and 1 respectively. The standoff distance for all of the charges was 15". The results of these tests are shown in Figure 5 and Figure 6 and Figure 7.

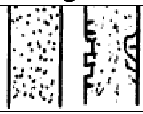
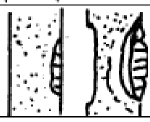
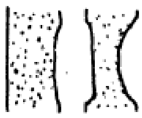
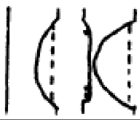
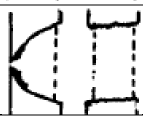
Figure 4 Panel 3 (Control) - 10lb of C4

Figure 5 Panel 2 (Control) - 7lb of C4

Figure 6 Panel 1 (Control) - 8lb of C4

4.2.2. The panel damage is classified based on criteria outlined in Table 3, which was developed for the United States Army.

Table 3 Damage classifications for spall and breach **(McVay, 1988)**

Damage Classification	Description	Diagram
No Damage	From no change in the condition of the wall to a few barely visible cracks	
Threshold Spall	From a few cracks and a hollow sound to a large bulge in the concrete with a few small pieces on the ground	
Medium Spall	From a very shallow spall to a third of the wall thickness	
Severe Spall	From just over a third of the wall thickness to almost breach	
Breach	From a small hole which barely lets light through to a large hole	

4.2.3. A summary of the control tests is provided in Table 4.

Table 4 Control test summary

Panel	Charge weight	Standoff	Result
3	10 lb C4	15"	Breach
2	7 lb C4	15"	Medium Spall
1	8 lb C4	15"	Medium Spall

4.2.4. From the damage shown in the control tests, it was decided to begin testing of Helix reinforced panels with 8 lb spherical charges of C4 at a standoff distance of 15".

4.3. Helix Breach Testing

4.3.1. Panel 7 (#3 bars at 7½" + 70 lb/yd Helix) and Panel 8 (#3 bars at 15⅓" + 70 lb/yd Helix) were both tested using 8lb of C4 at a standoff distance of 15". The results of these tests are shown in Figure 8 and Figure 9.

Figure 7 Panel 7 - 8lb of C4

Figure 8 Panel 8 - 8lb of C4

4.3.2. In both cases the panels spalled but did not breach. Based on the encouraging performance of panels 7 and 8, the decision was made to increase the charge size to 10lb.

4.3.3. Panels 4 (#3 bars at 5¾" + 30 lb/yd Helix), 5 (#3 bars at 7½" + 30 lb/yd Helix), 6 (#3 bars at 7½" + 50 lb/yd Helix), 9 (no rebar + 100 lb/yd Helix), and 10 (#3 bars at 5¾" + 50 lb/yd Helix) were tested using 10lb spherical charges of C4 at a standoff of 15". The results of these tests are shown in Figure 10 to Figure 1H.

Figure 9 Panel 4 - 10lb of C4

Figure 10 Panel 5 - 10lb of C4

Figure 11 Panel 6 - 10lb of C4

Figure 1H Panel 10 - 10lb of C4

4.3.4. A summary of the Helix breaching tests is provided in Table 5.

Table 5 Helix breach testing summary

Panel	Charge weight	Standoff	Result
4	10 lb	15"	Medium Spall
5	10 lb	15"	Breach
6	10 lb	15"	Severe Spall
7	8 lb	15"	Severe Spall
8	8 lb	15"	Severe Spall
9	10 lb	15"	Broken in 9 large pieces
10	10 lb	15"	Threshold Spall

4.3.5. Measurements were taken of the spall diameter and depth in order to quantify the damage from the breach tests. The diameter of the spall was measured in two orthogonal directions (D1, D2). The area of the spall was calculated assuming the shape of an ellipse, and the volume assuming an ellipsoid.

Table 6 Spall damage measurements

Panel	D1 (in)	D2 (in)	Depth (in)	Area (in^2)	Volume (in^3)
1	25	20	2.5	393	654
2	22	21	3	363	726
3*	48	48	6	1810	7238
4	10	11	1.5	86	86
5*	23	24	6	434	1734
6	19	20	4.5	298	895
7	10	9	2.25	71	106
8	16	15	3	188	377
9	-	-	-	-	-
10	2.5	4	1.5	8	8

*Breached

4.3.6. Where the specimen was breached, a spall depth equal to the slab thickness was used. This will provide an under-estimate of the total spall volume. However, for the purposes of this study, this will provide an adequate measure of the damage shown by the panel.

5. Literature Review

5.1. Several researchers have investigated the behaviour of fibre-reinforced concrete to near-field blasts and contact charges. A range of fibre types, volume fractions, and loading configurations were tested, but all concluded that adding fibre reinforcement to a concrete panel increased the breaching resistance in comparison to standard reinforced concrete panels subjected to the same load.

5.2. As part of a large series of tests for the United States Army, McVay (McVay, 1988) tested three walls with 80 lb/yd^3 of crimped steel fibres in addition to traditional reinforcing steel (#3 at 5.5"). The walls were tested with a cased C4 charge with charge weights of 14.4 lb and 7.1 lb at standoffs of 2' and 1.4' respectively. The addition of the fibre reinforcement reduced the level of damage from medium spall to threshold spall in comparison to a standard reinforced concrete specimen (same traditional reinforcing steel) subjected to the same load. When subjected to a 1.1 lb contact charge, the fibre reinforced wall had the same spall depth, however the spall area and spall velocity were reduced. McVay also noted that fewer crimped steel fibres were needed per cubic yard of concrete mix to reduce spall than straight steel fibres due to the increased fibre-concrete bond.

5.3. Yamaguchi et al (Yamaguchi, Murakami, Takeda, & Mitsui, 2011), tested polyethylene fibre reinforced concrete panels with dimensions of 600mmx600mm with thickness of 50mm and 100mm to cylindrical contact charges with charge weights of 100g and 200g. The panels all had one layer of reinforcing bars located at the middle depth of the panel. The 100mm panels used SD295A D10 (10mm diameter) bars at 120mm spacing while the 50mm panels use smooth 5mm bars at a spacing of 120mm. The authors observed that the polyethylene fibre reinforced panels were effective in reducing the spall damage and the launching of concrete fragments when compared to normal concrete. They also showed that the total damage experienced by panels subjected to a contact explosion could be estimated using the flexural toughness of fibre reinforced concrete, panel thickness, and charge weight according to the following equation:

$$\frac{C_d+S_d}{T} = \alpha + \beta \frac{T}{W^{1/3}} + \gamma\bar{\sigma}_b \tag{1}$$

where, C_d and S_d are the crater depth and spall diameter respectively (mm), T is the panel thickness (mm), W is the TNT equivalent charge weight (g), and $\bar{\sigma}_b$ is the flexural toughness coefficient. α, β, and γ are constants determined by experiment to be 1.9, -0.50, and -0.048 respectively. Yamaguchi et al. also showed that the inclusion of fibre reinforcement did not affect the breach diameter when compared to normal concrete.

5.4. In tests of a specific application, Coughlin et al. (Coughlin, Musselman, Schokker, & Linzell, 2010) tested portable fibre reinforced concrete vehicle barriers against contact charges. The barriers were roughly rectangular with dimensions of 3050mm x 1070mm x 610 mm and were all reinforced with standard reinforcing bars. Four fibre reinforced barriers and one standard concrete control barrier were tested using a C4 charge in contact with the base. Both a carbon fibre and nylon fibre reinforced barrier, each with a fibre volume fraction of 1.5%, were tested. Additionally two different mixes of synthetic and steel fibres were tested. The first barrier had a volume fraction of 2.5% of 30mm flat end steel fibres, 1.8% of 50mm polypropylene/polyethylene fibres, 0.6% of variable length polypropylene macro synthetic fibres, and 0.066% of variable length polypropylene micro synthetic fibres, making a total fibre volume fraction of 5.0%. The second barrier had a volume fraction of 2.0% of 30mm flat end steel fibres, 1.33% of 50mm polypropylene/polyethylene macro synthetic fibres, 0.4% of variable length polypropylene macro synthetic fibres, and 0.066% of variable length polypropylene micro synthetic fibres, making a total fibre volume fraction of 3.8%. The authors found that the fibre reinforced concrete limited the extent of damage and kept the damaged concrete more intact than the normal concrete barriers. They also found that there was little benefit from increasing the fibre volume fraction from 3.8% to 5% for the steel/synthetic fibre mix. It was also observed that the inclusion of fibres caused the fragments to be larger in size.

5.5. One of the most widely used methods for evaluating vulnerability to spall and breach is proposed in UFC 3-340-02 (U.S. Army, Navy and Air Force, December 2008) specifically for design use. It takes the form of two approximate threshold curves (one for spall and one for breach). The spall threshold curve is:

$$\frac{h}{R} = \frac{1}{-0.02511+0.01004\psi^{2.5}+0.13613\psi^{0.5}} \tag{2}$$

And the breach threshold curve is:

$$\frac{h}{R} = \frac{1}{0.028205+0.144308\psi+0.049265\psi^{2}} \tag{3}$$

Where, h is the concrete thickness (ft), R is the standoff distance (ft), and ψ is a spall parameter given by:

$$\psi = R^{0.926} f'^{0.308}_{c} W_{adj}^{-0.341} \left(\frac{W_{adj}}{W_{adj}+W_c}\right)^{1/3} \text{ for non-contact charges}$$

$$\psi = 0.527 R^{0.972} f'^{0.308}_{c} W_{adj}^{-0.341} \text{ for contact charges}$$

Where, f'c is the concrete compressive strength (psi), W_c is the steel casing weight (lb), and W_{adj} is the adjusted charge weight (lb) given by:

$$W_{adj} = B_f C_f W$$

Where B_f is a burst configuration factor (0.5 for free air, 1.0 for surface bursts), C_f is a cylindrical charge factor which can be taken as 1.0 for L/D and $R/W^{1/3}$ < 2.0, and W is the equivalent TNT charge weight (lb). It is important to note that the reinforcing is not considered by these threshold curves. The curves were obtained by combining tests with various traditional reinforcing ratios ranging from 0.05% to 2.5%.

6. Analysis

6.1. From the results of this test series, it is clear that the addition of Helix fibre reinforcement improves concrete resistance to breach and spall damage from near-field explosions. This can be seen by examining the results more closely. Panels 4 and 10 both had the same amount of traditional reinforcement (#3 @ 5.75") and were both subjected to the same charge and standoff (10lb @ 15") but had Helix dosages of 30 lb/yd^3 and 50 lb/yd^3 respectively. Increasing the Helix dosage by 20 lb/yd^3 reduced the spall area and volume by 91% (86.39 in^3 to 7.85 in^3). A similar trend was observed when comparing panels 5 and 6 which both had the same amount of traditional reinforcement (#3 @ 7.5") and were both subjected to the change charge and standoff (10lb @ 15"). In this case increasing the Helix dosage by 20 lb/yd^3, from 30 lb/yd^3 to 50 lb/yd^3, not only prevented breaching of the panel, but also reduced the spall area by 30%.

6.2. The addition of Helix reinforcement is most effective when combined with traditional reinforcing. The test results clearly show the effect of combining traditional reinforcing with Helix. Considering panels 10 and 6, both panels had the same Helix dosage and blast load, but differed in the reinforcement spacing, at 5.75" and 7.5" respectively. Decreasing the reinforcement spacing by 1.75" reduced the volume of spall by 99%. Similarly, comparing panels 7 and 8, decreasing the reinforcement spacing by 7.83" (from 15⅓" to 7½") reduced the spall volume by 72%.

6.3. Helix was not found to be effective as the sole reinforcement in a concrete panel. Panel 9, which only had Helix reinforcement (100 lb/yd^3), broke into nine large pieces when loaded with 10lb of C4 at 15". This highlights the requirement for Helix to be combined with traditional reinforcement for blast applications. Although traditional reinforcement is required in order for helix to be effective, Helix can be used to significantly reduce the amount of traditional reinforcement while still achieving the same or better breach and spall resistance. This can be seen by comparing Panels 1 and 8. Both were subjected to the same blast load (8lb @ 15"), but panel 8 replaced 67% of the reinforcement with 70 lb/yd^3 of Helix fibres (8% cost savings). Despite this considerable reduction in traditional reinforcement, panel 8 achieved a 42% reduction in spall volume in comparison to panel 1.

6. Conclusions

7.1. Explora Research conducted a series of blast tests on Helix reinforced concrete panels at the Pecos Research and Testing centre over the week of April 15th. The purpose of these tests was to investigate the blast resistant properties of Helix fibre reinforcement. The tests took the form of breaching (near-field) tests.

7.2. Breach testing was done using spheres of C4 at a standoff distance of 15". The charge weights were varied between 7 lb to 10 lb of C4. Helix fibre reinforcement was shown to provide a significant improvement to the breach and spall resistance of concrete panels containing at least a minimal amount of traditional reinforcing, reducing spall volume by as much as 91% and decreasing the occurrence of breaching. Using Helix fibre as the sole reinforcement for blast purposes was not found to be effective. However, Helix fibres can be used to significantly reduce the amount of traditional reinforcement while still achieving the same or better breach and spall resistance in addition to providing cost savings.

7. Recommendations

8.1. While the benefits of Helix fibre reinforcement for improving breach and spall resistance were demonstrated by this test series. A more extensive study is required in order to develop a quantitative model which could be used in design.

8.2. Helix fibre reinforcement may also provide improved performance to concrete under projectile impact. Ballistic testing can be undertaken to investigate the benefits Helix fibre reinforcement provides under these loads.

References

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Appendices

Appendix A: Casting Process

Panel 1 - Control

Panel 2 - Control

Panel 3 - Control

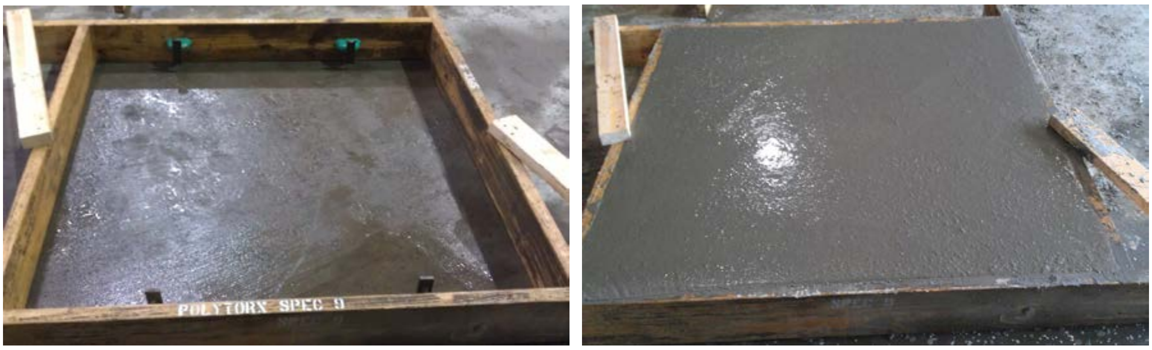
Panel 4 - Helix

Panel 5 - Helix

Panel 6 - Helix

Panel 7 - Helix

Panel 8 - Helix



Panel 9 - Helix