Resistance of multi-layered UHPFRC against in-service projectile: Experimental investigation and modelling prediction

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ABSTRACT

The present paper studies the ballistic performance of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) applying multi-layered concept against the 7.62 mm projectile at 840 m/s. Coarse basalt aggregates are incorporated in the UHPFRC under the premise of reducing the cement powder consumption and taking advantages of their superior ballistic resistance. We found that the designed triple-layered UHPFRC 16a1s(40)-8a1s(10)-16a1s(40) achieves a superior impact resistance compared to the single-layered reference, with a 32% reduction of the penetration depth. The improved resistance of the triple-layered UHPFRC is associated with the multiple effects of the coarse aggregate, the layer interface, the fibers direction in the thin middle layer, and the edge confinement of the rear layer. Moreover, a new analytical model is proposed to predict the penetration depth in the multi-layered UHPFRC, which can take the varying mechanical properties of the targeted layers into consideration. The results from this study shed light on understanding the ballistic performance of layered UHPFRC, and promote its application in protective constructions.

1. Introduction

The increasing risks of ballistic impacts in conflict areas or under terrorist attacks highlight the importance of strengthening specialized infrastructures, e.g. protective constructions and defense shelters. Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is a promising construction material [1,2], the outstanding mechanical characteristics of which can provide an effective protection to these infrastructures. Coarse aggregates are usually eliminated from conventional UHPFRC [3–5]. On the one side, using only fine aggregates in UHPFRC benefits its strength enhancement. On the other side, coarse aggregates can improve the impact resistance of cementitious targets [6,7]. The above facts, therefore, promote the idea of developing coarse-aggregated UHPFRC possessing the advantages of both the ultra-high strength of the matrix and the improved resistance provided by the coarse aggregates. Insufficient studies have been conducted to explore the ballistic performance of coarse-aggregated UHPFRC, i.e. most studies focus on conventional UHPFRC. Among the limited studies, Wu et al. tested the resistance of UHPFRC containing corundum [8] and basalt [9] aggregates against the 25.3 mm projectile, and claimed that the coarse aggregates are beneficial to reduce both the penetration depth and the impact crater size. It should be noted that their studies focus on the response of UHPFRC against large caliber projectiles (> 12.6 mm). In contrast, very few study investigates the resistance under small caliber arms, e.g. 7.62 mm projectile, although it is a common in-service weapon in many countries [6].

Furthermore, steel fibers in UHPFRC significantly enhance its toughness [10–12]. Fibers can prevent the severe concrete spalling at the rear side of the impacted structure, which may cause second injuries/damage on the people and objects behind it [13]. Three response regions appear in a UHPFRC target when it is under impact, namely the impact region, the tunnel region and the rear region [6,13,14]: (1) In the impact region, the UHPFRC is crushed by the projectile with concrete pieces ejected off from the surface. An impact crater is generated and cracking occurs around the crater as the stress waves are reflected several times inside the target. (2) In the tunnel region, a cylindrical tunnel is formed by the penetrating projectile. This region is mainly under compression, thus, the tunnel diameter is only slightly greater than the projectile diameter. (3) In the rear region, due to the wave reflection, the compressive waves generated by the projectile turn to be tensile ones, which can produce spalling and scabbing in the rear surface.

The above response regions show that the fracture characteristic of UHPFRC changes along the projectile trajectory. On that account, a homogeneous structure is not the most favorable option as it cannot take the full advantages of the ingredients in the UHPFRC target, e.g. (A).
the coarse aggregates and the steel fibers. An innovative approach to generate a more effective ingredient utilization and to improve the overall impact resistance is designing multi-layered target with ingredients varying according to the response regions [15,16]. Rather inadequate studies can be found in open literature regarding the ballistic analysis of multi-layered concrete. Shao et al. [18] investigated the resistance of a composite target containing a ceramic protective layer and an ultra-high strength concrete layer; their study exhibited that the ceramic balls in the protective layer contribute to eroding the projectile and deviating its trajectory. Lai et al. [17] developed a concrete target composed of a coarse-aggregated layer and a fiber-reinforced layer, and obtained that it has a decreased penetration depth and a reduced crater area. Quek et al. [15] designed a four-layered cementitious composite: the first and the last layers had hybrid fibers, the second layer had coarse aggregates, and the third layer was composed of plain mortar. It is claimed that the developed layered composite in their study has a superior ballistic resistance. Despite these benefits, compared to the numerous studies on single-layered targets, research on multi-layered concrete target is still insufficient, not to mention the multi-layered UHPFRC.

In addition, predicting the penetration depth in UHPFRC is essential for assessing its ballistic resistance. The cavity expansion theory is widely utilized to develop theoretical predicting models for concrete targets [19-21]. For instance, our previous study [22] proposed a nonlinear rate-dependent model to estimate the penetration depth in single-layered UHPFRC, showing a satisfying effectiveness. Nevertheless, most of the current prediction models are proposed for single-layered concrete with homogeneous properties in the whole target. Parameters in these models are obtained based on the overall responses of single-layered targets, and they cannot reflect the changing properties of layered targets. Therefore, using them for multi-layered targets can lead to inaccurate results. To the best of the authors’ knowledge, there is yet no predicting model available to estimate the penetration depth in UHPFRC composed of multiple layers. The present study develops layered UHPFRC with coarse basalt aggregates incorporated, which innovatively takes the advantages of the UHPC matrix, the coarse aggregates, as well as the layered structure. The ballistic resistances of the developed targets are evaluated against in-service 7.62 mm × 51 AP (armor-piercing) projectile at a velocity of around 840 m/s. The effects of the fibers and aggregates are discussed with the single-layered UHPFRC, while the potential enhancing mechanisms of the layered structure are revealed with the double-layered targets. Based on these, the triple-layered UHPFRC is designed, achieving the optimum arrangements of the fiber amount and the aggregate size with the optimal layer thicknesses. Moreover, an analytical model to predict the penetration depth in the multi-layered UHPFRC is proposed, on the basis of an improved cavity expansion theory. The proposed predicting model is able to account for the varying mechanical properties and the layers’ order in the multi-layered targets, which distinguishes this new model from previous models for the single-layered targets.

2. Materials and experimental methods

2.1. Materials and mix design

The recipes of the UHPFRC are presented in Table 1. The raw materials include: Portland Cement CEM I 52.5 R, limestone powder, micro-silica, standard sand, basalt aggregates of four size fractions (diameter: 2–5 mm, 5–8 mm, 8–11 mm and 8–16 mm), tap water, PCE based superplasticizer (35% solid content), and two types of steel fibers (straight fiber and hooked-end fiber, as shown in Fig. 1). The fractions of the materials are determined based on our previous studies [23] with the Brouwers mix design method [24,25]. More information about the chemical properties of the raw materials, the mix design and workability of the coarse-aggregated UHPFRC can be found in our previous studies [3,26].

2.2. Design of the layered UHPFRC target

The designed UHPFRC are listed in Table 2. The single-layered UHPFRC is labeled as group S1-4; while the double- and the triple-layered UHPFRC are labeled as groups D1-4 and T1-7, respectively. The letters a, s and h in the identification present the aggregate, the straight fiber (SF) and the hooked-end fiber (HF), respectively; the number before the letter a is the maximum aggregate size of the designed UHPFRC layer (in mm), while the numbers before s and h are the volume fractions of SF and HF in that layer; the layer thickness (in mm) is shown by the number inside the brackets. For instance, 8a1.5s(30)-16a (30)-8a1.5s(30) is a UHPFRC target composed of three layers with an equal thickness of 30 mm; the first and the third layers have 1.5% of SF and the maximum aggregate size is 8 mm; whereas the second layer has no fiber and the maximum aggregate size is 16 mm. In total 30 targets were tested, including 8 single-layered targets, 8 double-layered targets and 14 triple-layered targets.

2.3. Mixing and casting procedure

The mixing and casting of the UHPFRC samples were conducted at room temperature. The mixing procedure is as follows: dry mixing of all powders and sand for 2 min; adding 75% of the water and mixing for another 2 min; adding the superplasticizer with the remaining water and mixing for 4 min; adding the steel fibers and mixing for 3 min; subsequently adding the basalt aggregates and mixing for 4–6 min until they are well distributed in the mixture.

Cylindrical mould with a diameter of approximately 275 mm was utilized for casting the target. This diameter is more than 30 times of the projectile diameter, hence boundary effects can be eliminated [17,27]. The compressive, tensile and bond strengths of the designed UHPFRC (see Table 1) were tested using 100 mm cubes. For the multi-layered UHPFRC, the layers were cast one on top of another with a time interval of around 45 min. More information about the casting method can be found in our previous study [3]. Normal water curing method was applied and the tests were conducted at around 56 days.

2.4. Testing methods

A universal testing machine was adopted for the compression, tension and bond tests of the designed UHPFRC mixtures. The compressive strengths were measured based on EN 12390-3 [28], while the splitting tensile and interface bond strengths were tested according to EN 12390-6 [29,30]. For the penetration tests, in-service 7.62 mm × 51 AP projectile was utilized (see Fig. 2) [31]. The cylindrical UHPFRC target was mounted by a specially designed steel frame fixed on the ground to prevent its movement during the ballistic tests. As presented in Fig. 3, the top and bottom edges of the UHPFRC were clamped by two screws to simulate point supports [32]. The center of the frame has a hole with a diameter slightly smaller than the size of the UHPFRC target (Fig. 3a), thus, the spalling fragments from the distal face of the UHPFRC are not restrained and their traces can be observed by the damage on the white board behind the frame (Fig. 3b). After the penetration tests, the targets were cut along the axial direction with a saw cutting machine.

3. Experimental results

3.1. Static mechanical properties

The compressive strength σc,a and the splitting tensile strength σt,a of the designed UHPFRC at the age of 56 days are given in Table 3. Thanks to the dense particle size distribution resulted from the optimal mix designs, the coarse-aggregated UHPFRC achieve an ultra-high σc,a satisfying the strength condition of UHPFRC. A slight increase of σc,a is
even observed for the UHPFRC containing the 16 mm basalt aggregates than those with the 8 mm aggregates. This improved strength with the increase of the aggregate size is also reported in other studies [33–35]. Moreover, the UHPFRC with the hybrid fibers generates the highest increase of the aggregate size is also reported in other studies [33–35].

The difference of $\sigma_{a,s}$ is relatively small. The maximum difference is within 8%, as obtained by comparing $8a$ with $16a1r$. As suggested by previous ballistic studies, the penetration depth no longer decreases remarkably when the concrete strength is higher than a certain value, e.g. 90 MPa [9] ~100 MPa [36]. Therefore, in the ballistic performance analysis in Section 4, the influences of these different $\sigma_{a,s}$ on the impact resistances of the developed UHPFRC targets are neglected. More detailed information regarding the properties of the coarse-aggregated UHPFRC at the material level can be found in our previous study [37].

The interfacial bond strength $\sigma_b$ between the layers are listed in Table 4. Cohesive failure occurs during the bond splitting tests, i.e. cracking is observed to propagate through both layers in each specimen. Therefore, the obtained $\sigma_b$ of each specimen is associated with the properties of its two layers and the crack lengths in both layers. The maximum $\sigma_b$ is achieved by $8a1h-16a1s$, which is around 8.58 MPa. The minimum $\sigma_b$ is obtained by $8a-8a1s$ with a value of approximately 6.79 MPa. As depicted in Table 4, $\sigma_b$ is on the same order as the $\sigma_s$ of the plain UHPC, showing that the layers are strongly bonded. Nonetheless, due to the lack of steel fibers in the interfacial zone, the layer interface is still the weakest part in the UHPFRC target and potential interface cracking is expected during the ballistic test. The influences of the interface cracking are further analyzed in Sections 4.2 and 4.3.

3.2. Ballistic test results

The projectile before and after the ballistic test is shown in Fig. 4. When the projectile hits the UHPFRC, the large penetration velocity immediately invokes extremely high pressure on the projectile [18], and the friction between the projectile and the UHPFRC generates a very high temperature on their contact surface. Consequently, the bass jacket of the projectile partially melts and the projectile is splitted into separate parts, e.g. the hard core and the end cap (see Fig. 2b). The lead jacket is totally destroyed and it cannot be collected after the test. The bass jacket and end cap of the projectile are also severely damaged due to the combined effects of the large impact stress and the high temperature rising in the penetration process. The hard core continues to impact the UHPFRC after it separates from the bass jacket. The collisions with the UHPC matrix, the coarse aggregates and the fibers in the target result in very obvious scratches on the surface of the hard core (see Fig. 5).

The resistant capacity of the designed UHPFRC are evaluated in Table 5. The penetration depth $P$ is defined as the distance from the impact surface to the deepest point in the target, and the equivalent crater diameter $D_{eq}$ is calculated as $D_{eq} = \sqrt{D_1 D_2}$ (see Fig. 5a). The damage in the rear surface, i.e. cracks, spalling or scabbing, is not prominent in most targets (e.g. Fig. 5b). That being the case, it is used only for qualitative evaluations [38,39]:

- Level 1. No visible damage to hairline cracks.
- Level 2. Visible cracks without scabbing.
- Level 3. Heavy cracking.
- Level 4. Scabbing and spalling or shear plug without perforation.

A systematical analysis of the ballistic performances of the single-, double- and triple-layered UHPFRC is presented in Section 4.

4. Discussions

4.1. Response of single-layered UHPFRC

The $P$ and $D_{eq}$ of the single-layered targets S1-3 are shown in Fig. 6. The three groups have comparable $P$ of about 61 mm, indicating the

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Table 1

| Recipes of the UHP(FR)C: CEM = cement, LP = limestone powder, mS = micro-silica, S = sand, BA 2–5 = basalt aggregate with a diameter of 2–5 mm, BA 5–8 = basalt aggregates with a diameter of 5–8 mm, BA 8–11 = basalt aggregates with a diameter of 8–11 mm, BA 8–16 = basalt aggregates with a diameter of 8–16 mm, W = water (water from SP is included), SP = superplasticizer, SF = straight fiber, HF = hook-end fiber. |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| CEM (kg/m³) | LP (kg/m³) | mS (kg/m³) | S (kg/m³) | BA 2–5 (kg/m³) | BA 5–8 (kg/m³) | BA 8–11 (kg/m³) | BA 8–16 (kg/m³) | W (kg/m³) | SP (kg/m³) | SF (%) | HF (%) |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| 588.0 | 156.8 | 39.2 | 839.9 | 413.2 | 232.3 | 0 | 0 | 149.0 | 9.4 | 0 | 0 |
| 157.0 | 8.5 | 1.0 | 0.5 | 0.5 | 0.5 | 0 | 0 | 157.0 | 12.5 | 1.5 | 0 |
| 525.0 | 140.0 | 35.0 | 699.3 | 445.2 | 186.9 | 147.8 | 209.6 | 154.0 | 4.9 | 0 | 0 |
| 161.0 | 4.5 | 1.0 | 0 | 0 | 0 | 1.0 | 0 | 161.0 | 6.5 | 1.5 | 0 |

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Fig. 1. Fibers used in the UHPFRC.
insignificant effects of fiber geometry and fiber hybridization on the penetration depth. On the contrary, fiber hybridization decreases the damage size in UHPFRC, as confirmed by the smallest $D_{co}$ of S2 among the three groups. This phenomenon may be associated with the higher tensile strength of the S2 matrix. The hybridization of the short SF and the long HF can produce synergistic effects on the cracking control ability, i.e. the short fibers can effectively bridge micro-cracks while long fibers contribute more to the prevention of macro-cracks [40].

In comparing S1 with S4 in Fig. 6 demonstrates that larger aggregates can promote a superior resistance. $P$ and $D_{co}$ of S4 (with the maximum aggregate size of 16 mm) are about 11% and 16% smaller than those of S1 (with the maximum aggregate size of 8 mm). When the
4.2. Response of double-layered UHPFRC

Performances of the double-layered UHPFRC are discussed in this section, with the enhancing mechanisms of the layered structure addressed. As shown in Fig. 7, D1-3 have comparable P and Deq, indicating that the fiber geometry scarcely affects the ballistic resistance when the maximum aggregate size of the target is 8 mm. These agree with the observations in Section 4.1. In contrast, the damage distribution differs with different fibers when the maximum aggregate size is 16 mm. As presented in Fig. 8, serious spalling of concrete pieces is observed on the rear surface of D2 (with HF in the rear layer), whereas D3 (with SF in the rear layer) has slight damage, namely only hairline cracks appear on its back side. This distinct damage level indicates that for the UHPFRC with a maximum aggregate size of 16 mm, the short SF can provide a more effective damage control compared to the long HF. Possible reasons are illustrated in Fig. 9. Firstly, with the same fiber volume fraction, a larger number of short SF is added into the UHPFRC than the long HF, which results in the superior control on target cracking. Secondly, the distribution of the long HF in the 16 mm coarse-aggregated UHPFRC can be more inclined due to the large size of the aggregate and the long length of the HF. These inclined HF cannot provide a cracking resistance as efficient as the aligned fibers, because of their reduced pullout resistance at large inclinations [10]. Thirdly, the longer HF generates higher stresses in the surrounding concrete and produces a larger disturbed zone of matrix, leading to a more serious damage in the target [41].

Increasing the aggregate size in either the impact or the rear layers of the UHPFRC reduces P, and this reduction is more remarkable when the large aggregates are in the impact layer. For example, D1 has a 9% smaller P compared to S1, while D4 achieves a 20% decrease. This is

**Table 5**

Penetration test results of designed UHPFRC: Level 1. No visible damage to hairline cracks; Level 2. Visible cracks without scabbing; Level 3. Heavy cracking; Level 4. Scabbing and spalling or shear plug without perforation.

| Group | Identification | Penetration velocity (m/s) | Penetration depth (mm) | Equivalent crater diameter (mm) | Damage in the rear surface |
|-------|----------------|---------------------------|------------------------|-------------------------------|---------------------------|
|       | 1st sample     | 2nd sample                | 1st sample             | 2nd sample                    | Avg.                      | 1st sample | 2nd sample | Avg. | 1st sample | 2nd sample | Avg. | 1st sample | 2nd sample | Avg. |
| S1    | 8x1s(90)       | 838.5                     | 841.9                  | 62.0                          | 60.0                       | 61.0                    | 75.70      | 70.00       | 72.85 | Level 2    |
| S2    | 8x0.5s0.5h(90) | 839.3                     | 841.8                  | 61.0                          | 60.5                       | 60.8                    | 66.10      | 70.00       | 68.05 | Level 1    |
| S3    | 8x1h(90)       | 839.6                     | 841.6                  | 62.0                          | 61.0                       | 61.5                    | 74.10      | 75.22       | 74.66 | Level 2    |
| S4    | 16x1s(90)      | 840.7                     | 847.3                  | 55.0                          | 55.0                       | 55.0                    | 62.95      | 62.55       | 62.75 | Level 2    |
| D1    | 8x1s(45)-16x1s(45) | 842.6                   | 845.0                  | 57.0                          | 55.0                       | 56.0                    | 67.07      | 77.86       | 72.47 | Level 1    |
| D2    | 8x1s(45)-16x1s(45) | 845.2                   | 842.3                  | 54.0                          | 55.0                       | 54.5                    | 67.92      | 70.54       | 69.23 | Level 1    |
| D3    | 8x1h(45)-16x1s(45) | 845.4                   | 846.1                  | 59.0                          | 54.0                       | 56.5                    | 69.72      | 72.84       | 71.28 | Level 1    |
| D4    | 16x1s(45)-8x1s(45) | 841.0                   | 842.9                  | 51.0                          | 53.0                       | 52.0                    | 57.55      | 65.19       | 61.37 | Level 2    |
| T1    | 8x1.5s30-8x0.5h30-8x1.5s30 | 836.0                 | 846.3                  | 54.0                          | 58.0                       | 56.0                    | 67.19      | 69.50       | 68.35 | Level 2    |
| T2    | 8x1.5s30-8x0.5h30-8x1.5s30 | 837.9                | 850.2                  | 56.0                          | 60.0                       | 58.0                    | 80.00      | 61.60       | 70.80 | Level 2    |
| T3    | 8x1.5s30-16x1s30-8x1.5s30 | 841.8                 | 845.4                  | 55.0                          | 57.0                       | 56.0                    | 70.20      | 72.00       | 71.10 | Level 2    |
| T4    | 16x1.5s30-8x0.5h30-16x1.5s30 | 840.9                 | 845.9                  | 52.5                          | 51.0                       | 51.8                    | 53.08      | 59.54       | 56.31 | Level 1    |
| T5    | 16x1.5s30-8x1s30-16x1s30 | 842.5                 | 845.2                  | 54.0                          | 54.5                       | 54.3                    | 70.64      | 65.10       | 67.92 | Level 1    |
| T6    | 16x1s30-8x1s30-16x1s30 | 839.3                 | 841.5                  | 52.5                          | 52.0                       | 52.3                    | 67.92      | 65.19       | 66.56 | Level 1    |
| T7    | 16x1s30-8x1s30-16x1s30 | 838.5                 | 840.0                  | 49.0                          | 46.5                       | 47.8                    | 72.52      | 65.56       | 69.04 | Level 1    |
because in D1 the large coarse aggregate starts to play a role until the projectile reaches the rear layer, while in D4 its effect is activated immediately when the projectile touches the impact surface (see Fig. 10).

With regard to $D_{eq}$, increasing the maximum aggregate size of the impact layer shows a positive effect; however, the larger aggregates have almost no influence on $D_{eq}$ when they are added to the rear layer.

Moreover, the double-layered D4 has a smaller $P$ than the single-layered S4 with the large aggregates in the whole volume. This can be attributed to the effects of the layered structure. Firstly, the layer interface invokes more wave interactions in the double-layered UHPFRC and dampens the strength of the impact waves [42]. Secondly, the network of cracks inside the double-layered target along the layer interface contributes to an additional absorption of the projectile kinetic energy [15], as can be observed in the cross sections of D4 in Fig. 10. Thirdly, the interface cracking reduces the damage in the rear layer of the double-layered UHPFRC, and this stronger back side in turn provides a greater resistance to the projectile, in comparison to the single-layered UHPFRC undergoing substantial cracking in the whole target. Fourthly, the different maximum aggregate sizes in the two layers of D4 may generate different confinement levels. Since the projectile usually seeks a path of the least resistance [43], this different confinement therefore affects the projectile trajectory [44]. The deviation of the trajectory is not very obvious in Fig. 10b because of the small $P$ in D4. However, it can be clearly observed in D1 with a larger $P$ (see Fig. 10a), showing the change of the ballistic trajectory from a normal direction to an oblique one. Furthermore, it is worth mentioning that in spite of the interfacial cracks, layer delamination did not occur, i.e. the multi-layered UHPFRC targets are able to retain their integrity rather than disintegrate into separated layers.

4.3. Response of triple-layered UHPFRC

The improved resistance of the double-layered UHPFRC suggests the benefits of applying a layered structure. In this section, triple-layered UHPFRC is designed with the optimal arrangements of both the fiber amount and the aggregate size. The penetration results of T1-4 are presented in Fig. 11.

The influences of arranging the fibers in the layered UHPFRC can be obtained by comparing T1 with S1 or T2 with S3. As shown in Fig. 11, the fiber amount arrangement reduces both $P$ and $D_{eq}$, confirming that the fibers are more efficiently utilized when they are distributed in the two outer layers than in the middle part of the target. This is in line with the target fracture characteristics described in Section 1, i.e. cracking appears in the impact and rear regions, whereas the middle tunneling region is under compression with a confinement pressure and the contribution of the fibers is relatively limited in this region.

Furthermore, the comparable $P$ and $D_{eq}$ of T1 and T3 exhibit that the aggregate size in the middle layer of the target has negligible effects. On the contrary, the maximum aggregate size of the outer layers plays a role. As shown in Fig. 11, T4 has an 8% decreased $P$ than that of T1, and its $D_{eq}$ is remarkably reduced as well (approximately 21% smaller than that of T1). In addition, the rear surface damage of T1-4 are presented in Fig. 12. These targets have comparable damage levels, i.e. some visible cracks appear in the distal surface while no concrete scabbing is observed. This further confirms the advantage of the triple-layered UHPFRC in preventing the second damage caused by the spalling concrete from the rear surface. Therefore, taking into account both $P$ and the damage in the two outer surfaces, the design of T4 with larger aggregates and more fibers in the outer layers is recommended.

Different layer thicknesses are further considered to obtain the optimal layer design of the triple-layered UHPFRC. The results are plotted in Fig. 13. A clear decrease of $P$ is observed with the increase of the outer layer thickness from 20, 30 to 40 mm, corresponding to T5, T6.
It is noteworthy that T7 achieves the smallest $P$ among all the tested targets in this study, which may be attributed to the following factors: the large coarse aggregate, the layer interface, the direction of fibers in the thin middle layer, and the edge confinement of the thick rear layer. The effects of the coarse aggregate and the layer interface have been mentioned in Sections 4.1 and 4.2, respectively. As with the contribution of the middle layer, the 10 mm thin layer of T7 restrains the randomly distribution of the 13 mm SF; instead, it forces the fibers to orientate in a 2D plane, which maximizes the fiber efficiency [45]. Since the fibers are forced to be distributed perpendicularly to the penetration direction, they work as a steel reinforcing mesh and provide an enhanced resistance to the projectile. T7 also has the smallest damage in its rear region. This almost intact rear layer of T7 further provides an enhanced edge confinement at the distinct surface, and therefore, generates a higher resistance to the projectile.

Fig. 11. Impact results of triple-layered UHPFRC: T1-4 are corresponding 8a1.5s(30)-8a(30)-8a1.5s(30), 8a1.5h(30)-8a(30)-8a1.5h(30), 8a1.5s(30)-16a(30)-8a1.5s(30) and 16a1.5s(30)-8a(30)-16a1.5s(30), respectively.

and T7. It is noteworthy that T7 achieves the smallest $P$ among all the tested targets in this study, which may be attributed to the following factors: the large coarse aggregate, the layer interface, the direction of fibers in the thin middle layer, and the edge confinement of the thick rear layer. The effects of the coarse aggregate and the layer interface have been mentioned in Sections 4.1 and 4.2, respectively. As with the contribution of the middle layer, the 10 mm thin layer of T7 restrains the randomly distribution of the 13 mm SF; instead, it forces the fibers to orientate in a 2D plane, which maximizes the fiber efficiency [45]. Since the fibers are forced to be distributed perpendicularly to the penetration direction, they work as a steel reinforcing mesh and provide an enhanced resistance to the projectile. T7 also has the smallest damage in its rear region. This almost intact rear layer of T7 further provides an enhanced edge confinement at the distinct surface, and therefore, generates a higher resistance to the projectile.

The damage on the side surface of T5-7 is depicted in Fig. 14. It is interesting to find that although the triple-layered target has two layer interfaces, only the interface between the middle and the rear layers shows obvious cracks, while no crack can be observed in the other interface between the impact and the middle layers by naked eyes. This single interface cracking is associated with the stress wave phenomena inside the UHPFRC. The compressive stress wave generated by the projectile is reflected as a tensile wave upon its arrival at the rear surface of the target; then the tensile stress wave interferes with the original compressive wave, resulting in a descendingly compressive and ascendingly tensile wave [14,46]. When the amplitude of the resulting tensile wave exceeds the bond strength between the layers, cracking would localize at the layer interface. However, the wave propagation and the cracking at the interface between the middle and the rear layers dissipate the wave energy. Consequently, the amplitude of the
reflection wave is dampened below the bond strength when it reaches the other interface between the impact and the middle layers. Therefore, no cracking occurs at the interface near the impact surface.

5. Penetration depth predicting model

5.1. Predicting model for multi-layered UHPFRC

In our previous study [22], an analytical model is proposed based on an improved cavity expansion theory to predict the penetration depth in single-layered UHPFRC. In this section, the model is further extended for multi-layered UHPFRC. As shown in Fig. 15, a UHPFRC target with n layers is under impact; the projectile penetrates through the n-1 layers and stops inside the nth layer. The penetration process in this n-layered UHPFRC can then be divided into n + 1 stages: (1) a cratering stage with a depth of \(kd\), which ends at time \(t_1\) with a projectile velocity of \(V_1\); (2) the 1st tunneling stage in the 1st layer with a depth of \(H_1\), which ends at \(t_2\) with a projectile velocity of \(V_2\); (n) the n-th tunneling stage in the n-th layer until the projectile stops at the depth \(P\) and the velocity is 0.

The Newton’s second law of motion yields:

\[
F = -M \frac{dV}{dt} = -MV \frac{dV}{dx}
\]

where \(F\) is the axial force on the projectile head; \(M\) is the mass of the projectile. \(V\) and \(x\) are the projectile velocity and displacement at time \(t\).

It is assumed that the axial force at the cratering stage \(F_1\) is proportional to \(x\) [47,48], i.e. \(F_1 = cx\) [47]. Substitute \(F_1\) into Eq. (1), and solve the equation with the boundary conditions: \(x\left(t=0\right) = 0\), \(V\left(t=0\right) = V_0\) and \(x\left(t=t_1\right) = kd\), \(V\left(t=t_1\right) = V_1\), one obtains the expression of \(c\). Therefore, \(F_1\) is given as:

\[
F_1 = \frac{M(V_0^2 - V_1^2)}{(kd)^2}x
\]

for \(x \leq kd\)

where \(k = 0.707 + h/d\), with \(h\) and \(d\) being the diameter and head length of the projectile [48]. \(V_0\) and \(V_1\) are the initial projectile velocity and that at the end of the cratering stage, respectively.

The axial force at the 1st and the \(n\)th tunneling stages, i.e. \(F_2\) and \(F_{n+1}\), can be expressed as [22]:

\[
F_2 = \frac{\pi d^2 c s_{n+1}}{4} \left( A_n + B_n N_i \sqrt{\frac{\rho_1}{\alpha_{s,n}}} V_1 + C_n N_i \left( \frac{\rho_1}{\alpha_{s,n}} V_1 \right)^2 \right)
\]

for \(kd \leq x < H_1\)

\[
F_{n+1} = \frac{\pi d^2 c s_{n+1}}{4} \left( A_n + B_n N_i \sqrt{\frac{\rho_1}{\alpha_{s,n}}} V_n + C_n N_i \left( \frac{\rho_1}{\alpha_{s,n}} V_n \right)^2 \right)
\]

for \(H_1 + \cdots + H_{n-1} \leq x < P\)

where \(\alpha_{s,n}\) and \(\rho_0\) are the compressive strength and density of the nth layer. \(N_i\) and \(N_0\) are the shape coefficients of the projectile head [19]. Parameters \(A_n\), \(B_n\), and \(C_n\) are determined based on the theoretical solutions of a new cavity expansion model in our previous study [22], and they are solved according to the material properties of the nth layer.

The projectile velocity at the beginning of the 1st tunneling stage, viz. \(V_1\), can be obtained by the continuous condition of the axial force at the end of the cratering stage, i.e. \(F_1\left(t=t_1\right) = F_2\left(t=t_2\right)\) and the boundary condition \(V\left(t=t_1\right) = V_1\), \(x\left(t=t_1\right) = kd\), resulting in:

\[
M(V_0^2 - V_1^2) = \frac{\pi d^2 c s_{1}}{4} \left( A_1 + B_1 N_0 \sqrt{\frac{\rho_1}{\alpha_{s,1}}} V_1 + C_0 N_0 \left( \frac{\rho_1}{\alpha_{s,1}} V_1 \right)^2 \right)
\]

Substituting Eq. (3) into Eq. (1) yields:

\[
\frac{\pi d^2 c s_{1}}{4} \left( A_1 + B_1 N_0 \sqrt{\frac{\rho_1}{\alpha_{s,1}}} V_1 + C_0 N_0 \left( \frac{\rho_1}{\alpha_{s,1}} V_1 \right)^2 \right) = -MV \frac{dV}{dx}
\]

Integrating Eq. (6) provides the relation between \(x\) and \(V\) in the 1st layer. Then the projectile velocity at the end of the 1st tunneling stage, viz. \(V_2\), can be obtained by considering the initial condition \(V\left(t=t_1\right) = V_1\), \(x\left(t=t_1\right) = kd\) and the end condition \(V\left(t=t_2\right) = V_2\), \(x\left(t=t_2\right) = H_1\), which leads to:

\[
\frac{H_1 - kd}{D_{1,1}} = \ln \left(1 + \frac{B_1 N_0}{A_1} \sqrt{\frac{\rho_1}{\alpha_{s,1}}} V_1 + C_0 N_0 \rho_0 V_2^2 \right) + 2D_{1,1} \left( \tan^{-1} D_{1,1} - \tan^{-1} \left( \frac{2D_{1,1} C_1 N_1 \sqrt{\frac{\rho_1}{\alpha_{s,1}}} V_1 + D_{1,1}}{B_1 N_1} \right) \right) - \ln \left(1 + \frac{B_1 N_0}{A_1} \sqrt{\frac{\rho_1}{\alpha_{s,1}}} V_1 + C_0 N_0 \rho_0 V_2^2 \right) - 2D_{1,1} \left( \tan^{-1} D_{1,1} - \tan^{-1} \left( \frac{2D_{1,1} C_1 N_1 \sqrt{\frac{\rho_1}{\alpha_{s,1}}} V_1 + D_{1,1}}{B_1 N_1} \right) \right)
\]

where \(D_{1,1} = \frac{3M}{\pi d^2 c s_{1} N_0}\), \(D_{2,1} = B_1 N_1/\sqrt{A_1 C_1 N_1} - (B_1 N_1)^2\).

Fig. 14. Damage in the side surface: T5-7 are triple-layered samples corresponding to 16a1s(20)-8a1s(50)-16a1s(20), 16a1s(30)-8a1s(30)-16a1s(30) and 16a1s(40)-8a1s(10)-16a1s(40), respectively.
With a similar process, the projectile velocity at the end of the n-1th tunneling stage, viz. \( V_n \) (n ≥ 3), can be obtained by solving Eq. (8). A positive \( V_n \) indicates that the projectile penetrates through the n-1th layer; otherwise it stops inside the n-1th layer, and the problem returns to the case of an (n-1)-layered target.

\[
\frac{H_{n-1}}{D_{n-1}} = \left( 1 + \frac{B_{n-1}N_i}{A_{n-1}^{\frac{1}{2}}V_{n-1}} + \frac{C_{n-1}N_iD_{n-1}}{A_{n-1}^{\frac{1}{2}}V_{n-1}} \right) + 2
\]

\[
D_{n-1} \times \tan^{-1} \left( \frac{2D_{n-1}N_i}{B_{n-1}N_i} \frac{\rho_{n-1}}{A_{n-1}^{\frac{1}{2}}V_{n-1}} + \frac{C_{n-1}N_iD_{n-1}}{A_{n-1}^{\frac{1}{2}}V_{n-1}} \right)
\]

Substituting Eq. (4) into Eq. (1) and integrating the result provide the relation between \( x \) and \( V \) in the n-th layer. Letting \( V = 0 \) finally yields the penetration depth in the n-layered UHPFRC:

\[
P = D_{n-1} \ln \left( 1 + \frac{B_{n-1}N_i}{A_{n-1}^{\frac{1}{2}}V_{n-1}} + \frac{C_{n-1}N_iD_{n-1}}{A_{n-1}^{\frac{1}{2}}V_{n-1}} \right) + H_n + \ldots + H_{n-1}
\]

where

\[
D_{n-1} = \frac{2M}{\pi \rho_{n-1} C_{n-1}}
\]

\[
D_{n-1} = B_nN_i \sqrt{4A_nC_nN_i} - (B_nN_i)^2.
\]

### 5.2. Model validation

The penetration depths of the single-, double- and triple-layered UHPFRC: 16a1s(90), 8a1s(45)-16a1s(45) and 16a1s(20)-8a1s(50)-16a1s(20) are taken to validate the proposed predicting model. The input parameters are given in Tables 6 and 7, in which the elastic modulus is calculated by 

\[
E = 8010\sigma_{c,s}^{0.36} \text{ (MPa)} \quad [49].
\]

The detailed process of determining the parameters \( A, B \) and \( C \) is given in our previous study [22].

The penetration depths obtained by the experiments and the proposed model are compared in Table 8. In addition, the extensively utilized empirical formulae, namely ACE, modified NDRD and UKAEA formulae [50], are also presented. These empirical formulae are developed for single-layered concrete with homogeneous material properties in the whole target. Hence, equivalent material properties are taken as the inputs when using these formulae for the layered UHPFRC. For example, the equivalent compressive strength of the triple-layered target \( \sigma_{c,eq} \) is determined by the composite theory [51] as:

\[
\sigma_{c,eq} = (\alpha_{c,1}H_1 + \alpha_{c,2}H_2 + \alpha_{c,3}H_3)/(H_1 + H_2 + H_3)
\]

### Table 6

| Diameter d (mm) | Mass M (g) | CRH \( \psi \) | \( N_1 \) | \( N_2 \) |
|----------------|------------|----------------|--------|--------|
| 7.62           | 10.5       | 5.0            | 0.3076 | 0.065  |

![Fig. 15. Illustration of penetration process in an n-layered target.](image)

\( P \) is the penetration depth; \( H_i \) is the thickness of the i-th layer (i = 1, n-1); \( k \) is an empirical parameter and \( d \) is the projectile diameter. \( t_i \) and \( V_i \) are the time and projectile velocity at the end of the i-th layer, respectively. \( t_i \) and \( V_i \) are the time and projectile velocity at the end of the i-th tunneling stage (i = 2, n + 1).
6. Conclusions

Layered UHPFRC targets containing coarse basalt aggregates are developed in the present study, and their ballistic performances are evaluated against the in-service 7.62 mm × 51 AP projectile at a velocity of about 840 m/s. Moreover, a new penetration depth predicting model for the layered UHPFRC is developed and validated, which gives accurate predictions for the single- and multi-layered UHPFRC. Some specific conclusions can be drawn from the study:

1. The coarse basalt aggregates in the UHPFRC target reduce both the penetration depth P and the equivalent crater diameter Deq. The P and Deq of 16a1s(90) are about 11% and 16% smaller than those of 8a1s(90). The improved resistance can be attributed to the increased material strength and hardness provided by the coarse aggregates, and the erosion and deviation of the projectile, which contributes to the dissipation of the projectile kinetic energy.

2. Fiber geometry insignificantly affects the ballistic performance; when the maximum aggregate size of the target is 8 mm, but for the UHPFRC with a maximum aggregate size of 16 mm, the straight fiber can provide a more effective damage control compared to the hooked-end fiber. Possible reasons are related to the higher amount of the straight fiber, the reduced pullout resistance of the inclined hooked-end fiber, and the smaller disturbed zone in UHPC with the short straight fiber.

3. For the double-layered UHPFRC, increasing the aggregate size in either layer decreases P. The double-layered UHPFRC 16a1s(45)-8a1s(45) has an approximately 20% smaller P in comparison to the single-layered target 8a1s(90). Possible enhancing mechanisms concerning the double-layered target include the layer interface that dampens the impact waves, the interfacial cracking that promotes the energy consumption, the reduced damage in the back side that provides a higher resistance, and the different confinement levels of the two layers caused by the different aggregate sizes.

4. For the triple layered UHPFRC, fiber amount arrangement in the layered structure reduces both P and Deq and the design of utilizing larger aggregates and more fibers in the outer layers is recommended. Furthermore, in spite of its 10% less cement dosage, the designed triple-layered UHPFRC 16a1s(40)-8a1s(10)-16a1s(40) achieves a 32% reduced P compared to that of 8a1s(90). This smallest P is associated with the multiple effects of the coarse aggregate, the layer interface, the direction of fibers in the thin middle layer, and the edge confinement of the thick rear layer.

5. The proposed prediction model is able to account for the varying mechanical properties and the layers’ order in the multi-layered targets, and it successfully predicts the penetration depths with accuracies higher than 95%. On the other hand, the empirical formulae underestimate the penetration depths. Compared to the ACE formula and the modified NDRC formula, the UKAEA formula with the composite theory provides predictions with a relatively higher accuracy, but it fails to distinguish the effects of the layers’ order on the impact resistance.

CRediT authorship contribution statement

Y.Y.Y. Cao: Methodology, Investigation, Data curation, Formal analysis, Writing - original draft. P.P. Li: Investigation. H.J.H. Brouwers: Supervision, Writing - review & editing. Q.L. Yu: Conceptualization, Supervision, Project administration, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was carried out under the funding of China Scholarship Council and Eindhoven University of Technology. Furthermore, the authors wish to express their gratitude to late Ing Ad Verhagen for sharing his experience on the layered concrete tests and Ing. D. Krabbenborg from the Dutch Defense Academy for organizing the UHPFRC ballistic tests. The following organizations are also gratefully acknowledged for providing the important assistance in conducting the ballistic tests: Knowledge Center Weapon System and Ammunition from the Dutch Ministry of Defense.

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Table 8

| Targets          | Velocity (m/s) | Penetration depth P (mm) and error (%) | Test          | Proposed model (error) | ACE (error) | Modified NDRC (error) | UKAEA(error) |
|------------------|----------------|---------------------------------------|---------------|------------------------|-------------|-----------------------|--------------|
| 16a1s(90)        | 840.7          | 55.0                                  | 55.5 (0.9)    | 46.4 (−15.7)           | 36.1 (−34.4)| 50.4 (−8.4)           |              |
|                  | 847.3          | 55.0                                  | 56.1 (2.0)    | 46.9 (−14.8)           | 36.4 (−33.9)| 51.0 (−7.3)           |              |
| 8a1s(45)-16a1s(45)| 842.6          | 57.0                                  | 56.4 (−1.1)   | 47.0 (−17.6)           | 36.4 (−36.2)| 51.0 (−10.6)          |              |
|                  | 845.0          | 55.0                                  | 56.6 (2.9)    | 47.2 (−14.3)           | 36.5 (−33.3)| 51.2 (−6.9)           |              |
| 16a1s(20)-8a1s(50)-16a1s(20)| 842.5    | 54.0                                  | 56.3 (4.4)    | 47.0 (−13.0)           | 36.4 (−32.7)| 51.0 (−5.5)           |              |
|                  | 845.2          | 54.5                                  | 56.6 (3.9)    | 47.2 (−13.4)           | 36.5 (−33.1)| 51.3 (−5.9)           |              |
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