Submitted: 20.04.2023.

Accepted for publication: 12.05.2023.

Determination of the effects of the rebar-cement bond parameters variation in UHPFRC using FA and ANN

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https://doi.org/10.2298/SOS230420029B

Abstract:

The experimental study included the design and production of ultra-high-performance steel fiber-reinforced concrete (UHPFRC). The physical and mechanical properties of UHPFRC were investigated in a laboratory setting. To investigate the properties of UHPFR concrete, three types of concrete and over 70 samples were used. Following that, samples were created to test the anchors' load-bearing performance. Six concrete slabs with a total of 108 pre-installed anchor samples and six concrete slabs with 108 post-installed chemical anchor samples were created. The analysis of the test findings comprised all individual results as well as the definition of the relationship between the anchor's tensile load capacity and other parameters. To accurately determine the individual influence of the investigated factors as well as their combined impact, a factorial experiment, and artificial neural networks were used in addition to normal statistical numerical studies. It was determined that both approaches offer advantages. The results obtained show matches in certain parts. Due to the way data is processed in different ways, there are also significant differences between them.

Keywords: *Construction materials; Steel fibers; Low-cost primary raw materials; Mechanical properties; Mathematical modeling.*

1. Introduction

A high number of prefabrication plants and numerous successful construction projects conveyed with precast concrete elements, partially or in their entirety, demonstrate that this technology is still highly effective and cost-efficient [1]. Precast elements are manufactured under controlled conditions and strict supervision, which ensures high requirements for mechanical properties and performances [2]. Due to the high-quality manufacturing and extreme durability, prefabricated elements achieve a long service life. In recent period, the durability issues with concrete structures influenced the majority of countries to gradually increase the minimum requirements for corrosion resistance of steel reinforcement [3].

Over the last few decades, a favorable environment has been created for the development of innovative building materials. One of the most important innovations is the development of reactive powder concrete (RPC) [4]. Consequently, ultra-high-performance concrete (UHPC) was developed. UHPC exhibits compressive strengths higher than 150 N/mm^2 and brittle behavior. Thereby, steel fibers are usually employed to improve their characteristics. The material thus obtained is called ultra-high-performance fiber-reinforced concrete (UHPFRC). This concrete shows a ductile post-peak behavior, which depends on the fiber length and shape [5]. The mix of steel fibers enhances the toughness of the UHPFRC matrix; it improves the tensile strength (>7 N/mm^2) and ductility of UHPFRC to prevent or

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delay the development of the crack [6]. Different designs and applications of structural elements for building or bridge constructions using UHPFRC have been conveyed [7-8]. The cross-section and weight of reinforced concrete beams had increased as the height of building structures and the span of bridges had expanded. Concrete strength has been improved to compensate for the increased weight of concrete beams. UHPFRC enables the design of thin and durable load-bearing structures. The flexural behavior of prestressed UHPFRC girders is significantly superior to that of normal concrete (NC) girders for a similar cross-sectional geometry [9]. However, the cost of raw materials in a UHPFRC structure, such as quartz sands and steel fibers, is getting higher, and construction expenses are considerably raised by using UHPFRC to build the entire structure [10]. Furthermore, it was found that when bending failure occurs, the stress in the compressed zone is substantially lesser than the UHPFRC's compressive strength [11]. There are two options for solving this issue. The first one is to insert more steel reinforcements or prestressed tendons in the tension zone to increase the bearing capacity of the beam. The second option is to replace UHPFRC with normal concrete in the compression zone. In the first case, the beam must be designed to have sufficient capacity, because adding reinforcement will increase the weight. Too much reinforcement in the tension zone will cause the beam to suffer over-reinforcement damage, which is harmful to the beam. The second alternative lowers expenses while maintaining the beam capacity. Therefore, UHPFRC can be replaced by NC in the compression zone. Although NC has a low compressive strength, concrete parts in thin constructions are typically prestressed to reduce deflection and cracking. The quality of the reinforcement's bonding to the surrounding concrete is critical for structural performance [12].

1.1. Research Background

Static tests and numerical simulations have been extensively adopted to probe the mechanical performance of studs embedded in normal-strength concrete (NC) [13]. Buttry [14] performed a static experiment on steel-NC composite structures and demonstrated that the shear-bearing resistance of studs in NC was mainly dominated by concrete properties. Ding [15] studied the static behavior of studs through static tests and finite element (FE) simulations and noted that the shear bearing capacity of each stud in the bidirectional specimens improved when the size and tensile strength of the studs increased, whereas the stud’s aspect ratio had no significant impact on the ultimate shear capacities of the studs. Additionally, push-out tests have been widely adopted [16]. It is suggested that the influence of steel beam type on the ultimate shear capacities of stud connectors cannot be ignored, and the quality of stud welding should be strictly controlled.

Research on the mechanical behavior of stud connectors embedded in steel-NC composite beams is relatively novel, and some practical formulas for the ultimate shear resistance and load-slip curves of studs have been developed by considering stud geometry and concrete properties [17,18]. Besides the usual installment of anchors during concreting, post-installed anchors can also be used since the development of drilling technology has led to their widespread use. Post-installed anchors consist of different types of anchors such as expansion anchors, undercuts anchors, bonded anchors, and screw anchors. All of them can be used for structural and non-structural purposes, and they can be used on-site for fixing both temporary and permanent elements [19].

Researchers have studied the shear performance of studs embedded in high-strength concrete (HSC) or steel fiber-reinforced concrete (SFRC). These studies showed that the crack width of HSC and SFRC concrete slabs was small (≤0.1 mm) or no obvious cracks appeared at the failure of pushout specimens. The shear capacity of studs significantly improved because of the high concrete compressive strength [20, 21].

Reinforcing bars embedded in the concrete or subsequently embedded in concrete can be identified and considered as screw anchors based on their shape and dimensions. The arrangement of the pins on the reinforcement bars largely coincides with the thread pitch of the screw anchor. Research in the field of anchors in the form of reinforcing bars and screw anchors can be analyzed together. One of the most extensive studies in the field of screw anchors in NC was done by Kuenzlen [22]. The research included the examination of 500 screw anchors with an anchoring depth of 30 to 110 mm. Based on the effective anchoring depth, he proposed a formula for determining the bearing capacity of screw anchors by introducing a reduction factor of 0.85 for the effective anchoring depth. Other authors, standards, and regulations also propose their formulas by which the bearing capacity of anchors can be determined. Most of the existing formulas for calculating the bearing capacity are based on theoretical assumptions or limited experimental results. In the proposed forms, the diameter of the anchor and the compressive strength of the concrete are most often taken into account. However, the range from 30 to 200 N/mm^2 is very difficult to be covered with just one formula. In the case of high-strength concrete, the application of fibers affects the behavior of the concrete under stress, and therefore it is impossible to use formulas for the load capacity of anchors equally in all classes of concrete strength. Increasing the compressive strength of the concrete in which the anchors are embedded up to 7 times does not lead to an increase in the bearing capacity of the anchors at that level. The amount of applied fibers in ultra-high-strength concrete significantly affect the load-bearing behavior of anchors [23]. This is especially important for pre-installed anchors, where fibers can affect wedging, which in cracked concrete can affect the post-peak behavior of the anchor.

1.2. Research Significance and Novelty

The use of fibers to produce ultra-high-strength concrete is an important and unique topic that has received insufficient attention in the literature. The amount of fibers used varies depending on the purpose of the concrete and the performance required. The application of fiber varies from 1 % by volume to as much as 5 % in some cases. The stress behavior of these concretes largely depends on the amount of applied fibers. Therefore, it is expected that the behavior of anchors in such concrete depends on the number of applied fibers in ultra-high-strength concrete. Examining the behavior of anchors in concrete with different amounts of fibers gives a relationship between the number of fibers in the concrete and the bearing capacity of the anchor. By applying mathematical modeling, it is possible to determine the impact itself on other important parameters that affect the load capacity of the anchor.

On the other hand, due to the price of ultra-high-strength concrete and possible negative effects on the environment, in the case of its application, it is necessary to reduce the elements of this concrete to the minimum possible extent. In the case of composite constructions or structural elements, the space for connecting parts with anchors is limited. Therefore, the anchoring depth is an important factor that must be precisely determined, and its influence on the load capacity of the anchors is determined.

The goal of the research is to determine the level of significance of the anchoring depth and the number of fibers in the concrete on the load capacity of the anchor by employing mathematical modeling via an artificial neural network (ANN).

2. Experimental design

2.1. Materials and methods

The experiment included the testing of two types of anchors: pre-installed and post-installed. Pre-installed anchors were installed during concreting itself, while post-installed anchors were placed as chemical anchors in drilled holes in the concrete samples. For the experiment, ultra-high-strength concrete mix designs were made with a volume fraction of fibers of 1, 3, and 5 %. B500B rebar with diameters 10, 12, and 16 mm, was chosen for the anchors, while dimensions 2, 4, 6, 8, 10, and 12 cm were adopted for the anchoring depths. The test program stipulates that for each anchoring depth, two samples are made so that the result of the test is the mean value of the two results obtained.

The following properties were tested for each type of concrete: compressive strength, flexural strength, and modulus of elasticity by SRPS EN 12390-3:2019 (Testing hardened concrete - Part 3: Compressive strength of test specimen), SRPS EN 12390-5:2019 (Testing hardened concrete - Part 5: Flexural strength of test specimens) and SRPS EN 12390-13:2021 (Testing hardened concrete - Part 13: Determination of secant modulus of elasticity in compression), respectively. Due to the size effect, all tests were performed in parallel on several sample sizes, except for the modulus of elasticity of concrete. The compressive strength test was performed on half of the prisms 4×4×16 cm samples, cubes with edges of 10 cm, cylinders with a diameter of 15 cm, and a height of 30 cm. The tensile strength by bending was tested on prisms 4×4×16 cm, and prisms 10×10×40 cm. The modulus of elasticity was tested on cylindrical samples with a diameter of 15 cm and a height of 30 cm. The reinforcement has been tested and the characteristics are to the requirements for type B500B rebar. The test determined yield stress, tensile strength, and elongation.

A two-component epoxy compound was employed for the post-installed anchors. Initial concrete drilling was conveyed with classic concrete drill bits. The holes for placing the anchor were 1 mm larger than the anchor diameter. Cleaning with compressed air was carried out after drilling. Subsequently, the anchor with epoxy mass was placed in the prepared hole. Testing of post-installed anchors was performed 3 days after installation.

A fine-grained mixture of UHPFRC with a maximum grain size of 0.5 mm was investigated. The UHPFRC was composed of cement CEM I 52.5 R, silica fume, quartz powder, quartz sand (0.125–0.5 mm), water, and a high-range water reducer. High-strength steel fibers (fy > 2500 MPa), with a length of 10-15 mm and a diameter of 0.15–0.17 mm, were added to the mixture. The steel fiber ratio was chosen from 1 % to 5 % by vol., leading to an enhanced ductile behavior and good pouring quality. Higher ratios do not necessarily result in significantly better ductility and bond behavior of anchors [24], but in ineffective pouring, since local conglomerations of fibers often take place without proper bond to the concrete matrix. Steel fibers were used rather than non-metallic fibers, since a wide range of experience exists and only corrosion of the concrete surface occurs, without significant effect on the durability of the structure [25].

All specimens were produced without external vibrators. The slump flow of the mixture was about 650–700 mm [26, 27]. Mix design for all three types of concrete is given in Tab. I. The adopted amount of cement for all mixtures is 950 kg/m^3, constant water binding ratio of 0.2. Quartz sand has a maximum aggregate grain size of 0.5 to 1 mm.

Tab. I Mix design of experimental concretes.

Sample	Cement (kg/m^3)	Silica fume (kg/m^3)	Water (kg/m^3)	Quartz powder (kg/m^3)	Quartz sand (kg/m^3)	Fibre (kg/m^3)	Admixture (kg/m^3)	Density (kg/m^3)
M1	950	200	230	320	612	78.5	53	2443
M2	950	200	230	320	558	235.5	53	2509
M3	950	200	230	320	531	392.5	53	2640

UHPFRC concrete is made according to a special procedure to enable an even distribution of fibers in the hardened concrete structure. The homogeneity of the concrete mixture was checked on spreading tests of the fresh concrete mixture. When spreading the concrete, it was visually checked whether there is an accumulation of fibers in the concrete. The concrete consistency was designed by spreading it from 650 to 700 mm according to EN

12350-8. In addition to spreading, the time required for fresh concrete to spread to a diameter of 500 mm was also measured according to EN 12350-8. To check the design of the composition of concrete mixes, measurements were made of the volumetric mass of fresh concrete. Tab. II provides the parameters for the fresh concrete mix.

Tab. II Test results of fresh concrete.

Sample	Slump-flow (mm)	Time t_{500} (s)	Density (kg/m^3)
M1	660	9	2454
M2	680	10	2521
M3	660	9	2655

2.2. Test-setup

Load application was provided by uniform displacement using a hand jack with a custom loading plate as shown in Fig. 1. A self-reacting frame of ~300 mm in diameter was used throughout the study; the clear distance of 300 mm diameter was adopted to avoid confining the projection of the concrete cone failure for the deeper embedment anchors tested. According to the Concrete Capacity method, the failure cone has an angle of 30° leading to a failure surface diameter for the 120 mm embedment anchors of ~200 mm which is within the support triangle used. The load and displacement of the anchor were continuously monitored and recorded using calibrated sensors to capture the load-displacement behavior. This has provided the ability to measure anchor displacement directly from the head to ensure that the displacement recorded is the actual displacement of the anchor not affected by elongation that could be present in the loading system.

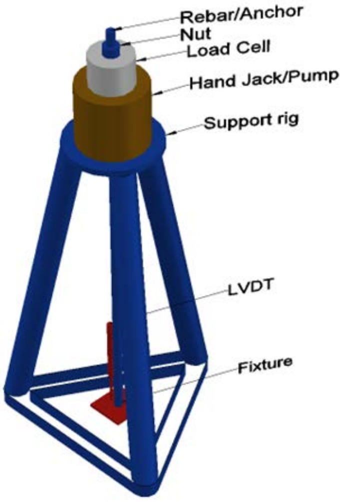

Fig. 1. The displacement using a hand jack with a custom loading plate.

All anchors were embedded in a 1.5×1.0×0.15 m plate, respecting the limits for mutual influence during extraction. Six panels for pre-installed anchors and six panels for post-installed anchors were made. Eighteen test anchors are installed on each plate respecting the limits between two anchors based on the anchorage depth. The anchoring depths d_a were from 2 to 12 cm with a step of 2 cm. To place all the anchors on the planned plate, the distance between the anchors with an anchoring depth of 2, 4, and 6 cm was reduced because the zone of influence with those anchors is significantly smaller than with other anchors. A scheme of the placement of the anchors on each of the plates is shown in Fig. 2.

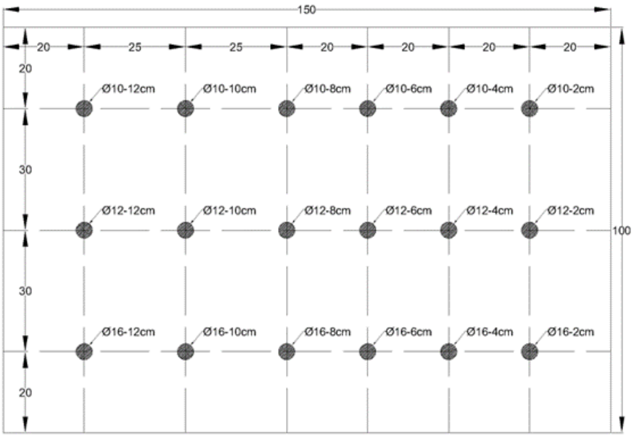

Fig. 2. Scheme of installation anchors in the plate.

3. Results and discussion

3.1. Mechanical Properties of Experimental Concrete Samples

Testing of hardened concrete samples was conveyed at the age of 28 days, while the load capacities of the anchors were determined over a period of 28 to 40 days due to the scope of the test [28, 29]. All test results obtained on hardened concrete are given in Tab. III.

Tab. III Test results of hardened concrete samples.

Sample	Compressive strength (N/mm^2)			Flexural strength (N/mm^2)		Modulus of elasticity (GPa)
	Prisms 4×4×16 cm	Cubes 10 cm	Cylinders 15×30 cm	Prisms 4×/4×16 cm	Prisms 10×10×40 cm	Cylinders 15×30 cm
M1	132.2	130.1	115.6	16.4	13.1	43.1
M2	148.1	144.0	128.0	25.0	18.9	45.3
M3	162.6	154.2	138.2	28.9	22.0	46.1

3.2. Properties of Rebar for Anchors

Before preparing the anchor for installation, the reinforcement was tested. The test results are given in Tab. IV.

Tab. IV Test results of rebar for anchors.

Nominal diameter (mm)	Yield stress (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
10	576	668	10.8
12	554	640	9.9
16	525	628	9.0

3.3. Results of Anchor Testing

A set of experimental results of anchor pullout tests conducted on pre-installed anchors is shown in Tab. V, and post-installed anchors in Tab. VI. Tables V and VI give concrete types, anchor diameters, anchoring depth, maximum force during testing, and type of failure. The maximum test force shown in the tables is the average of the two obtained results. The type of anchor failure is shown by the letters I - pull out, C - concrete failure, and S - steel failure (anchor failure). The tests were performed at an age of concrete of 28 to 40 days. The increase in concrete strength during that period was not considered.

Tab. V Test results of pre-installed anchors.

Concrete	Ø (mm)	d_a (cm)	Force (kN)	Failure type	Concrete	Ø (mm)	d_a (cm)	Force (kN)	Failure type
M1	R10	2	16.1	I	M2	R12	8	70.3	S
M1	R10	4	26.3	C	M2	R12	10	71.3	S
M1	R10	6	39.8	C	M2	R12	12	71.1	S
M1	R10	8	50.1	S	M2	R16	2	29.3	C
M1	R10	10	51.0	S	M2	R16	4	61.4	C
M1	R10	12	50.6	S	M2	R16	6	110.4	C
M1	R12	2	21.4	C	M2	R16	8	125.0	S
M1	R12	4	32.1	C	M2	R16	10	124.7	S
M1	R12	6	59.8	C	M2	R16	12	125.9	S
M1	R12	8	70.7	S	M3	R10	2	32.9	C
M1	R12	10	71.4	S	M3	R10	4	49.0	C
M1	R12	12	72.0	S	M3	R10	6	51.0	S
M1	R16	2	24.4	C	M3	R10	8	50.9	S
M1	R16	4	45.5	C	M3	R10	10	51.7	S
M1	R16	6	79.7	C	M3	R10	12	52.0	S
M1	R16	8	96.0	C	M3	R12	2	36.7	C
M1	R16	10	99.5	C	M3	R12	4	59.9	C
M1	R16	12	115.1	C	M3	R12	6	69.9	C-S
M2	R10	2	25.0	C	M3	R12	8	70.3	S
M2	R10	4	40.7	C	M3	R12	10	71.0	S
M2	R10	6	51.4	S	M3	R12	12	72.3	S
M2	R10	8	51.7	S	M3	R16	2	40.8	C
M2	R10	10	52.0	S	M3	R16	4	84.7	C
M2	R10	12	51.0	S	M3	R16	6	120.0	C-S
M2	R12	2	26.7	C	M3	R16	8	126.1	S
M2	R12	4	50.9	C	M3	R16	10	125.4	S
M2	R12	6	63.2	C	M3	R16	12	124.9	S

Tab. VI Test results of post-installed anchors.

Concrete	Ø (mm)	d_a (cm)	Force (kN)	Failure type	Concrete	Ø (mm)	d_a (cm)	Force (kN)	Failure type
M1	R10	2	6.9	I	M2	R12	8	50.3	I-C
M1	R10	4	16.7	I	M2	R12	10	54.1	I-C
M1	R10	6	32.9	C	M2	R12	12	71.2	S
M1	R10	8	36.3	C	M2	R16	2	13.0	I
M1	R10	10	46.9	S	M2	R16	4	36.6	I-C
M1	R10	12	49.3	S	M2	R16	6	52.2	I-C
M1	R12	2	7.8	I	M2	R16	8	53.7	I-C
M1	R12	4	23.8	C	M2	R16	10	84.9	C-S
M1	R12	6	44.3	C	M2	R16	12	100.0	S
M1	R12	8	50.1	C	M3	R10	2	7.6	I
M1	R12	10	52.7	C	M3	R10	4	22.8	I
M1	R12	12	70.2	S	M3	R10	6	44.6	I-C
M1	R16	2	13.3	I	M3	R10	8	54.1	S
M1	R16	4	36.2	C	M3	R10	10	53.0	S
M1	R16	6	48.7	C	M3	R10	12	51.3	S
M1	R16	8	54.2	C	M3	R12	2	9.8	I
M1	R16	10	69.1	C	M3	R12	4	37.1	I
M1	R16	12	102.1	S	M3	R12	6	49.1	I-C

Concrete	Ø (mm)	d_a (cm)	Force (kN)	Failure type	Concrete	Ø (mm)	d_a (cm)	Force (kN)	Failure type
M2	R10	2	7.3	I	M3	R12	8	63.7	C-S
M2	R10	4	19.0	C	M3	R12	10	71.3	S
M2	R10	6	39.3	C	M3	R12	12	73.6	S
M2	R10	8	48.2	C-S	M3	R16	2	13.1	I
M2	R10	10	50.2	S	M3	R16	4	40.0	I
M2	R10	12	50.9	S	M3	R16	6	50.1	I-C
M2	R12	2	9.4	I	M3	R16	8	68.2	C-S
M2	R12	4	27.4	I	M3	R16	10	102.1	S
M2	R12	6	48.5	I-C	M3	R16	12	104.2	S

3.4. Analysis of the Results

The analysis of the obtained anchor test results can be done from several aspects. The results can be analyzed in terms of the number of fibers in the concrete, the anchor diameter, and the anchoring depth. Based solely on the quantity of applied fibers in the concrete, it is possible to assume that the deeper the anchoring depth, the larger the influence of the amount of applied fibers in the concrete on the bearing capacity of the anchors. This conclusion is imposed using both pre-installed and post-installed anchors.

When it comes to the diameter of the anchors, the data clearly show that larger anchors carry more, which was expected for both pre-installed and post-installed anchors. When it comes to lower amounts of applied fibers in concrete with pre-installed anchors, the relationship between anchor load capacity and anchor diameter is linear. The linear dependence with pre-installed anchors is lost as the number of fibers increases. The situation is slightly different with post-installed anchors. The relationship between the diameter of the anchor and its bearing capacity is difficult to determine, especially for anchoring depths of less than 8 cm.

Based on the test findings for anchoring depth, the previously placed anchors achieve their maximum bearing capacity after a particular depth. The anchoring depth at which the maximum capacity is reached mostly depends on the diameter of the anchor. In the case of post-installed anchors, the relationship between anchor capacity and anchoring depth can be given in the form of linear dependence with a slightly lower degree of certainty.

Based on the initial findings, it is obvious that the examination of anchor load capacity necessitates the employment of novel and sophisticated technologies. Furthermore, it is not possible to analyze pre-installed anchors and post-installed anchors together due to the different types of load capacity. Because numerous parameters influence the load capacity of anchors, and not all of them are equally significant, two methodologies were utilized for analysis: factorial analysis and artificial neural networks. By analyzing these two approaches, it is necessary to determine the degree of influence of the anchoring depth parameters, the diameter of the anchor, and the number of fibers in the concrete on the bearing capacity of the anchor. The acquired results should then be compared, and conclusions taken based on the analytical results.

3.5. Factorial Analysis

Setting up the experiment requires defining the factors - parameters that are considered in the analysis. Three factors have been adopted that affect the load capacity of anchors. Limit values are defined for factors, as well as a certain number of values between the limits. With the adopted factors and the number of levels within the parameters, the factorial experiment is of form 3×6×3. A factorial experiment with three parameters and 3+6+3 levels per parameter is very complicated for computational processing. There are several ways to solve this problem. Due to the very complicated solution, further analysis of the factorial experiment was done using the MINITAB 17 TRIAL Academic software.

The results of the factorial analysis are given in Tab. VII for pre-installed anchors and Tab. VIII for post-installed anchors. All the results obtained by the program are given in the tables. The two columns Contribution and p-value (significance) are important. In the contribution column, the percentage values of the contribution to the output data, that is to the load capacity of the anchor, are obtained. Significance (p-value) is a statistical quantity that gives the probability with which it can be claimed that the obtained value of the contribution of the parameter affects the output data.

Based on the data from Tab. VII and Fig. 3, it is clear that the two dominant factors on the load capacity of pre-installed anchors are the anchoring depth and the diameter of the anchor. The number of fibers in concrete has a significantly smaller contribution to the load capacity of the anchor. Also, combinations of depth and diameter factors have a significantly higher contribution compared to the other two factor combinations. Based on the values shown in Tab. VIII and Fig. 3, it can be concluded that with subsequently installed anchors, the greatest contribution to the load capacity is the anchoring depth. The contribution of the combined influence of the number of fibers in concrete and the diameter of the anchor can be neglected by other factors and their combinations. Tab. VIII shows that in addition to a very small contribution, the significance of the variable is above 0.05, which concretely means that the contribution of this combination of factors can be ignored.

Tab. VII Results of the factorial analysis of pre-installed anchors.

Source	DF	Seq SS	Contribu.	Adj. SS	Adj. MS	F-Value	p-value
Model	72	66985	98.50%	66985	1633.8	47.99	0.000
Linear	10	58343	85.79%	58343	5834.3	171.37	0.000
A-fiber	3	5548	8.16%	5548	1849.3	54.32	0.000
B-depth	5	28688	42.18%	28688	5737.6	168.53	0.000
C-radius	2	24106	35.45%	24106	12053.2	354.04	0.000
2-way interact.	31	8642	12.71%	8642	278.8	8.19	0.000
A*B	15	1517	2.23%	1517	101.2	2.97	0.005
A*C	6	1558	2.29%	1558	259.7	7.63	0.000
B*C	10	5567	8.19%	5567	556.7	16.35	0.000
Error	30	1021	1.50%	1021	34.0		
Total	71	68006	100.00%				

Tab. VIII Results of the factorial analysis of post-installed anchors.

Source	DF	Seq SS	Contribu.	Adj. SS	Adj. MS	F-Value	p-value
Model	72	44424.4	98.98%	43850.4	1252.87	47.99	0.000
Linear	10	40221.0	90.53%	40221.0	4022.10	171.37	0.000
A-fiber	3	4497.7	10.12%	4497.7	1499.24	54.32	0.000
B-depth	5	30297.2	68.20%	30297.2	6059.44	168.53	0.000
C-radius	2	5426.1	12.21%	5426.1	2713.04	354.04	0.000
2-way interact.	31	3752.4	8.45%	3629.4	145.18	8.19	0.000
A*B	15	903.4	2.03%	903.4	60.23	2.97	0.001
A*C	9	123.0	0.28%	123.0	20.50	7.63	0.074
B*C	10	451.0	6.14%	2726.0	272.60	16.35	0.000
Error	22	451.0	1.02%	573.9	15.94		
Total	71	44424.4	100.00%				

Looking at both types of anchors, it is common that the greatest contribution to the load capacity of pull-out anchors is the anchoring depth. With both types of anchors, in addition to the anchoring depth, the diameter of the anchor also makes a significant contribution to the bearing capacity. The number of fibers in the concrete in both cases should not be neglected, but the contribution is significantly smaller than the other two factors.

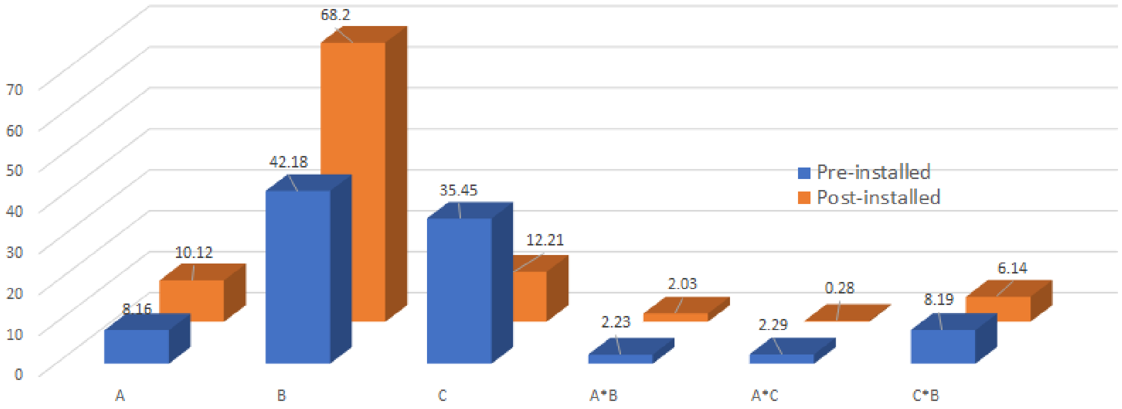

Fig. 3. Influences of factors on anchor load capacity - factorial analysis.

3.6. ANN modeling

The application of artificial neural networks is a specific data processing procedure in experimental research. The specificity of the procedure is that in the first place, it is necessary to find an adequate neural network, and only then it is possible to analyze the obtained parameters [30]. Finding and adopting a neural network is an iterative process. Depending on the type of problem that is analyzed at the beginning, it is necessary to adopt the type of neural network. In the case of adopted experimental research, perceptron multi-layer neural networks were adopted. In addition to the type of neural network, the type of neurons in the network is determined, that is, the activation function. A sigmoidal function was chosen as the activation function of the neuron, which can give values between -1 and +1 for the output of the neuron.

When processing the results of neural networks, depending on the data available for training, i.e., learning the neural network, they can be unstable or sensitive to input data. To analyze the sensitivity and stability of networks, a method of checking was designed. Each neural network is tested on three different data sets. Data sets vary in number, and data are randomly selected from the database. Taking into account that the results from the base are taken by a random sample and that their number changes through three iterations, observing the error between the experimental results and the results obtained with the neural network, the sensitivity or stability of the neural network was evaluated. The assessment was made based on the root mean square deviation between the experimental results and the results obtained by the neural network.

Based on the setting, it was adopted that the training of neural networks is performed according to the following number of randomly selected data: 1) first training on 90 % randomly selected data; 2) second training on 85 % randomly selected data; and 3) third training on 80 % randomly selected data.

The process of training neural networks includes the adoption of optimal values of the weighting coefficients, and at the same time, the calculation of the load capacity of the anchors was performed for all input data. The values thus calculated were used for comparison with the actual experimental values obtained. The calculated values of the root mean square deviation of neural network training are denoted by $U_{rmse,x}$, where X represents the percentage of used results from the database. For each of the neural networks considered, training was done as specified with the three data sets, and the values $U_{rmse,90}$, $U_{rmse,85}$, and

$U_{rmse,80}$ were obtained. After that, the values of the root mean square deviation of the neural network testing were calculated and denoted by $T_{rmse,y}$, where Y represents the remaining percentage of the used results from the database. For each of the considered neural networks, testing was done with the remaining data after training the neural network. Therefore, after each training and calculation of $U_{rmse,x}$ the values of $T_{rmse,10}$, $T_{rmse,15}$, and $T_{rmse,20}$ were also calculated. Since the values for $U_{rmse,x,}$ and corresponding values for $T_{rmse,y}$ were calculated, the obtained results were evaluated.

For the pre-installed anchors, the ANN with the designation 3-5-2-1 gave the best results overall in training and testing. The 3-5-2-1 ANN was adopted for further processing in the parametric analysis of pre-installed anchors. The results are shown in Tab. IX. In the test results of subsequently installed anchors, the neural networks showed some instability during training, that is, sensitivity to the choice of results. All networks were tested to confirm the results obtained during training. During testing, all networks showed instability and sensitivity to the choice of results, except for the 3-5-3-1 ANN. Considering the training and testing results, the 3-5-3-1 ANN was chosen as the best for further parametric analysis. The results are shown in Tab. IX.

Tab. IX Mean square deviation results of training and testing selected ANN-s.

Neural Network	$U_{rmse,90}$	$U_{rmse,85}$	$U_{rmse,80}$	$\overline{U}_{rmse}$	$T_{rmse,10}$	$T_{rmse,15}$	$T_{rmse,20}$	$\overline{T}_{rmse}$
3-5-2-1	2.498	1.720	1.434	1.884	4.966	4.435	4.655	4.686
3-5-3-1	2.088	2.407	2.570	2.355	7.799	6.844	7.622	7.421

After adopting the best ANN for each of the databases, parametric analysis was started. Parametric analysis with neural networks requires a special procedure. The procedure consisted of the fact that for each experimental data, two input data were fixed, while the third one was varied and the value was calculated in the adopted neural network. That is how it was calculated for each database: 1) when the fiber percentage was varied, 72x3 total 216 data were calculated; 2) when the anchor size was varied, 72x3 total 216 data were calculated, and 3) when the anchoring depth was varied, 72x6 total 432 data were calculated.

After that, for each case, the maximum difference from the obtained data was calculated, which is denoted by Δi, where i is one of the input parameters. Calculating the value of Δi - the influence of parameters is calculated according to Equation 1:

$$U_i = \frac{\Delta_i}{\Delta_1+\Delta_2+\Delta_3}\,[\%] \qquad [1]$$

The parametric analysis of the test results of pre-installed anchors using the 3-5-2-1 neural network resulted in the following influence of the parameters:

1. Anchorage depth: 43.6 %
2. Anchor diameter: 40.0%
3. The number of fibers used: 16.4%

Parametric analysis of the test results of post-installed anchors with the adopted neural network 3-5-3-1 obtained the following influence of parameters:

1. Anchorage depth: 59.1 %
2. Anchor diameter: 21.0 %
3. The number of fibers used: 19.9 %

4. Conclusions

Following experimentally obtained results on rebar-cement bond parameters in UHPFR concrete and individual factor analysis, the obtained data were additionally processed using factorial analysis and artificial neural networks. The mathematical analyses provided a closer preview of the influence of each individual considered parameter on the load capacity of the anchor. The outcomes of factorial analysis (FA) and artificial neural network (ANN) were noticeably comparable with pre-installed anchors, while different outputs were obtained for post-installed anchors. The main results are summed up below:

- Anchoring depths are the most important factor in the FA, while anchor diameter is the dominant factor in ANN.
- Both approaches demonstrated that anchoring depth and anchor size had a significant impact on the load capacity of pre-installed anchors. No significant difference was found between the obtained impacts for the mentioned parameters.
- The influence of the number of fibers used in concrete on the load capacity of anchors varies depending on the approach. According to FA, the influence is 8.16%, while with ANN the percentage is significantly higher at 16.4%. The difference can be explained by the fact that factorial analysis considers and computes the combined influence of factors.
- With post-installed anchors, the dominant influence in both approaches is the anchoring depth and it was 68.2% (FA) and 59.1% (ANN).
- A significant difference arises in the calculations of the factor of the diameter of the anchor and the number of applied fibers in the concrete. For the anchor diameter, the influence of 12.21 % and 21.0 % were obtained for FA and ANN, respectively. Similarly, for the number of fibers, an influence of 10.21 % and 19.9 % were obtained for FA and ANN, respectively. The conclusion is that with chemical anchors, none of the factors considered can be ignored.
- In the analysis of the load capacity of anchors depending on the number of applied steel fibers in ultra-high strength concrete with an increase in anchoring depth, regardless of the size and type of anchors, the influence of the number of applied fibers in concrete can be ignored. If the construction requires shallow anchoring depths, the inclusion of more fibers in the concrete should be considered to increase the load capacity of the anchors.
- For the concrete used in the experiment, with smaller and medium anchoring depths, the size of the anchor has a significantly smaller influence on the load capacity of the anchor. When the anchoring depths are greater, for all amounts of applied fibers, the size of the anchor almost linearly increases with the load capacity of the anchor.

It can be concluded that both approaches gave relatively similar processing results when it comes to anchor load test results. When choosing an approach for data processing, one should keep in mind what the ultimate goals are. Artificial neural networks make it possible to continue to use them after training and to increase their accuracy by expanding the database.

Acknowledgments

This investigation is financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract No.: 451-03-47/2023-01/ 200012).

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Одређивање ефекта параметара везе арматура-цемент у УХПФР бетону коришћењем факторске анализе и вештачких неуронских мрежа

Резиме:

Експериментална студија је обухватила пројектовање и производњу бетона ојачаног челичним влакнима ултра високих перформанси (УХПФРЦ). Физичка и механичка својства УХПФРЦ испитивана су у лабораторијским условима. За испитивање својстава УХПФРЦ бетона коришћене су три врсте бетона и преко 70 узорака. Након тога, направљени су узорци за испитивање носивости анкера. Израђено је шест бетонских плоча са укупно 108 претходно уграђених анкера и шест бетонских плоча са 108 накнадно уграђених хемијских анкера. Анализом резултата испитивања обухваћени су сви појединачни резултати, као и дефинисање везе између носивости анкера на затезање и варираних параметара. У циљу прецизног *утврђивања индивидуалног утицаја испитиваних фактора, као и њиховог комбинованог утицаја, поред уобичајених статистичких нумеричких студија коришћени су факторска анализа и вештачке неуронске мреже. Утврђено је да оба приступа имају своје предности. Резултати који су добијени показују подударања у појединим деловима. Због начина обраде података у различитим приступима постоје и значајне разлике међу њима.*

Кључне речи: *Грађевински материјали; Челична влакна; Економичне минералне сировине; Механичка својства; Математичко моделовање.*