Cement and Concrete Composites 68 (2016) 109–122

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Energy absorption capacity of a sustainable Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) in quasi-static mode and under high velocity projectile impact

R. Yu [a, b, *], P. Spiesz [b, c], H.J.H. Brouwers [b]

[a] State Key Lab of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan 430070, PR China
[b] Department of the Built Environment, Eindhoven University of Technology, The Netherlands
[c] ENCI HeidelbergCement Benelux, The Netherlands

ARTICLE INFO

Article history:
Received 18 July 2015
Received in revised form
25 January 2016
Accepted 10 February 2016
Available online 15 February 2016

Keywords:
Sustainable
Ultra-High Performance Fibre Reinforced Concrete (UHPFRC)
Energy absorption capacity
Quasi-static mode
High velocity projectile impact

ABSTRACT

This paper investigates the energy absorption capacity of a sustainable Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) in quasi-static mode and under high velocity projectile impact. The design of the sustainable concrete mixtures aims on achieving a densely compacted cementitious matrix with a relatively low binder amount, employing the modified Andreasen & Andersen particle packing model. The experiments on UHPFRC are performed using a 4-point bending test and high velocity projectile impact tests. The obtained results show that although the utilization of hybrid steel fibre enhances the mechanical properties of the developed UHPFRC, the application of fibres with hooked ends is crucial in improving the energy absorption capacity of the sustainable UHPFRC in quasi-static mode. However, under high velocity projectile impact, the UHPFRC mixture with hybrid fibres shows a much better energy absorption capacity than the one with hooked steel fibres only, particularly in resisting the scabbing at the rear surface. The intrinsic mechanisms for the energy absorption capacity of the sustainable UHPFRC in quasi-static mode and under high velocity projectile impact are studied and analysed.

1. Introduction

As a result of increasing concerns regarding the public and structural 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. In addition, not only the important infrastructural buildings have to be protected against impact loads but also smaller technical facilities can cause serious damage upon failure. For example, the protection of tanks used for storing liquefied petroleum gas (LPG) at gas stations in densely populated areas is an important aspect and demands the application of suitable materials. 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]. The damaging effect of these projectiles is devastating as the projectile is penetrating unhindered through ordinary concrete or steel and causes scabbing of the concrete at the back side. The spalling of the concrete generates small fragments that act as further projectiles and contribute to the damaging effect of the original projectile [7,8]. 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, it can be concluded that a strong concrete matrix and high content 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 [9–13]. With the development of concrete technology and chemical admixtures, a series of new materials (advanced superplasticizers, nanosilica et al.) become available for production of concrete with superior properties. Not only the new materials but also new insights in the particle packing allowed the design of concrete mixes

* Corresponding author. State Key Lab of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan 430070, PR China.
E-mail addresses: r.yu@tue.nl, r.yu@whut.edu.cn (R. Yu).

http://dx.doi.org/10.1016/j.cemconcomp.2016.02.012
0958-9465/

that have higher strength, deformation capacity and durability than normal strength concrete (NSC) [14–16]. Based on the requirements of a strong concrete matrix and a high content of steel fibres, the developed concept of Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) can be a good candidate to be utilized in protective structures. For example, Bindiganavile et al. [9] demonstrated that UHPFRC has a higher impact resistance than other types of concretes. Their impact tests were carried out with a 60 kg drop-mass, hitting a variable span beam specimen from heights of up to 2.5 m. To cover a large range of loading rates, Parant et al. [11] 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. Their results showed that with an increase in the strain rate, the modulus of rupture and the uniaxial tensile strength increase. Habel and Gauvreau [12] presented an experimental and analytical study of load rate-dependent characteristics of UHPFRC. The results of this study show a significantly increased strength and fracture energy of the dynamically loaded plates when compared to quasi-static loading. Lai and Sun [13] studied the dynamic behaviour of UHPFRC with different steel fibre volume fractions under impact using the split Hopkinson pressure bar device. Three aspects of the testing: a gimbal device, wave shaping, and direct strain measurement were used to increase experimental accuracy. Results indicate that UHPFRC has obvious strain rate effects. The peak stress, peak strain, elastic modulus, and area under the stress-strain curve increase with increasing strain rate. When the strain rate exceeds a threshold value, specimens with and without fibres begins to fracture. At high strain rate the unreinforced specimens fracture into small parts while fibre reinforced ones only have fine cracks on the edges. A visco-elastic damage model of UHPFRC is proposed based on a nonlinear visco-elastic model and the material damage measured by the ultrasonic wave velocity method. Máca et al. and Sovjak et al. [6,17] investigated the impact resistance of UHPFRC against fired bullets. It was verified experimentally that the optimal fibre content in the UHPFRC mixture is 2% by volume. No improvement in all damage parameters was observed when the fibre volume fraction was increased from 2% to 2.5% or 3%. Wu et al. [3] investigated the projectile penetration of ultra-high performance cement based composites at 510–1320 m/s. The experimental results confirmed that UHPFRC has an excellent projectile impact resistance, for instance in reducing the depth of penetration (DOP) and the crater dimensions of the rigid projectile, as well as protecting the structure and deflecting the terminal ballistic trajectory of the abrasive projectile. Additionally, it is demonstrated that UHPFRC has excellent impact resistance capacity under explosive loadings [38–40]. However, in all of the investigations mentioned above, a large amount of cement or binders were normally utilized in the UHPFRC production, which is not in line with the theme of sustainable development.

In previous publications of the authors [18–23,41], it has been addressed how to produce a UHPFRC with relatively low binder amount, by employing the modified Andreasen & Andersen particle packing model and using mineral admixtures. Moreover, it has been demonstrated that such a UHPFRC is sustainable and has a lower environmental impact compared to conventional UHPFRCs. Nevertheless, the research focusing on the energy absorption capacity of such a sustainable UHPFRC is rather scarce, and it is unclear whether this UHPFRC would be sufficient for protection purposes.

Consequently, the objective of this study is to investigate the energy absorption capacity of the sustainable UHPFRC in quasi-static mode and 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 UHPFRC properties are quantified by employing 4-point bending test for the quasi-static conditions and high velocity projectile impact tests for the dynamic conditions.

2. Materials and methods

2.1. Materials

The cement used in this study is Ordinary Portland Cement (OPC) CEM I 52.5 R, provided by ENCI HeidelbergCement (the Netherlands). A polycarboxylic ether based superplasticizer is used to adjust the workability of concrete. Limestone powder is used as a filler to replace cement. A commercially available nano-silica in slurry is applied here as pozzolanic material. Two types of sand are used, one is a river dredged 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 distribution of the used granular materials is shown in Fig. 1. Additionally, three types of steel fibres are utilized, as shown in Fig. 2: 1) long straight fibre (LSF), length = 13 mm, diameter = 0.2 mm; 2) short straight fibre (SSF), length = 6 mm, fibre diameter = 0.16 mm; 3) hooked fibre (HF) length = 35 mm, diameter = 0.55 mm. The densities of the used materials are shown in Table 1. The oxide compositions of the used cement, limestone powder and nano-silica are presented in Table 2.

2.2. Experimental methodology

2.2.1. Mix design of the sustainable UHPFRC

In this study, based on the approach shown in Refs. [18,20,22], the modified Andreasen and Andersen model is utilized again to design the sustainable UHPFRC, which is shown as follows [24,25]:

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

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.

The proportions of each individual solid 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 [26].

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

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.

As commonly known, the quality of the curve fit is assessed by the coefficient of determination (R^2), since it gives a value for the correlation between the grading of the target curve and the composed mix. Therefore, the coefficient of determination (R^2) is utilized in this study to obtain the optimized mixture given by:

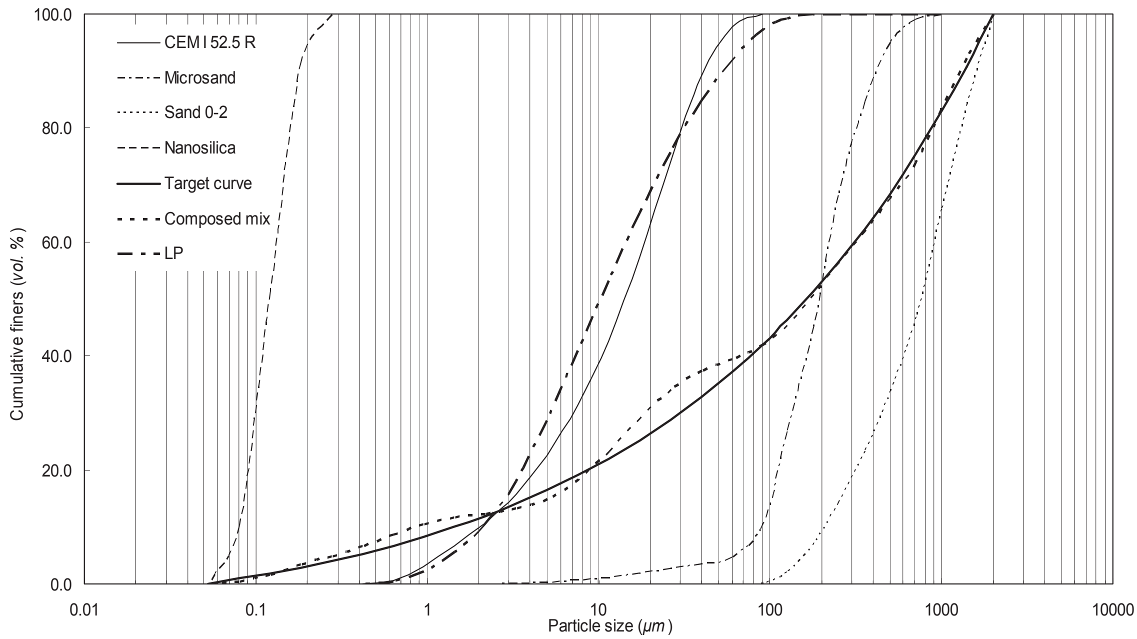


Fig. 1. Particle size distribution of the involved ingredients, the target curve and the resulting integral grading curve of the mixture.

Fig. 2. Steel fibres used in this study.

Table 1
Information on the used materials.

Materials	Type	Specific density (kg/m^3)
Cement	CEM I 52.5 R	3150
Filler	Limestone powder	2710
Fine sand	Microsand	2720
Coarse sand	Sand 0-2	2640
Superplasticizer	Polycarboxylate ether	1050
Pozzolanic material	Nano-silica (nS)	2200
Fibre-1	Long steel fibre (13/0.2)	7800
Fibre-2	Short steel fibre (6/0.16)	7800
Fibre-3	Hooked steel fibre	7800

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(P_{mix}\left(D_i^{i+1}\right) - P_{tar}\left(D_i^{i+1}\right)\right)^2}{\sum_{i=1}^{n}\left(P_{mix}\left(D_i^{i+1}\right) - \overline{P_{mix}}\right)^2} \quad (3)$$

Where $\overline{P_{mix}} = \frac{1}{n}\sum_{i=1}^{n} P_{mix}(D_i^{i+1})$, which represents the mean of the entire distribution.

The UHPFRC mixture developed in this study applying the optimized particle packing model are listed in Table 3. It can be noticed that the utilized binder amount is relatively low as for UHPFRC. The resulting integral grading curve of the developed reference mixture (without fibres) is shown in Fig. 1 ($R^2 = 0.99$). In addition, the steel fibres are added into the designed concrete matrix with different hybridizations and proportions. In all the mixtures, the total utilized fibre amount is 2% by the volume of concrete.

2.2.2. Mixing procedure

In this study, the concrete is produced following the procedure described in Ref. [18]. Before the hybrid fibres are added into the concrete mixture, the fibres are mixed together for one minute. The mixing is always executed under laboratory conditions with dried and tempered aggregates and powder materials. The room temperature while mixing and testing is constant (about 21 °C).

2.2.3. Mechanical properties of UHPFRC

After mixing, the fresh UHPFRC mixtures are cast in moulds with the sizes of 100 mm × 100 mm × 500 mm and 100 mm × 100 mm × 100 mm. The beams and cubes are demoulded approximately 24 h after casting and subsequently cured in water at about 21 °C. After curing for 28 days, the compressive strengths of the cubes are determined according to EN 12390-3 [27], and the beams are subjected to the 4-point bending test as described in EN 12390-5 [28]. For the 4-point bending test,

Table 2
Oxide composition of employed cement, limestone powder and nano-silica.

Substance	Cement (mass %)	Limestone powder (mass %)	Nano-silica (mass %)
CaO	64.60	89.56	0.08
SiO_2	20.08	4.36	98.68
Al_2O_3	4.98	1.00	0.37
Fe_2O_3	3.24	1.60	–
K_2O	0.53	0.34	0.35
Na_2O	0.27	0.21	0.32
SO_3	3.13	–	–
MgO	1.98	1.01	–
TiO_2	0.30	0.06	0.01
Mn_3O_4	0.10	1.605	–
P_2O_5	0.74	0.241	0.15
Cl^-	0.05	–	0.04

Table 3
Recipes of the developed UHPFRC.

No.	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%	SSF vol%	HF vol%
Ref.	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0	0	0
1	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0	0	2
2	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0.125	0.375	1.5
3	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0.5	0	1.5
4	594.2	265.3	221.1	1061.2	24.8	176.9	44.2	0	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, SSF: Short straight fibre, HF: Hooked fibre, Ref. reference sample with fibres).

the span between the two supported points at the bottom side is 400 mm. To obtain the flexural load over the middle deflection curve, a Linear Variable Differential Transformer (LVDT) mounted on the surface of the tested samples is utilized to record the mid-deflection. During the test, the set-up is running in a displacement control mode, which is set at 0.1 mm/min. The test device and a scheme of the sample during the test are illustrated in Fig. 3. Before the test, the calibration of the used LVDT is done. For all the tests, at least three samples are executed for each mixture.

2.2.4. Energy absorption capacity of UHPFRC in quasi-static mode

In this study, the energy absorption capacity of the developed sustainable UHPFRC in quasi-static mode is determined by employing JSCE SF-4, in which the area under the load-deflection plot up to a deflection of span/150 is treated as the energy consumed during the test. Hence, the 4-point bending tests are executed firstly, and then the area under the load-deflection plot is calculated in MATLAB.

2.2.5. Energy absorption capacity of UHPFRC under high velocity projectile impact

To produce an appropriate concrete sample for the high velocity projectile impact test, the fresh concrete is cast in the moulds with the sizes of 500 mm × 500 mm × 100 mm (as shown in Fig. 4). Due to the fact that the developed UHPFRC has good workability (self-compacting properties), the fresh concrete is poured onto the centre of the mould directly, without applying any vibration. After 3 days, the samples are demoulded and cured in water. After curing for 28 days, all the samples are removed from water and prepared for the impact tests.

In this study, one type of in-service bullet (7.62 mm) is utilized for the impact test, as shown in Fig. 5a and b. The launching set-up for this bullet is illustrated in Fig. 5c. The bullet impact velocity is about 830 m/s, which can be measured by a radar sensor fixed on the launcher (as shown in Fig. 5d). Following STANAG 2280 [29], the distance between target concrete plate and the launch point is 30 m, and a witness plates is 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,

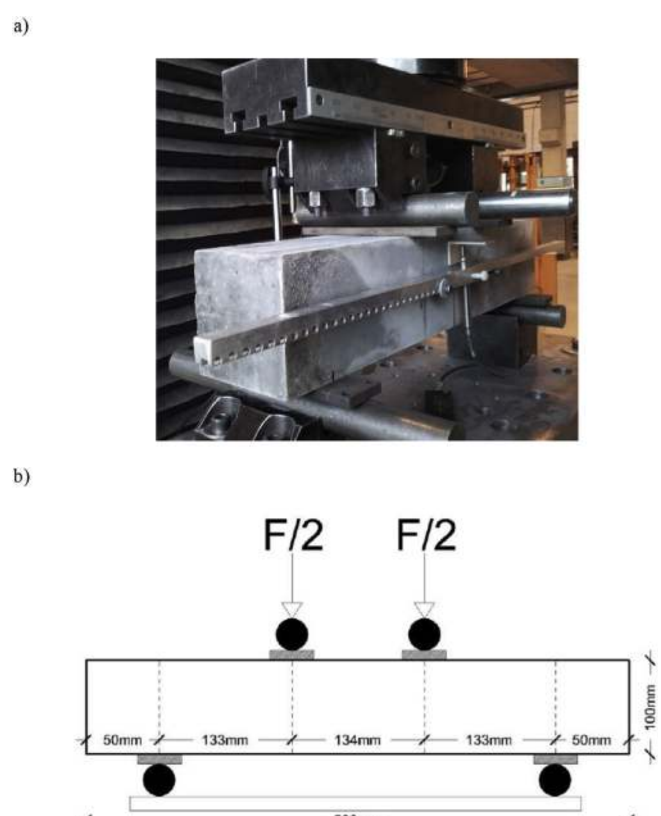
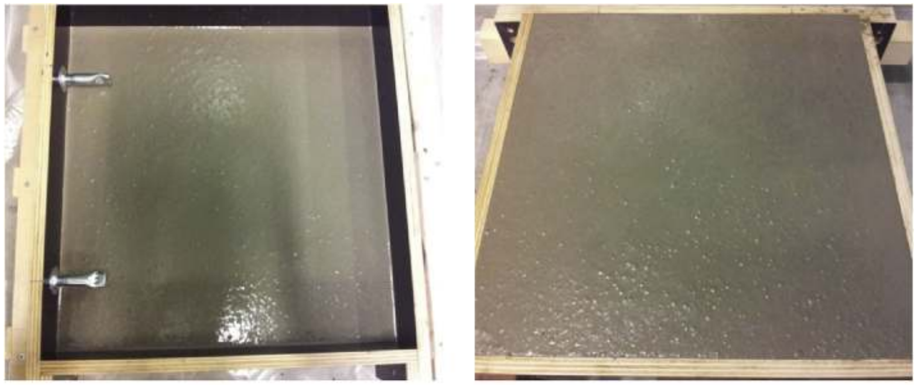


Fig. 3. Employed 4-point bending test device (a) and schema a sample during the test (b).

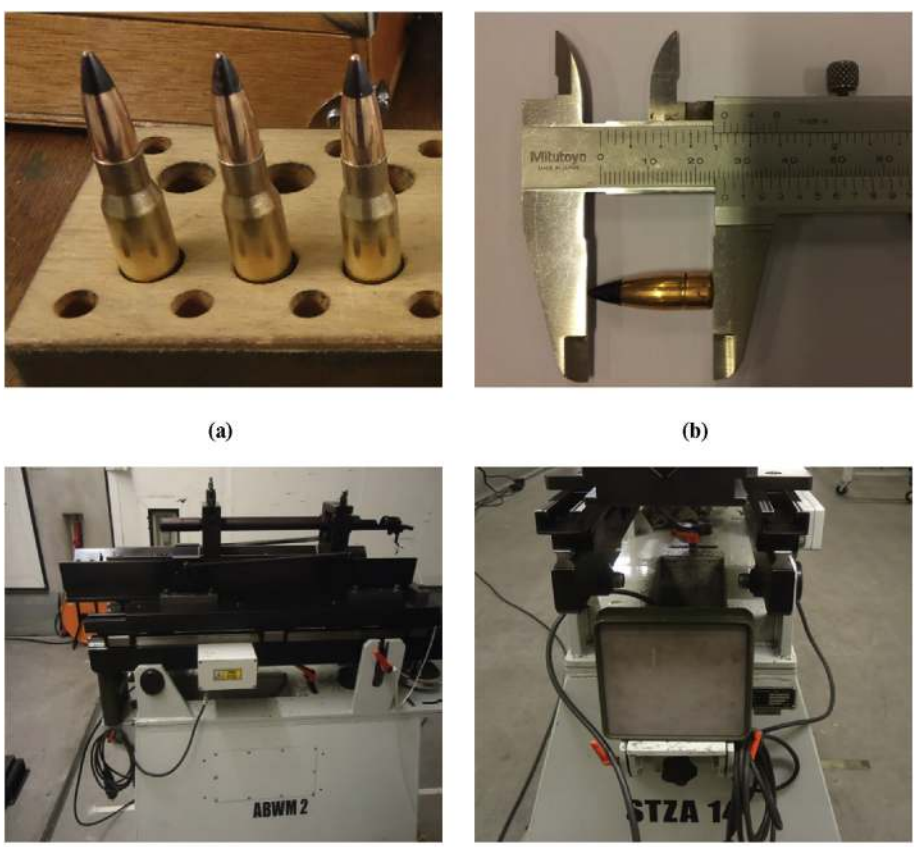


(a) (b)

Fig. 4. Utilized wooden moulds (a) and the cast concrete sample in fresh state (b).

two high speed cameras are used to monitor the front and rear sides of the concrete target. The rate of the utilized high speed cameras are 26,143 fps (frame per second) and 21,052 fps for the front and rear camera, respectively. The scheme of the shooting set-up is shown in Fig. 6.

Based on STANAG 2280 [29], a group of 3 individual shots is fired against each concrete plate, as shown in Fig. 7. The distance between the hits should be in the range from 25 mm to 120 mm. After a series of 3 shots, the target and witness plates should be examined for signs of perforation of the target. It is possible to confirm the perforation of the target only based on the reaction of the witness plate (e.g. a round passing through a sandbag wall but being caught on the witness plate). The targets and witness plates should be inspected after each shot. Moreover, during the projectile impact test, the concrete slab is fixed on a heavy frame (as shown in Fig. 8), and the frame is fixed to the ground. Hence, the frame and sample position will not be influenced by the projectile impacts. Two high speed cameras are installed at the side of the sample, and sufficient light is provided surrounding the concrete slab.



(a) (b)

(c) (d)

Fig. 5. Utilized in-service bullet (7.62 mm) (a), impact projectile from the bullet (b), utilized bullet launcher (c) and the radar sensor used to measure the projectile velocity.

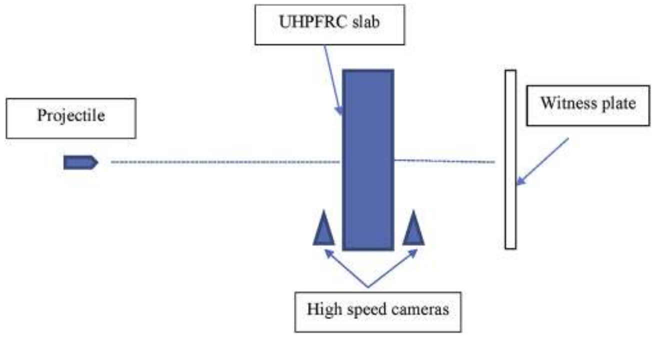


Fig. 6. Scheme of the projectile impact tests.

3. Experimental results and discussion

3.1. Mechanical properties of UHPFRC

Fig. 9 and Table 4 illustrate the compressive strength of the developed UHPFRC. It can be found that the addition of steel fibres (for every type and combination) can effectively improve the compressive strength the UHPFRC composite. In addition, the 28 days compressive strength of all the designed UHPFRC mixtures fluctuates around 135 MPa, which is obviously larger than the normal strength concrete (NSC) and high strength concrete (HSC). Moreover, and the difference between the results obtained from different mixtures is relatively small. For instance, the mixture with HF and SSF shows the highest compressive strength at 28 days (136.5 MPa), while the strength of mixture with only HF is the lowest - 129.2 MPa. Furthermore, in the mixtures HF + LSF + SSF, HF + LSF and HF + SSF, the HF amount is the same (1.5% Vol), and their compressive strengths follow the order: HF + SSF > HF + LSF + SSF > HF + LSF. This can be attributed to the combined effect of the hybrid fibres in restricting the cracks development. The homogeneity of the tested samples is very important to improve the compressive strength. As can be easily understood, with the same volumetric amount, the SSF has the largest fibre number compared to the other used fibres. Hence, in this study, the UHPFRC mixture with HF + SSF is more homogeneous and its compressive strength can be the highest, compared to the sample with HF + LSF or HF only.

Fig. 10 presents the 4-point bending test results of the developed sustainable UHPFRC. The load/mid-deflection curves can be mainly divided into three parts: elastic section, strain hardening section and strain softening section, as shown in Fig. 11. From the beginning of the test until the moment when the first crack appears, the linear section part of the curve can be observed. Due to the fact that the tested UHPFRC is very stiff, very small mid-deflections of the samples are recorded. In this study, the first crack deflection for all the samples fluctuates around 0.01 mm. After the first crack appears, the strain hardening section starts, the multiple cracks will generate on the bottom surface of the tested beam (as shown in Fig. 10). In this process, the fibres in concrete will mainly endure the load and limit the growth of the generated cracks, until the peak force is reached. When the fibres in concrete can not restrain anymore the further growth of the small cracks, the fibres will be pulled out and the endurable force of the test beam will decrease, which reflects the initiation of the strain softening section. Nevertheless, due to the different characteristics of the fibres and the binding force between the fibres and concrete matrix, the strain softening behaviour of the concrete can be very different. In this study, it is important to notice that the endurable force of the mixtures with SSF (e.g. HF + LSF + SSF and HF + LSF) decreases relatively quickly after reaching the peak force, while for concrete with only HF or HF + LSF a relatively slow decreasing trends are observed. The decreasing rates of the residual load of the tested UHPFRCs follow the order: HF < HF + LSF < HF + LSF + SSF < HF + SSF, which also implies that the addition of SFF is inefficient for improving the energy absorption capacity of the developed UHPFRC. The phenomena mentioned above can be attributed as the different crack resistance capacity for different steel fibres. For the mixture with hook ended steel fibres (HF), the hooks can effectively hold the matrix and resist the cracks development, which cause that the endurable force of the UHPFRC with only HF decreases relatively slowly, as shown in Fig. 10. Due to the fact that the straight steel fibres have relatively smaller crack resistance capacity than the hook ended steel fibres, so when the HF is partly replaced by LSF or SSF, the endurable forces of the UHPFRC samples decrease relatively quickly.

3.2. Energy absorption capacity of UHPFRC in quasi-static mode

In this study, the JSCE SF-4 [30] is employed to evaluate the energy absorption capacity of the developed sustainable UHPFRC in quasi-static mode, and the results are shown in Fig. 12 and Table 5. It can be noticed that all the calculated energy absorption capacities are in the range from 25 to 35 J. Moreover, the calculated energy absorption capacity of the sustainable UHPFRC with HF and the one with HF + LFS are obviously larger than that with HF + LSF + SSF or HF + SSF, which are in line with the obtained 4-point bending test

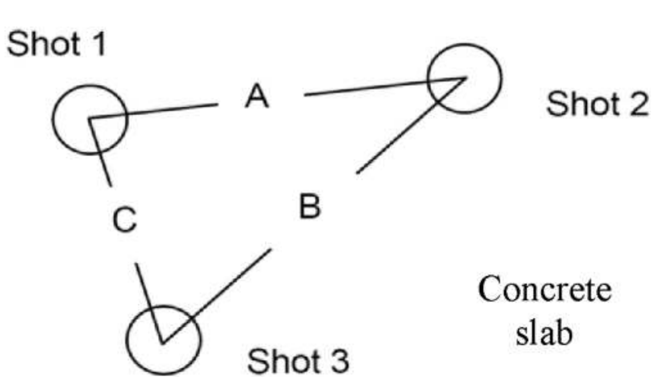


Fig. 7. Impact pattern of individual projectiles.

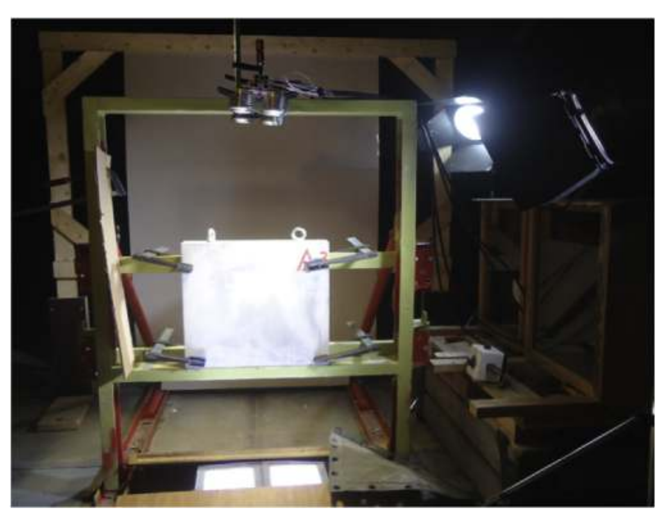


Fig. 8. Installed sample before the testing.

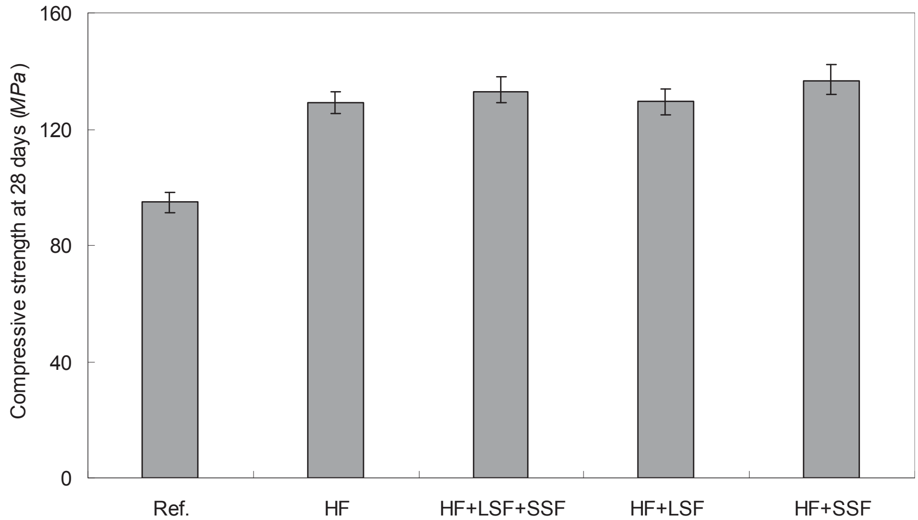


Fig. 9. Compressive strength of the developed sustainable UHPFRC.

Table 4
Compressive strength of the developed UHPFRC.

Compressive strength (MPa)	Ref.	HF	HF + LSF + SSF	HF + LSF	HF + SSF
1	96.5	127.7	137.9	125.1	135.5
2	98.2	125.6	131.5	133.9	138.6
3	94.9	131.1	135.9	130.6	132.1
4	94.5	126.6	129.3	127.8	136.8
5	94.8	133.0	132.6	129.9	133.4
6	91.1	130.6	130.8	129.1	142.0
Average	95.0	129.1	133.0	129.4	136.4
Standard deviation	2.16	2.64	2.98	2.68	3.28

(Ref. represents the reference sample without steel fibres; HF, HF + LSF + SSF, HF + LSF, HF + SSF represent the developed UHPFRC mixtures with different steel fibres combinations, respectively).

results (Fig. 10). Therefore, it can be concluded that the addition of SSF is inefficient in improving the energy absorption capacity of UHPFRC. This phenomenon can be attributed to the different geometric dimensions between the used steel fibres. Due to the relatively short length and lower binding force with the concrete matrix, many SSF can be pulled out after reaching the peak force, and the load endurable capacity of the tested beam decreases relatively quickly during the post-cracks process [31–34]. In contrary to the characteristic of SSF, HF shows a greater ability in restraining the development of macrocracks. As commonly known,

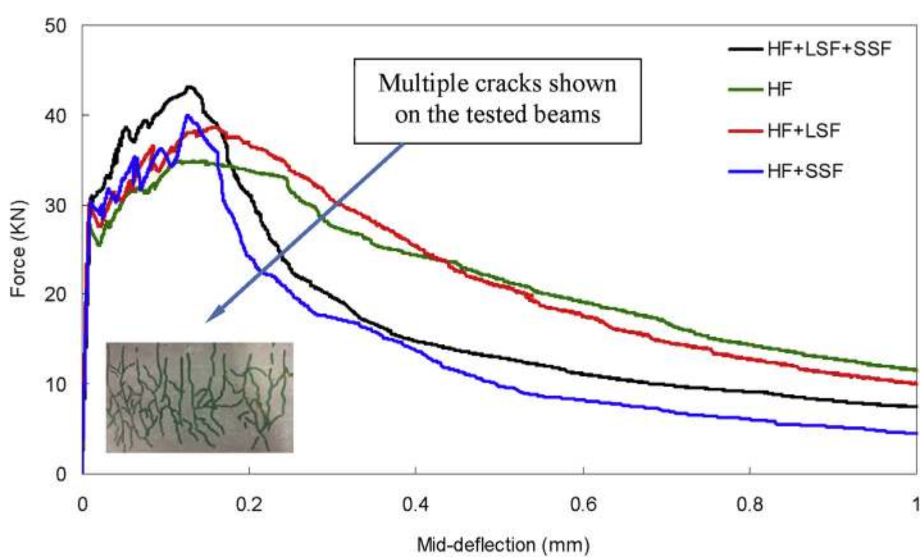


Fig. 10. 4-point bending test results of the designed UHPFRC (HF, HF + LSF + SSF, HF + LSF and HF + SSF represent the mixtures No. 1 to 4, as shown in Table 3).

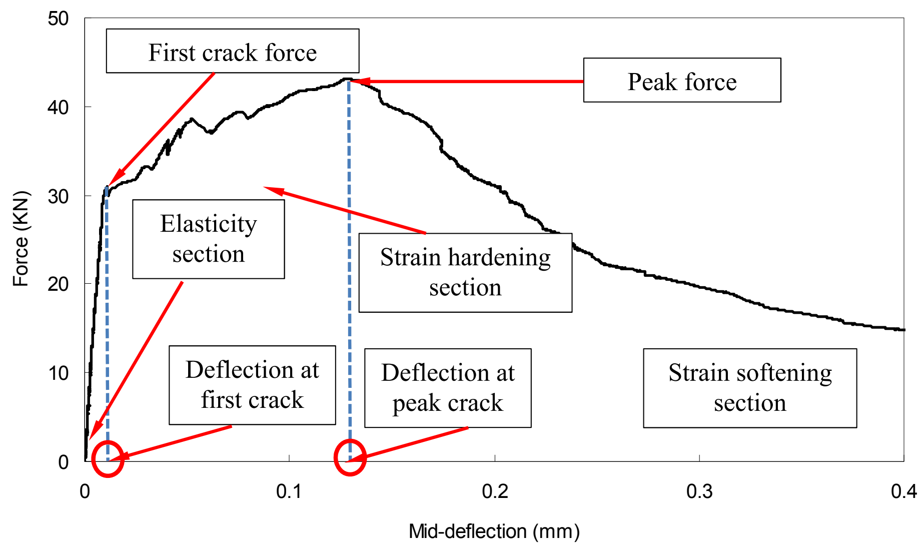


Fig. 11. Key parameters of UHPFRC subjected to 4-point bending test.

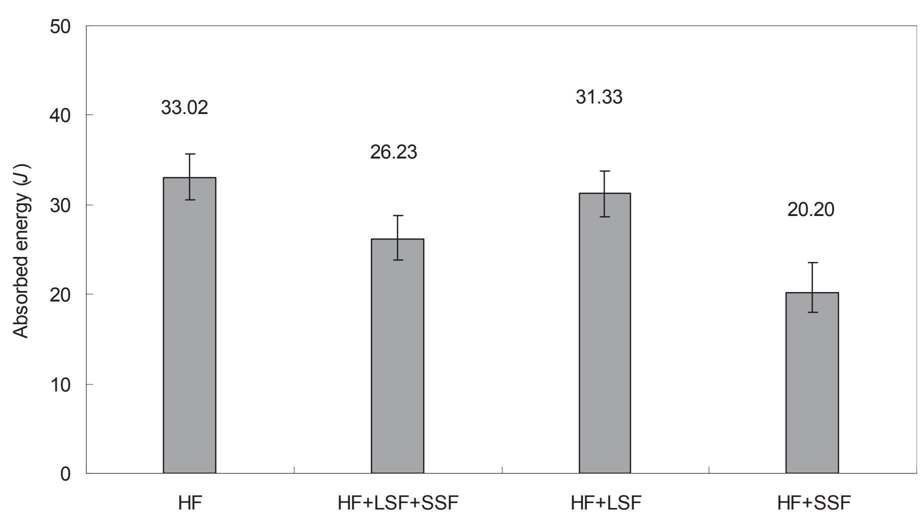


Fig. 12. Absorbed energy of the sustainable UHPFRC in quasi-static mode based on JSCE SF-4.

Table 5
Energy absorption amount of the developed UHPFRC in quasi-static condition.

Absorbed energy (J)	HF	HF + LSF + SSF	HF + LSF	HF + SSF
1	35.62	23.97	–	23.47
2	30.56	25.69	32.56	–
3	32.89	28.79	33.79	21.05
4	33.91	28.02	30.01	17.99
5	–	27.11	28.61	19.62
6	32.12	23.80	31.68	18.87
Average	33.02	26.23	31.33	20.20
Standard deviation	1.70	1.91	1.83	1.92

(HF, HF + LSF + SSF, HF + LSF, HF + SSF represent the developed UHPFRC mixtures with different steel fibres combinations).

the hooks at the ends of HF can improve the coupling force between the fibres and concrete matrix, which causes that a higher force is needed to pull this fibre type out (compared to SSF) [35,36]. Hence, during the strain softening process, HF can still bridge the macro-cracks, thus a higher amount of energy is needed to pull the HF out.

In general, based on the obtained experimental results, it can be concluded that although the utilization of hybrid steel fibre can enhance the mechanical properties of the developed UHPFRC, the application of fibres with hook ends is crucial for improving the energy absorption capacity of the sustainable UHPFRC in quasi-static mode. However, due to the fact that the energy release or impact occurring in practice is dynamic, it is also very important to clarify the energy absorption capacity of the developed sustainable UHPFRC in the dynamic mode, which is presented in the following part.

3.3. *Influence of the resistance against bullet impact depending on the fibre reinforcement*

In this section, the dynamic performance of the sustainable UHPFRC under high velocity projectile impact is evaluated. Based on the experimental results shown in Section 3.2, two UHPFRC mixtures (HF and HF + LSF, mixtures 1 and 3 as shown in Table 3) are chosen for the projectile impact tests, since these two mixtures have relatively high and similar energy absorption capacity in the quasi-static mode.

Figs. 13 and 14 present the front and rear surfaces of the sustainable UHPFRC slabs with HF + LSF during the first shot. It can be noticed that upon the moment when the projectile initially contacts the concrete target (Fig. 13b), a relatively small crater (similar to the diameter of the used projectile) and a large amount of dust is generated. Subsequently, many cracks grow surrounding the crater, whose size simultaneously increases (Fig. 13c). Then the growth of the crater stops and a large amount of small fragments fly off the concrete, opposite to the projectile impact direction (Fig. 13d 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 results in small cracks, without causing serious perforation or scabbing damage (as shown in Fig. 14).

Fig. 15 illustrates the appearance of both the front and the rear surfaces of the UHPFRC target after the first shot and three shots. 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 the concrete slab, and their penetration depths are 5.7 cm, 6.0 cm and 6.8 cm. From Fig. 15b and d, it can be noticed that some locally distributed cracks appear after each shot. After three shot, 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 bullet (7.62 mm, velocity ≈ 830 m/s) can cause only a local damage to the concrete target, and the developed UHPFRC slab with HF + LSF can well resist this impact.

As commonly known, there are several phenomena associated with projectile impact effects on concrete targets [7]. Generally, high compressive loading at the attack face leads to cratering, while the tensile loading at the rear face can cause scabbing. 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. As the penetration depth increases, the projectile will stick to the concrete target rather than rebound. Further increases in the 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. For low barrier thickness to projectile diameter ratios (less than 5) the pieces of scabbed concrete can be large in size and have substantial velocities. As the projectile velocity further increases, 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 concluded by Sovják et al. [6,37], 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 shows much better impact resistance ability in reducing the spalling, scabbing and penetration depth.

To understand the effect of different fibres on the impact resistance capacity of concrete, the dynamic performance of the sustainable UHPFRC with single type of fibres (HF) under the bullet (7.62 mm, velocity ≈ 830 m/s) impact (first shot) is shown in Figs. 16 and 17. In general, the high speed camera photos presented in Fig. 16 are similar to those shown in Fig. 13, which implies that these two UHPFRC mixtures (with hybrid or single types of fibres)

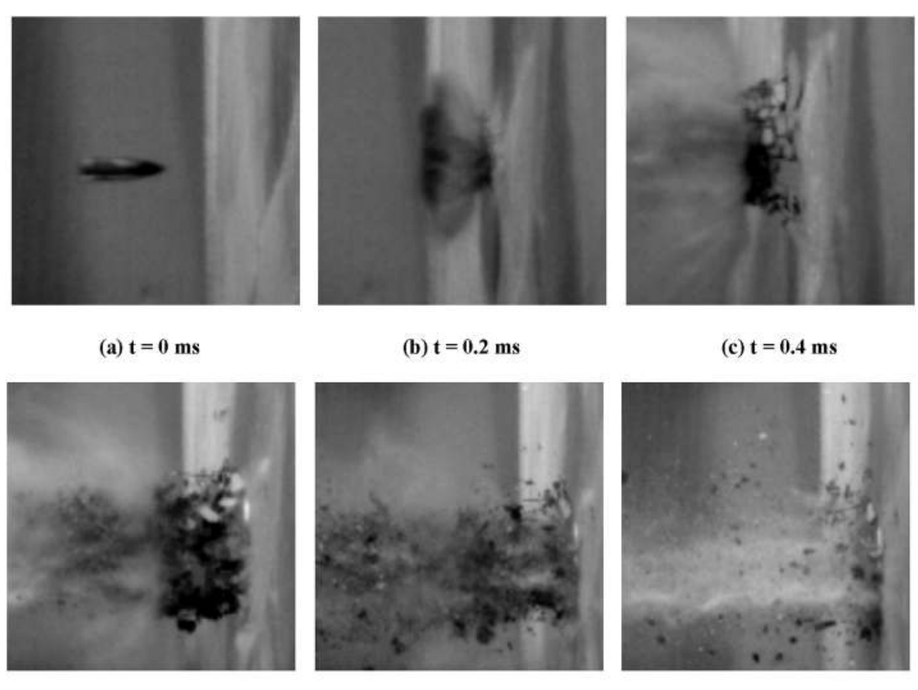


Fig. 13. Dynamic performance of the UHPFRC with hybrid fibres (HF + LSF) under the bullet (7.62 mm, velocity ≈ 830 m/s) impact (front surface, first shot).

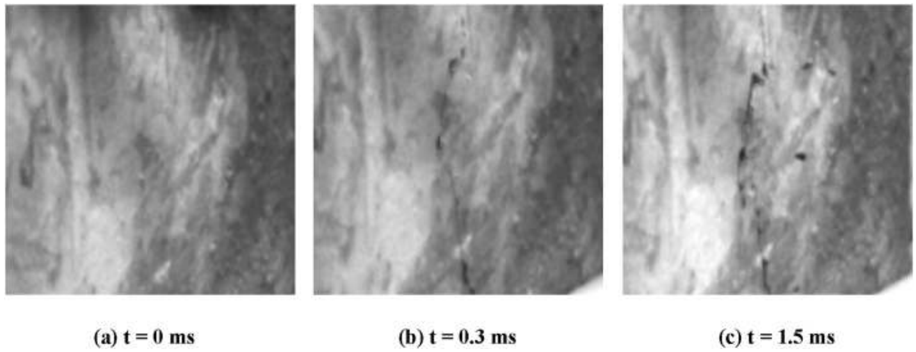


Fig. 14. Dynamic performance of the UHPFRC with hybrid fibres (HF + LSF) under the bullet (7.62 mm, velocity ≈ 830 m/s) impact (rear surface, first shot).

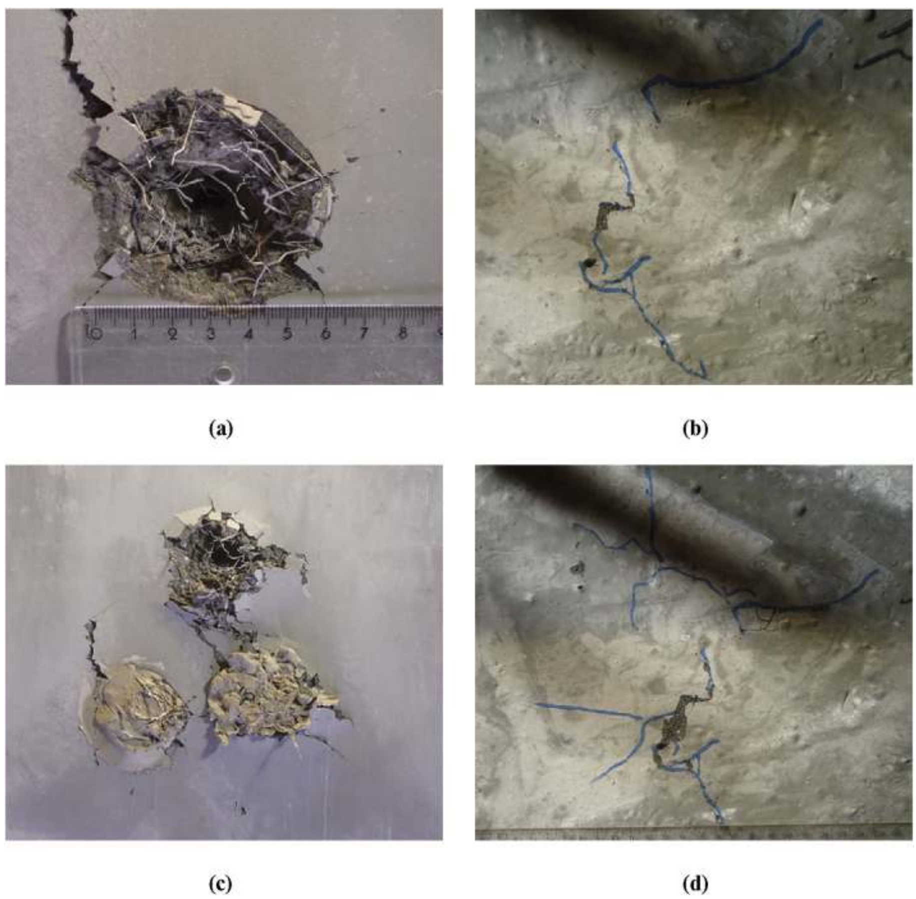


Fig. 15. Front and rear appearance of the tested UHPFRC slab with hybrid fibres: (a) front surface after the first shot, (b) rear surface after the first shot, (c) front surface after three shots, (d) rear surface after three shots.

have similar dynamic behaviour under the bullet (7.62 mm, velocity ≈ 830 m/s) impact at the front surface. Nevertheless, some differences can still be observed between Figs. 13 and 16. For instance: 1) some debonded steel fibres can be observed in Fig. 16d and e; 2) after the impact loading, the generated fragments from the concrete with single types of fibres are larger than those from the concrete with hybrid fibres. It is important to notice that the bullet impact could not only cause cracks but also very obvious scabbing at the rear surface of the sustainable UHPFRC with singe type of fibres. Although all three projectiles could be blocked inside the concrete slab, the rear surface of the concrete target has been damaged (as shown in Fig. 18). As described previously, once the scabbing begins to occre, the depth of penetration increases rapidly [7]. Here, the penetration depths of these projectiles are 6.5 cm, 6.8 cm and 7 cm, which are larger than those measured in the UHPFRC with hybrid fibres (HF + LSF). The detailed information on the obtained experimental results are presented in Table 6.

In practice, the scabbing at the rear surface of concrete structure is also very dangerous, since the flying fragments can cause the secondary damage to the human and objects standing behind the concrete element. Hence, to design a safe and reliable concrete structure, the scabbing at the rear surface of concrete under impact should be effectively limited. In this study, under the same impact circumstances (bullet 7.62 mm, velocity ≈ 830 m/s), the UHPFRC

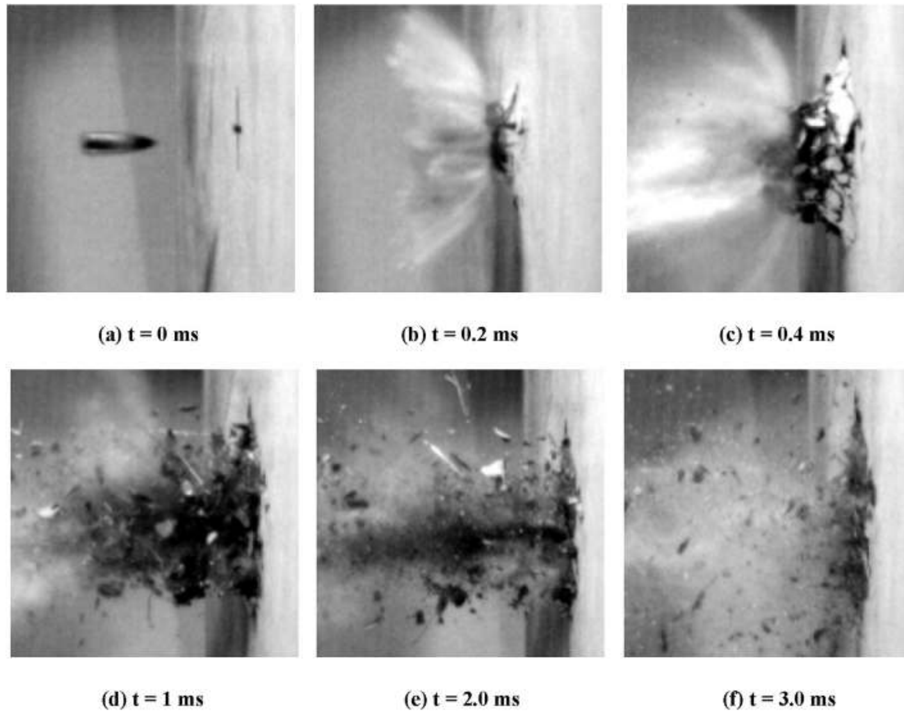


Fig. 16. Dynamic performance of the UHPFRC with single sized fibres (HF) under the bullet (7.62 mm, velocity ≈ 830 m/s) impact (front surface, first shot).

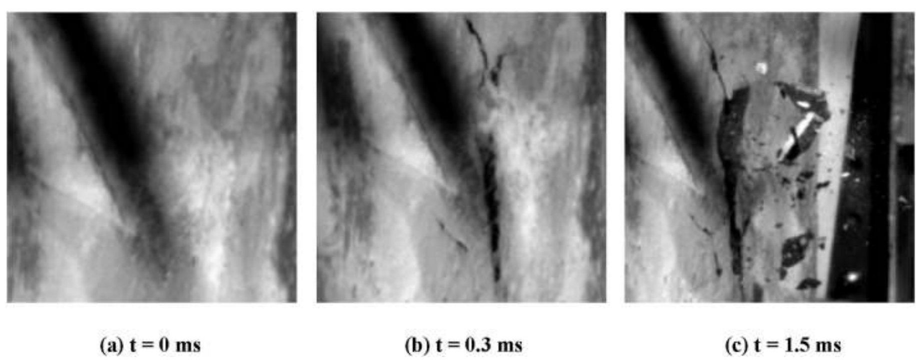


Fig. 17. Dynamic performance of the UHPFRC with single sized fibres (HF) under the bullet (7.62 mm, velocity ≈ 830 m/s) impact (rear surface, first shot).

with hybrid fibres (HF + LSF) shows a better scabbing resistance ability than the one with only HF. This can be attributed to the hybrid fibres which can effectively resist the cracks development and dissipate the impact energy. In most cases, the short fibres can bridge the micro-cracks while the long fibres are more efficient in preventing the development of macro-cracks, which causes that the stress in the hybrid fibres reinforced concrete can be well distributed and its mechanical properties can be improved [35]. Hence, when impact happens, the generated stress is relatively homogeneously distributed in the UHPFRC with hybrid fibres, and the growths of micro and macro cracks are simultaneously restricted. However, in the case of UHPFRC with single type of fibres (HF), the development of micro-cracks is not disturbed, which causes that the macro-cracks can quickly appear and part of the concrete may debond from the whole concrete structure.

Consequently, based on the obtained experimental results, it can be concluded that the addition of hybrid fibres (HF + LSF) is beneficial for improving the scabbing resistance capacity of UHPFRC under high velocity (≈830 m/s) bullet impact and reduce the projectile penetration depth.

3.4. Intrinsic mechanism analysis

According to the obtained experimental results, it can be noticed that the conclusions drawn in Section 3.3 are not in a line with those shown in Section 3.2. In the quasi-static mode, it is experimentally demonstrated that the long hooked steel fibre (HF) addition is the most important factor to improve the energy absorption capacity of UHPFRC. Nevertheless, when the developed UHPFRC is under high velocity projectile impact, it is found that the hybridization design of the utilized steel fibres is more helpful in enhancing the energy dissipation ability of UHPFRC, particularly for the scabbing resistance capacity. This phenomenon can be attributed to the difference between the employed experimental evaluation methods.

In the quasi-static mode, the energy absorption ability of UHPFRC is evaluated by comparing the area under the load-deflection plot obtained from 4-point bending test. The test is

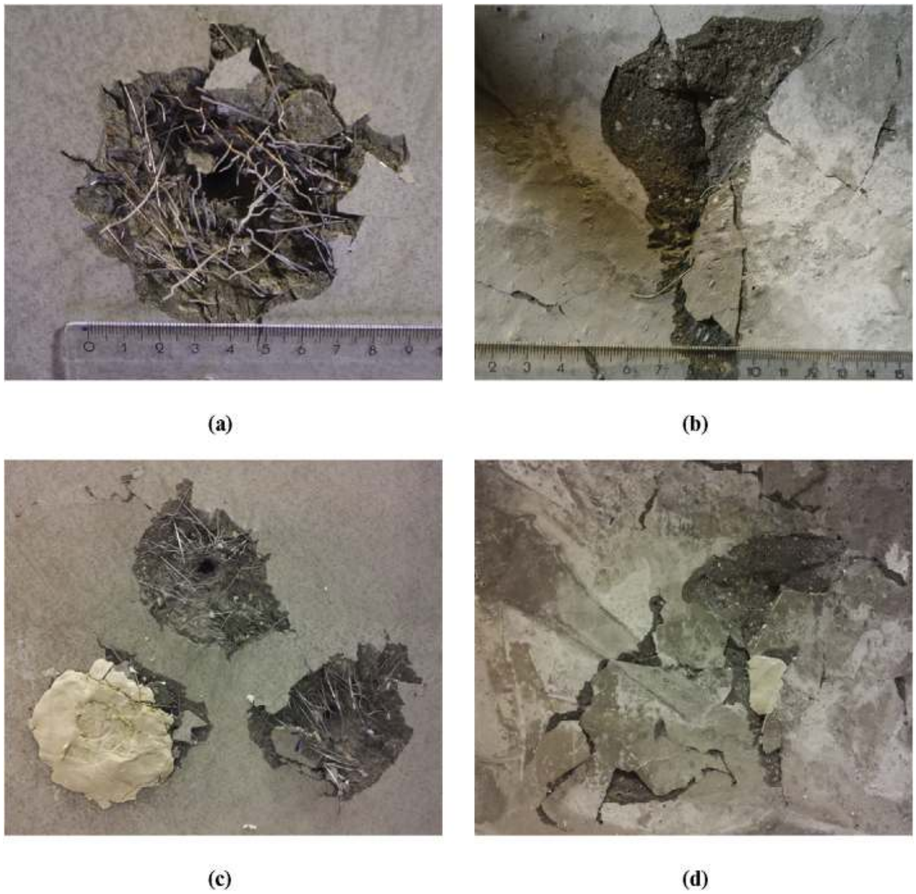


Fig. 18. Front and rear appearance of the tested UHPFRC slab with single type of fibres: (a) front surface after the first shot, (b) rear surface after the first shot, (c) front surface after three shots, (d) rear surface after three shots.

Table 6
Results obtained from the projectile impact tests.

Impact velocity (m/s)	UHPFRC with hybrid fibres			UHPFRC with single type of fibres		
	Residual velocity (m/s)	Crater diameter (cm)	Penetration depth (cm)	Residual velocity (m/s)	Crater diameter (cm)	Penetration depth (cm)
827.2	0	5.8	5.7	–	–	–
832.6	0	5.8	6.0	–	–	–
830.0	0	6.5	6.8	–	–	–
831.7	–	–	–	0	7.5	6.5
827.7	–	–	–	0	8.0	6.8
829.8	–	–	–	0	7.5	7.0

executed in quasi-static conditions, which means the used fibres have enough time to be pulled out. Compared to the straight steel fibres, the hooked steel fibres have much larger grip force with the concrete matrix, which causes that more energy will be consumed in the fibres pullout process. Therefore, the energy absorption capacity of UHPFRC with only hooked steel fibres is larger than that of the mixture with hybrid steel fibres. However, the high velocity projectile impact test is substantially different from the quasi-static 4-point bending test. Due to the relatively high velocity of bullet, the impact occurs in a very short time (μs scale), which causes that only local damages appear in the sustainable UHPFRC target (as shown in Figs. 15 and 18). As mentioned before, the short fibres can bridge the micro-cracks while the long fibres are more efficient in preventing the development of macro-cracks, which causes that the stress in the hybrid fibres reinforced concrete can be well distributed [36]. Hence, for the sustainable UHPFRC with hybrid fibres under high velocity projectile impact, the crack growths arround the local damage area of UHPFRC can be well restricted and spalling fragment sizes are relatively small (as shown in Fig. 13). Yet, in the case of the UHPFRC with a single fibre type, the applied hooked fibres (HF) can not homogeneously distribute the stress and limit the cracks (especially the micro-cracks) development. Therefore, some macro-cracks are easily created and can freely grow during the impact process, which facilitates the generation of the scabbing at the rear surface of the UHPFRC target.

Consequently, to well resist the impact from high velocity projectile, the restriction of crack growth is the most important technical point. In practice, to produce a protective structure with great impact resistance capacity, the developed sustainable UHPFRC with hybrid steel fibres (HF + LSF) should be a suitable choice.

4. Conclusions

This paper evaluates the energy absorption capacity of a sustainable UHPFRC in quasi-static mode and 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 experimental studies on UHPFRC are performed by employing 4-point bending test and high velocity projectile impact tests. From the obtained results the following conclusions can be drawn:

- With the same concrete matrix and steel fibre dosage (2% vol), different steel fibres have different contributions to the properties of the sustainable UHPFRC. For instance, the addition of short straight fibres (SSF) can significantly improve the homogeneity of the concrete mixture and simultaneously enhance its compressive strength (about 135 MPa), while the ternary hybrid fibres are beneficial in increasing the peak force of UHPFRC in the 4-point bending test (about 43.1 kN).
- Although the utilization of hybrid steel fibres can enhance the mechanical properties of the developed UHPFRC, the application of fibres with hooked ends is crucial for improving its energy absorption capacity in quasi-static mode. This can be attributed to the fact that the hooks at the ends of HF can improve the coupling force between the fibres and concrete matrix, which causes that a higher force is needed to pull this fibre type out (compared to SSF or LSF). Hence, during the strain softening process, HF can still bridge the macrocracks, and still a large amount of energy is needed to pull the HF out.
- The developed sustainable UHPFRCs can block the fired bullet (7.62 mm) with a velocity about 830 m/s. However, it is experimentally demonstrated that the application of hybrid fibres (HF + LSF) is more efficient than using only HF in improving the energy dissipation capacity of concrete target, particularly in resisting the scabbing at the rear surface of the UHPFRC target.
- The difference of the UHPFRC energy absorption capacity between the quasi-static mode and under high velocity projectile impact can be attributed to the difference between the employed experimental evaluation methods. Due to the fact that the 4-point bending test is executed in quasi-static condition, the used fibres have enough time to be pulled out. Hence, the hooked fibre is more efficient than straight fibre in absorbing the external energy.
- Differently from the quasi-static test, the high velocity projectile impact occurs in a very short time (μs scale), which causes that only local damages appear in the sustainable UHPFRC target. Therefore, with the application of hybrid fibres, the stress can be homogeneously distributed and the cracks growth can be effectively restricted surrounding the local damage area. Consequently, to produce a protective structure/element with great impact resistance capacity, the developed sustainable UHPFRC with hybrid steel fibres (HF + LSF) should be a suitable candidate.

Acknowledgements

The authors wish to express their gratitude to MSc. Nikos Kanavas, MSc. Xu Gao, Capt. Leon Kaim, Ing. Jan Pieter Zeeman for assisting the experimental work. Moreover, the appreciation goes to the following sponsors of the Building Materials research group at TU Eindhoven: Graniet-Import Benelux, Kijlstra Betonmortel, Struyk Verwo, Attero, ENCI HeidelbergCement, Provincie Overijssel, Rijkswaterstaat Zee en Delta - District Noord, Van Gansewinkel Minerals, BTE, V.d. Bosch Beton, Selor, Twee "R" Recycling, GMB, Schenk Concrete Consultancy, Geochem Research, Icopal, BN International, Eltomation, Knauf Gips, Hess ACC Systems, Kronos, Joma, CRH Europe Sustainable Concrete Centre, Cement&BetonCentrum, Heros and Inashco (in chronological order of joining).

List of symbols and abbreviations

Symbols

D	Particle size μm
D_{max}	Maximum particle size μm
D_{min}	Minimum particle size μm
P_{mix}	Composed mix
P_{tar}	Target curve
$P(D)$	A fraction of the total solids being smaller than size D
q	Distribution modulus
R^2	Coefficient of determination
RSS	Sum of the squares of the residuals

Abbreviations

HF	Hooked Fibre
JSCE	Japan Society of Civil Engineers
LSF	Long Straight Fibre
LSM	Least Squares Method
OPC	Ordinary Portland Cement
SSF	Short Straight Fibre
SSM	Solid Suspension Model

References

[1] B.M. Luccioni, R.D. Ambrosinia, R.F. Danesia, Analysis of building collapse under blast loads, Eng. Struct. 26 (1) (2004) 63–71.
[2] P.M. Booker, J.D. Cargile, B.L. Kistler, V.L. Saponara, Investigation on the response of segmented concrete targets to projectile impacts, Int. J. Impact Eng. 36 (2009) 926–939.
[3] H. Wu, Q. Fang, X.W. Chen, Z.M. Gong, J.Z. Liu, Projectile penetration of ultra-high performance cement based composites at 510–1320 m/s, Constr. Build. Mater. 74 (2015) 188–200.
[4] M. Beppu, K. Miwa, M. Itoh, M. Katayama, T. Ohno, Damage evaluation of concrete plates by high-velocity impact, Int. J. Impact Eng. 35 (2008) 1419–1426.
[5] H.M. Wen, Y.X. Xian, A unified approach for concrete impact, Int. J. Impact Eng. 77 (2015) 84–96.
[6] R. Sovják, T. Vavřiník, j. Zatloukal, P. Máca, T. Mičunek, M. Frydrýn, Resistance of slim UHPFRC targets to projectile impact using in-service bullets, Int. J. Impact Eng. 76 (2015) 166–177.
[7] R.P. Kennedy, A review of procedures for the analysis and design of concrete structures to resist missile impact effects, Nucl. Eng. Des. 37 (1976) 183–203.
[8] Q.M. Li, S.R. Reid, H.M. Wen, A.R. Telford, Local impact effects of hard missiles on concrete targets, Int. J. Impact Eng. 32 (2005) 224–284.
[9] V. Bindiganavile, N. Banthia, B. Aarup, Impact response of ultra-high-strength fibre-reinforced cement composite, ACI Mater. J. 99 (2002) 543–548.
[10] M.H. Zhang, M.S.H. Sharif, G. Lu, Impact resistance of high-strength fibre-reinforced concrete, Mag. Concr. Res. 59 (3) (2007) 199–210.
[11] E. Parant, P. Rossi, E. Jacquelin, C. Boulay, Strain rate effect on bending behaviour of new ultra-high-performance cement-based composite, ACI Mater. J. 104 (2007) 458–463.
[12] K. Habel, P. Gauvreau, Response of ultra-high performance fibre reinforced concrete (UHPFRC) to impact and static loading, Cem. Concr. Comp. 30 (10) (2008) 938–946.
[13] J. Lai, W. Sun, Dynamic behaviour and visco-elastic damage model of ultra-high performance cementitious composite, Cem. Concr. Res. 39 (2009) 1044–1051.
[14] H.J.H. Brouwers, H.J. Radix, Self-compacting concrete: theoretical and experimental study, Cem. Concr. Res. 35 (2005) 2116–2136.
[15] G. Hüsken, H.J.H. Brouwers, A new mix design concept for each-moist concrete: A theoretical and experimental study, Cem. Concr. Res. 38 (2008) 1249–1259.
[16] M. Hunger, H.J.H. Brouwers, Flow analysis of waterpowder mixtures: application to specific surface area and shape factor, Cem. Concr. Comp. 31 (1) (2009) 39–59.
[17] P. Máca, R. Sovják, P. Konvalinka, Mix design of UHPFRC and its response to projectile impact, Int. J. Impact Eng. 63 (2014) 158–163.
[18] R. Yu, P. Spiesz, H.J.H. Brouwers, Mix design and properties assessment of

Ultra-High Performance Fibre Reinforced Concrete (UHPFRC), Cem. Concr. Res. 56 (2014) 29–39.
[19] R. Yu, P. Tang, P. Spiesz, H.J.H. Brouwers, A study of multiple effects of nano-silica and hybrid fibres on the properties of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) incorporating waste bottom ash (WBA), Constr. Build. Mater. 60 (2014) 98–110.
[20] R. Yu, P. Spiesz, H.J.H. Brouwers, Effect of nano-silica on the hydration and microstructure development of Ultra-High Performance Concrete (UHPC) with a low binder amount, Constr. Build. Mater. 65 (2014) 140–150.
[21] R. Yu, P. Spiesz, H.J.H. Brouwers, Static properties and impact resistance of a green Ultra-High Performance Hybrid Fibre Reinforced Concrete (UHPHFRC): experiments and modeling, Constr. Build. Mater. 68 (2014) 158–171.
[22] R. Yu, P. Spiesz, H.J.H. Brouwers, Development of an eco-friendly Ultra-High Performance Concrete (UHPC) with efficient cement and mineral admixtures uses, Cem. Concr. Comp. 55 (2015) 383–394.
[23] R. Yu, P. Spiesz, H.J.H. Brouwers, Development of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC): towards an efficient application of binders and fibres, Constr. Build. Mater. 79 (2015) 273–282.
[24] A.H.M. Andreasen, J. Andersen, Über die Beziehungen zwischen Kornabstufungen und Zwischenraum in Produkten aus losen Körnern (mit einigen Experimenten), Kolloid-Zeitschrift 50 (1930) 217–228 (In German).
[25] J.E. Funk, D.R. Dinger, Predictive Process Control of Crowded Particulate Suspensions, Applied to Ceramic Manufacturing, Kluwer Academic Publishers, Boston, the United States, 1994.
[26] G. Hüsken, A Multifunctional Design Approach for Sustainable Concrete with Application to Concrete Mass Products, PhD thesis, Eindhoven University of Technology, Eindhoven, the Netherlands, 2010.
[27] BS EN 12390–3, Testing Hardened Concrete Part 3: Compressive Strength of Test Specimens, British Standards Institution-BSI and CEN European Committee for Standardization, 2009.
[28] BS EN 12390–5, Testing Hardened Concrete – Part 5: Flexural Strength of Test Specimens, British Standards Institution-BSI and CEN European Committee for Standardization, 2009.
[29] STANAG 2280, Test Procedures and Classification of the Effects of Weapons on Structures, North Atlantic Treaty Organization (NATO), 2010.
[30] JSCE Standard SF-4, Method of Test for Flexural Strength and Flexural Toughness of Fibre Reinforced Concrete, Japan Society of Civil Engineers (JSCE), 1984.
[31] T. Vincent, T. Ozbakkaloglu, Influence of fiber orientation and specimen end condition on axial compressive behavior of FRP-confined, Constr. Build. Mater. 47 (2013) 814–826.
[32] N. Banthia, F. Majdzadeh, J. Wu, V. Bindiganavile, Fiber synergy in Hybrid Fiber Reinforced Concrete (HyFRC) in flexure and direct shear, Cem. Concr. Comp. 48 (2014) 91–97.
[33] N. Ganesan, P.V. Indira, M.V. Sabeena, Bond stress slip response of bars embedded in hybrid fibre reinforced high performance concrete, Constr. Build. Mater. 50 (2014) 108–115.
[34] N. Banthia, R. Gupta, Hybrid fiber reinforced concrete (HyFRC): fiber synergy in high strength matrices, Mater. Struct. 37 (10) (2004) 707–716.
[35] S. Grünewald, Performance-based Design of Self-compacting Fibre Reinforced Concrete, Delft University of Technology, Delft, the Netherlands, 2004.
[36] I. Markovic, High-performance Hybrid-fibre Concrete – Development and Utilisation, Ph.D. thesis, Technische Universität Delft, 2006.
[37] R. Sovják, T. Vavřiník, P. Máca, J. Zatloukal, P. Konvalinka, Y. Song, Experimental investigation of Ultra-high Performance Fibre Reinforced Concrete slabs subjected to deformable projectile impact, Procedia Eng. 65 (2013) 120–125.
[38] Proceedings of the 9th International Conference on the Mechanical and Physical Behaviour of Materials under Dynamic Loading. 2009. Brussels, Belgium.
[39] Proceedings of the Second International Symposium on Ultra-High Performance Concrete. 2008. Kassel, Germany.
[40] Proceedings of the Third International Symposium on Ultra-High Performance Concrete. 2012. Kassel, Germany.
[41] R. Yu, L. van Beers, P. Spiesz, H.J.H. Brouwers, Impact resistance of a sustainable Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) under pendulum impact loadings, Constr. Build. Mater. 107 (2016) 203–215.