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# Enhancing the performance under close-in detonations with polymer reinforced CRC

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**ABSTRACT**: Compact Reinforced Composite, CRC, is a high-strength cement-based composite possessing an enormous flexural and energy-absorbing capacity due to close-spaced high strength steel reinforcement and a high-strength cement-based fiber DSP matrix. The material has been used in various construction projects including as protection for explosion hazards. In connection with explosive impact, the fraction of shear reinforcement needed to obtain full flexural capacity is controlled by the stand-off distance. For close-in detonations, a high fraction of shock reinforcement is needed to obtain full flexural capacity without breaching. This paper introduces an efficient method for implementing high fractions of polymer shock reinforcement into a CRC element. Experimental tests and a preliminary finite element analysis were performed to assess the potency of this material.

**KEYWORDS**: CRC, reinforcement, shock, polymer, finite element.

## 1 INTRODUCTION

Advanced high performance concrete composites and their response to blast loading is an area of continuing interest within the field of civil engineering. Polymer reinforcement in such concrete composites and elements for protective applications include glass, aramid (Kevlar) or polyvinyl alcohol fibre bundles.

HPFRC (High-Performance Fibre-Reinforced Concrete) of any kind refers to fibre-reinforced cement-based materials particularly developed for specific applications where strength, toughness, ductility, and energy absorption are fundamental properties. These properties in HPFRC are obtained by using large quantities of superplasticizers, high volumes of micro-silica, low water-cement ratio, high fractions of small discrete fibres, and the absence of any coarse aggregate.

A HPFRC like FDSP (Fibre-reinforced Densified Small Particle systems) used in CRC (Compact Reinforced Composite) applications holds compressive strength in the range of 150 to 400 MPa. (Bindiganavile et al. 2002).

This paper introduces an efficient method for implementing high fractions of polymer shock reinforcement into an element.

The term *shock reinforcement* refers to reinforcement in the out-of-plane direction implemented to avoid shock-initiated disintegration of a structural element.

The term *fiber bundles* refers to a large number of parallel fibres of the same length that have been spun to a cord.

The composite presented in this paper is patented by Composhield A/S Denmark. The numerical modelling of the work presented in this paper is being carried out as a part of ongoing project with the APTES group.

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## 2 EFFECTS OF CLOSE-IN DETONATIONS

Detonation and explosion, which are commonly used synonymously, produce a shock front travelling faster than the speed of sound. Blast wave propagation can be treated mathematically on the basis of thermodynamics by solving the conservation equations analytically (Kinney and Graham, 1985). A contact or a close-in detonation is characterized by no, or only limited, stand-off distance from the explosive charge to e.g. a structural element, and it generates shock waves in the element of up to 30 times the speed of sound, pressures of up to 20 GPa, and strain rates of up to $10^8$ $s^{-1}$ depending on the material and charge size.

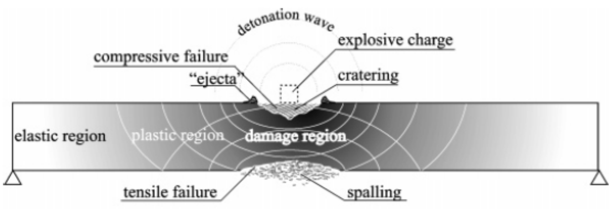


**Figure 1. Contact detonation on a concrete plate, regions of different stress states and failure situations**

A common effect of close-in detonations on concrete structures is spalling, which leads to disintegration of the structural element. Spalling is caused by the free surface reflection of the shock wave induced in the structural element by a high-pressure air blast, and occurs whenever the dynamic tensile rupture strength of the structure is exceeded. Although it is a complex process, reasonable analytical spall estimates can be obtained for concrete by assuming elastic material behaviour and instantaneous spall information. Specifically, spall thicknesses and velocities for both the normal and oblique incidence of the shock wave on the back face of the structural element can be calculated.

## 3 COMPACT REINFORCED COMPOSITE

Compact Reinforced Composite (CRC) is a Fibre-reinforced Densified Small Particle system (FDSP), combined with a close-spaced, high-strength, longitudinal flexural rebar arrangement.

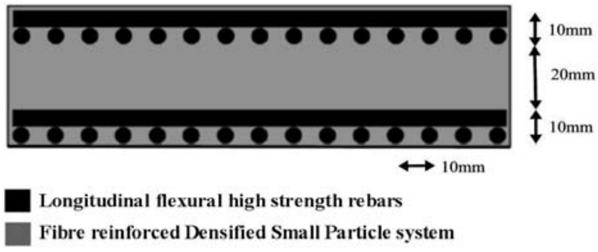


**Figure 2. Principle of a 50mm CRC deck**

The addition of small discrete fibres to the DSP matrix makes it more homogeneous and transforms it from a brittle to a ductile material. Because the fibres are randomly oriented and very closely spaced throughout the matrix, they are more effective than conventional reinforcement for bridging across cracks, and the presence of the fibres also provides some post-cracking ductility. The ultimate shear strength increases with an increase in fibre volume fraction, and in some cases full flexural capacity can be reached in elements without stirrups just by using fibres. (Khuntia et al., 1999)

## 4 IMPROVED COMPACT REINFORCED COMPOSITE FOR CLOSE-IN DETONATION

CRC improved for close-in detonation is a Fibre-reinforced Densified Small Particle system (FDSP), combined with a close-spaced high-strength longitudinal flexural rebar arrangement laced together in the out-of-plane direction using polymer lacing to avoid shock initiated disintegration of the structural element.

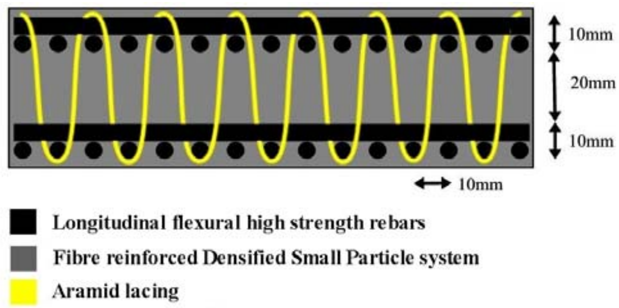


**Figure 3. Principle of 50 mm CRC deck improved for close-in detonation**

Aramid (Kevlar) was developed in the late sixties as a new class of polymers—para-oriented polyamides (aramids)—possessing internally rigid molecular chains in an extended confirmation. Like glass and carbon fibres, the tensile stress-strain curve of aramids is almost linear up to the point of failure. The details are shown in Table 1.

The combination of low density with high-strength and elastic modulus gives aramid the highest specific tensile strength and a reasonably high specific modulus, even when compared with carbon fibre (Nanni, 1992).

**Table 1** - Characteristics for aramids

| Specific gravity | Tensile strength [MPa] | Elastic modulus [GPa] | Elongation [%] |
|---|---|---|---|
| 1.39 – 1.45 | 2640 – 3040 | 75.5 – 127.5 | 2.0 – 4.2 |

## 5 EXPERIMENTAL WORK

Two panels of 50 mm thickness, which were tested, are included in the paper. In Table 2 the dimensions of the panels, charge size, and stand-off are shown. The panels were reinforced by 1800 MPa orthogonal longitudinal flexural high-strength steel rebars on both faces Φ 5 mm, and a centre-to-centre spacing of 10 mm as shown in Figure 4. The cover layer was 3 mm. The panels were simply supported by a steel frame with a free inner dimension of 500 x 500mm. The panels were tested under identical support conditions, but under different boundary conditions, to gain sufficient anchor length.

**Table 2 –** Dimensions, charge size and stand off

| Panel | Dimension [mm] | Charge PETN (TNT equiv.) [kg] | Distance* [mm] | Distance** [mm] |
|---|---|---|---|---|
| 1 | 50x600x600 | 1.0 (1.3) | 40 | 85 |
| 2 | 50x1200x1200 | 3.5 (4.5) | 40 | 126 |

* Distance surface of charge to surface deck ** Distance (eqv. TNT) centre of charge to surface panel

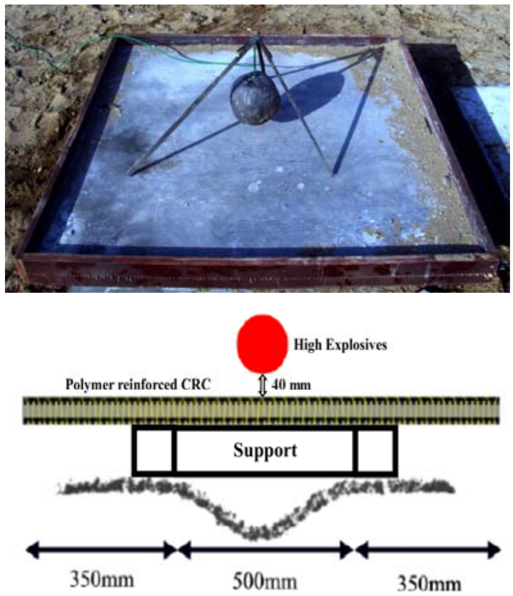


**Figure 4. Experimental setup for 50x1200x1200 panel – 3.5kg of PETN HE**

The tests presented in this paper were based on a matrix design that offers sufficient workability and maximum design strength and ductility. The formula used for these mix proportions was:

$$V_b = \frac{1 - V_{agg} - V_f}{w/c \cdot \frac{3150}{1000} + 1} \qquad (1)$$

$$V_w = 1 - V_{agg} - V_b - V_f$$

## 6 EXPERIMENTAL RESULTS

a. **Observations (Panel 1): 50 x 600 x 600 – 1 kg PETN / 4 cm**

Plastic deflection was measured as 18 mm. Very little anchor failure was observed. The cover layer on the front side (warm side) suffered from scabbing. No lacing was cut over and all longitudinal rebars were intact. The cover layer on the rear side (cold side) spalled, but the lacing was intact, as shown in Figure 5.


**Figure 5. 50x600x600mm – 1 kg PETN / 4 cm - a) Rear side b) Front side**

b. **Observations (Panel 2): 50 x 1200 x 1200 – 3.5 kg PETN / 4 cm**

Plastic deflection was measured to 60 mm. Very little anchor failure was seen. The cover layer on front side (warm side) suffered from severe scabbing. Locally, some lacing was cut over, but all longitudinal rebars were intact. The cover layer on the rear side (cold side) spalled, but the lacing was intact as shown in Figure 6.



**Figure 6. 50x1200x1200mm – 3.5 kg PETN / 4 cm - a) Rear side b) Front side**

## 7 FINITE ELEMENT MODELLING

In this paper, only simulations for the 1200x1200 mm PCRC panel are presented. 1/8 of the panel has been modeled. The vertical end boundary on the modeled panel is fully constrained to implement the effect of sufficient anchor length, as commented upon in the experimental work. That simplification is acceptable, as the cantilever part of the 1200x1200 mm panel's only function is to attain sufficient anchor length for the rebars.

Additionally, symmetrical features have been added to the model. Concrete matrix and aramid lacing are modeled as solid elements and rebars have been modeled as beam elements. Bonds between rebars and matrix are modeled using a fully constrained surface contact. The panel is modelled as simply supported by a steel frame with a free inner dimension of 500 x 500mm. This steel frame does not appear visually in the simulations. The real and FE model of rebar and lacing arrangement is shown in Figure 7.

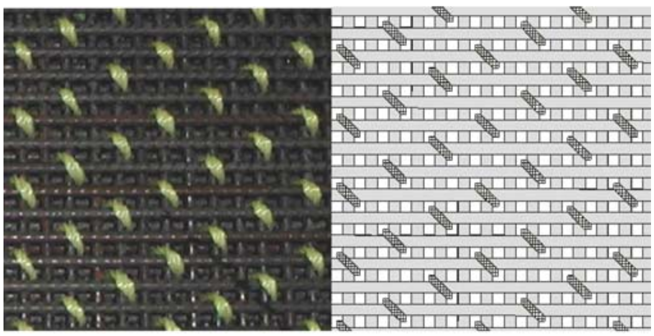

**Figure 7. (a) Rebar and lacing arrangement (b) FE model**

## 8 NUMERICAL SIMULATION

To demonstrate the effect of using aramid lacing as shock reinforcement, simulations on a similar model with reduced amount of aramid are also presented. The aramid lacing is modeled using an isotropic elastic material model that includes strain rate effects.

The numerical simulation of 50mm thick 1200x1200mm PCRC panel with 100% aramid lacing and when aramid lacing is reduced by 50% is shown in Figure 8 and Figure 9 respectively.

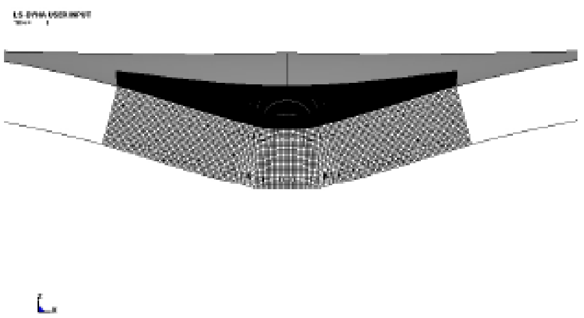

**Figure 8. 50 mm thick PCRC panel with 100% aramid lacing**

**Figure 9. 50 mm thick PCRC panel with 50% aramid lacing**

The results from numerical simulations clearly indicate that the spalling and damage was more significant when the aramid lacing was reduced to 50 % as compared to 100 % aramid lacing.

## 9 CONCLUSION

The main purpose of this test was to demonstrate the potential of this modified CRC composite subjected to close-in detonation. Demonstrations were made on two polymer reinforced CRC panels improved for close-in detonation with dimensions as follows: Panel 1: 50x600x600mm and Panel 2: 50x1200x1200mm. The panels were subjected to 1.0kg and 3.5kg of PETN, respectively, at a stand-off distance of 4 cm surface-to-surface for both panels. The results showed no breaching of or any damage to the reinforcing bars. For Panel 1, plastic deflection was measured as 18 mm. Very little anchor failure was seen. The cover layer on the front side (warm side) suffered from scabbing (cratering). No lacing was cut over and all longitudinal rebars were intact. The cover layer on the rear side (cold side) spalled, but the lacing was intact. For Panel 2, plastic deflection was measured as 60 mm. Very little anchor failure was seen. The cover layer on the front side (warm side) suffered from severe scabbing (cratering). Locally, some lacing was cut over, but all longitudinal rebars were intact. The cover layer on the rear side (cold side) spalled, but the lacing was intact. The numerical modelling of the work presented in this paper is being carried out as part of an ongoing project with the APTES group.

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