Acta Polytechnica CTU Proceedings **53**:7–12, 2025
`https://doi.org/10.14311/APP.2025.53.0007`

Published by the `Czech Technical University in Prague`

PRODUCTION OF STEEL-CONCRETE COMPOSITE COLUMNS FOR BLAST TESTS

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Abstract. The resistance of structures to explosive impacts is a highly relevant issue in modern engineering. During an explosion, structures are subjected to extreme dynamic loads, which necessitate advanced materials and reinforcement strategies. UHPFRC, with its evenly distributed steel fibres, exhibits exceptional mechanical properties that make it well-suited for blast-resistant applications. Combining UHPFRC with steel reinforcement is expected to significantly mitigate structural damage under explosive loading.

This article focuses on the process of production of testing steel-concrete column specimens under axial compressive load for evaluating their blast resistance. The initial section describes the test elements and the objectives of the experiment. The following section outlines the design and material properties of the concrete mixtures used. Subsequently, the production process, including formwork preparation and casting, is detailed. Finally, the results achieved from ongoing testing are briefly introduced.

Keywords: Concrete, ultra-high performance fibre-reinforced concrete, blast resistance, steel-concrete composite.

1. Introduction

Explosions are most often associated with industrial accidents or acts of terrorism. In recent years, the increasing threat of terrorist or war attacks, particularly in developed countries, has highlighted the critical need for designing structures capable of withstanding the extreme overpressure loads generated by explosions [1, 2].

While steel-concrete composite structures are widely used globally, primarily for their economic efficiency, their behaviour under blast loading has not been thoroughly investigated. During an explosion, normal-strength concrete is highly susceptible to severe damage and collapse, necessitating reinforcement design to mitigate such risks. Explosions generate extreme local loading that is difficult to predict, requiring reinforcement to be designed with a high level of complexity [3]. The use of UHPFRC offers a promising solution, as its dispersed steel fibres provide uniform reinforcement throughout the entire volume of the element [4, 5]. When combined with steel components in a composite structure, this material has the potential to achieve significantly greater blast resistance compared to conventional steel-concrete composites using normal-strength concrete [4, 6, 7].

This article is focused on the process of production of steel-concrete column specimens intended to experimental blast resistance tests. In the end of the article a summary of the findings from the ongoing testing is shown. These tests represent only a part of a complex research project focused on the blast resistance of steel-concrete structures. The experimental design, numerical analysis, and data evaluation were conducted by the Faculty of Civil Engineering at the Czech Technical University (CTU), which also serves as the lead institution for the entire research project. The optimization of concrete mixtures, material property testing, and production of experimental specimens were performed by the Klokner Institute (KI).

2. Description of specimens

A total of ten column specimens were designed and prepared for the experiment, grouped into three fundamental types. Type 1 represented a plain steel column with no infill and it was used as a reference. Type 2 was a composite steel-concrete column filled with normal-strength concrete (NSC) with a compressive strength of 30+ MPa and type 3 represented composite steel-concrete columns filled with ultra-high-performance concrete (UHPC) with a compressive strength of 120+ MPa.

All columns were based on hot-rolled HEA 220 steel profiles fabricated from structural steel grade S355. Each steel profile was sealed with steel plates at both ends to ensure uniform load distribution and structural integrity. Additional side plates were attached to the specimens to assist with handling and positioning

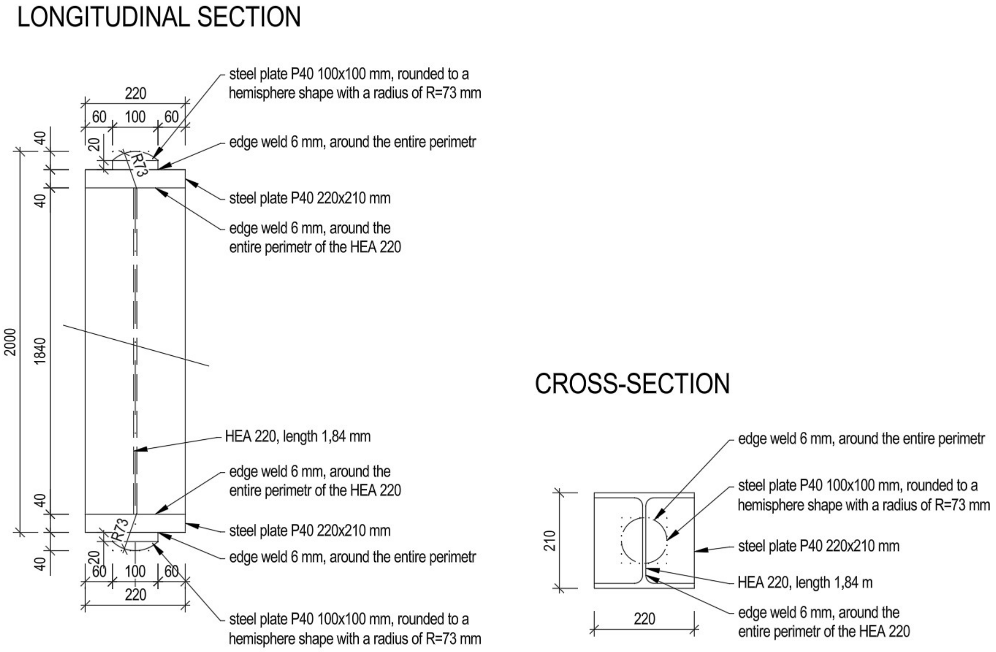

Figure 1. Detailed description of the steel parts of the specimens.

during the experiment. These side plates, however, had no structural function and did not influence the test results. To ensure composite action between the steel column and the infill concrete shear connectors in the form of bend reinforcement were welded onto the steel column.

To replicate realistic boundary conditions, steel spherical joints were installed at both ends of the columns. These joints simulated ideally pinned connections, allowing for uniform stress distribution of the axial compressive load across the specimen's cross-section. Additionally, the spherical joints facilitated accurate representation of pinned boundary conditions in subsequent numerical analyses.

The following Table 1. shows description of the specimen. Figure 1 illustrates the cross-section and longitudinal section of the test specimen.

Specimen	**Specimen description**
1a, 1b, 1c	Steel only column
2a, 2b, 2c	NSC-filled steel column
3a, 3b, 3c	UHPFRC-filled steel column

Table 1. List of prepared specimens and their description.

3. Material properties

As previously stated, a key objective of this part of the experimental program was to compare the performance of only steel columns with NSC-filled and UHPFRC-filled columns. The mix designs were adopted from the previous part of the experimental program, which focused on the blast resistance of composite slabs, where concrete mixtures for NSC and UHPFRC had already been developed and optimized by Klokner Institute [8].

The mixture is characterized by a very low water-cement ratio, self-compacting character, and exceptional material properties. Reinforcing was provided by dispersed steel fibres in volume of 1.5 % of the total volume. This fibre volume ensured required mechanical properties while maintaining good workability. The key material properties of the UHPFRC mixtures at 28 days are presented in Tables 2 to 4. Since the casting had to be performed over two days, two sets of results are presented in the table.

In case of NSC specimens the same concrete mixture as in the previous part of the experimental program was used [8]. The key material properties of the NSC mixtures at 28 days are presented in Tables 5 and 6. Since the casting had to be performed over two days, two sets of results are presented in the table.

4. Production

The prepared steel columns fabricated from steel sections were transported to Klokner institute, where the concrete casting for the samples was carried out. Samples were casted in horizontal position with flanges upright. This arrangement allowed the column flanges to serve as lost formwork, eliminating the need for additional formwork preparation. The casting process needed to be divided in phases, because only one side of the columns could be casted at the time. Between the castings, a two-day technological break was required, after which the samples were rotated to the other side and the second part of the casting was be carried out.

In case of NSC, the concrete was compacted using an immersion vibrator (NSC). Because of the self-

Material temperature [°C]	Flow test [mm]	Bulk density [kg m^{-3}]	Average speed of UZ signal [km s^{-1}]		Modulus of elasticity cylinder 150/300 mm [MPa]
			beam 150/150/700 mm	cylinder 150/300 mm	
25.0	285×290	2 430	4.64	4.62	44.9
28.3	240×245	2 410	4.61	4.58	44.7

Table 2. Material properties of UHPFRC.

Compressive strength [MPa]				Flexural strength [MPa]	
beam 40/40/160 mm	cube 100 mm	cylinder 100/200 mm	cylinder 150/300 mm	beam 40/40/160 mm	beam 150/150/700 mm
176.5	144.3	132.4	129.8	33.3	13.5
152.0	134.3	131.2	122.0	29.1	11.7

Table 3. Material properties of UHPFRC – compressive and flexural strength.

Flexural tensile strength at crack initiation $f_{fc,tm,fl}$ [MPa]	Residual flexural strength for deflection of [MPa]			Direct tensile strength at crack initiation $f_{fc,tm,cr}$ [MPa]	Residual direct tensile strength $f_{fc,tm,res,i}$ for deflection of [MPa]	
	0.5 mm	3.5 mm	5.0 mm		0.5 mm	3.5 mm
11.2	12.6	11.7	9.1	8.5	6.4	4.3
9.6	11.5	10.5	9.1	5.8	5.8	3.8

Table 4. Material properties of UHPFRC – direct tensile and flexural tensile strength.

Material temperature [°C]	Slump test [mm]	Bulk density [kg m^{-3}]	Modulus of elasticity cylinder 150/300 mm [MPa]	Average speed of UZ signal [km s^{-1}]	
				beam 150/150/700 mm	cylinder 150/300 mm
22.1	100	2 370	33.0	4.57	4.53
22.3	110	2 360	33.1	4.55	4.54

Table 5. Material properties of NSC.

Flexural strength beam 150/150/700 mm [MPa]	Compressive strength [MPa]			
	cube 100 mm	cube 150 mm	cylinder 100/200 mm	cylinder 150/300 mm
4.03	60.7	55.4	52.3	49.5
3.95	59.1	50.2	50.2	47.3

Table 6. Material properties of NSC – flexural and compressive strength.

compacting character of the mixture, the samples from UHPFRC needed not to be compacted. Few days after the first part of casting it was necessary to rotate each sample around its longitudinal axis to the opposite position, so it was possible to cast the second side of the section.

The casting process was processed in the Klokner's Institute laboratories. The UHPFRC specimens were cast in two batches with a total volume of 0.45 m^3. Similarly, the NSC specimens were cast in two batches with a total volume of 0.5 m^3. Following casting, the concrete surfaces were treated with an evaporation retardant and covered with plastic foil. The surfaces were treated with water during the first two days after casting. After 28 days, the specimens were transported to the University of Pardubice, where the blast tests were performed. In Figures 2 and 4 process of casting of the test samples is shown. All the prepared specimens can be seen in Figure 3.

Figure 2. Process of casting of the test specimens.

FIGURE 3. Process of casting of the test specimens.

FIGURE 4. Process of casting of the test specimens.

5. EXPERIMENTAL TEST

As it was mentioned above all specimens were transported to University of Pardubice, Institute of Energetic Materials, where blast experiments were performed.

For the purposes of these tests on columns subjected to axial loading, it was necessary to design a specialized testing apparatus that would met all the requirements for durability, functionality, and easy handling of the specimens. The axial loading was designed corresponding to a corner-column loading of multiple-story building as 1 300 kN in characteristic values.

After multiple iterations, the final arrangement was determined to be a statically indeterminate frame, loaded by prestressing induced by a hydraulic jack. The frame was arranged vertically to avoid parasitic bending. The hydraulic jack was positioned at the bottom of the frame, protected by a steel box to prevent any damage. The testing apparatus is shown in the following Figure 5.

FIGURE 5. Testing apparatus.

Specimen no.	Type	Axial load [kN]
1a	Type 1 (steel only)	1 300
2a	Type 2 (steel with NSC infill)	1 300
2b		100
3a	Type 3 (steel with UHPFRC infill)	1 300
3b		100

TABLE 7. Material properties of NSC – flexural and compressive strength.

Before the experiment, the elements were positioned vertically in the testing apparatus. The values of the axial compressive loads applied to the elements using a hydraulic press are provided in Table 7. The outer face of the steel flange in the middle of its height was loaded with a contact explosion of 0.8 kg of Semtex 1A moulded to rectangular shape. The blast loading was constant throughout all specimen. During the experiment the time history of displacement of each specimen flange was recorded with the use of 4 channels of photonic-doppler velocimetry (PDV). Also, the testing frame was equipped with strain gauges on both pillars to check axial load in specimens a and to measure residual load after the blast. After the explosive tests was performed, the specimens were also subjected to visual examination.

In this phase, it was decided to test only 5 out of the total 10 specimens. Experiments results from the first set were used to further complex and detailed evaluation. This evaluation promising some option to make changes and optimization for the second set of specimens, which should be tested in near future.

The design of the testing apparatus and evaluation of the test results was carried out by the Faculty of Civil Engineering at the Czech Technical University (CTU).

6. Results

A key finding from the ongoing evaluation of test results is the positive impact of infill concrete on the overall resistance of the steel profile. Steel specimens without concrete infill exhibited significant damage. During the explosion, steel fragments from the flange in direct contact with the charge were torn off. These fragments also caused a damage on the flange on the opposite side of the element (Figure 6). Specimens with concrete infill experienced overall significantly smaller damage. Concrete infill prevented fragmentation of the steel flange in contact with explosive. The concrete infill experienced of crushing and spalling on the sides of the specimen in the area closest to the explosion. Unlike the steel only specimens without concrete infill, almost no visible damage occurred to the opposite flange.

Figure 6. Side view of specimen no. 1a.

Tests results also shown positive effect of excellent mechanical properties of UHPFRC. Concrete infill made of NSC (Figure 7) experienced considerably bigger damage than UHPFRC infill (Figure 8).

The effect of axial compressive force was not evaluated, as not all unloaded samples were tested in the first set of the experiments. This evaluation will be possible after all the samples have been tested.

7. Conclusion

This part of research project was focused on behaving steel-concrete columns subjected to contact blast loading. The emphasis of the experimental tests was focused both on comparing performance chosen types of steel-concrete composite columns under axial compressive load. The axial load 1 300 kN simulates a corner-column loading of multiple-storey building. To fulfil project goals three types of column specimens were produced. One type was steel only, the other two were steel-concrete specimens with NSC and UHPFRC infill.

Figure 7. Side view of specimen no. 2a.

Figure 8. Side view of specimen no. 3a.

The emphasis of this article is description of production of the test specimens which was carried out by Klokner Institute (KI). Both UHPFRC and NSC mixtures had been optimized in the previous part of the experimental program. In the end of the article a summary of the findings from the ongoing testing are described.

Overall, better blast resistance was achieved with specimens with concrete infill. Concrete infill prevented fragmentation of steel profile. The positive effect of the excellent mechanical properties of UHPFRC on blast resistance can be observed. Specimens with UHPFRC experienced considerably smaller damage than specimens with NSC infill. The results from the first completed set of tests will be used for the further numerical assessment and possible optimization of test set-up for the second part of specimens. Test conception, numerical assessment and evaluation of results was carried out by Faculty of Civil Engineering of CTU.

Acknowledgements

The article was written with the support of the grant project of the Czech Science Foundation – project No. 22-33039S.

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