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Blast resistance of multi-layered concrete slabs

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Abstract. This paper compares blast resistance of multi-layered and single-layered concrete panels having different thickness and reinforcement and subjected to various explosive charges. The panels were analysed by ultrasound measurements before the application of blast loading; the velocity of transfer of ultrasound waves through the panels was determined. The same measurement was conducted after exposing the panels to contact explosion and the damage was evaluated based on the determined changes. Nine panels were tested, four of them single-layered and five of them multi-layered. The weights of Pentrite explosive charges were 150 g, 300 g and 500 g. The results show that multi-layered panels are suitable for the protection of soft targets or as cladding of load-bearing structures.

1. Introduction

With increasing geopolitical stress in the world in recent years, blast loading becomes a very important type of accidental load of structures that should not be neglected. It is of particular importance mainly for critical infrastructures such as dams, bridges or power plants [4, 5] where it is normally taken into account in the design phase. However, the terrorists do not aim just on these key engineering structures. Very often, they attack public buildings or open spaces where there is a great accumulation of people. Therefore, it is important to focus on the development of materials suitable for increasing blast resistance of existing structures or for protective barriers.

The presented research compared blast resistance of ultra-high performance concrete (UHPC) panels with and without internal damping layer and with different types of dispersed reinforcement. The panels were exposed to contact blast of Pentrite explosive charges weighing 150 g, 300 g or 500 g. The main observed parameter was the velocity of transfer of ultrasound waves through the panel in specified points (orange dots in figure 1) and its change after the explosion.

2. Experiments

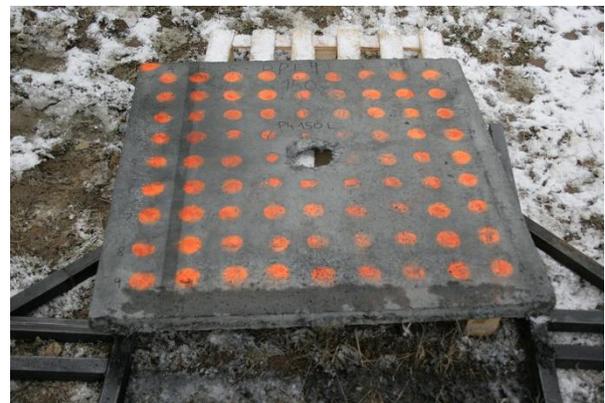
2.1. Specimens

The size of tested panels was 1x1 m. Nine different panels were tested. Further characteristics of particular specimens are summarized in table 1. An example of one panel before and after loading is given in figures 1 and 2.



Table 1. List of tested panels.

Type	Mixture	Damping layer	Thickness [mm]	Explosive charge [g]
A1	Z1	-	50	300
A2	Z1	-	50	150
A3	Z2	-	50	300
A4	Z2	-	50	150
A5	Z3	Rubber	150	300
A6	Z3	Rubber	150	500
A7	Z3	Rubber	150	300
A8	Z3	Rubber	150	500
A9	Z2	Gang Nail plate	100	500

**Figure 1.** A panel before the explosion.**Figure 2.** A panel after the explosion.

2.2. Concrete

Three different UHPC mixtures were used. The composition of the mixtures is given in table 2.

Table 2. UHPC mixtures.

Compound	Z1 [kg/m ³]	Z2 [kg/m ³]	Z3 [kg/m ³]
Cement	600.0	600.0	600.0
Water	140.0	140.0	140.0
Basaltic aggregate	1710.0	1710.0	1710.0
Superplasticizer	22.0	22.0	22.0
Microsilica	80.0	80.0	80.0
Dramix OL13 steel fibres	80.0	80.0	80.0
Dramix 80/30 steel fibres	-	30.0	60.0
Krampe Harex PM6/18 steel fibres	2.0	2.0	2.0
Recycled steel fibres (cord wires)	60.0	30.0	-
Fibrex A1 steel fibres	5.0	5.0	5.0

Compressive strength of UHPC at the age of 28 days f_c was measured on 150 mm cubes according to [1]. Flexural tensile strength at the age of 28 days $f_{t,fl}$ was tested on 100x100x400 mm beams by four-point bending test according to [2]. The results are summarized in table 3.

Table 3. Mechanical properties of UHPC mixtures.

Mixture	f_c [MPa]	$f_{t,fl}$ [MPa]
Z1	124.2	7.9
Z2	123.4	8.9
Z3	126.0	9.8

2.3. Explosive

Pentrite explosive was used. The charges were attached to the surface in the central part of the panels by industrial adhesive tape.

Pentrite is preferred for this type of tests due to its high explosion strength, explosiveness and chemical stability. The explosion energy of Pentrite is 5810 kJ/kg and detonation velocity is 8266 m/s. Pentrite is widely used mainly for the production of fragmentation and blasting-fragmentation charges.

3. Results

3.1. Panels without damping layer

In the first stage, panels with different types of dispersed reinforcement and without damping layer (A1 to A4) were tested. The charge of 300 g of Pentrite was used in case of panels A1 and A3. Smaller charge of 150 g was applied to panels A2 and A4 to compare the effects of different charges. The evaluation of damage was carried out by analysing measured ultrasound pulse velocities with the use of SVD_{ult} software developed by Štefan and Foglar [3].

Figures 3 and 4 show just the resulting damage extent for panels A3 and A4. The higher is the difference between pulse velocities before and after the explosion, the higher is the damage of the panel in the given point. In figures 5 and 6, detailed analysis of panels A1 and A2 is presented. Each column shows (from top to bottom): the ultrasound pulse velocity before the explosion; after the explosion; damage extent; and composed image of the real panel and measured damage extent.

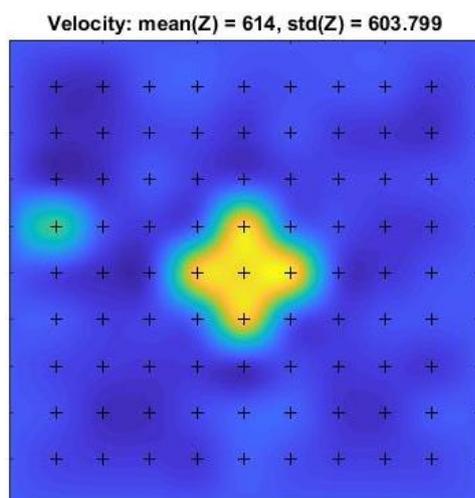


Figure 3. Panel A3.

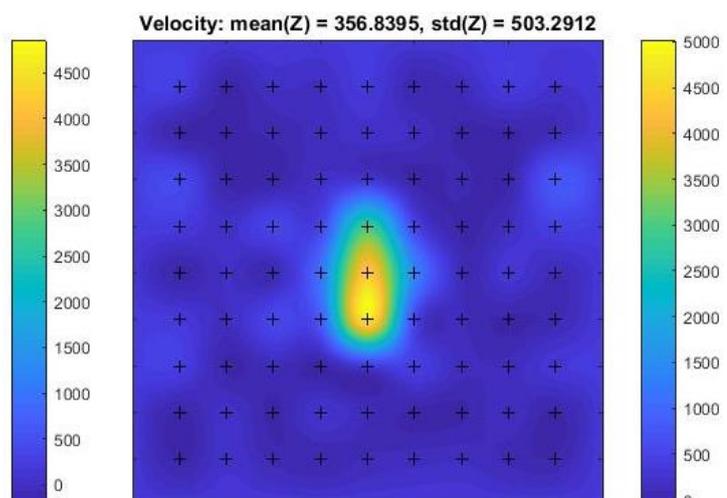
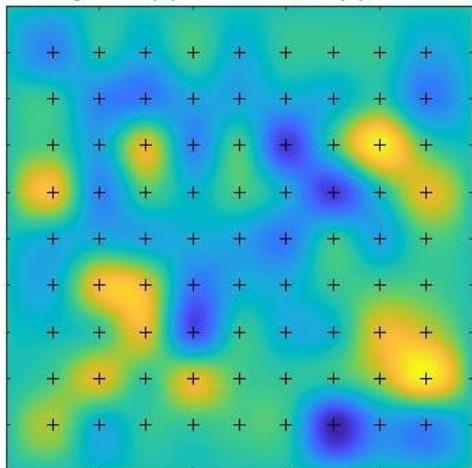
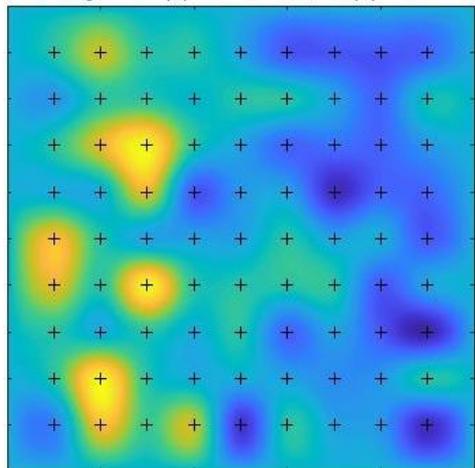


Figure 4. Panel A4.

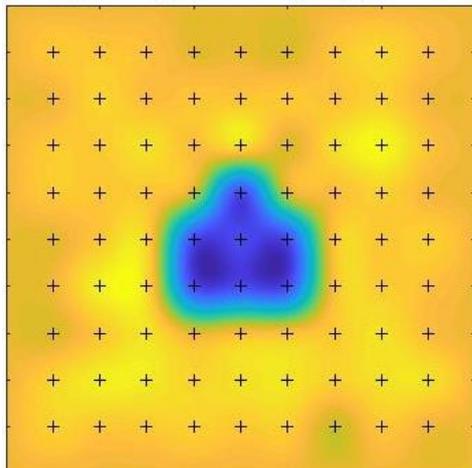
Velocity: mean(Z) = 5529.9877, std(Z) = 130.1944



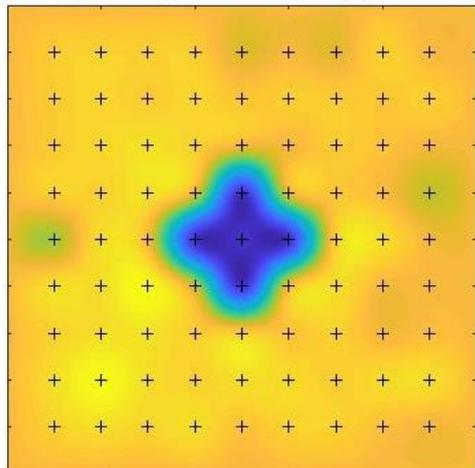
Velocity: mean(Z) = 4690.6049, std(Z) = 81.232



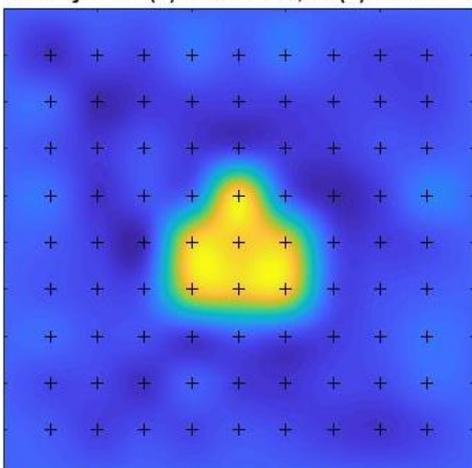
Velocity: mean(Z) = 3712.7284, std(Z) = 703.0324



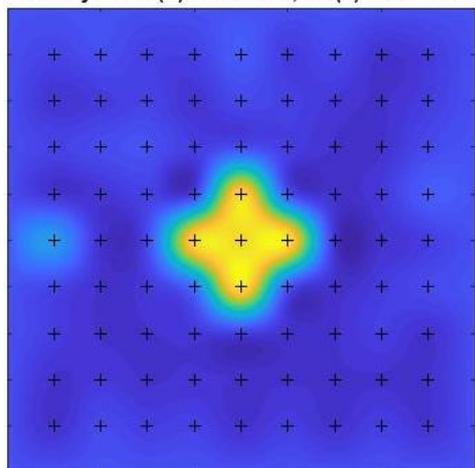
Velocity: mean(Z) = 4244.7531, std(Z) = 681.0281



Velocity: mean(Z) = 1817.2593, std(Z) = 675.5728



Velocity: mean(Z) = 468.2346, std(Z) = 692.6411



Velocity: mean(Z) = 3712.7284, std(Z) = 703.0324



Figure 5. Panel A1.

Velocity: mean(Z) = 4244.7531, std(Z) = 681.0281

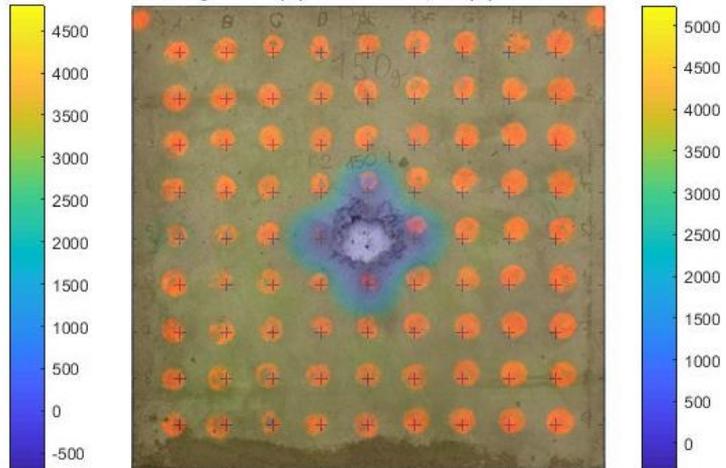
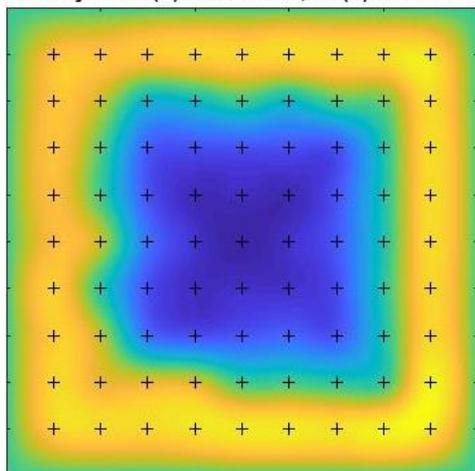


Figure 6. Panel A2.

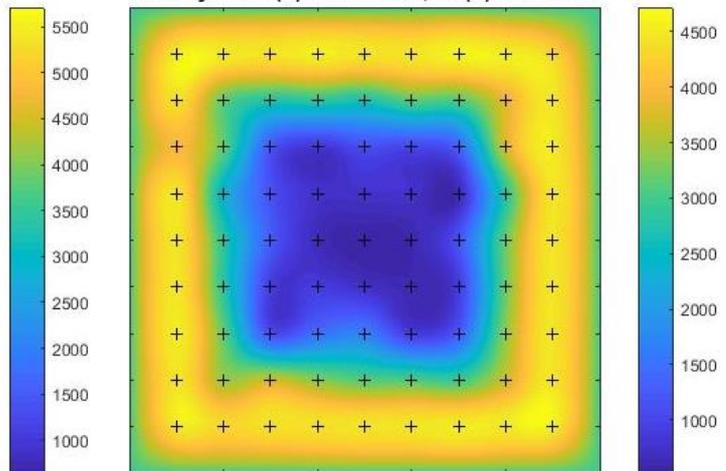
3.2. Panels with damping layer

In the second stage, tests of multi-layered panels were carried out. Panels A5 (figure 7) and A7 (figure 9) that contained rubber damping layer were exposed to 300 g charge. The sequence of particular images is the same as in figures 5 and 6. Panels A6 (figure 8) and A8 (figure 10) with the same damping layer were loaded by 500 g Pentrite. Just the damage extents are shown in figures 9 and 10.

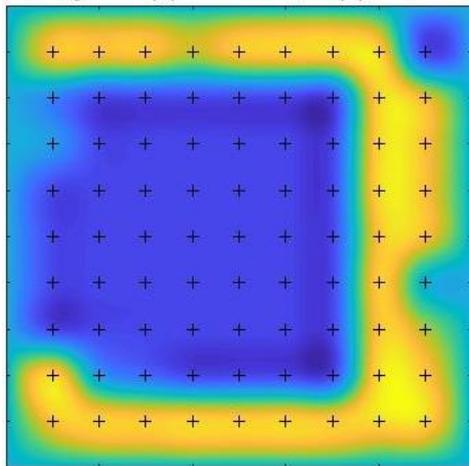
Velocity: mean(Z) = 3538.1481, std(Z) = 687.1217



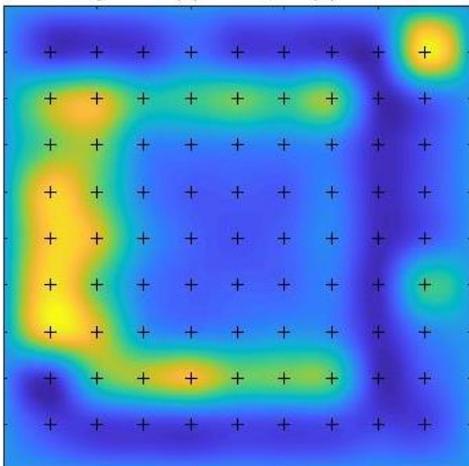
Velocity: mean(Z) = 2997.3457, std(Z) = 589.9486



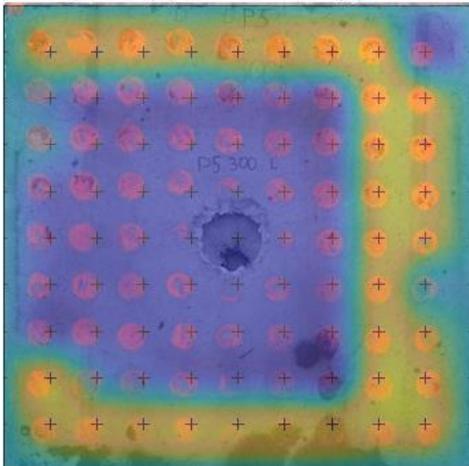
Velocity: mean(Z) = 1951.3086, std(Z) = 781.8152



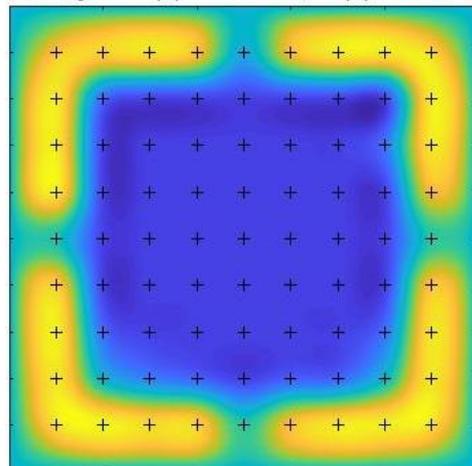
Velocity: mean(Z) = 1727, std(Z) = 625.5512



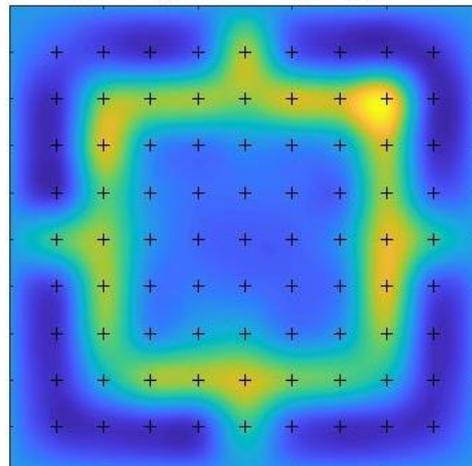
Velocity: mean(Z) = 1951.3086, std(Z) = 781.8152



Velocity: mean(Z) = 1732.8765, std(Z) = 666.9971



Velocity: mean(Z) = 1287.4568, std(Z) = 406.9744



Velocity: mean(Z) = 1732.8765, std(Z) = 666.9971

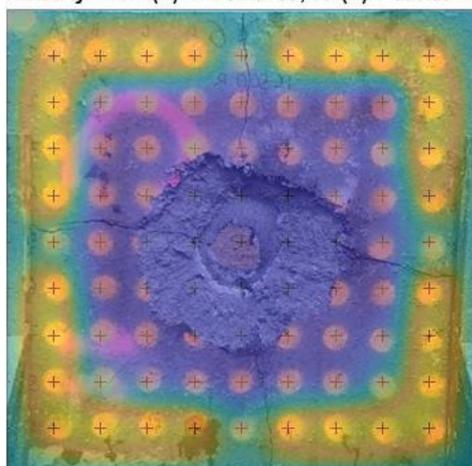


Figure 7. Panel A5.

Figure 8. Panel A6.

Velocity: mean(Z) = 1356.1975, std(Z) = 450.302

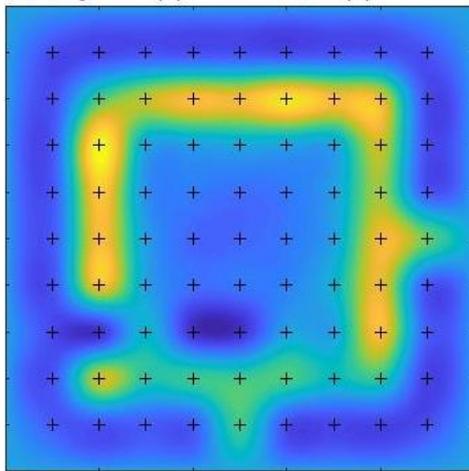


Figure 9. Panel A7.

Velocity: mean(Z) = 1535.5556, std(Z) = 434.9447

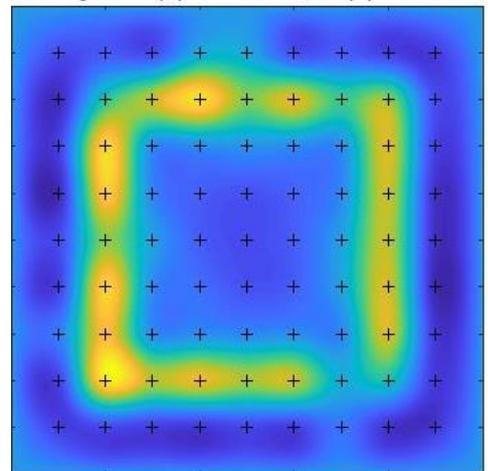
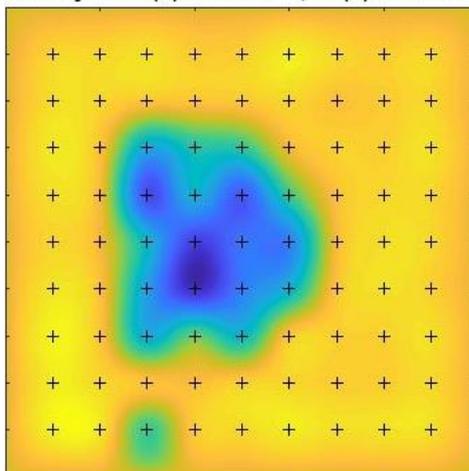


Figure 10. Panel A8.

Velocity: mean(Z) = 3937.5802, std(Z) = 509.7576



Velocity: mean(Z) = 1777.4444, std(Z) = 490.0095

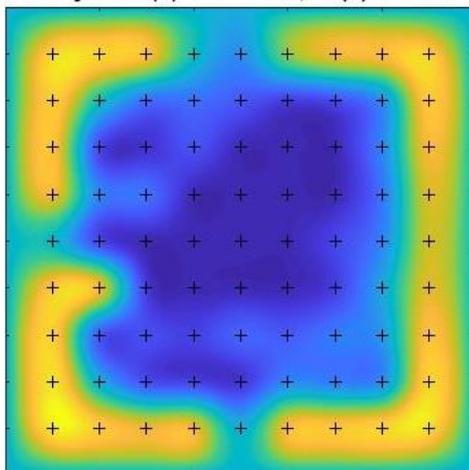
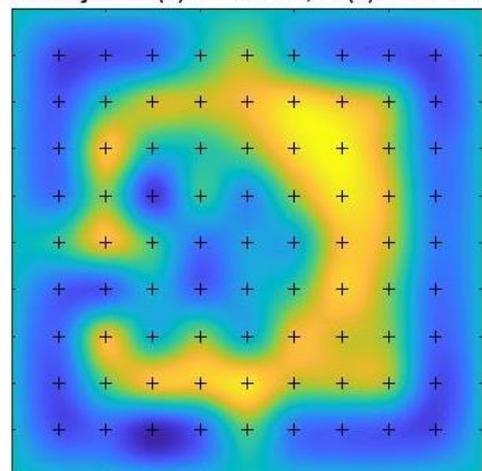


Figure 11. Panel A9.

Velocity: mean(Z) = 2166.0864, std(Z) = 452.4315



Velocity: mean(Z) = 1777.4444, std(Z) = 490.0095

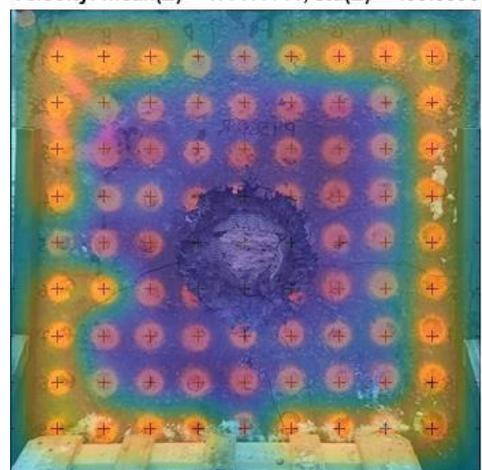


Figure 12. Panel A9.

Figures 11 and 12 show multi-layered panel A9 with damping layer made of gang-nail steel plates. The order of the images is the following: ultrasound pulse velocity before the explosion (figure 11

top); after the explosion (figure 11 bottom); damage extent (figure 12 top); composed image of the real panel and measured damage extent (figure 12 bottom).

4. Conclusions

In case of panels without the damping layer, the damage extent was directly proportional to the weight of explosive used. The damage was concentrated in the blast area.

For single-layered panels the influence of different type of dispersed reinforcement was also observed. The damage of panels A1 and A2 (made of Z1 concrete containing more recycled steel fibres from cord wires from discarded tyres) was slightly higher when compared to panels A3 and A4 (made of Z2 concrete containing half the amount of recycled steel fibres).

The damage of multi-layered panels seems to be smaller, but distributed over larger area around the point of explosion. Moreover, horizontal and vertical cracks occurred in these panels. The total absorbed explosion energy is higher and the amount of released debris is lower in case of multi-layered panels. Therefore, the multi-layered panels are more suitable as protective barriers or claddings of load-bearing structures.

Acknowledgments

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