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Experimental investigation of projectile impact local damage on cementitious composite slabs

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Abstract: This paper describes the projectile impact resistance of cement based composite slabs. The resistance is evaluated on the basis of the presented experimental program. In the experiment, local damage was inflicted by impact of defined projectiles on specimens made from normal strength concrete (NSC), steel fiber-reinforced concrete (FRC), ultra-high performance concrete (UHPC) and ultra-high performance fiber-reinforced concrete (UHPFRC) with different fiber content. Deformable ogive-nose projectiles with diameter of 7.92 mm and mass of 8.04 g with impact velocity about 700 m/s were in the experiment hitting center of the specimens. Data from the measured and visual evaluation of specimen damage were used for comparison of specimen projectile impact resistance in relation to the used material.

1. Introduction

When high explosives such as aerial bombs, grenades and improvised explosive devices detonate, primary fragments from device casing are created. These fragments are thrown by the blast shock in all directions from the explosion centre. Debris and material from the ground surface such as rock, gravel etc. can be also changed into dangerous projectiles by kinetic energy obtained from blast shock or shock wave.

Fragment/projectile impact induces local concrete response (see Fig. 1) that is different from global response inflicted by shock wave. High-pressure pulse by fragment or projectile impact on the front face results in spalling. The compressive stress wave created by penetration into concrete is reflected at the rear face of structural element as a tensile wave causing scabbing [1]. Scabbing results in dangerous secondary fragments which travel into the space behind the structure/structural element. With fragment/projectile penetration relates also perforation or depth of penetration when the structural element is not completely perforated. It was shown by tests that 50% penetration of element thickness generates problem of scabbing and for 63% or more penetration, one may expect full perforation [2]. Another possible local responses described in [3] are cone cracking and plugging for punching-shear inflicted by projectile impact and radial cracking for low energy impacts. The magnitude of damage depends on a variety of factors such as impact velocity, the mass, geometry and material properties of the projectile or fragment, as well as the material properties and reinforcement of the concrete target structures. [4]

Concrete and similar cement-based composites are commonly used as building materials for the protective structures and prefabricated parts designated for increased protection against shock wave, projectile impact and flying debris of existing structures. Use of fiber-reinforced concrete and new cementitious composites can further improve protection level of the structures according to their better mechanical properties and higher energy dissipation capacity. In this paper are presented results from experimental study of projectile impact local damage on cementitious composite slabs with compressive strengths of 40–150 MPa. Deformable ogive-nose projectiles were chosen for the experiment. Projectile had diameter of 7.92 mm, mass of 8.04 g and impact velocity about 700 m/s. The effects of different mechanical properties and the presence of steel fibers are discussed.

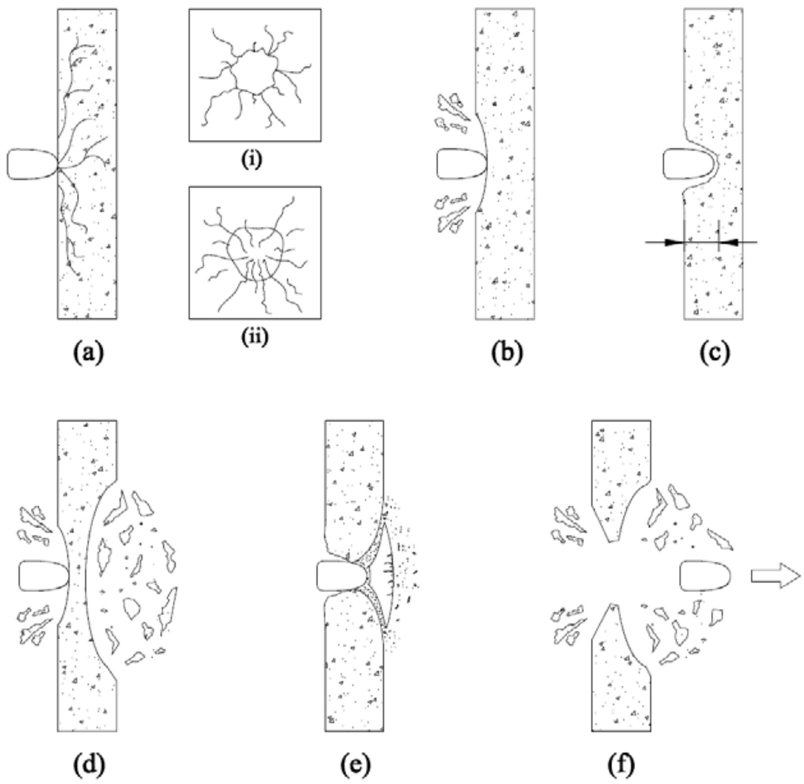


Fig. 1. Types of local response: (a) radial cracking -- (i) front face a (ii) rear face, (b) spalling, (c) penetration, (d) scabbing, (e) cone cracking & plugging, (f) perforation. [5]

2. Materials

For the experimental investigation of the projectile impact resistance of cement based composite 5 different mixes were chosen. Purposely were chosen cement based materials from whole scale of these materials - from traditional building materials to the new hi-tech materials. Most commonly used material represents normal strength concrete (NSC) and Fibre Reinforced Concrete (FRC) with 0,63 % of steel fibers in volume. Fibers had fiber ratio[1] 30/0.38, tensile strength of fibers is 2000 MPa. High-strength composites represents Ultra High Performance Concrete (UHPC) and Ultra High Performance Fibre Reinforced Concrete (UHPFRC) with two different fiber contents - 1 and 2 % in mix volume. Fibers for UHPFRC were steel with ratio 13/0.15 and tensile strength 2400 MPa. Mix design of both UHPFRC was taken from [6].

After casting, all specimens (for impact resistance and for mechanical properties testing) were covered with plastic sheets and stored at room temperature for 24 hours. Specimens were then taken out of their molds and stored in a water tank at 20°C for an additional 27 days. Testing was therefore conducted 28 days after casting. Measured mechanical properties are written in Table 1, where E is modulus of elasticity, f_c represents compressive strength and f_t tensile strength, f_{tm} is flexural strength in three-point bending test and finally G_f is fracture energy.

[1] Fiber ratio λ is defined as length/diameter.

Table 1. Mechanical properties of tested materials.

Cement based composite	E [GPa]	f_c [MPa]	f_t [MPa]	f_{tm} [MPa]	G_f [J/m^2]
NSC	35.8	40.0	3.6	5.5	83
FRC	28.9	48.0	-	6.0	1202
UHPC	47.1	122.0	6.8	11.6	0
UHPFRC 1 %	45.1	148.5	7.8	27.0	12 535
UHPFRC 2 %	56.3	151.7	10.5	29.2	12 404

3. Experimental program

Experimental tests of projectile impact resistance was performed on rectangular slabs with dimensions 300x400 mm and thickness of 50 mm. Test specimen was placed in special mount with simulation of point supports by two screws in each corner. In the case of test setup was each specimen impacted by one projectile to its center. Projectiles were fired from the distance 20 m from specimen. Muzzle velocity of each projectile was measured by shooting chronograph and mean value was 712m/s. Proposed type of projectile was 7.62x39 FMJ (Fig. 2) which is typical soft-core deformable bullet. This projectile has ogival nose, diameter of 7.92 mm, mass of 8.04 g, muzzle velocity of about 720 m/s and initial energy 2030 J.

In total 14 slabs were tested for impact loading. Depth of penetration, diameters of spalling and scabbing craters was measured after each test. Relevant was also measuring weight of specimens before and after the projectile impact to determine the weight lost by specimen's damage.

Fig. 2. Projectile 7.62x39 FMJ.

4. Results and discussion

The results of projectile local impact damage on specimens are summarized in Table 2. Individual resistance of every type of cement based composite will discussed in this part of paper. *NSC* had only very low resistance to projectile impact. Spalling craters on the front face did not have large diameter, but scabbing craters were relatively big and deep (Fig. 3). Typical response for *NSC* was fracture across the height of specimen caused by bending. This problem can be covered with reinforcement. But size of the local damage is not reduced until diameter of projectile is comparable with distance of bars in the reinforcement [7]. However low impact resistance of *NSC* to projectile impact was expected.

Another commonly used building material - *FRC* had noticeable improve in resistance to projectile impact. Presence of steel fibers prevented to specimen's fracture, as shown on Fig. 4, but flexural cracks was still observed. Most important improve was in significant reduce in mass loss of specimens. All specimens was also perforated thus the resistance to projectile impact is still low.

Table 2. Local impact damage on specimens.

Cement based composite	Number of specimens	Spalling [mm]	Scabbing [mm]	Penetration?	DoP[2] [mm]	Mass loss [g]
NSC	2	88	141	Yes for all	-	569
FRC	4	72	90	Yes for all	-	202
UHPC	2	148	161	Yes for all	-	642
UHPFRC 1 %	2	85	N/A	No for all	20	88
UHPFRC 2 %	4	73	0	No for all	20	53

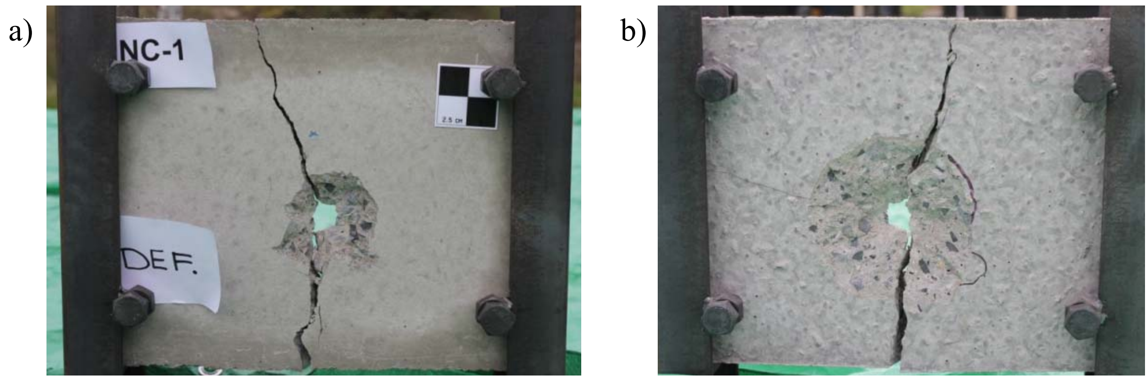


Fig. 3. Damage on specimens made from NSC: front face damage (a) and rear face damage (b).

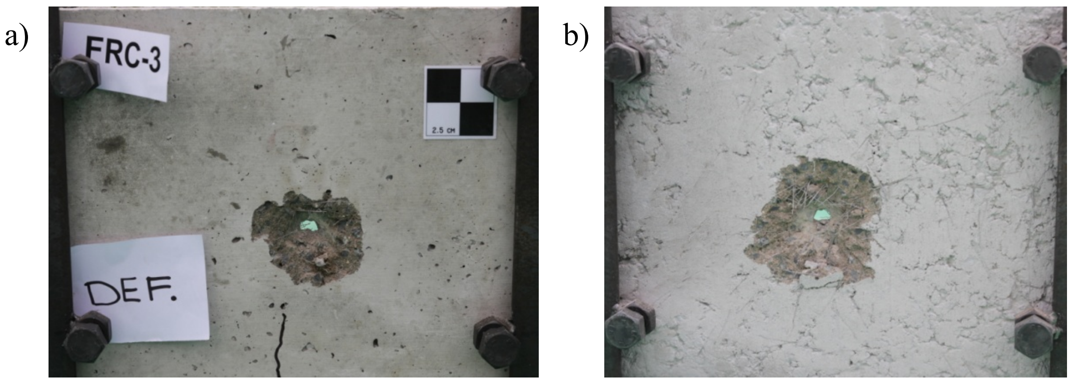


Fig. 4. Damage on specimens made from FRC: front face damage (a) and rear face damage (b).

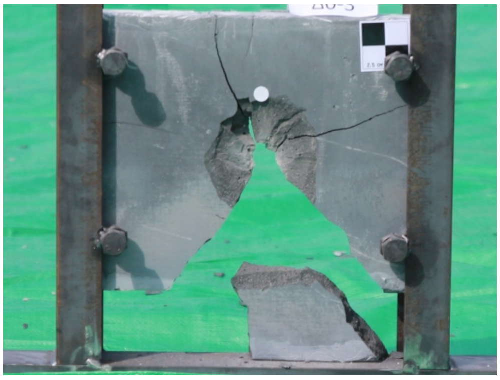
UHPC had three times bigger compressive strength and nearly two times bigger tensile strength than *NSC*. Nevertheless increase in strength caused brittle behavior of this cementitious composite. Lack of ductility and energy dissipation were the main reasons for massive damages on slabs from *UHPC*. Fig. 5 shows typical damages on slab from *UHPC*: large deep spalling and scabbing craters, complete perforation and brittle fracturing into big pieces. In the case of *UHPC* slabs damage, total destruction can be interpreted. Small sharp debris flying several meters behind specimens were also observed. This results demonstrates, that only ultimate strength increasing doesn't lead to better resistance to this extreme dynamic loading.

Addition of steel fibers into brittle *UHPC* matrix radically changed behavior of the material in quasi-static and impact loading thanks to fiber-bridging effect. Tensile strength was increased by

[2] Depth of Penetration (DoP)

pseudo-strain hardening and crack softening behavior was also observed. Thus projectile impact local damages were for *UHPFRC* slabs reduced. Specimens from *UHPFRC* containing 1 % of steel fibers shown very good resistance to projectile impact. Spalling crater diameter was significantly reduced but craters was still followed with few cracks (Fig. 6). Principal improve in the projectile impact resistance was in scabbing reduction. No scabbing crater was created and area of scabbing damage was small. Big effect of fibers to scabbing reducing was described also in [8]. Radial cracking from scabbing area centre was currently produced on rear side. Finally, no perforation for all specimens was similarly observed.

a)



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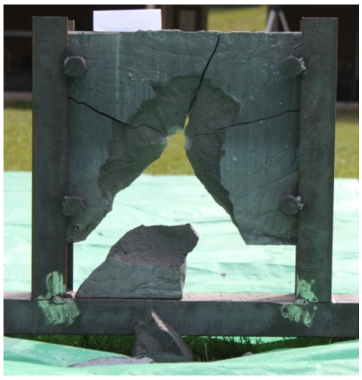

Fig. 5. Damage on specimens made from UHPC: front face damage (a) and rear face damage (b).

a)

b)

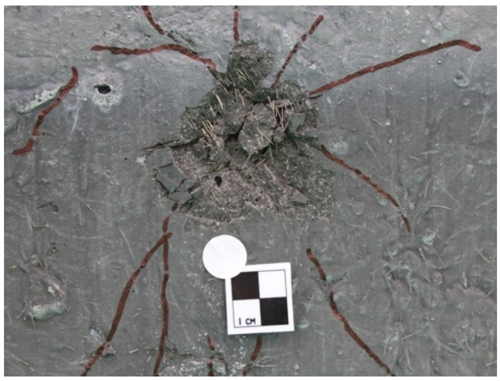

Fig. 6. Damage on specimens made from UHPFRC containing 1 % of steel fibers: front face damage (a) and rear face damage (b).

Increase of fiber content to 2 % in mix volume brought another resistance improvement. It can be said that spalling was limited just to close neighbourhood of crater from projectile penetration. No flexural or other cracks on the front face was created. Fig. 7 shows photography of tension damage on specimen's rear face. Damaged material was held by effect of fibers in the body of slab thus no dangerous flying debris were created. High resistance of *UHPFRC* with 2% fibers content to projectile impact is proved by very little mass loss of specimens as written in Table 2. According to [7, 8] there was no effect of fibers to depth of penetration.

5. Conclusion

The projectile impact resistance of five cement based composites was experimentally evaluated on total of 14 specimens. NSC and FRC commonly used as building material had low projectile impact resistance and big local damages of their specimens were described. Experiments also demonstrated massive local damages on specimens made from brittle UHPC. Outstanding mechanical properties of UHPFRC and ductility provided by fiber-bridging effect rapidly reduced local damages. Best projectile impact resistance was performed with 2% fiber content in UHPFRC mix volume. It was found that fibers had essential influence on spalling, scabbing and cracking resistance. But fibers had no effect on depth of penetration.

a) b)

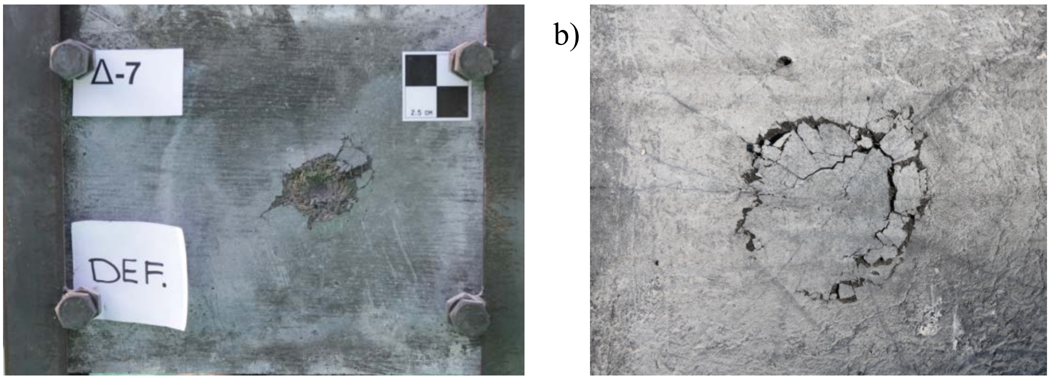

Fig. 7. Damage on specimens made from UHPFRC containing 2 % of steel fibers: front face damage (a) and back face damage (b).

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