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Evaluation of Blast Resistance of Fiber Reinforced Composite Specimens under Contact Blast Load

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Abstract. This paper presents results of experimental programme which took place in 2014, 2015 and 2016. Experiments were focused on the resistance of full scale concrete panels subjected to contact blast loading. Specimens were loaded by contact blast by plastic explosive. All specimens were reinforced concrete slabs made of fiber concrete. Basalt mesh and textile sheets were added to some of the experiments for creating more heterogeneous material to achieve better resistance of the specimens. Evaluation of experiments was mainly focused on the damaged area on the contact side and soffit of the specimens. Dependency of the final damage of concrete panels on the weight of explosive and concrete strength was assessed.

1. Experimental program

Experimental measurements of behaviour of concrete panels loaded by contact blast supplements the measurement of the resistance of specimens against soffit explosion. The experimental programme took place in 2014, 2015 and 2016 in the Boletice military area with cooperation of the Czech Army and University of Defence, University of Pardubice.

Specimens with dimensions 6.0 x 1.5 x 0.3 m are made of reinforced fibre concrete. The specimens were concrete slabs 6 m in length, 1.5 m in width and 0.3 m in thickness. The steel reinforcement was 11 pcs ∅ 16 mm reinforcing bars every 140 mm on both surfaces, ∅ 10 mm every 150 mm as an outer transverse reinforcement, and shear reinforcement was provided by ∅ 8 mm links (9 pcs/m^2) [3]. Cover of the stirrups was 50 mm. Explosive was made of pentaerythriol tetranitrate also known as PET or CAS 78-11-5 with TNT equivalent 1.3 [7] [4].

Each specimen can be theoretically divided into three parts according to the blast loading. The middle part was subjected to soffit blast and then inspected with ultrasound device for the internal cracks. This procedure provided information whether edge parts of specimens are affected by soffit blast or not. Edge parts of the specimen were reserved for contact blast experiment. Scheme of the experiment is presented in Figure 1. Eleven specimens were loaded in total, ten of them with two explosives on both edges of the panel. In total twentyone measurements were performed. Damage of the specimen on each side was assessed.

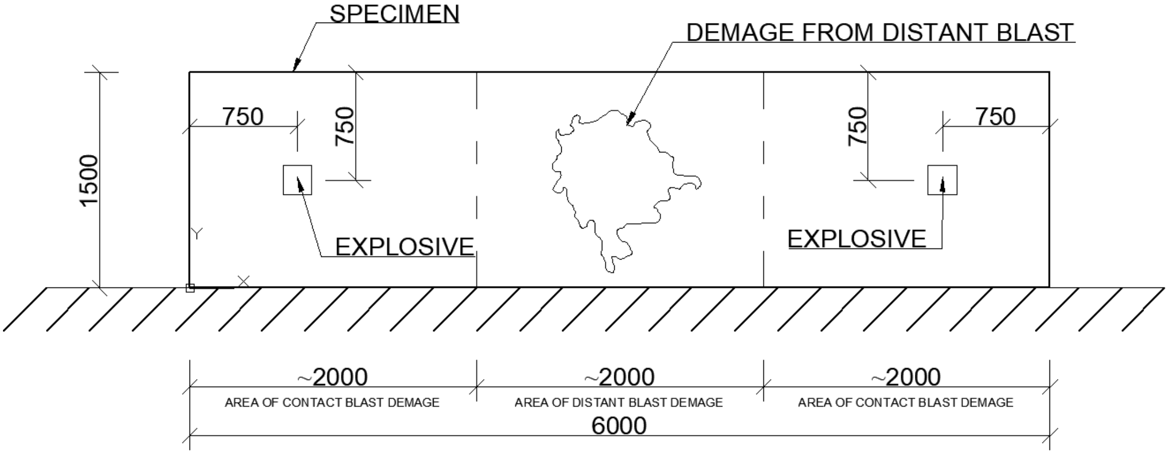

Figure 1. Scheme of the experiment

2. Blast resistance of the specimens

In this chapter, experimental results are provided; the tested specimens are assessed in terms of damaged area on both sides of the specimen, shape of the damaged area and type of the damage. More results and information are presented in [1].

The experiment was performed using eleven specimens. Specimens were numbered chronologically according the order of the experiment. Specimens No. 12 to 19 and No. 21 to 23 were tested for contact blast resistance. Ten of the specimens were loaded by two explosives, one on the left and one the right side of the specimen. Both explosives were initiated simultaneously. The weight of the explosive charge differs from 0.5 kg to 4.2 kg. Different concrete mixes were used. Cubic strength of the concrete vary from 68.5 MPa to 129.8 MPa [2]. Fibers with tensile strength 2200 MPa and length 13 and 35 mm were used in the concrete. Amount of the fibers and exact compressive strength of the each specimen is presented in Table 1.

Heterogeneity of specimens No.17 and No.18 was raised by adding basalt meshes into the structure of the concrete panel. Specimen No.17 contained only one basalt mesh in the middle of the concrete cover at the soffit of the specimen. Specimen No.18 contained five basalt meshes. Two of them were placed at the middle of the concrete cover and the rest of the meshes were placed between the concrete reinforcement layers with spacing of 50-70 mm [5] [6]. Recycled textile sheets with thickness of 50 mm were inserted into specimen No.19 to increase its heterogeneity.

Specimen No. 12 was loaded by explosives of 1.0 kg on the right side and 1.4 kg on the left side. Damage of the specimen on the both sides can be seen in Figure 2. Final damages on the left and right side of the specimen were very similar by its character. Also damaged areas on the contact and soffit of the panel were very similar. The blasts did not achieve puncture of the specimen. On the contact side, the blast damaged area is not deeper than the cover layer. Reinforcement was not damaged by the blast. On the soffit of the specimen, the damage is deeper than the cover layer, but the rebars were not damaged or bent. The damaged area on the soffit was approximately 2.5 times bigger than damage on the contact side. The damaged areas had circular shape on both sides of the panel. Concrete in the perimeter of the damaged area was affected by cracks. Some of the cracks on the left contact side reached edge of the specimen.

Figure 2. Specimen No. 12 after contact blast loading, 1.4 kg charge left left contact side, left right soffit, 1.0kg charge right left contact side, right right soffit

Specimen No. 13 was loaded by explosives with weight 1.0 kg on the right side and 0.5 kg on the left side. Damage of the specimen on the both sides can be seen in the Figure 3. As well as the specimen No.12, specimen was not punctured through. The damage on the contact side did not reach depth of cover layer and reinforcement was not deformed by the blast. Shape of the damaged area was a circle. Soffit showed only few major crack on the right side and the surface was bulged out of the specimen. On the left soffit there were not marks of the damage at all.

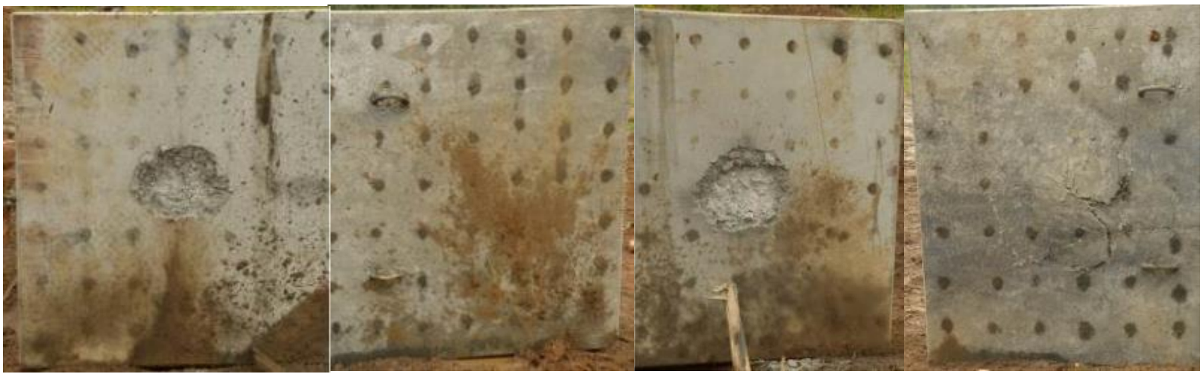

Figure 3. Specimen No. 13 after contact blast loading, 1.4 kg charge left left contact side, left right soffit, 2.8 kg charge right left contact side, right right soffit

Specimen No. 14 was loaded by explosives with weight 2.8 kg on the right side and 1.4 kg on the left side. Damage of the specimen on the both sides can be seen in the Figure 4. Specimen was punctured through on the right side. Shape of the puncture was circle and was the same as in case of the damaged area of surfaces on both sides of panel. Area of damaged surface on the contact side was approximately 43% of the soffit on the right side and 30% on the left side. There were no cracks on the contact side. The soffit on the right side was strongly disturbed by cracks, left side was not disturbed by cracks. Some of the wides cracks reach edges of the specimen. Crack were mostly perpendicular to the perimeter of the damaged area.

Figure 4. Specimen No. 14 after contact blast loading, 1.4 kg charge left left contact side, left right soffit, 2.8 kg charge right left contact side, right right soffit

Specimen No. 15 was loaded by explosives with weight 1.4 kg only on the left side. Damaged of the specimen can be seen in the Figure 5. The specimen was not punctured. Damaged area depth was mostly lower than the concrete layer. Damage on the contact side was approximately 25 % of the damage on the soffit. Reinforcement was not damaged on both sides of the panel. Type of damage was more close to pulling out failure than punching shear failure. On the contact side, there were cracks that reached edges of the specimen. Cracks on the soffit were perpendicular to the perimeter of the damaged.

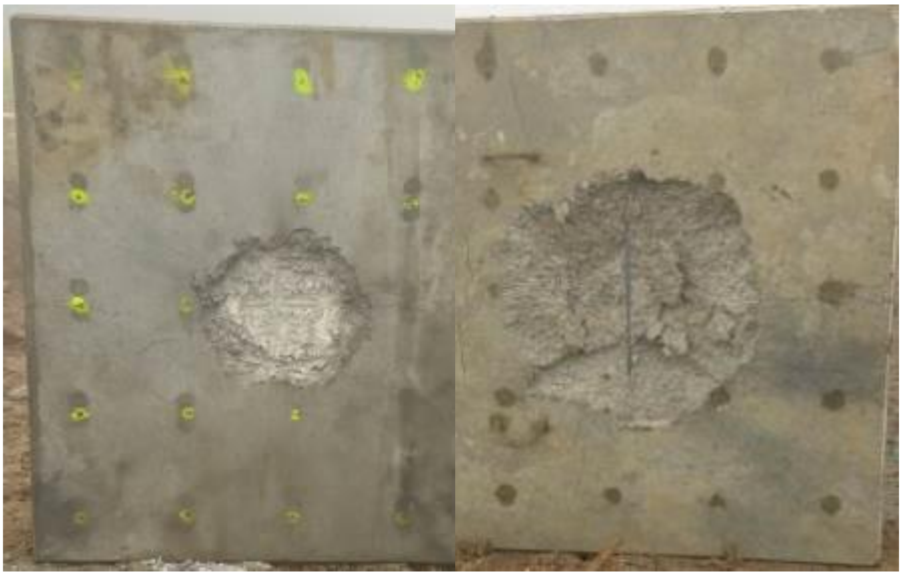

Figure 5. Specimen No. 15 after contact blast loading, 1.4 kg charge left left contact side, left right soffit

Specimen No. 16 was loaded by explosives with weight 2.8 kg on the right side and 1.4 kg on the left side. Damage of the specimen on the both sides can be seen in Figure 6. Specimen on the both sides was not punctured through. Shape of the damaged area on the contact side was circular, on the soffit it was more similar to the rectangle. Reinforcement on the contact blast was not deformed but the depth of damaged area reach the reinforcement. Steel bars were deformed and bent out of the panel on the right side of soffit, on the left side reinforcement was not damaged. Type of damage was similar to specimen No.15. There was a very dense mesh of microcracks on the contact blast. Cracks on the right side of soffit were wider and some of them reached edges of the specimen.

Figure 6. Specimen No. 16 after contact blast loading, 2.8 kg charge left left contact side, left right soffit, 2.0 kg charge right left contact side, right right soffit

Specimen No. 17 was loaded by explosives with weight 2.0 kg on the right side and 2.8 kg on the left side. One ballast mesh was added into the cover layer. Charge on the left side was placed on the side with basalt mesh in cover layer. Charge on the right side was placed on the opposite side of the specimen. Damage of the specimen on both sides can be seen in Figure 7. Specimen was not punctured on both sides. Damage on the right contact side was similar to the failure due to punching shear but the depth was equal to cover layer. The reinforcement was not damaged. Shape of the damaged area was circular. Area of the damage on the contact side was approximately 65% of the damaged area on the soffit. The soffit was damaged more and the shape of the damaged area was irregular. The type of the failure corresponded with the delamination of the concrete layers. Most of the damaged area was a delaminated layer to the depth of the basalt mesh. Second delaminated layer consists of concrete the depth basalt mesh to the depth of reinforcement bars. Reinforcement on the soffit was practically undamaged. Damage on the left contact side of the specimen was deeper than the cover layer. The reinforcement was unbroken but little bent. Type of the damage was similar to the punching shear failure. Damage area on the soffit was rectangle shape with the depth slightly more than the cover. Reinforcement was only little bent. Soffit side on the left side was not broken into the layers as the right soffit side was.

Figure 7. Specimen No.17 after contact blast loading, 2.8 kg charge left left contact side, left right soffit, 4.2 kg charge right left contact side, right right soffit

Specimen No. 18 was loaded by explosives with weight 4.2 kg on the right side and 2.8 kg on the left side. Damage of the specimen on both sides can be seen in the Figure 8. Ballast meshes were added into the cover layer in the both sides and between reinforcement. Specimen was not punctured. The damage on the left and right side was similar in its shape and type. The shape of the damaged area on contact blast was circular and was more similar to punching shear failure. The damage reached deeper than the cover layer. Reinforcement was little bent but not broken. Damaged area on the soffit was more complex than damaged area on the contact side. Shape of the damaged area was ellipse and similar to pulling out failure. Reinforcement was heavily bent but not broken. Under the reinforcement mesh there were pieces of the panel that were bigger than the spacing of the reinforcement or ballast mesh. Perimeter of the damaged area was broken by many cracks in the radial direction. Crack which crossed radial cracks and copying perimeter of the damaged area was detected approximately in the distance 220 mm from the damaged area.

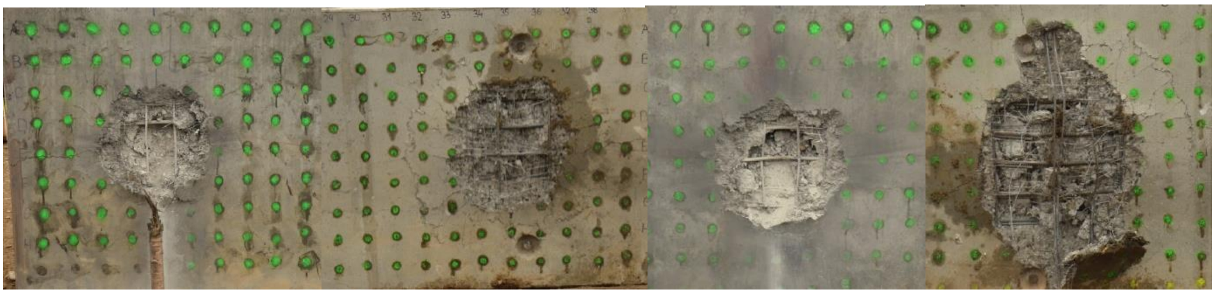

Figure 8. Specimen No. 18 after contact blast loading, 2.8 kg charge left left contact side, left right soffit, 4.2 kg charge right left contact side, right right soffit

Specimen No. 19 was loaded by explosives with weight 4.2 kg on the right side and 2.8 kg on the left side. Damage of the specimen on the both sides can be seen in the Figure 9. The recycled textile sheets were added to the specimen between reinforcement layers. The specimen was not punctured. Type of the failure on the both sides was similar to the specimen No. 18. On the contact side, it was caused by the punching shear failure, on the soffit by the tension failure. On both sides the depth of the damage was bigger than the cover layer. On the contact side the reinforcement was broken. On the soffit the reinforcement was bent but not broken. Cracks could be seen on the soffit. Cracks are radial to the damaged area. Some of them were reaching edge of the specimen. As well as in the case of No. 17 there was a crack perpendicular to the radial cracks but not continuous.

Figure 9. Specimen No. 19 after contact blast loading, 2.8 kg charge left left contact side, left right soffit, 4.2 kg charge right left contact side, right right soffit

Specimen No. 21 was loaded by explosives with weight 4.2 kg on the right side and 2.8 kg on the left side. Damage of the specimen on the both sides can be seen in the Figure 10. The specimen was punctured on both sides. Type of the failure on the both sides was similar in its type. Shape of the damage area on both sides and surfaces was circular. On the contact side and soffit, it was caused by punching shear failure. On the both sides the reinforcement was broken and on the soffit reinforcement was broken and bent out of the specimen. Cracks could be seen on the on the soffit. Cracks are radial to the damaged area. Damaged area on the right contact side is approximately 2,5 times smaller than on the soffit. On the right side damage on the contact side is approximately 3 times smaller than on the soffit.

Figure 10 Specimen No. 21 after contact blast loading, 2.8 kg charge left left contact side, left right soffit, 4.2 kg charge right left contact side, right right soffit

Specimen No. 22 was loaded by explosives with weight 4.2 kg on the right side and 2.8 kg on the left side. Damage of the specimen on both sides can be seen in the Figure 11. Ballast meshes were added into the cover layer in the both sides and between reinforcement. Specimen was punctured through on the right side. Damage on the left and right side was similar in its type. Damage on the contact side and soffit was caused by punching shear failure. Damaged area on the contact side was approximately 55% of the damaged area on the right soffit and 70% on the left side. Reinforcement on the contact side was not deformed. Reinforcement on the soffit is broken and bent out of the panel. On the soffit there was evident delamination caused by adding basalt mesh. As well as in the case of specimen No. 17 the first delaminated layer contains concrete from the surface to the depth of the first basalt mesh. Second delaminated layer was from basalt mesh to the reinforcement. Perimeter of the damaged area was broken by cracks on the soffit.

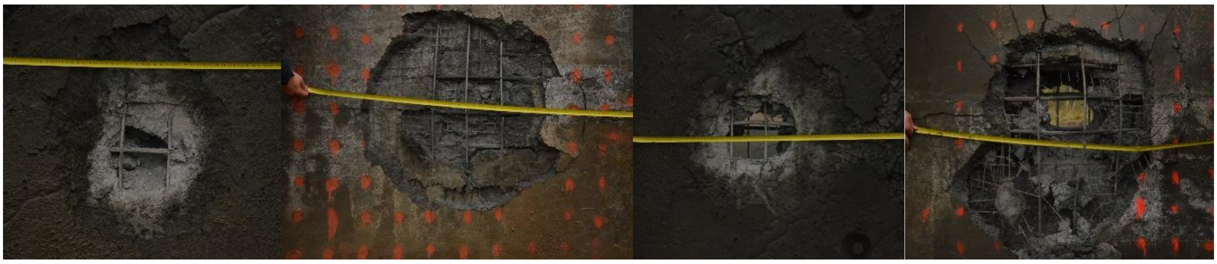

Figure 11. Specimen No. 22 after contact blast loading, 2.8 kg charge left left contact side, left right soffit, 4.2 kg charge right left contact side, right right soffit

Specimen No. 23 was loaded by explosives with weight 4.2 kg on the right side and 2.8 kg on the left side. Damage of the specimen on the both sides can be seen in the Figure 12. Textile sheets were added to the specimen between reinforcement layers. The specimen was not punctured. On the contact side, it was caused by punching shear failure, on the soffit by the tension failure. On the left contact side damage did not reach the reinforcement. On the rightside damage was deeper than the cover layer. Reinforcement was not damaged. Reinforcement on the soffit was broken on the right and left side. Damaged area on the contact side was approximately 86% of the damaged area on the right soffit and 68% on the left side. Cracks could be seen on the soffit. Cracks are radial to the damaged area. Some of them were reaching edge of the specimen.

Figure 12. Specimen No. 23 after contact blast loading, 2.8 kg charge left left contact side, left right soffit, 4.2 kg charge right left contact side, right right soffit

Table 1 presents summary of the experiment in the terms of the damaged area on the different specimens. It is apparent that there is a dependency of the final damage on the value of the concrete strength and also amount of fibres in the specimen. Specimen No. 16 with strength 129.5 MPa, but much shorter fibres, was damaged little more than specimens with lower concrete strength on the soffit but the damage on the contact side was lower. Figure 13 and 14 presents dependency of damaged area to the weight of the explosive. Adding elements for increasing the heterogeneity in specimens No. 18 and No. 19 rapidly decreased the final damage of the specimens. This phenomenon can be caused by the change of the mass density within the specimen on the boundary between concrete and the added elements. On this boundary, the overpressure wave from the explosive is partially rebounded back and partially goes through. Using this system, the wave can be distributed to a wider area and the overpressure decreases. Specimens No.18, No. 19, No. 22 and No. N23 has also showed different type of the failure on the contact side than the other specimens.

Table 1. Summary of the area damaged by the explosion on the different specimens

Specimen		No. 12	No. 13	No. 14	No. 15	No. 16	No. 17	No. 18	No. 19	No. 21	No 22	No 23
Cubic strengh		68.5 MPa	66.9 MPa	73.2 MPa	76.1 MPa	129.5 MPa	125.8 MPa	77.9 MPa	78.3 MPa	127.1 MPa	121.6 MPa	91.6 MPa
Fibres FE dl.13mm f_{ct} = 2200MPa		-	-	-	-	120 kg/m^3	80 kg/m^3	120 kg/m^3	80 kg/m^3	80 kg/m^3	120 kg/m^3	80 kg/m^3
Fibres FE dl.25mm f_{ct} = 400MPa		-	-	-	-	-	-	-	-	-	-	-
Fibres FE dl.35mm f_{ct} = 2200MPa		40 kg/m^3	80 kg/m^3	40 kg/m^3	80 kg/m^3	-	80 kg/m^3	-	80 kg/m^3	80 kg/m^3	-	-
Fibres FE dl. 55mm f_{ct} = 2200MPa		-	-	-	-	-	-	-	-	-	-	80 kg/m^3
Puncture	Left side	0	0	0	0	0	0	0	0	0,15 m^2	0	0
	Right side	0	0	0.046 m^2	0	0	0	0	0	0,225 m^2	0	0
Damaged area not deeper than cover layer – soffit	Left side	0.465 m^2	0	0.361 m^2	0.402 m^2	0.433 m^2	0.122 m^2	0.16 m^2	0.12 m^2	0.48 m^2	0.567 m^2	0.313 m^2
	Right side	0.415 m^2	0.071 m^2	0.609 m^2	0	0.454 m^2	0.55 m^2	0.18 m^2	0.07 m^2	0.496 m^2	0.557 m^2	0.306 m^2

Damaged area deeper than cover layer – soffit	Left side	0.142 m^2	0	0.111 m^2	0.083 m^2	0.081 m^2	0.037 m^2	0.12 m^2	0.12 m^2	0.37 m^2	0.240 m^2	0.232 m^2
	Right side	0.077 m^2	0	0.354 m^2	0	0.115 m^2	0.102 m^2	0.14 m^2	0.11 m^2	0.38 m^2	0.400 m^2	0.216 m^2
Damaged area not deeper than cover layer – contact side	Left side	0.216 m^2	0.111 m^2	0.121 m^2	0.128 m^2	0.106 m^2	0.087 m^2	0.16 m^2	0.13 m^2	0.15 m^2	0.309 m^2	0.214 m^2
	Right side	0.165 m^2	0.122 m^2	0.266 m^2	0	0.268 m^2	0.134 m^2	0.21 m^2	0.10 m^2	0.225 m^2	0.399 m^2	0.263 m^2
Damaged area deeper than cover layer – contact side	Left side	0.037 m^2	0	0	0.023 m^2	0.005 m^2	0.010 m^2	0.11 m^2	0.08 m^2	0.075 m^2	0.056 m^2	0
	Right side	0.026 m^2	0	0.066 m^2	0	0.101 m^2	0.067 m^2	0.13 m^2	0.10 m^2	0.111 m^2	0.075 m^2	0.037 m^2

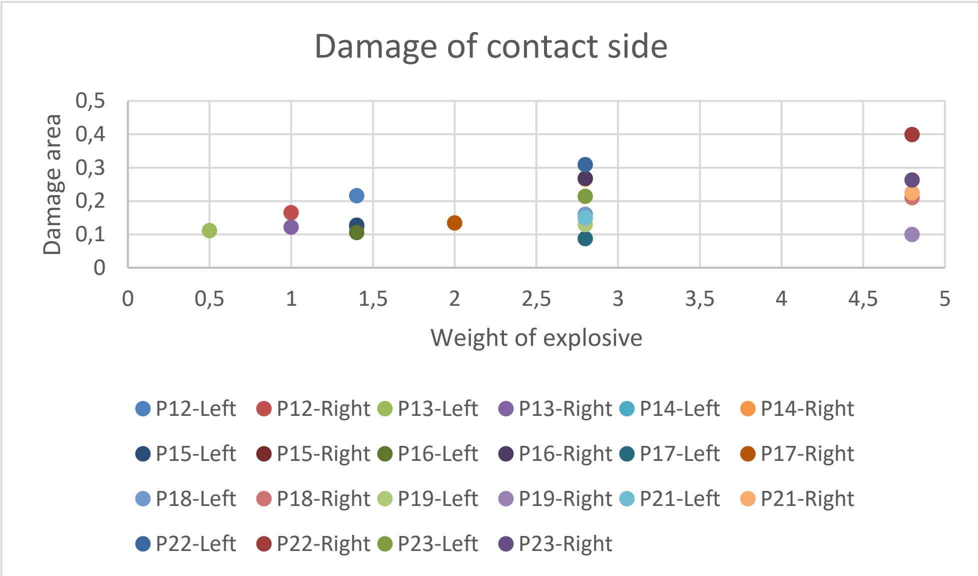

Figure 13. Dependency of the damaged area and the weight of the explosion – contact side

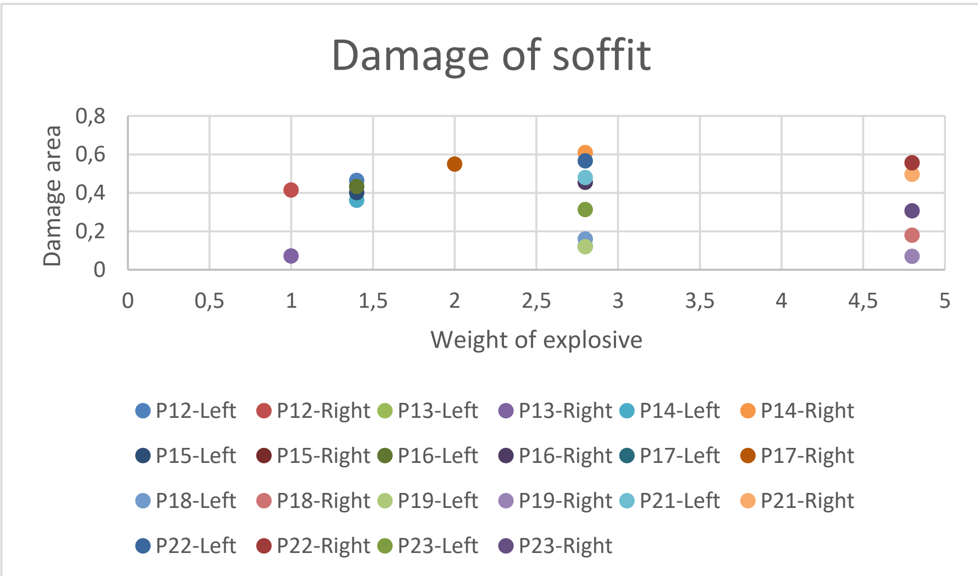

Figure 14. Dependency of the damaged area and the weight of the explosion – soffit

3. Conclusion

Experiments focused on the resistance of the concrete specimens against contact blast were presented in this paper. Different types of concrete specimens were tested. Each specimen differed by the concrete strength and amount of the fibres. Elements for increasing the heterogeneity were added to several specimens. Results of the experiments indicate that it is possible to mitigate the damage caused by the blast even if the blast load increases and the strength of concrete does not increase reasonably; the key lies in increasing the heterogeneity of the specimen.

Implementation of fibres to the concrete panel and increasing the concrete strength seems to be two of the key factors influencing the blast resistance. Results of the experiments also indicate that increasing heterogeneity of the panel is very significant for reducing its damage. Specimen with basalt meshes and recycled textile sheets experience the most significant difference in the results. Specimens with these elements were less damaged even if the concrete strength is lower than of other specimens. The type of concrete failure also varies depending on the side of the panel. Concrete surface on the contact side was often punctured. Concrete surface on the soffit was mostly spalled.

Acknowledgements

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