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Experimental and numerical analysis of blast response of High Strength Fiber Reinforced Concrete slabs

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ABSTRACT

High Strength Fiber Reinforced Concrete (HSFRC) presents great advantages when compared with conventional concrete under static loads and thus, it constitutes a promising material to withstand extreme loads. The experimental results of blast tests performed on HSFRC slabs including different types of hooked end steel fibers are presented and numerically analyzed in this paper. The numerical simulation was able to reproduce the experimental results and it confirms that for the same fiber content, shorter fibers provide greater blast resistance, showing smaller craters and spalling at the back face.

1. Introduction

The addition of fibers to concrete allows reducing its brittle nature and leads to a notable increase in energy absorption capacity. High Strength Fiber Reinforced Concrete (HSFRC) [1] and Ultra High Performance Fiber Reinforced Concrete (UHPFRC) [2] present great advantages for withstanding extreme actions when compared with conventional concrete and constitute promising materials for protective structures that help save lives improving the strength and durability of buildings and infrastructure under extreme loads. Even though the available experimental results show their potential applications, more research is required to improve the understanding of their behavior and to assess their response under extreme actions like blast loads. Studies on the behavior of HSFRC [3] and UHPFRC [4] under high strain rate loads are still limited [5].

The benefits in damage control, accelerations and displacements in HSFRC elements when comparing them to conventional concrete elements have been confirmed [6]. Higher ductility [7,8], lower permanent deformation [7], higher load bearing capacity [8], crack control [8] and greater ability to absorb energy without fragmentation [7–9] than conventional concrete panels were also found in the case of UHPFRC panels exposed to blast loads.

Available experimental results show that blast resistance increases with the increase of fiber volume and that different types of steel fibers have similar effects improving blast strength [9,10]. Fibers addition can prevent concrete spalling from slabs rear face and cracks on slab front face [11]. The panels are less likely to fail and they present higher strength with greater extension of damage than conventional concrete specimens due to micro cracking [12]. Multiple failure modes are observed including matrix and aggregates cracking, aggregate/matrix and fiber/matrix debonding and fibers pull-out [12].

The results of blast tests made on HSFRC and UHPFRC elements under close or contact explosions are very scarce [13–15] and available empirical methods [16] are not able to accurately predict spalling damage [13]. More tests are required for a better understanding of HSFRC and UHPFRC performance under blast loads and to assess the effect of different types and contents of fibers on blast response and blast damage. Moreover, taking into account the complexity of HSFRC and UHPFRC behavior combined with that of impact and blast loads, a deep knowledge of the material behavior together with material models and robust numerical tools are required for a proper design of elements under extreme actions.

Available models for the simulation of fiber reinforced materials can be classified in macro and meso-models. In macro-models the composite behavior is represented as a unique homogeneous material with average properties [17–19]. Constitutive laws and material parameters are directly obtained from tests. The main advantage of these models is the use of material information that is relevant for the structural scale. The main disadvantage is the need of performing several tests since the contribution of the fibers is not explicitly considered. This drawback

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Table 1
Blast tests description.

Test type	Test 1	Test 2	Test 3
			
TNT_{eq} mass [kg]	0.049	0.244	0.488
Height[a] [m]	0.0175	0.2425	0.2725

[a] Explosive gravity center height over slab (m).

can be avoided using models derived in the meso-scale that explicitly take into account matrix, fibers, and interface collaboration. The counterpart is that they are computationally expensive. Thus, multi-scale approaches [20,21] are normally used to represent the composite behavior at the macro-scale. There are very few models adequate for the simulation of UHPFRC under impact or blast loads [22]. Except for a few models [10,23], most meso-models and multiscale models have been developed and calibrated for static loads and do not take into account the strain rate effect on the components and on the fibers pull-out behavior. The response of HSFRC to impact and blast loads is usually simulated with explicit codes like hydrocodes using available macro-models that were originally developed for concrete [24]. The analysis of fibers contribution and the effect of fibers geometry on mechanical properties can contribute reducing the required number of tests to calibrate these homogeneous models.

This paper presents the experimental and numerical analysis of blast tests performed on HSFRC slabs incorporating different types and contents of steel fibers in a High Strength Concrete (HSC) matrix. The role of fibers controlling cracking, scabbing and spalling under close in explosions is clearly shown. Based on the comparison of numerical and experimental results, some recommendations for the numerical simulation of blast loads on HSFRC using homogeneous equivalent models originally developed for concrete are also provided.

2. Experimental

2.1. Blast tests description

Three different types of blast tests (see Table 1) were performed on HSFRC slabs varying the explosive masses and stand-off distances. The square slabs of 550 mm side and 50 mm thickness were supported on a highly reinforced steel frame leaving a free span of 460 mm. The frame has L shape plates at the corners to prevent the slabs going upwards due to the negative phase of the blast wave. A gel-like explosive formed by a semi-plastic mass consisting of a gelatin nitroglycerine and nitrocellulose incorporating ammonium salts and additives was used for the blast tests. It has a nominal TNT equivalence of 0.65 in weight. In all cases, the explosive had cylindrical shape and the detonator was located in the center of the upper surface. In blast Tests 1 the explosive was on the slab while in Tests 2 and 3 the explosive was supported on an expanded polystyrene block. Blast pressures time histories resulting from different amounts of explosive were recorded using pressure sensors (Honeywell 180PC) in order to verify the TNT equivalence of the commercial explosive used in the tests. The pressure sensors were located at 15 and 18 m from the explosive and at 1 m height from the ground surface [25]. The minimum standoff distance of 15 m was defined in order to not exceed the pressure range of the sensors. The sampling rate was 50,000 points per second.

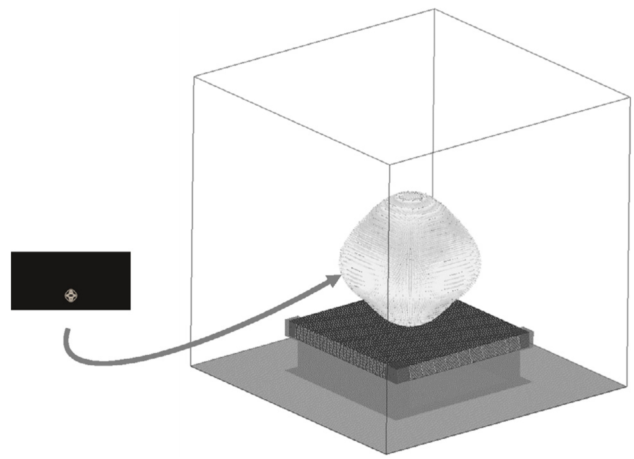

Fig. 1. Numerical model of the blast tests.

Table 2
Concretes: type and content of fibers and mechanical properties.

Concrete type	P	L_{30}-40	L_{30}-80	L_{60}-40	L_{60}-80
Fibers		L_{30}	L_{30}	L_{60}	L_{60}
Fibers length [mm]		30	30	60	60
Fibers diameter [mm]		0.38	0.38	0.75	0.75
Fiber content [kg/m] - volume [%]		40 - 0.5	80 - 1.0	40 - 0.5	80 - 1.0
f_L [MPa]	7.6 (0.5)	7.6 (0.6)	8.4 (0.6)	7.6 (0.9)	7.6 (0.9)
f_{max} [MPa]	7.6 (0.5)	11.1 (2.2)	15.9 (1.1)	12.0 (3.6)	18.5 (2.3)
f_{R1} [MPa]	–	7.3 (2.8)	13.1 (0.2)	7.0 (2.4)	13.9 (1.7)
f_{R3} [MPa]	–	9.6 (3.5)	14.5 (1.8)	11.3 (3.4)	17.6 (2.2)
fibers/mm^2	–	0.016 (0.004)	0.039 (0.002)	0.009 (0.004)	0.019 (0.002)
FRC class [27]		7e	13d	7e	13d

(*) Average (standard deviation).