EXPERIMENTAL EVALUATION OF UHPFRC SLABS SUBJECTED TO CONTACT EXPLOSION UNDER VARIOUS LOADING CONDITION

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ABSTRAKT

Tento příspěvek prezentuje výsledky získané z rozsáhlého experimentálního programu zaměřeného na výbuchovou odolnost vysokopevnostního drátkobetonu (UHPFRC). Celkově bylo vyzkoušeno 28 kompozitních desek o rozměrech 1000 x 1000 mm. Prvky byly zatíženy jak kontaktním, tak i blízkým výbuchem. V rámci experimentu byla na vybraných vzorcích měřena rychlost spodního povrchu při zatížení výbuchem pomocí PDV. Každý vzorek byl dále snímám dvěma vysokorychlostními kamerami pro lepší přehled vývoje trhlin a poškození spodního povrchu.

Velký počet vzorků zatížených výbuchem při různých dispozičních uspořádáních (váha výbušniny, vzdálenost od vzorku) umožňuje statistické vyhodnocení výbuchové odolnosti a následné srovnání zkoušených materiálů s dosavadními výsledky dostupnými v literatuře.

V rámci tohoto příspěvku jsou prezentovány pouze výsledky a závěry získané z vizuálního vyhodnocení jednotlivých střel. Výsledky měření rychlosti spodního povrchu panelu a další data získaná během experimentu včetně srovnání výsledků s výsledky dostupnými v literatuře budou publikovány separátně.

KLÍČOVÁ SLOVA

Výbuchová odolnost • Kontaktní výbuch • Drátkobeton • Typy porušení prvku, Scaled distance

ABSTRACT

This paper presents outcomes of an experimental program focused on blast performance of the ultra-high performance fiber concrete (UHPFRC) slabs material. Twenty-eight UHPFRC slabs, made of two different premixes were loaded by blast (contact and close-in). The spall development and velocity of the ejected debris were measured. Spall development was measured by high speed camera and velocity by photon doppler velocimetry. Inner damage of each specimen measured with the use of ultrasonic pulse velocity method. Results from PDV and high-speed cameras and ultrasonic pulse velocimeter will be presented separately.

The sufficient quantity of specimens tested with varying load conditions (blast weight and blast distance) provided statistically sufficient data for the evaluation of UHPFRC blast resistance and behaviour.

KEYWORDS

Blast resistance • Contact blast • Fibre reinforced concrete • Failure modes, Scaled distance

1. EXPERIMENTAL SETUP

Specimens were made of two proprietary UHPFRC materials with compressive strength 180 mPa (Premix A) and 150 mPa (Premix B). Amount and length of fibers in each concrete mixture were similar as well as other material characteristics. Specimen dimensions were 1000 x 1000 mm x 100, 150 and 200 mm. In order to eliminate the effect of the side reflection of pressure wave, the specimen proportions were numerically tested and evaluated as sufficient. The pressure wave reached the bottom side of the specimen and caused the damage under the blast charge sooner than it reached side sides and reflected back.

In order to evaluate known approaches of RC and UHPFRC blast resistance prediction, different scaled distances were used for each experiment. The charge of SEMTEX 1A explosive varied from 100 g to 1000 g. Clear distance between slab's top surface and explosive varied from 0 mm (contact blast) to 100 mm (close-in blast). Each explosive was situated in the centre of the slab. Shape of the explosive was cylinder with dimeter/length ration equal to one. The detonation point was positioned approximately 20 mm below the top surface of blast charge.

Specimens were placed on a 720 mm high steel frame (Fig. 1). On the top, three steel plates were welded peripherally to avoid falling specimen from the steel frame during the blast. Supporting of the specimens with steel frame enabled considering boundary conditions as simply supported slab in both directions.

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Fig. 2*: Specimen with the explosive charge and mirror under specimen.*

2. EXPERIMENTAL RESULTS

The results are divided according to the specimen failure mode (Fig. 2). One of main goals was to describe boundary conditions for each failure mode. Many of specimens was placed on the boundary of two different failure modes. Finding of the failure mode boundaries was reached by changing scaled distance and scaled thickness for each shot. Most of the specimens reached crater and spall failure mode. Three of them were damaged only by spall and no crater appeared. Six of the specimens reached breach failure mode. Three reached crater failure mode and two were not damage at all. Overview of parameters of each shot and reached failure mode is presented in Tab. 1. Terminology used for the description of the specimen damage is presented in Fig. 3. Results of each specimen are presented afterwards. However, due to limited extent of this paper only few selected figures of the damaged specimens are presented.

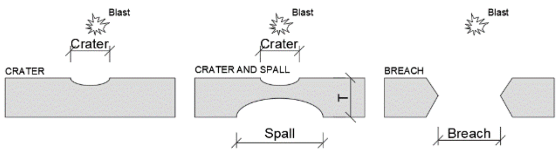

Fig. 2*: Different failure modes.*

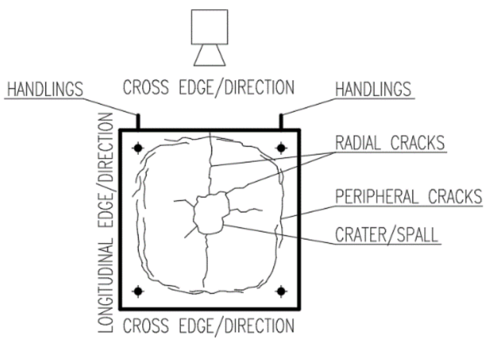

Fig. 3*: Specimen with the explosive charge and mirror under specimen.*

Tab. 1: *List of specimens tested during the experimental programme and their results.*

Shot number	Premix	Spec. thick.	Expl. weight	Expl. length	Distance	Failure mode	Scaled distance
[-]	[-]	[mm]	[g]	[mm]	[mm]	[-]	[m/kg$^{1/3}$]
1	A	100	400	61	0	Breach	0.051
2	A	100	200	58	0	C.&Spall	0.060
3	A	150	400	66	0	C.&Spall	0.057
4	A	100	400	74	100	No dam.	0.192
5	A	100	1000	90	60	C.&Spall	0.119
6	A	100	400	60	10	C.&Spall	0.062
7	A	100	200	58	0	C.&Spall	0.060
8	A	200	1000	95	20	C.&Spall	0.087
9	B	100	400	700	100	Spall	0.187
10	A	100	400	700	100	Spall	0.187
11	A	100	400	700	100	No dam.	0.187
12	A	100	400	700	0	Breach	0.062
13	A	100	400	60	0	Breach	0.050
14	A	150	1000	96	0	Breach	0.070
15	A	200	1000	90	30	C.&Spall	0.092
16	A	100	200	55	25	C.&Spall	0.094
17	B	100	300	70	100	C.&Spall	0.205
18	B	100	300	70	0	C.&Spall	0.068
19	B	200	500	75	0	C.&Spall	0.063
20	B	100	1000	80	60	Breach	0.110
21	B	100	200	50	100	Spall	0.204
22	B	100	150	45	25	C.&Spall	0.086
23	B	150	500	75	40	C.&Spall	0.110
24	B	100	500	75	20	Breach	0.087
25	B	100	100	47	25	Crater	0.103
26	B	150	400	64	30	Crater	0.092
27	B	100	800	76	60	C.&Spall	0.114
28	B	200	300	50	0	Crater	0.041

2.1. Specimens with crater failure or no damage

Two specimens (Nr. 4 and 11) resulted with no damage at all. Both specimens were made of Premix A. Three specimens (Nr. 25; 26 and 28) resulted with only crater failure mode, Premix B. Thicknesses of the specimens were 100, 150, and 200 mm respectively.

Specimen Nr. 4 (Fig. 4) experienced visible damage only on the soffit. Contact side was not damaged at all, even the cracks were not observed on the specimen surface. On the soffit there was an area heavily protuberant out of the specimen. This area was bounded by the peripheral crack and divided by four radial cracks. These cracks proceeded from the centre of the area towards its edge but did not propagate further. Therefore, the surface outside the protuberant area was not damaged at all.

Specimen Nr. 11 was damaged on the contact side only with one crack located on the edge with handlings. The soffit was damaged in the similar manner as the specimen Nr. 4 but in smaller scale. There was an area bounded by peripheral crack which would be spalled but wasn’t. This area was cracked with few radial cracks. However, these cracks did not reach peripheral crack. On the contrary to the specimen Nr. 4, there was one longitudinal crack that proceed from the edge of the to be spalled area and reached edge with handling and the opposite one.

Fig. 4*: Specimen Nr. 4 contact side (left) and soffit (right).*

The specimen Nr. 25 resulted with crater with diameter 30-40 mm and depth approximately 5 mm. On the soffit, there was no damage at all. Cracks appeared only on the soffit in the very centre of the specimen.

Crater in the case of specimen Nr. 26 had diameter 120-170 mm and was 38 mm depth. The area around the crater was slightly cracked with radial cracks. Some of them reached the edge with the handlings. The bottom side was not spalled but the to be spalled area was clearly marked by the peripheral crack. In this area some cracks were observed concentrating in the centre of the surface. The area outside the to be spalled area was cracked only by few radial cracks. These cracks were directed in the longitudinal direction (in the direction towards the camera).

Specimen Nr. 28 (Fig. 5) experienced damage on the contact side was 160-170 mm in diameter with depth of crater 33 mm. Except for the crater, there were obviously peripheral cracks in the distance 80 mm from the edge of the crater. Area marked by the peripheral crack was damaged by the few radial cracks with one reaching edge with handlings. Soffit side was damage in the same manner as in the case of specimens Nr. 25 and 26. The area was not spalled but the cracks were clearly marking the area which would be spalled. Radial cracks proceeded in the centre of the surface and some of them propagated towards the edge with the handlings copying the cracks on the contact side.

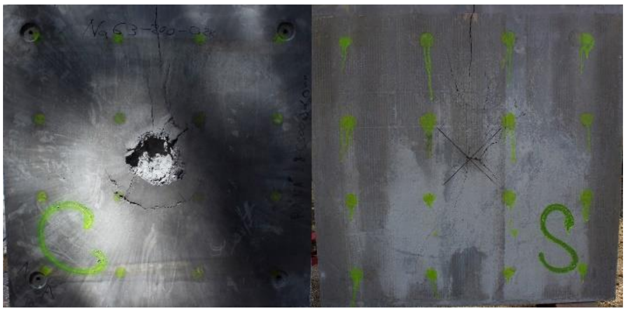

Fig. 5*: Specimen Nr. 28 contact side (left) and soffit (right).*

As already mentioned, the specimens Nr. 4 and 11 were rated as with no damage results, surfaces on the soffit were cracked and protuberant from the specimen. Regardless the absence of the damage on the contact side, both cases were on the boundary line between crater failure mode and crater and spall damage mode. Sometimes these results are classified as threshold spall. Despite that both specimens were made of same material and were loaded by the same conditions, some differences in the results were observed. These differences consisted only from the number of cracks on the soffit and contact side.

Specimens Nr. 25, 26 and 28 present the influence of the scaled distance. Specimen Nr. 28 with the lowest scaled distance and highest scaled distance, suffered more damage on the contacts than specimens Nr. 26 a 25. The specimen Nr. 26 had only lower scaled distance and scaled thickness as specimen Nr. 25 but it was more damaged on the both sides. Specimen Nr. 25 was not damaged at the soffit despite the specimen lowest thickness.

2.2. Specimens with crater and spall failure mode

The most of the specimens were damaged by crater and spall. Shape of the damage on the contact side was mostly regular circle. Damage shape on the soffit was in most cases circular but in some cases the damage area was more rectangular. Ratio of crater and spall damage diameter varied from 0.32 to 0.71 with spall damage always greater than crater. of damage. As the crater and spall failure mode was reached mostly, results were divided into four groups. For better presentation, it was divided according to the damage extent. For specimens damaged contact sides and soffits see Fig. 6.

First group contains specimens Nr. 9 (Fig. 6), 10, 17 and 21. Each specimen was 100 mm thick. Scaled distance was very similar to each other. Specimens in this group were damaged only by the spall and no crater occurred. In the case of specimen Nr. 10 and 21, spall diameter was very small with diameter 30 – 60 mm and 40 mm, respectively. The depth was maximally 10 mm and there was no damage on both surfaces expect from the before mentioned small spall. Specimens Nr. 9 and 17 were damaged on the soffit by the spall with diameter 265 – 318 mm and 235 – 300 mm. Depths were 33 mm and 15 mm. There were no cracks observed on all specimens.

Fig. 6*: Specimen Nr. 9 contact side (left) and soffit (right).*

Second group contains specimens Nr. 2 (Fig. 7), 16 and 22. All the specimens were 100 mm thick. Damage of all specimens can be described as pure crater and spall. There were no cracks on both surfaces at all. Specimen Nr. 2 ended with crater with depth 27 mm and diameter 115 - 160 mm. Spall was 55 mm depth with diameter 255 – 280 mm. Specimen Nr. 16 resulted in crater with depth 10 mm and 70 – 90 mm wide in diameter. Bottom surface was damaged by the spall 210 – 270 mm in diameter and 34 mm depth. In case of specimen Nr. 22, specimen was damaged by the crater with diameter 70 – 100 mm and 15 mm depth. Spall damage was 35 mm depth and 250 – 280 mm in diameter. All the previously described damages were circular in their shapes.

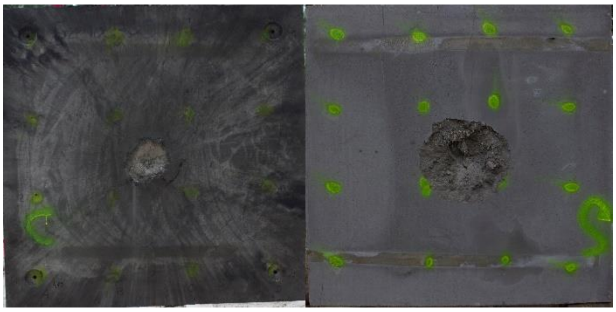

Fig. 7*: Specimen Nr. 2 contact side (left) and soffit (right).*

Fig. 8*: Specimen Nr. 23 contact side (left) and soffit (right).*

Third group consists of specimens Nr. 6, 7, 18, 19, 23 (Fig. 8) and 27. Specimen Nr. 23 was carried on specimen with thickness 150 mm. In case of specimen 19, specimen was 200 mm thick. Other shots were performed on specimen 100 mm thick. Damage of these specimens can be described as crater and spall with one main radial crack and only few or no secondary radial cracks and peripheral cracks. Specimen Nr. 6 was damaged by the crater with diameter 145 – 158 mm and depth 24 mm. Soffit was damaged by spall with diameter 242 – 290 mm and depth 74 mm. Contrary to contact side with only one radial crack, soffit was damaged by one main radial crack and few shorter and tighter. Specimen Nr. 7 ended with the crater damage with depth 38 mm and 135 – 156 mm in diameter. Spall damage depth was 57 mm and diameter 260 – 286 mm. Only one radial crack appeared on both surfaces. Specimen Nr. 18 ended with the crater depth 38 mm and diameter 185 – 190 mm. Spall diameter was 260 – 300 mm and depth 60 mm. As well as in case of specimen Nr. 7, only one radial crack appeared on both surfaces, but the crack was thinner and accompanied by few peripheral cracks on the contact side. Specimen Nr. 19 ended with almost same damage depth on both surfaces; 62 mm on the contact side and 65 mm on the soffit. Damage on the contact was perfectly circular; 200 mm in dimeter. On the soffit, extend of the damage was higher in comparison to other specimens with diameter varying from 425 to 535 mm. As well as in the specimen 7, specimen 19 was cracked only by one radial crack identical on both surfaces. Damage of the specimen 23 can be described as almost perfect circle crater with diameter 135 – 150 mm and depth 40 mm. There was one radial crack on the contact side. Contrary to the other specimens in this group, soffit was damaged by few radial cracks. One proceeded from the spall and reached the cross edge without handlings. Other cracks were oriented in the direction towards the edge with handlings. None of the cracks propagated through the specimen thickness. Spall damage was mostly hold by the fibers and therefore did not spall completely out of the specimen. Spall diameter was 335 – 380 mm and depth in fully spalled area was 40 mm. Specimens Nr. 27 ended with crater with depth only 7 mm and diameter 123 – 135 mm. Spall damage was deeper, 61 mm, and wider, 355 – 379 mm. Both surfaces were cracked. On the contact side, only one radial crack appeared. It started at the edge with handlings and propagated towards the damage centre but did not reached it. Soffit was cracked by three cracks behaving in the same manner as the crack on the contact side.

Last group consists of specimens Nr. 3, 5 (Fig. 9), 8 and 15 (Fig. 10). Two specimens (Nr. 8 and 15) were carried out on specimen with thickness 200 mm. Specimen Nr. 3 was performed on specimen 150 mm thick and specimen Nr. 5 on 100 mm thick specimen. All these specimens were damaged by the crater and spall. In addition to this a lot of cracks on at least one surface were observed. Specimen Nr. 3 ended with crater depth 46 mm and diameter 161 – 185 mm. Contact surface was damaged by the peripheral cracks oriented in longitudinal direction. These cracks were not continuous but reached the edge with handlings. Peripheral cracks were not observed on the contact side. Soffit was damaged by the 59 mm depth spall; diameter of spall damage was 257 – 294 mm. Surface was damaged by the radial cracks as well. Two main cracks were directed in longitudinal direction. Crack, which propagated towards the edge with handlings, reached the edge with handlings. This edge was also damaged by more cracks oriented in cross way. In addition to these main radial cracks, other radial cracks propagated from the damaged area. However, these cracks did not reach the side edge. Surface layer between the cracks was protuberant from the specimen but fibers held them. Shot 5 created crater on the contact side with diameter 130 – 158 mm and depth 10 mm. Cracks observed on the surface were peripheral and radial. Peripheral cracks were mostly located near the longitudinal edges. Radial cracks were oriented in the same manner as in case of specimen Nr. 3. Main cracks propagated in the damaged area. Soffit was damaged by the spall with diameter 250 – 293 mm and depth 60 mm. Only radial cracks were observed on the soffit. Contrary to most of the specimens, peripheral cracks on the specimen loaded by shot 5 were oriented in all direction. However, the wide crack was oriented in longitudinal direction and propagated towards both cross edges. Few other cracks reached the specimen´s edges as well. Shot 8 caused very similar damage as in case of specimen Nr. 3. Crater depth was 45 mm, diameter 167 – 185 mm. Soffit damage diameter was 360 – 430 mm and depth 65 mm. System of the cracks was similar to the specimen Nr. 3 with one main radial crack oriented in longitudinal direction and other shorter radial cracks. Peripheral cracks were not observed at all. Shot 15 caused cater with diameter 180 – 220 mm and depth 25 mm. Edges with handlings were damaged by cross and radial cracks which proceeded from the crater. Spall on the soffit was rather large-size with diameter 400 – 500 mm and depth 60 mm. However, only middle part was ejected from the specimen. Other area was damaged by the radial cracks, bulged out of specimen but not separated from the slab. Area of spall was clearly marked by the peripheral cracks. One main crack propagated through the specimen from the edge with handlings to the opposite one. Other radial cracks propagated mostly towards the edge with handlings which were damaged by the cross section.

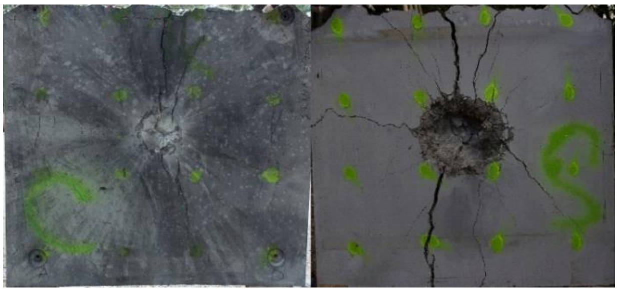

Fig. 9*: Specimen Nr. 5 contact side (left) and soffit (right).*

Fig. 10*: Specimen Nr. 15 contact side (left) and soffit (right).*

2.3. Specimens with breach failure mode,

Six specimens ended with breach failure mode. Four of these specimens were made of UHPFRC with higher compressive strength (specimen Nr. 1, 12, 13 and 14). Thickness of the specimens was 100 mm in five cases and 150 mm in one case.

Specimen Nr. 1 ended in breach with diameter 84 - 89 mm. Ratio between crater depth and spall depth was approximately 1:1. Therefore, half of the specimen's thickness was damaged by the crater and the second half by the spall. Crater diameter was 180 – 200 mm and spall diameter was approximately 1.5 times greater (280 – 300 mm). Contact side as well as soffit were cracked in the similar way. There was one main radial crack proceeding from the edge of the damaged area and reaching the edge with the handlings. This crack propagated fully through the thickness of the specimen. Similar crack was situated in the opposite direction but did not reach the edge of the specimen. There were also smaller peripheral cracks near the edges of the specimens (more obvious in the longitudinal direction). These cracks were as well as radial crack almost identical on both sides.

Specimen Nr. 12 (Fig. 11) and 13 had identical arrangement as the specimen Nr. 1. Therefore, these specimens were used to set the statistical scatter (discussed later) of results with similar scaled thickness and scaled distance. Visually damage of both specimens was very similar to the specimen Nr. 1. Crater diameter was 170 - 200 and 180 - 200 mm, respectively. Breach diameter was 55 - 74 mm in case of specimens Nr. 12 and 80 – 118 mm in case of specimen Nr. 13. Damage depth on the contact side was 40 mm in case of specimen Nr. 12 and 30 mm in case of specimen Nr. 13. On both specimen's contact sides there was one main longitudinal crack proceeding from the damage area to the edge with handlings and secondary cracks located in the opposite direction. These radial cracks were accompanied by the peripheral cracks on the longitudinal edges. On the soffit, damage diameter varied between 265 - 280 mm and 290 – 300 mm, respectively. System of the cracks was similar to the contact side. One main crack directed in the longitudinal crack proceeded from the damage area to the edge with handling and few secondary cracks proceeded from the opposite direction. These cracks were accompanied by the peripheral cracks located near the longitudinal edges. In both cases the delamination of the upper edge with handling occurred. Examination showed absence of the fibers in this area. This phenomenon was probably caused by the concreting technique.

Fig. 12*: Specimen Nr. 11 contact side (left) and soffit (right).*

Specimen Nr. 14 (Fig. 12) ended in breach with diameter 56 – 58 mm. This was in contrary to the surface damage diameter very small. On the contact side, there was a crater with diameter 230 - 300 mm and depth 40 mm. There were no perpendicular cracks which would have been proceeded from the damage area. However, the surface was heavily damaged by the peripheral cracks near the edges of specimen. Central damaged area varied from the other specimens. Surface layer on the boundaries of the damaged area was separated from the specimen but due to fibers did not fall out. Therefore, surface on the boundaries of the damage area was protuberant from the specimen. Damage on the soffit was different from the other specimens. Spall damage was relatively large with diameter 460 – 410 mm and depth 110 mm. Radial crack system was typically with six radial cracks uniformly distributed on the surface. All cracks propagated towards the side edge. Contrary to the contact side, there was no peripheral cracks at all.

Specimen Nr. 20 (Fig. 13) ended in the breach with diameter 40 – 50 mm. Crater diameter was 140 - 180 mm but its depth was minimal and evaluated as 0 mm. Therefore, almost all the damages of the specimen were caused by the spall, on the contact side only the surface was damaged. There was only one radial crack connecting the damaged area and edge with handlings. This crack run through the specimen thickness. Therefore, on the soffit this main crack was also evident. Contrary to the only one radial crack, there were peripheral cracks situated to the almost perfect circle. Opposite surface was damaged by the spall with diameter 295 – 310 mm. Depth of the damage was evaluated as the full specimen thickness. There was no peripheral crack but there were a lot of radial cracks. Except for the before mentioned main one, all cracks were situated near longitudinal edges or cross edge without handlings. No crack reached the edge.

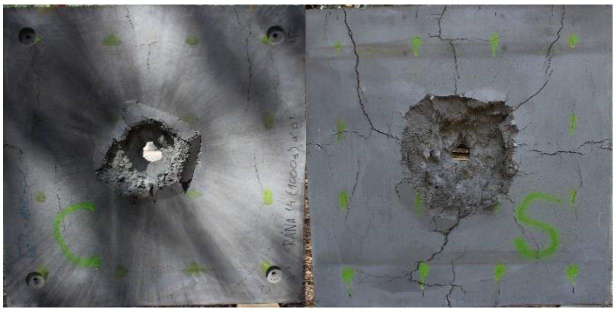

Fig. 12*: Specimen Nr. 14 contact side (left) and soffit (right).*

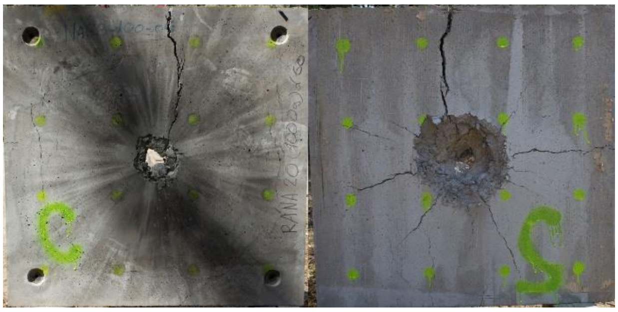

Fig. 13*: Specimen Nr. 20 contact side (left) and soffit (right).*

Specimen Nr. 24 ended with the smallest breach diameter, 13 – 24 mm, from all the breach specimens. Contrary to the specimen Nr. 20, the damage depth on the contact side was higher; 35 mm. Crater diameter varied from 145 mm to 170 mm. Crack´s system was similar to the specimen Nr. 20, with one radial crack going through the specimen thickness and peripheral cracks. Soffit was damaged by the spall with diameter 295 – 310 mm and depth approximately 70 mm. Only the surface layer was spalled on the boundaries of the spall. At the distance approximately 20 – 50 mm from the edges of the damage, the depth abruptly increased to the full depth of spall. Crack´s system was similar to the specimen Nr. 20 as well. It means only few short peripheral cracks and many radial cracks which proceeded from the spall but did not reach the edge of specimen.

Fig. 14*: Specimen Nr. 24 contact side (left) and soffit (right).*

3. CONCLUSIONS

Two types of UHPFRC were tested for their contact and close-in blast resistance. Materials with compressive strengths 180 mPa and 150 mPa were tested. A set of fourteen slabs, dimensions 1000 x 1000 mm, were tested for both materials. The thicknesses of specimens was 100, 150 and 200 mm with majority of 100 mm thick specimens. The blast loading was created using SEMTEX 1A explosive. Weight of explosive varied from 100 g up to 1000 g. The distance between top surface and the explosive charge varied from 0 to 100 mm.

Most of the experiments resulted by crater and spall failure mode, accordingly one of the goals was to find boundaries between the failure modes. The damaged area was clearly visible and restricted. On the contact side, the damaged surface was located mostly at the blast charge. The extent of damage on the soffit was slightly higher than on the contact side. The spalled debris were large parts or a very fine powder owed to the homogeneous structure of the UHPFRC material.

Visual observations revealed two different systems of cracks on both surfaces. Most of the specimens were damaged by radial cracks. These cracks were relatively wide and very similar on both the contact side and soffit. In some cases, radial cracks propagated fully through the thickness of the specimen or reached the edge of the specimens. The second system of cracks consists of the peripheral cracks which were observed near the specimen edges. These cracks were located only on the surface and did not propagate deeper into the specimen.

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