Dynamic performance of a sustainable Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) under high velocity projectile impact

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Yu, R.; Spiesz, P.; Brouwers, H.J.H.

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1. Introduction

As a result of increasing concerns regarding public and structure safety in recent decades, the energy absorption capacity of sensitive and important infrastructure or objects having a high-risk potential needs to be seriously considered [1-3]. For instance, nuclear power stations have to resist the impact load caused by incidents or terrorist attacks. Pillars of bridges having a large span have to resist the impact load of land or water vehicles. Moreover, intentional events, such as terrorist attacks, also have to be seriously considered nowadays, since the use of rockets and other ballistic weapons against civil or military targets in conflict areas is a serious problem for the protection of peacekeeping forces and local population [4-6]. Hence, it can be summarized that a strong demand for a suitable building material with a great energy absorption capacity exists in both civil and military fields.

From the available literature [7-11], a strong concrete matrix and a large amount of steel fibres are beneficial for improving the energy absorption capacity of concrete, since the damage of concrete matrix and pullout of steel fibres can absorb large quantity of energy released during the impact process. Based on these requirements, the newly developed (at the beginning of 1990s) Ultra-high performance fibre-reinforced concrete (UHPFRC) can be a good candidate to be utilized in protective structure. The investigation regarding the UHPFRC under impact loadings can be found in the available literature. For example, Bindiganavile et al. [7] demonstrated that UHPFRC has a higher impact resistance than other types of concretes. To cover a large range of loading rates, Parant et al. [9] employed two dynamic/impact tests using the four-point bending set-up on thin UHPFRC slabs with three quasi-static loading rates (3.3×10^{-6}, 3.3×10^{-4} and 3.3×10^{-3} m/ s) and a block-bar device with a bar velocity of 5.55 m/s. Habel and Gauvreau [10] presented an experimental and analytical study of load rate-dependent characteristics of UHPFRC. Lai and Sun [11] studied the dynamic behavior of UHPFRC with different steel fibre volume fractions under impact using the split Hopkinson pressure bar device. Máca et al. and Sovjak et al. [6, 12] investigated the impact resistance of UHPFRC against fired bullets. Wu et al. [3] investigated the projectile penetration of ultra-high performance cement based composites at 510–1320 m/s. However, in all of these investigation mentioned above, a large amount of cement or binders are normally utilized in the UHPFRC production, which is not in accordance with the theme of sustainable development.

Based on the authors' research and experience [13-16], it is possible to produce a UHPFRC with relatively low cement amount employing modified Andreasen & Andersen particle packing model and appropriate application of mineral admixtures [17]. Moreover, it is demonstrated that this developed UHPFRC is sustainable and has less environmental impact compared to the other UHPFRCs. Nevertheless, the research focusing on energy absorption capacity of the sustainable UHPFRC is scarce, and it is unclear whether this newly developed UHPFRC would be sufficient for protections.

Consequently, according to these premises mentioned above, the objective of this study is to investigate the dynamic behaviour of the sustainable UHPFRC under high velocity projectile impact. The design of concrete mixtures aims to achieve a densely compacted cementitious matrix with a relatively low binder amount, employing the modified Andreasen & Andersen particle packing model.

2. Experimental program

2.1 Raw materials

The cement used in this study is Ordinary Portland Cement (OPC) CEM I 52.5 R, provided by ENCI (the Netherlands). A polycarboxylic ether based superplasticizer is used to adjust the workability of concrete. The limestone is used as a filler to replace cement. A commercially available nano-silica in a slurry (AkzoNobel, Sweden) is applied as pozzolanic material. Two types of sand are used, one is normal sand in the fraction of 0-2 mm and the other one is a microsand in the 0-1 mm size range (Graniet-Import Benelux, the Netherlands). The particle size distributions of the used granular materials are shown in Figure 1. Additionally, two types of steel fibres are utilized, as shown in Figure 2: 1) long straight fibre (LSF), length = 13 mm, diameter = 0.2 mm; 2) hooked fibre (HF) length = 35 mm, diameter = 0.55 mm.

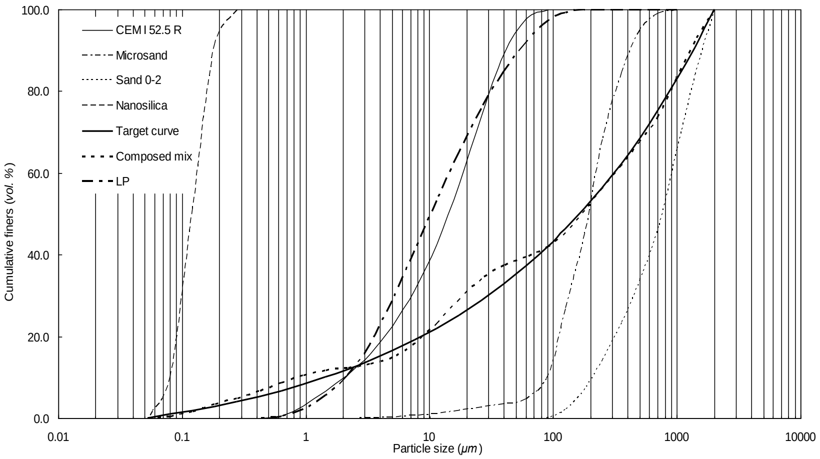


Figure 1: Particle size distribution of the involved ingredients, the target curve and the resulting integral grading curve of the mixtures

Figure 2: Steel fibres used in this study

2.2 Mix design

Here, the modified Andreasen and Andersen model is utilized to design the concrete mixtures, which is shown as follows [17, 18]:

$$P(D) = \frac{D^q - D_{\min}^q}{D_{\max}^q - D_{\min}^q} \tag{1}$$

where D is the particle size (μm), $P(D)$ is the fraction of the total solids smaller than size D, D_{max} is the maximum particle size (μm), D_{min} is the minimum particle size (μm) and q is the distribution modulus (based on the recommendation of [19], the q is 0.29 in this study).

In the concrete mixture design, the modified Andreasen and Andersen model (Eq. (1)) acts as a target function for the optimization of the composition of mixture of granular materials. The proportions of each individual material in the mix are adjusted until an optimum fit between the composed mix and the target curve is reached, using an optimization algorithm based on the Least Squares Method (LSM), as presented in Eq. (2). When the deviation between the target curve and the composed mix, expressed by the sum of the squares of the residuals (RSS) at defined particle sizes, is minimized, the composition of the concrete is considered optimal [20].

$$RSS = \frac{\sum_{i=1}^{n} \left(P_{mix}(D_i^{i+1}) - P_{tar}(D_i^{i+1}) \right)^2}{n} \tag{2}$$

where P_{mix} is the composed mix, the P_{tar} is the target grading calculated from Eq. (1), and n is the number of points (between D_{min} and D_{max}) used to calculate the deviation.

The UHPFRC mixtures developed in this study applying the optimized particle packing model are listed in Table 1. It can be noticed that the utilized binder amount is relatively low in this study. In addition, the steel fibres are added into the designed concrete matrix with an appropriate hybridization design (as shown in Table 1). In the mixture, the total fibre amount is 2% by the volume of concrete.

Table 1: Recipes of the developed UHPFRC

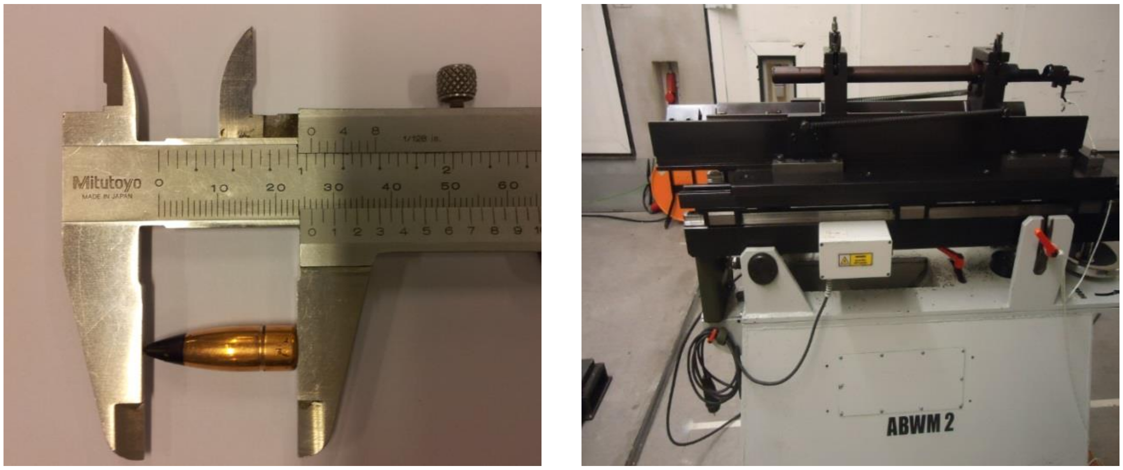
C kg/m^3	LP kg/m^3	M-S kg/m^3	N-S kg/m^3	nS kg/m^3	W kg/m^3	SP kg/m^3	LSF vol. %	HF vol. %
594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0.5	1.5

(C: Cement, LP: Limestone powder, M-S: Microsand, N-S: Normal sand, nS: Nano-silica, W: Water, SP: Superplasticizer, LSF: Long straight fibre, HF: Hooked fibre)

2.3 Experimental process

To produce an appropriate concrete sample for the high velocity projectile impact test, the fresh concrete is cast in the mould with the size of 500 mm × 500 mm × 100 mm. Due to the fact that the developed sustainable UHPFRC has good workability, the fresh concrete is poured in the middle of the mould, without applying vibration (i.e. treated as self-compacting concrete). After 3-4 days, the samples are demoulded and cured in the water. After curing for about 28 days, all the samples are taken from the water and prepared for the shooting test.

In this study, one type of in-service bullet (7.62 mm) is utilized for the impact test, as shown in Figure 3a. The launching set-up for this bullet is illustrated in Figure 3b. The bullet impact velocity is about 830 m/s, which can be measured by a radar sensor fixed on the launcher. According to STANAG 2280 [21], the distance between target concrete plate and the launch point is 30 m, and a witness plates are placed behind the target with a minimum air gap of 100 mm between the target and the witness plate. Here, the used witness plate is hardboard with a thickness of about 2 mm. To clearly understand the performance of the developed sustainable UHPFRC under high velocity projectiles impact, two high speed cameras are used to record the variation of both front and rear sides of the concrete target. The rate of the utilized high speed cameras are 26143 fps (frame per second) and 21052 fps for the front and rear camera, respectively.



(a) (b)

Figure 3: Utilized in-service bullet head (7.62 mm) (a),and the bullet launcher (b)

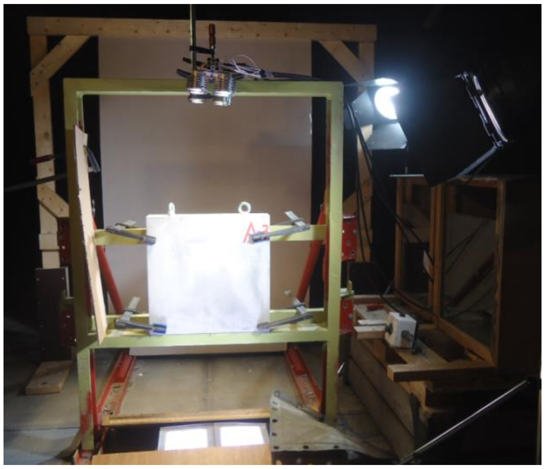
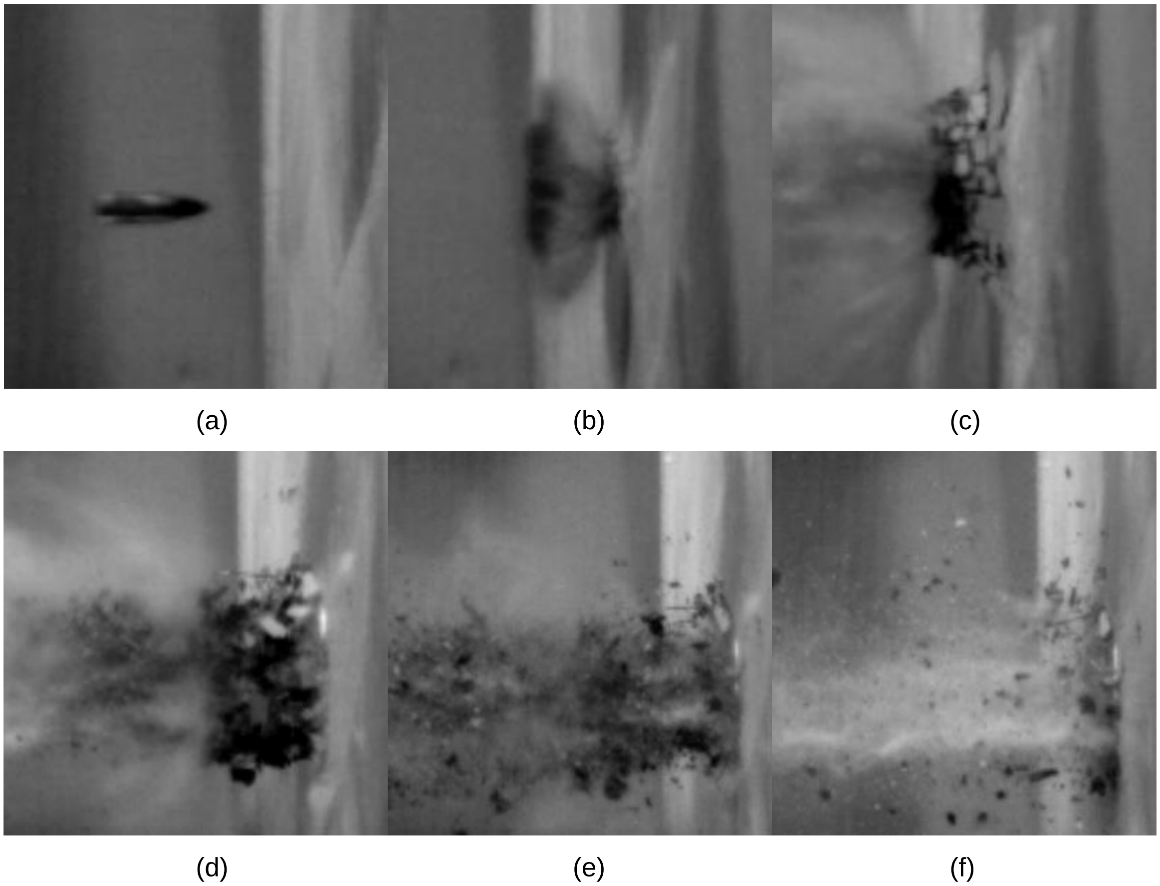


Figure 4: Installed sample before the testing

Based on STANAG 2280 (2009), a group of 3 individual shots is fired at the appropriate range on each concrete plate. The distance between hits should be in the range from 25 mm to 120 mm. After each shoot, the target and witness plates should be examined. During the shooting test, the concrete slab is fixed on a heavy frame (as shown in Figure 4), and the frame is fix on the ground. Hence, the frame and sample position will not be influenced by the projectile impact. Two high speed cameras are installed at the side of the sample, and sufficient light is provided surrounding the concrete slab.

3. Results and discussions

Figures 5 and 6 present the variation of front and rear surfaces of the sustainable UHPFRC during the first shoot. It can be noticed that the moment when the projectile initially contact with the concrete target (Figure 5b), a relatively small crater (similar as the diameter of the used projectile) and a large amount of dust are generated. Subsequently, many cracks grow sounding the crater and the size of the crater increase simultaneously (Figure 5c). Then the growth of crater stops and a large amount of small fragments fly off the concrete target, opposite to the projectile impact direction (Figures 5d and e). On the rear surface of the UHPFRC target, it is important to find that the bullet impact (7.62 mm, velocity ≈ 830 m/s) only result in several small cracks, without causing serious perforation or scabbing damages.

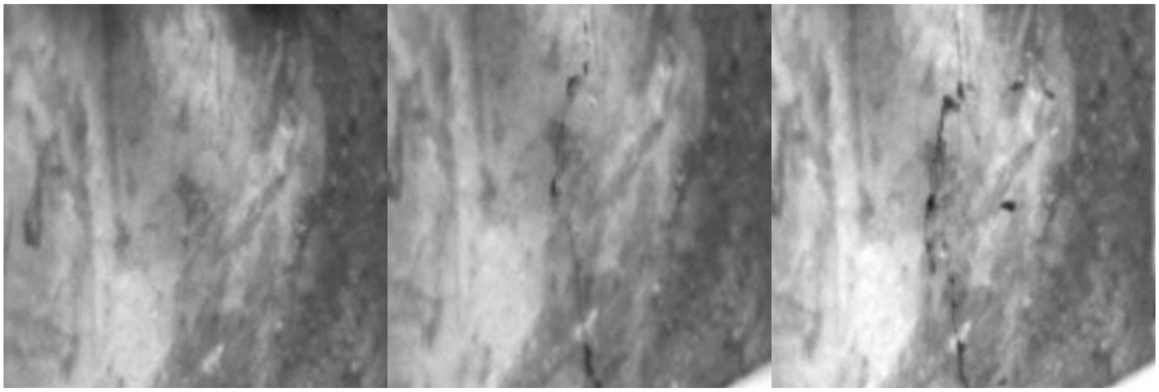

(a) (b) (c)

(d) (e) (f)

Figure 5: Dynamic performance of the UHPFRC with hybrid fibres under the bullet (7.62 mm, velocity ≈ 830 m/s) impact (front surface, first shoot)

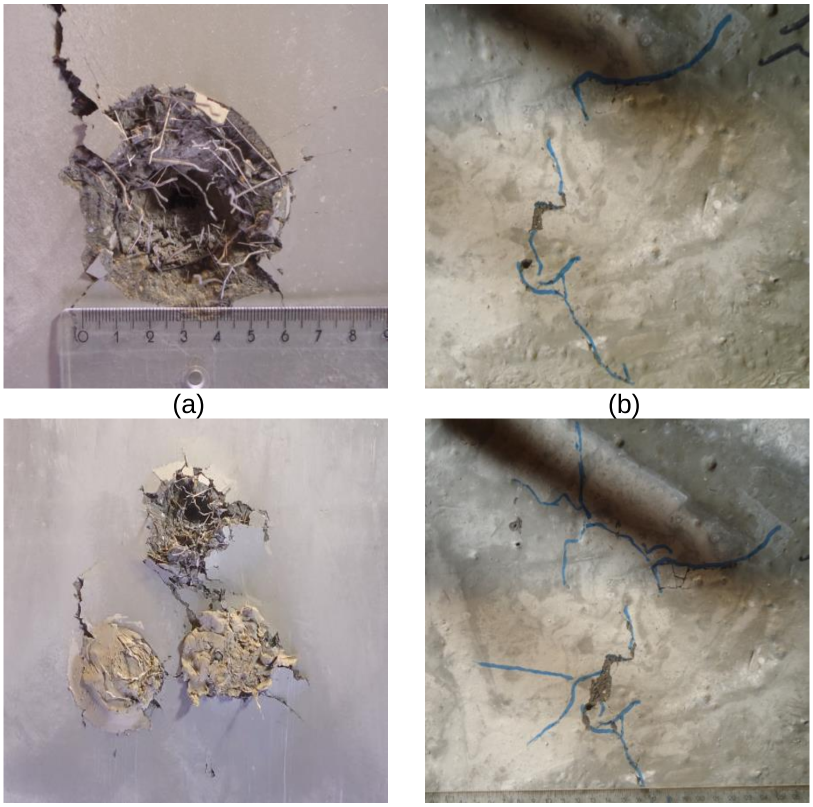
Figure 7 illustrates the appearance of both the front and rear surface of the UHPFRC target after first shoot. Based on the measurement, it can be found that the diameter and volume of these generated craters have similar diameters and volumes, which fluctuate around 6 cm and 30 cm^3, respectively. Moreover, all the three impact projectiles are blocked inside of the concrete, and their penetration depths are 5.7 cm, 6.0 cm and 6.8

cm. From Figures 7b and d, it can be noticed that some locally distributed cracks appear after each shoot. After three times shoot, the scabbing at the rear surface of the concrete target is very limited. Based on these obtained experimental results, it can be summarized that the used bullet can cause very locally damages to the concrete target, and the developed UHPFRC target can well resist this impact.



(a) (b) (c)

Figure 6: Dynamic performance of the UHPFRC with hybrid fibres under the bullet (7.62 mm, velocity ≈ 830 m/s) impact (rear surface, first shoot)



(a) (b)

(c) (d)

Figure 7: Front and rear appearance of the tested UHPFRC slab with hybrid fibres: (a) front surface after the first shoot, (b) rear surface after the first shoot, (c) front surface after three times shoot, (d) rear surface after three times shoot

As commonly known, there are several phenomena associated with projectile impact effects on concrete targets [22]. When the impact velocities are relatively small, the projectile will strike the concrete target and bounce off without creating any local damage. With an increase of the impact velocity, pieces of concrete are ejected off of the concrete impacted face. This spalling forms a spall crater that extends over a substantially greater area than the cross-sectional area of the striking projectile. As the velocity continues to increase, the projectile will penetrate the target to depths beyond the depth of the spall crater, forming a cylindrical penetration hole with a diameter only slightly greater than the projectile diameter. Further increases in velocity produce cracking of the concrete on the back surface followed by scabbing of concrete from this rear surface. The zone of scabbing is normally much wider but not as deep as the front face crater. Once scabbing begins, the depth of penetration will increase rapidly. As the projectile velocity increases further, perforation of the target will occur as the penetration hole extends through to the scabbing crater and the projectile may subsequently exit from the rear face of the target with a residual velocity. In this study, due to the relatively high impact velocity and energy, the bullets penetrate into the concrete target and cause a cylindrical penetration hole beyond the depth of the spall crater. However, the scabbing is difficult to be observed at the concrete rear surface after the impact loadings, which may be attributed to the application of hybrid steel fibres in UHPFRC. As be announced by Sovják et al. [6], the added steel fibres in UHPFRC can well grip the concrete matrix and dissipate the impact energy during the impact process. Hence, compared to normal strength concrete, high strength concrete and plain UHPC, UHPFRC show much better impact resistance ability in reducing the spalling, scabbing and penetration depth.

4. Conclusions

This paper presents the dynamic performance of a sustainable Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) under high velocity projectile impact. The design of concrete mixtures aims to achieve a densely compacted cementitious matrix with a relatively low binder amount, employing the modified Andreasen & Andersen particle packing model. The obtained results show that the bullets penetrate into the concrete target and cause a cylindrical penetration hole beyond the depth of the spall crater. However, the scabbing is difficult to be observed at the concrete rear surface after the impact loadings, which may be attributed to the application of hybrid steel fibres in UHPFRC. Hence, to produce a protective structure, the developed sustainable UHPFRC with hybrid fibres is a good choice.

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Authors:

MSc. Rui Yu
Dr. -Eng. Przemek Spiesz
Prof.dr.ir Jos Brouwers
Eindhoven University of Technology
Faculty of the Built Environment
P.O. Box 513
5600 MB Eindhoven
E-mail: R.Yu@tue.nl