Finite element analysis of Polymer reinforced CRC columns under close-in detonation

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ABSTRACT:

Polymer reinforced Compact Reinforced Composite, PCRC, is a Fiber reinforced Densified Small Particle system, FDSP, combined with a high strength longitudinal flexural rebar arrangement laced together with polymer lacing to avoid shock initiated disintegration of the structural element under blast load. Experimental and numerical results of two PCRC columns subjected to close-in detonation are presented in this paper. Additionally, a LS-DYNA material model suitable for predicting the response of Polymer reinforced Compact Reinforced Concrete improved for close-in detonation and a description of the LS-DYNA multi-material Eulerian method for modeling the blast event is also presented in this paper.

Keywords:
CRC, HPC, Polymer,Shock,Close-in detonation, FEA, LS-DYNA

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 fiber bundles.

HPFRC (High Performance Fiber Reinforced Concrete) of any kind refers to fiber 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 fibers, and the absence of any coarse aggregate.

This paper introduces an efficient method for implementing high fractions of polymer shock reinforcement in a CRC element. Additionally, the paper provides the information and data needed to formulate a LS-DYNA material model suitable for predicting the response of Polymer reinforced CRC improved for close-in detonation, and a description of the LS-DYNA multi-material Eulerian method for modeling the blast event.

PCRC - POLYMER REINFORCED COMPACT REINFORCED COMPOSITE

Polymer reinforced Compact Reinforced Composite is a Fiber reinforced Densified Small Particle system, FDSP, combined with a 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.
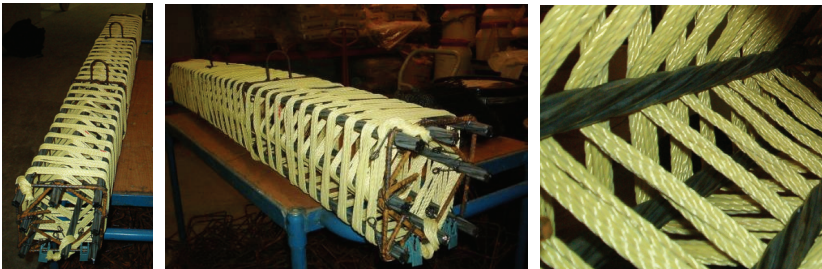

Figure 1: Polymer reinforced Compact Reinforced Composite column

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 fibers, the tensile stress-strain curve of aramids is almost linear up to failure.

The combination of low density with high strength and elastic modulus gives aramid the highest specific tensile strength of any material and a reasonably high specific modulus even when compared with carbon fiber. The average values of the elastic modulus (E), the maximum stress (σ_{max}), and the corresponding strain (ε) can be found in [1]

EXPERIMENTAL WORK

Two PCRC columns, with dimensions 1600x200x200mm, are included in this paper. In Table 1 the dimensions of the columns, charge size, and stand-off are shown.
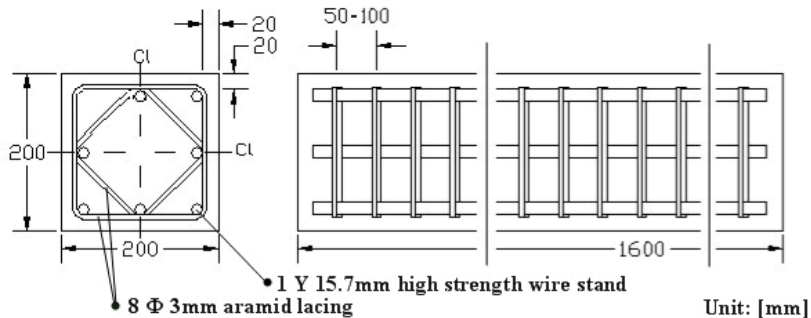

Figure 2: Reinforcement arrangement in tested PCRC columns

The columns are reinforced by 8 Y 15.7mm 1860 MPa longitudinal flexural high strength wire stands. As shock reinforcement 8 Φ 3mm aramid windings has been used for every 50mm or 100mm for *Column 1* and *Column 2,* respectively. Reinforcement arrangement, effective height and cover layer is shown in Figure 2.

Table 1: Dimensions, charge size, stand off and aramid configuration

Column	Dimension [mm]	PETN [kg]	Stand off [mm]	Aramid per [mm]
1	1600x200x200	7.6	400	50
2	1600x200x200	7.6	400	100

Figure 3: Experimental setup – column, steel frame and high explosive charge
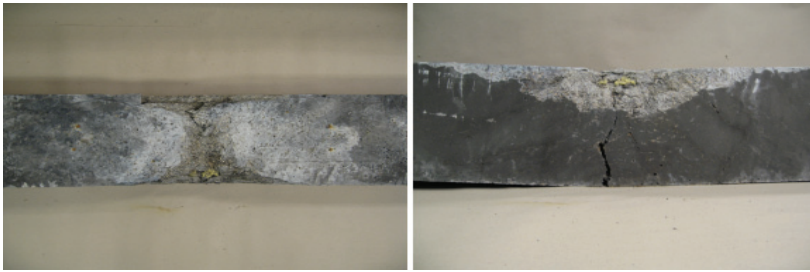

Figure 4: Damage on *Column 1* – aramid lacing for every 50mm
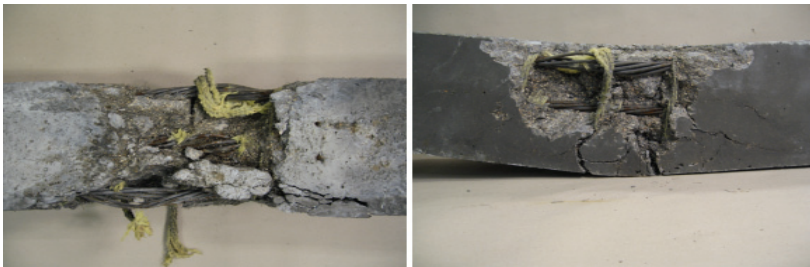

Figure 5: Damage on *Column 2* – aramid lacing for every 100mm

CONCRETE MATERIAL MODEL REL3

To predict the response of Polymer reinforced CRC improved for close-in detonation, the LS-DYNA material model 72REL3 developed by K&C is used. The 72REL3 concrete material model has a default model parameter generation feature that requires the user to specify only the unconfined compression strength and, for transient analysis,

the concrete density must also be specified. This parameter generator is based on a well-known 45.6 MPa unconfined compressive strength concrete [2].

Of significant importance using the default model parameter generation feature for modeling high strength fiber reinforced concrete, is to correct the fracture energy by changing the parameters for tensile strength and tensile softening for the material. The parameter b_2 in the LS-DYNA REL3 governs tensile softening in the post-peak regime as the stress-strain curve moves from maximum to residual failure surface. The parameter b_2 is determined by performing a single element analysis fitting the parameter until the area under the stress-strain curve for a uniaxial unconfined tensile test coincides with the fracture energy for the fiber matrix.

The static tensile strength (f_{ts}) and fracture energy (G_f) for a 160 MPa FDSP matrix with 4 vol% steel fibers is approximately f_{ts} = 25 MPa and G_f =10.000 N/m. [3]   The corresponding b_2 parameters is by tensile single element analysis found to b_2 = -7.3 and is shown in Figure 6 in combination with the default generated stress-strain curve for a 160 MPa concrete with an approximately G_f= 200 N/m.
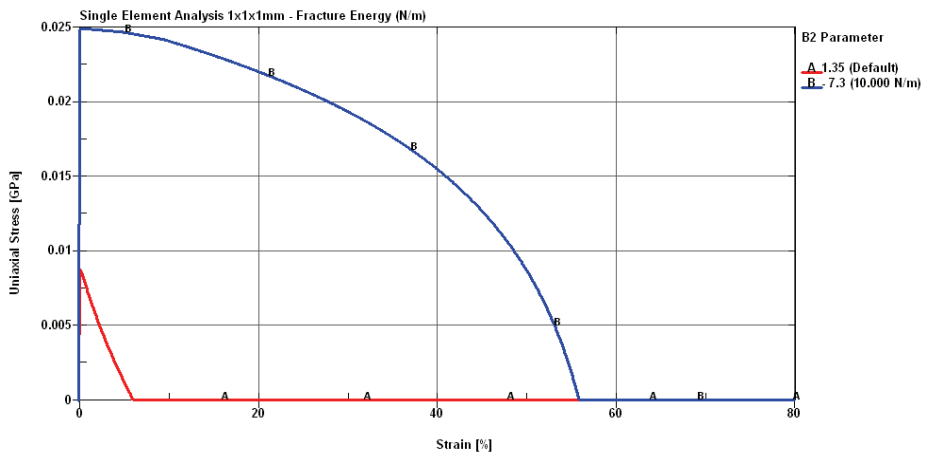

Figure 6: Single element analysis for stress-strain relationship in LS-DYNA material model 72REL3 comparing b_2 parameters for uniaxial tensile softening.

Deviating from the generated data also, the *lamda strech* factor should be set to 1 since the strain-rate effect on the strain capacity should only increase if the model is used as a complete smeared model for a whole reinforced structure. The fiber reinforced concrete matrix (without reinforcement/steel bars) itself, does not gain any significant extra tension strain capacity due high strain rates.

MODELLING THE BLAST EVENT

Modeling the blast event using the multi-material Eulerian method several stages need to be modeled; setting up the geometrical model, detonation of the charge, formation of the blast wave, expansion of the blast wave in surrounding medium and interaction of the blast wave with the column.

Several methods can be adopted to set up a geometrical model for the explosive charge and the surrounding air. In this case for the charge, only 1/8 of a high explosive charge is modeled using triple symmetry. Adopting the Eulerian method for air and high explosive, element formulation *option 11* is selected in the *SECTION_SOLID* keyword, and the material are defined with the *ALE_MULTI-MATERIAL_GROUP* keyword. Interaction between blast wave and column is controlled by the *CONSTRAINED_LAGRANGE_IN_SOLID* keyword.
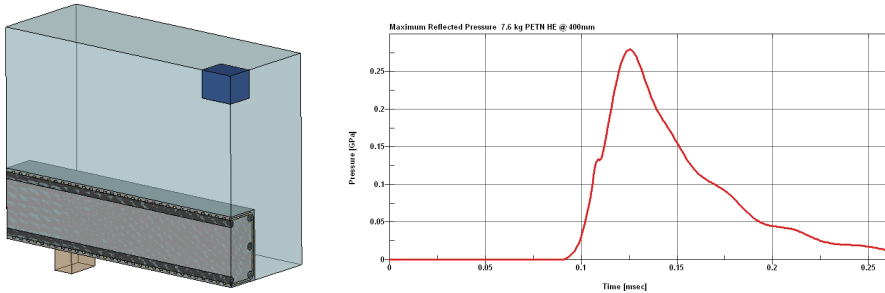

Figure 7: Geometrical setup with explosive charge and pressure historic

Plastic Bonded Explosives (PBX) normally consists of a mixture of RDX or PETN and a binder, such as polystyrene or polyester. The PBX explosive used in this test is PETN (85/15) consisting of 85 % PETN and 15 % non explosive oil based binder.

The explosive material is modeled with *MAT_HIGH_EXPLOSIVE_BURN* and is ignited at the center of the charge using the command *INITIAL_DETONATION*. After ignition the evolution of the explosive charge is controlled by the Jones-Wilkins-Lee (JWL) equation of state *EOS_JWL*. Parameters for PETN explosives are given in Table 2. [4]

Table 2: Parameters for modeling PETN explosives

HE	Density [g/cm^3]	Detonation Vel. [m/s]	PCJ [GPa]	ω	A [GPa]	B [GPa]	R$_1$	R$_2$	E$_0$ [GPa]
PETN (85/15)	1.480	7200	20.500	0.30	373.80	3.647	4.2	1.10	7.00

SETTING UP THE GEOMETRICAL MODEL

A quarter of the columns have been modeled using double symmetry. 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 columns are modeled as simply supported by a steel frame with a free inner dimension of 1160mm.
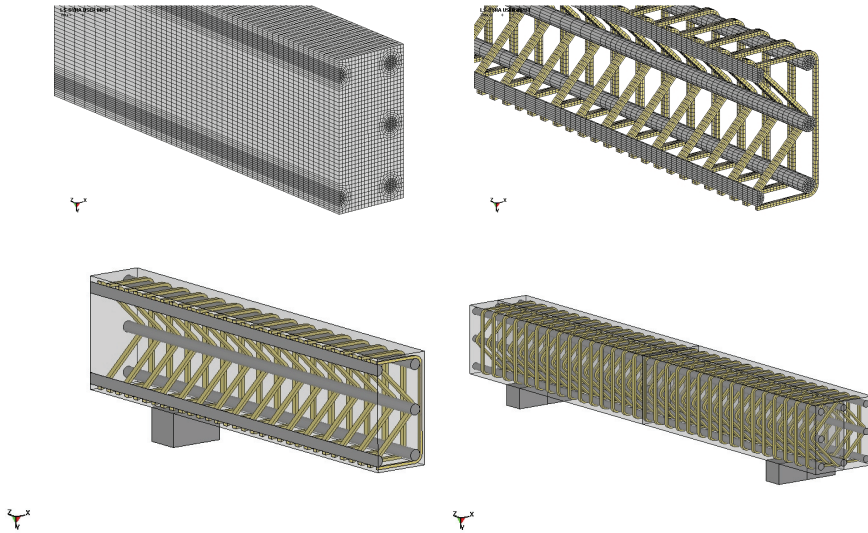

Figure 8: Geometrical model of PCRC column

Identical geometrical models have been used to model both *Column 1* and *Column 2* by modifying the material parameters for aramid lacing instead of changing the geometrical model for aramid lacing, as pointed out in Table 3. The aramid lacing is modeled using an isotropic elastic material model that includes strain rate strength enhancement.

Table 3: Modified material parameters for modeling the reduced amount of aramid lacing in the same geometrical model.

	Tensile strength [MPa]	Elastic modulus [GPa]	Failure strain [%]
Column 1	2400	100	3
Column 2	1200	50	3

NUMERICAL SIMULATIONS

The numerical results are presented in 2 steps; *damage on concrete matrix* and *deformation of reinforcement*.

In *damage on concrete matrix,* the elements are set to erode when the load bearing capacity of an element is depleted. After analyzing a simulation *without* erosion, the erosion feature is implemented by using the **MAT_ADD_EROSION* keyword controlled by strain. For both simulations the concrete matrix is damaged but *Column 1* has a smaller disintegration zone than *Column 2*.

In *deformation of reinforcement,* the deformation and damage of reinforcement are shown by comparing the simulation with aramid lacing per 50mm and the material parameter modified aramid lacing per 100mm. The analysis showed for both columns tensile yielding in the longitudinal wire stands but no tensile rupture of the aramid lacing. The measured strain for aramid lacing in *Column 1* is smaller than for *Column 2,* which indicates that the disintegration in smaller for *Column 1* than for *Column 2*

DAMAGE ON CONCRETE MATRIX

Figure 9: Maximum damage on *Column 1* – aramid lacing for every 50mm

Figure 10: Maximum damage on *Column 2* – aramid lacing for every 100mm

DEFORMATION OF REINFORCEMENT

Figure 11: Maximum deformation of reinforcement in *Column 1*

Figure 12: Maximum deformation of reinforcement in *Column 2*

SUMMARY AND CONCLUSIONS

Two Polymer reinforced CRC columns have been tested experimentally and numerically. The columns were both subjected to 7.6kg of PETN HE (85/15) at a stand-off distance of 400mm. The columns had the dimensions; 1600x200x200mm and were both reinforced by 8 Y 15.7mm 1860 MPa longitudinal flexural high strength wire stands. As shock reinforcement 8 Φ 3mm aramid lacing has been used for every 50mm or 100mm for *Column 1* and *Column 2,* respectively. For both columns the concrete matrix was damaged, and inspection indicates that both columns suffered from bending failure due to tensile yielding in the longitudinal wire stands. The finite element analysis shows for both columns tensile yielding in the longitudinal wire stands but no tensile rupture of the aramid lacing. The measured strain of aramid lacing in *Column 1* is smaller than for *Column 2,* which indicates that the structural disintegration is smaller for *Column 1* than for *Column 2*. Based on the finite element analysis and inspection of the tested columns, it can be concluded that the amount of aramid lacing has a positive effect on the performance. Avoiding tensile yielding in the longitudinal wire stands by increasing the amount of wire stands would improve the performance of the PCRC columns.

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