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Original Empirical Research

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Modeling of Shear Strength of Ultra-High-Performance Concrete Beams Using Statistical Learning Tools

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Introduction. Ultra-high-performance concrete (UHPC) combines high strength and crack resistance with low permeability, making it ideal for structures operating under aggressive environmental conditions and high loads. The growing use of UHPC in construction makes necessary the development of scientifically grounded methods for designing structures made with this material. The aim of this study is to develop engineering methods for calculating the shear strength of UHPC I-beams using statistical learning techniques. The models were based on extensive datasets, including both the authors' own experimental results and data from other researchers.

Materials and Methods. Artificial neural networks (ANNs) and regression analysis methods were used to develop the models. The tasks were implemented using the STATISTICA software package.

Results. Nonlinear expressions were developed for engineering calculations, allowing for the determination of the shear strength of UHPC-beams accounting for the shear span and structural parameters, including section geometry, UHPC strength characteristics, and fiber and shear reinforcement ratios. The proposed formulas reduce the discrepancy between theoretical and experimental data by up to 2.4 times compared to calculation by methods adopted in codes. The formulas are applicable to beams unreinforced in shear as well as those with fiber and shear reinforcement.

Discussion and Conclusion. The results confirm the applicability of regression models and ANNs for calculating the shear strength of UHPC beams, particularly in cases where traditional analytical solutions are difficult to formalize. The reliability of the developed models is supported by statistical analysis, including verification of regression equation adequacy and comparison with existing code-based methods.

Keywords: ultra-high-performance concrete, I-beams, regression analysis, artificial neural networks, shear force

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Оригинальное эмпирическое исследование

Моделирование сопротивления поперечным силам балок из сверхвысокопрочного бетона инструментами статистического обучения

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Аннотация

Введение. Сверхвысокопрочный бетон (СВПБ) сочетает в себе высокую прочность и трещиностойкость, низкую проницаемость, что делает его эффективным для конструкций, эксплуатируемых в условиях действия агрессивных сред и высоких нагрузок. Расширение практики применения СВПБ в строительстве требует разработки соответствующих научно обоснованных методов расчета изготовленных с его применением конструкций. Одним из малоизученных вопросов является сопротивление изгибаемых СВПБ-конструкций действию поперечных сил. В настоящей работе предложены расчетные зависимости для определения прочности наклонных сечений двутавровых балок из СВПБ, разработанные с применением методов машинного обучения. Для регрессий составлены и структурированы обширные экспериментальные выборки с широкими диапазонами параметров, оказывающих влияние на сопротивление поперечным силам.

Материалы и методы. При построении моделей использованы искусственные нейронные сети (ИНС) и методы регрессионного анализа. Для решения задач использован инструментарий программы STATISTICA.

Результаты исследования. Разработаны нелинейные зависимости для инженерных расчетов, позволяющие производить расчет сопротивления СВПБ-балок поперечным силам с учетом влияния пролета среза нагружения и конструктивных параметров, включая геометрию сечения, прочностные характеристики СВПБ, а также коэффициенты фибрового и поперечного стержневого армирования. Результаты подтверждают применимость регрессионных моделей и ИНС для расчетов прочности наклонных сечений СВПБ-балок, как для сложно формализуемой задачи. Достоверность полученных моделей подтверждена статистическим анализом, включая проверку адекватности уравнений регрессии и их сравнение с нормативными методиками расчета.

Обсуждение и заключение. Предложенные формулы позволяют снизить расхождение между теоретическими и экспериментальными данными в сравнении с нормативными методиками до 2,4 раза. Формулы применимы как для расчета балок с неармированными наклонными сечениями, так и для балок с фибровым и поперечным стержневым армированием.

Ключевые слова: сверхвысокопрочный бетон, двутавровые балки, регрессионный анализ, искусственные нейронные сети, поперечные силы

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Introduction. Ultra—high-strength concretes (hereinafter referred to as UHPCs) with dispersed (fiber) reinforcement are a relatively new class of concretes characterized by high strength and endurance, durability and frost resistance. Similarly to other types of fine-grained concrete, one of the areas of rational use of UHPC are structures with small cross-sectional profile thicknesses. An example of bent structures of this type are I-beams of superstructures and decking structures operated under the influence of aggressive environments.

The improvement of approaches to calculating the transverse forces of UHPC- beams is largely focused in two directions: construction of finite element models using nonlinear diagrams of deformation of UHPC and reinforcement as well as the refinement of formulas for engineering calculations of beam strength. The formulas of the NF P18-710 manual can be cited as an example of existing regulatory methods for calculating bending SVP structures for transverse forces. Similarly to Eurocode 2, the NF P18-710 formulas are based on the method of truss analogy. At the same time, the Eurocode 2 methodology assumes that all transverse force in elements with transverse reinforcement is perceived only by clamps (concrete resistance is taken into account only in elements without transverse reinforcement). In its turn, in NF P18-710, the resistance (contribution) of concrete is assigned both for elements with and without transverse reinforcement. Separate terms account for the contribution of fiber. What also differs in a way from Eurocode 2 is the NF P18-710 approach to calculating the strength of thin walls. Hence Eurocode 2 provides for this calculation only for elements with transverse reinforcement, while NF P18-710 contains calculation formulas for both elements with and without transverse reinforcement.

The method of calculating transverse forces of SP 360.1325800 "Steel-Reinforced Concrete Structures" replicates that of the set of rules of SP 63.13330 "Concrete and Reinforced Concrete Structures. Basic Provisions" with the replacement of the strength characteristics of ordinary concrete with similar ones of steel-fiber concrete — in the formula for wall strength, R_{fb} is used instead of R_b, and in the formula for calculating inclined sections, R_{fbt} is used instead of R_{bt}. The R_{fbt} resistance corresponds to the top of the deformation diagram of steel fiber concrete under axial tension.

The downside of the normative methods is the incomplete consideration of factors affecting the resistance of beams to transverse forces. This makes it necessary to develop alternative approaches based on the analysis of experimental data and the use of modern computing technologies.

The aim of this study was to obtain engineering methods for calculating the resistance to transverse forces of I-beams by means of statistical learning tools such as neural network and regression analysis. Representative databases were employed as training and test samples of the models, including both the authors' own tests and other researchers' experiments.

Materials and Methods. There are lots of problems facing construction science that cannot be tackled by means of traditional computational methods. In such cases, an accelerated search for new solutions is possible using data management technologies employing a large accumulated volume of results from field and numerical experiments. In materials science literature, this stage of the development of science is referred to as its "fourth paradigm" [1].

In recent years, artificial intelligence technologies have been extensively used for calculating structures as an alternative to classical modeling methods [2] defined as the ability of a computer to simulate intelligent human actions by searching for algorithms for tackling complex problems. A critical part of artificial intelligence is machine learning which is used in order to investigate trends and is aimed at forecasting using algorithms for calculations based on the data involved in training [3]. Machine learning is known for its capacity to capture nonlinear relationships between input and output data that are challenging to formulate. Machine learning has been applied in inspecting and monitoring building structures, optimization, reliability assessment and prediction of material properties [4].

Artificial neural networks (ANN) are computational models that simulate biological neural structures. Their basic elements (neurons) process information by means of dynamically responding to input signals. The key feature of such networks is their adaptability: unlike classical algorithms operating according to strict rules, ANNs are trained on a large amount of data adjusting the parameters of connections. The ANN is based on weighted connections between neurons that constitute an architecture with one or more layers. During the learning process, the system iteratively optimizes the weighting coefficients that determine the strength of the interaction of the elements. For forecasting and regression tasks, single-layer ANNs are commonly used as the simplest type of architecture with direct connections [5, 6].

Analyzing the relationships between processes and factors calls for the use of specialized mathematical methods. *Regression analysis* has become widespread making it possible to quantify the influence of independent variables (predictor factors) on the investigated dependent value (the resulting response).

This method enables one to:

– identify the degree of impact of each factor on the outcome;

– identify the closeness of correlations between the analyzed parameters;

– design predictive models based on the identified dependencies.

In this paper, ANN and regression analysis are used in order to obtain calculation formulas for calculating the resistance to transverse forces of I-beams made of ultra-high-strength concrete and fibrocrete. The STATISTICA toolkit is used to solve the problems.

Research Results. Given the structure of formulas for the strength of inclined sections accepted in the norms, the regression analysis aimed at developing an engineering methodology for calculating I-beam SVP beams was carried out in two stages. At the first stage, a regression model of the strength of beams with no fiber and rod transverse reinforcement was obtained

$$Q = Q_b = f\,(x_1, x_2, x_3, x_4, x_5, x_6), \tag{1}$$

where x_1 (a/h_0), x_2 (b_w), x_3 (h_0), x_4 (R), x_5 (μ_s), x_6 (φ_f) are factor arguments; a/h_0 is a section span; b_w and h_0 is the wall thickness and working section height; R is the strength of concrete; μ_s is the coefficient of longitudinal reinforcement.

$$\varphi_f = \frac{(b_f - b_w)\cdot t_f}{b_w \cdot h_0},$$

where b_f, t_f is the width and thickness of the shelf.

The database for the first stage was a sample based on the results of transverse force tests of rectangular and I-beams made of high-strength and ultra-high-strength concrete with no fiber and transverse core reinforcement discussed in literature [7–41].

At the second stage, the load-bearing capacity of beams reinforced with fibers and having no rod transverse reinforcement is assumed to be equal to:

$$Q = Q_b + Q_f,$$

after that, the formula for the contribution of fibers Q_f was identified by selecting the parameters of a regression model in the following form

$$Q = y + f\,(x_1, x_2, x_3, x_4),$$

where y is the contribution of concrete Q_b according to formula (1); x_1 (b_w), x_2 (h_0), x_3 (R_{bt}), x_4 (μ_s).

The database for the second stage was compiled based on the results of our and other tests for the transverse force of T- and I- UHPC beams reinforced with fibers but with no transverse reinforcement. [7, 13, 36, 37, 39, 42–49].

At both stages, the order is set for obtaining regression dependencies:

1. Choosing a functional form.
2. Assessing the model parameters.
3. Testing the validity of the model.

Choosing a functional form for Q_b is carried out by visual analysis instrumental in the initial assessment of data, identifying common patterns and trends. As it is possible to design only three-dimensional graphs (surfaces), a few of them will be required for visual analysis of the dependence. Having considered these surfaces (Fig. 1), the equation of dependence of the variable y on x_1, x_2, x_3 and x_4 should have a complex nonlinear form.

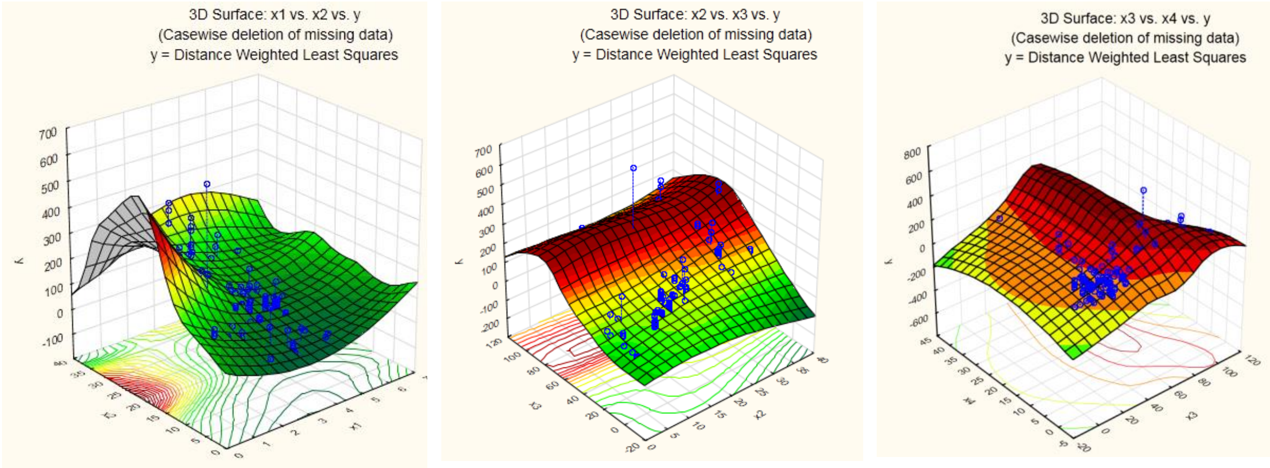


Fig. 1. Three-dimensional graphs (surfaces) of the dependence y on x_1, x_2, x_3 and x_4

In order to visualize descriptive statistics of experimental data, so-called "box diagrams" are designed (Fig. 2) that can be used for the data to be evaluated for distribution structure, outliers, uniformity of observations, etc. As can be seen, the variables x_1, x_5 and x_6 are closely located near their average value. The variables x_2, x_3, x_4 and y have a symmetrical distribution. The dependent variable y has the largest variation.

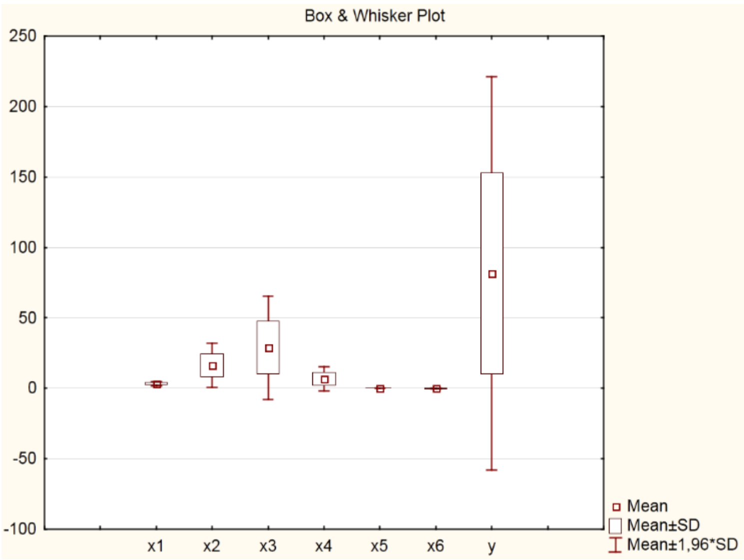


Fig. 2. «Box» diagrams

In order to rule out multicollinearity of variables, a matrix of paired correlation coefficients has been compiled (Fig. 3). It is believed that the presence of correlation coefficients over 0.75–0.80 in absolute value indicates multicollinearity between variables. In order to eliminate multicollinearity, these factors must be excluded from the model.

Color map of correlations (Spreadsheet1)
N=217 (Casewise deletion of missing data)
r>= -1 -0,80 -0,60 -0,40 -0,20 0 0,20 0,40 0,60 0,80 1

Variable	x1	x2	x3	x4	x5	x6	y
x1	1,000000	0,115219	-0,010061	-0,062375	-0,007534	-0,015013	-0,185571
x2	0,115219	1,000000	0,595526	-0,099337	-0,088854	-0,304818	0,655836
x3	-0,010061	0,595526	1,000000	-0,015954	-0,089723	-0,014764	0,716017
x4	-0,062375	-0,099337	-0,015954	1,000000	0,235650	0,420090	0,141043
x5	-0,007534	-0,088854	-0,089723	0,235650	1,000000	0,158945	0,212631
x6	-0,015013	-0,304818	-0,014764	0,420090	0,158945	1,000000	-0,069764
y	-0,185571	0,655836	0,716017	0,141043	0,212631	-0,069764	1,000000

Fig. 3. Diagram of correlations

In our case, there might be multicollinearity between variables x_2 and x_3. For verification, a method was used to analyze the sensitivity of input variables while building a neural network model — the process of evaluating the influence of input variables (features) on the output of the model, i.e., on the result of forecasting or classification. This analysis enables us to assess how changes in the input data or model parameters affect the output of the neural network and helps us understand which features are most important for the model and which of them can be excluded (Fig. 4).

	Sensitivity analysis (Spreadsheet1) Samples: Train					
Networks	x3	x2	x5	x1	x4	x6
5.MLP 6-3-1	4,656816	3,938443	3,029732	1,856225	1,091346	1,005235

Fig. 4. Sensitivity analysis of *y*

While building a neural network model, all the input variables received sensitivity values greater than 1. This means that all of the 6 input variables should be retained in our regression equation.

Identifying the coefficients of the model Q_b was carried out using the least square method (LSM) that involves a range of statistical prerequisites being met. The most important of these conditions is homoscedasticity, the constancy of the variance of random errors in the model. Violation of this requirement (heteroskedasticity) results in the following: the application of Student's t-test and Fischer's F-test becomes incorrect. Hence in the presence of heteroscedasticity, the results of regression analysis cannot be considered statistically reliable.

The STATISTICA package makes use of graphical analysis in order to identify heteroscedasticity. To this end, a graph is deisgned where the values of the variable y are plotted along the abscissa axis, and its deviations along the ordinate axis (Fig. 5). As can be seen, the values are randomly distributed (exceeding confidence limits) causing one to assume that there is no heteroscedasticity.

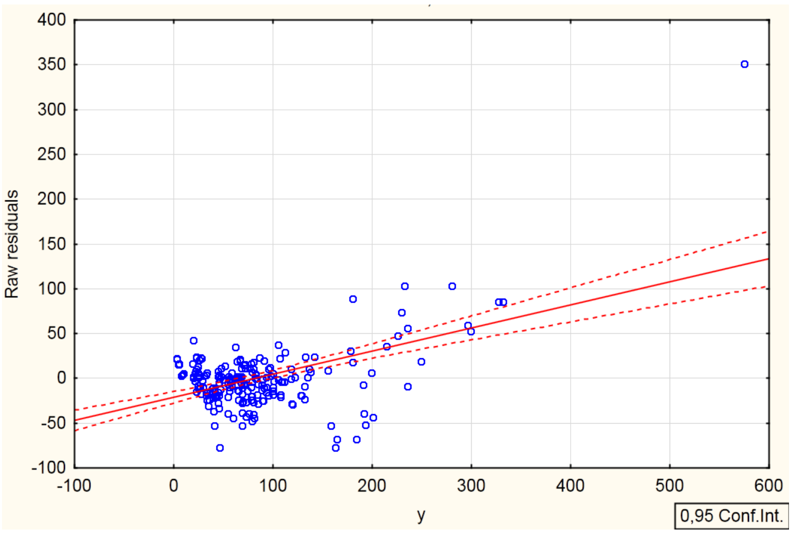


Fig. 5. Graph of the dependence of the residuals on the variable *y*

Hence the calculation of the parameters of the nonlinear regression equation can be calculated using LSM. To this end, the user regression block of the STATISTICA program is used allowing one to enter an arbitrary type of equation. It is based on a complex nonlinear model taking the following form:

$$y = a_0 {x_1}^{m1} x_2 x_3 {x_4}^{m2} {x_5}^{m3} (1 + a_1 x_6)\left(1 + a_2 \frac{1}{\sqrt{x_3}}\right). \quad (2)$$

The results of assessing the parameters a_0, a_1, a_2, m_1, m_2 and m_3 of function (2) in the STATISTICA software are presented in Fig. 6. The first column of the table contains estimates of the regression parameters making it possible to write an analytical representation of the equation:

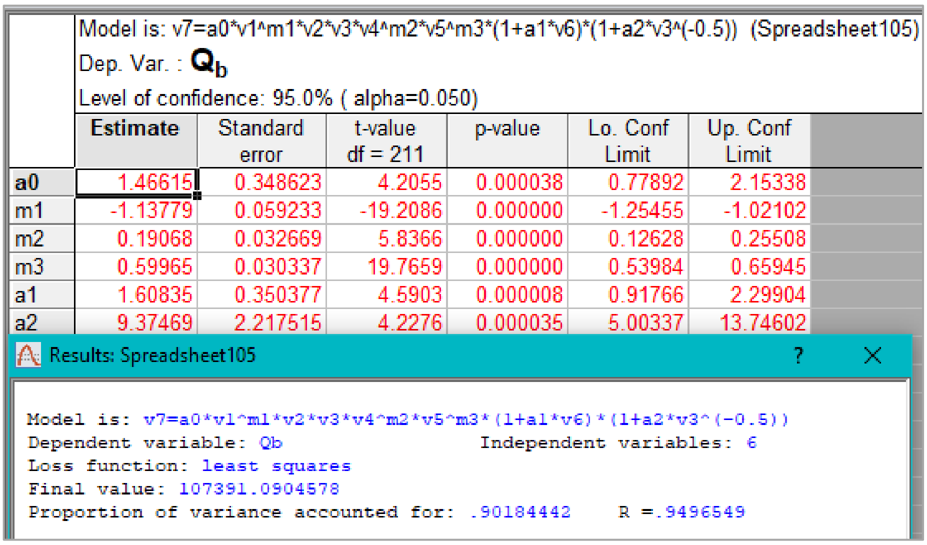
$$y = 1{,}466 {x_1}^{-1{,}14} x_2 x_3 {x_4}^{0{,}2} {x_5}^{0{,}6} (1 + 1{,}6 x_6)\left(1 + 9{,}4 \frac{1}{\sqrt{x_3}}\right). \quad (3)$$

Column 3 contains calculated values of t-statistics, quantifying the significance of the predictor effect on the dependent variable. This indicator is calculated as the following ratio:

t = (coefficient estimates)/(standard error of the coefficient).

The value of the indicator reflects the number of standard deviations by which the coefficient estimate differs from zero. It has been empirically found that coefficients with t-values beyond [–2;2] have sufficient reliability to be used in predictive models. At the same time, the higher the absolute value of statistics, the less likely it is that the coefficient will be mistakenly recognized as significant and the forecasts of the model will be more stable.

The fourth column contains the p-values that are the lowest levels of significance (probability of rejection of a fair hypothesis) for which the calculated verification statistics lead to rejection of the null hypothesis. To this end, the p-value is compared with the generally accepted standard significance levels of 0.05 or 0.01.


Model is: v7=a0*v1^m1*v2*v3*v4^m2*v5^m3*(1+a1*v6)*(1+a2*v3^(-0.5)) (Spreadsheet105)
Dep. Var. : Q_b
Level of confidence: 95.0% (alpha=0.050)

	Estimate	Standard error	t-value df = 211	p-value	Lo. Conf Limit	Up. Conf Limit
a0	1.46615	0.348623	4.2055	0.000038	0.77892	2.15338
m1	-1.13779	0.059233	-19.2086	0.000000	-1.25455	-1.02102
m2	0.19068	0.032669	5.8366	0.000000	0.12628	0.25508
m3	0.59965	0.030337	19.7659	0.000000	0.53984	0.65945
a1	1.60835	0.350377	4.5903	0.000008	0.91766	2.29904
a2	9.37469	2.217515	4.2276	0.000035	5.00337	13.74602

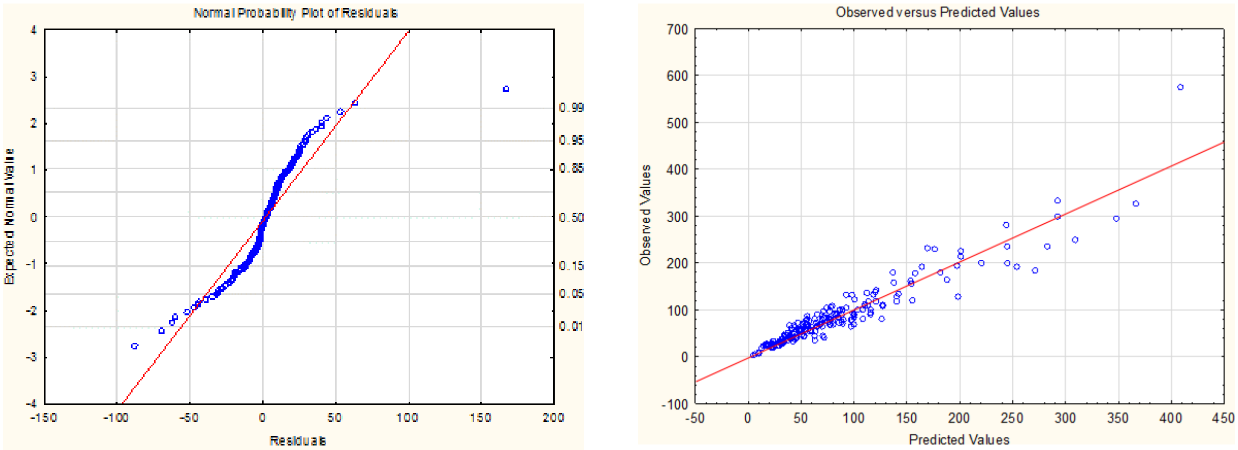
Results: Spreadsheet105

```
Model is: v7=a0*v1^m1*v2*v3*v4^m2*v5^m3*(1+a1*v6)*(1+a2*v3^(-0.5))
Dependent variable: Qb                    Independent variables: 6
Loss function: least squares
Final value: 107391.0904578
Proportion of variance accounted for: .90184442     R =.9496549
```

Fig. 6. Result of calculating the parameters of the regression equation Q_b

Based on the values of the above parameters shown in Fig. 6 and the high values of the multiple correlation index (R ≈ 0.95), it can be argued the parameters of equation (3) are statistically significant.

The validity of the model is closely associated with the fulfillment of the basic assumptions regarding the regression residuals ε_i which include the independence and absence of autocorrelation of the residuals, as well as their normal distribution. If the chosen regression model describes the true dependence well, the residuals should be independent normally distributed random variables with zero mean. In the residue distribution diagram (Fig. 7*a*), the points lie along a straight line — the residue distribution is normal. In the scattering diagram (Fig. 7*b*) the points are located close to a straight line drawn at an angle of 45 ° to the coordinate axes. This indicates that the response is close to the observed values.



a) *b)*

Fig. 7. Distribution diagrams: *a* — of the residuals; *b* — of scattering

At the *second stage* of the regression analysis, a dependence was designed for the strength of UHPC beams with fiber reinforcement with no bar cross reinforcement. A general view of the function is the following:

$$Q = Q_b + Q_f.$$

Inserting y instead of Q_b calculated based on (3) and replacing the contribution of the fibers with the function from x_1 (b_w), x_2 (h_0), x_3 (R_{bt}), x_4 (μ_s), we get

$$Q = y + f(x_1, x_2, x_3, x_4). \quad (4)$$

In order to calculate the basic statics of all of the factors of the model, a matrix of paired correlations was designed (Fig. 8). It was found that the arguments x_2 and y have a very high pair correlation (more than 0.7).

Variable	Correlations (Spreadsheet1) Marked correlations are significant at p < ,05000 N=56 (Casewise deletion of missing data) Means	Std.Dev.	x1	x2	x3	x4	y	Q
x1	4,4821	0,9861	1,000000	0,031394	0,216939	-0,508297	0,166597	0,276947
x2	37,6357	18,9912	0,031394	1,000000	0,616026	-0,203521	0,831776	0,783928
x3	1,3526	0,5999	0,216939	0,616026	1,000000	-0,573725	0,597728	0,635939
x4	0,0394	0,0187	-0,508297	-0,203521	-0,573725	1,000000	-0,253158	-0,160484
y	98,9823	53,7237	0,166597	0,831776	0,597728	-0,253158	1,000000	0,834242
Q	279,6782	183,3429	0,276947	0,783928	0,635939	-0,160484	0,834242	1,000000

Fig. 8. Matrix of paired correlations

The analysis of paired correlation coefficients enabled us to identify only explicit cases of linear relationship between the predictors. However, the key problems in designing multiple regression models lie in multicollinearity, a situation where there is a systemic linear relationship between several factors at a time. In order to quantify the degree of multicollinearity, an analysis of the determinant of the correlation matrix of factors is used. The closer the determinant value is to zero, the higher the degree of linear dependence between the variables and the more distinct the problem of multicollinearity, as well as the less reliable estimates of the model parameters (Fig. 9).

$$R := \begin{pmatrix} 1 & 0.031394 & 0.216939 & -0.508297 & 0.166597 & 0.276947 \\ 0.031394 & 1 & 0.616026 & -0.203521 & 0.831776 & 0.783928 \\ 0.216939 & 0.616026 & 1 & -0.573725 & 0.597728 & 0.635939 \\ -0.508297 & -0.203521 & -0.573725 & 1 & -0.253158 & -0.160484 \\ 0.166597 & 0.831776 & 0.597728 & -0.253158 & 1 & 0.834242 \\ 0.276947 & 0.783928 & 0.635939 & -0.160484 & 0.834242 & 1 \end{pmatrix}$$

$$detR := |R| \qquad detR = 0.014$$

Fig. 9. Calculation of the determinant of the matrix of paired correlation coefficients

Proximity to zero of the determinant of the matrix of paired correlation coefficients ($detR$ = 0,014) means that there is multicollinearity between the arguments. One of the ways to account for the internal correlation of factors is to switch to combined regression equations, i.e. to those reflecting not only the influence of the factors, but also their interaction. A combination of our factor arguments in the model $Q = y + f(x_1, x_2, x_3, x_4, x_1 \cdot x_2 \cdot x_3 \cdot x_4)$ will thus be included in the first degree and specification will be a complex linear dependence. The nonlinear nature of the relationship of the model is confirmed by means of the shapes of the constructed three-dimensional surfaces of the dependence of the variable Q on its arguments (Fig. 10).

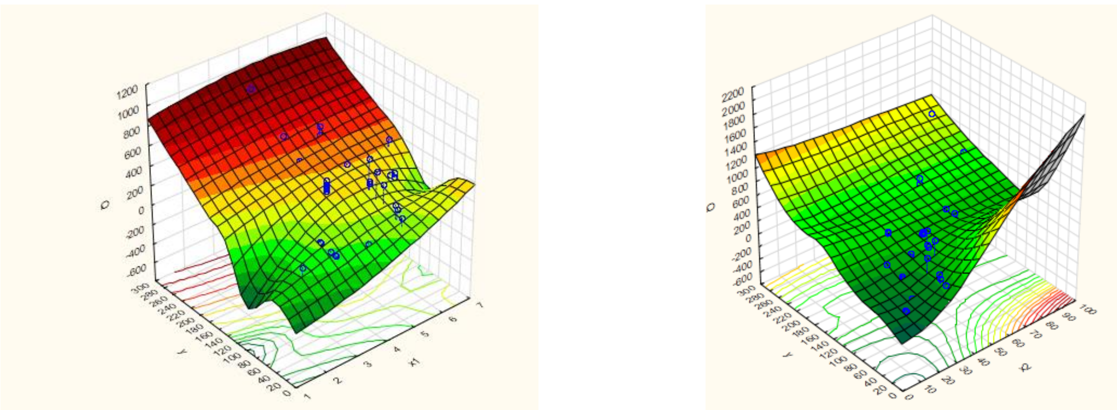


Fig. 10. Three-dimensional graphs (surfaces) of the dependence of Q on x_1 and x_2

The sensitivity analysis (Fig. 11) indicates the need to participate in the regression of all of the variables, with the largest contribution expected to be made by the variable y (contribution of concrete Q_b).

Networks	Sensitivity analysis (Spreadsheet1) Samples: Train				
	y	x2	x4	x3	x1
1.MLP 5-4-1	106,7567	30,73866	8,477698	8,374472	2,453012

Fig. 11. Sensitivity analysis of *Q*

As a result of the study, it was decided to use the dependency as a model specification:

$$Q = y + a_0 x_1 x_2 x_3{}^{m3} x_4{}^{m4}\left(1 + 2\frac{1}{\sqrt{x_2}}\right). \tag{5}$$

The results of *assessing the parameters* of regression in the software STATISTICA are shown in Fig. 12.
Having substituted the parameter values in (5), the following general form of the equation is obtained:

$$Q = y + 5{,}46 x_1 x_2 x_3{}^{0{,}95} x_4{}^{0{,}65}\left(1 + 2\frac{1}{\sqrt{x_2}}\right).$$

The values of the *t*-value and the *p*-value indicate a good selection of the regression equation and the statistical significance of its coefficients (Fig. 13). The multiple correlation index *R* = 0.91 highly evaluates the proximity of the combined influence of the factors on the result.

	Model is: v6=v5+a0*v1*v2*v3^m1*v4^m2*(1+2*v2^(-0.5)) (Spreadsheet108) Dep. Var. : **Q** Level of confidence: 95.0% (alpha=0.050)					
	Estimate	Standard error	t-value df = 53	p-value	Lo. Conf Limit	Up. Conf Limit
a0	5.458100	2.014278	2.709706	0.009052	1.417971	9.498230
m1	0.948995	0.205740	4.612603	0.000026	0.536334	1.361656
m2	0.646525	0.127836	5.057442	0.000005	0.390117	0.902932

Results: Spreadsheet108 ?

```
Model is: v6=v5+a0*v1*v2*v3^m1*v4^m2*(1+2*v2^(-0.5))
Dependent variable: Q                          Independent variables: 5
Loss function: least squares
Final value: 322009.0360973
Proportion of variance accounted for: .82582846     R =.90875105
```

Fig. 12. Result of calculating the parameters of the regression equation *Q*

Effect	Model is: v6=v5+a0*v1*v2*v3^m3*v4^m4*(1+2*v2^(-0,5)) (Spreadsheet1) Dep. Var. : Q				
	1 Sum of Squares	2 DF	3 Mean Squares	4 F-value	5 p-value
Regression	5907108	3,00000	1969036	324,0869	0,00
Residual	322009	53,00000	6076		
Total	6229117	56,00000			
Corrected Total	1848804	55,00000			
Regression vs.Corrected Total	5907108	3,00000	1969036	58,5768	0,00

Fig. 13. Results of the multidimensional dispersion analysis

The fourth column (Fig. 13) shows Fischer's F-statistics which serve to *check the validity of the model*. The fifth column (p) shows the significance of Fischer's F-statistics – the critical value of the quantile of the Fischer distribution rejecting the null hypothesis of the absence of the factor influence. The statistical significance of the regression equation is thus recognized, i.e. there is a relationship between the above features, and the observational results are in good agreement with the assumption of its specification. The normal probability graph (Fig. 14) confirms the normal distribution of the residuals of the regression model.

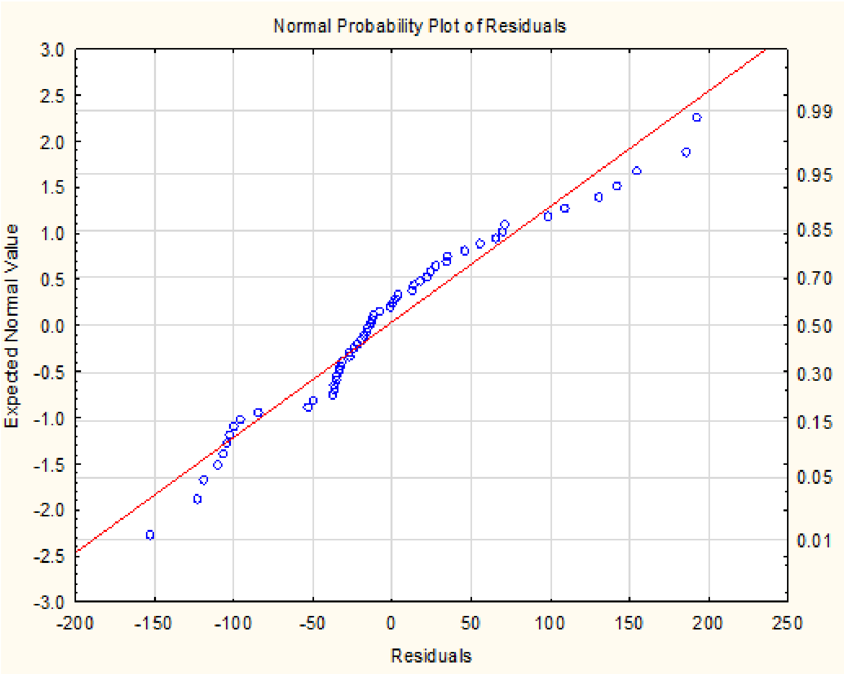


Fig. 14. Diagrams of the distribution of the residuals

The autocorrelation between the arguments of the model leads one to struggle confirming the correctness of the choice of specification. In this case, it is necessary to perform a comparative analysis between alternative regression models. E.g., as an alternative, quation (6) of the joint influence can be taken without accounting for the factor x_2:

$$Q = a_0 x_1^{m_1} x_3^{m_3} x_4^{m_4} y \tag{6}$$

The resulting parameters of this regression are in Fig. 15.

Model is: v6=a0*v1^m1*v3^m3*v4^m4*v5 (Spreadsheet1)
Dep. Var. : Q
Level of confidence: 95.0% (alpha=0.050)

	Estimate	Standard error	t-value df = 52	p-value	Lo. Conf Limit	Up. Conf Limit
a0	3,640638	1,354431	2,687946	0,009635	0,922773	6,358504
m1	0,471554	0,205487	2,294819	0,025811	0,059215	0,883893
m3	0,428909	0,123765	3,465514	0,001069	0,180556	0,677261
m4	0,323869	0,089391	3,623062	0,000661	0,144493	0,503245

Fig. 15. Result of calculating the parameters of the regression equation (6)

The classic determination coefficient R^2 ranging from 0 to 1 serves as a basic indicator of the explanatory ability of the model. Nevertheless this indicator has a considerable limitation: its value increases monotonously as any of the regressors is added, even statistically insignificant ones. This effect is due to the mathematical nature of R_2 itself making it unsuitable for comparing models with different numbers of predictors and choosing the optimal specification. In order to overcome these disadvantages, alternative approaches have been developed, such as the use of adjusted R_2 allowing for a more objective comparison of models of different dimensions, but also protects the limitations of the original R_2 method, and the Akaike information criteria (AIC) and the Bayesian Schwarz criterion (BIC/SC). The AIC criterion is less strict on the number of parameters and is preferable for small samples, while BIC/SC penalizes the complexity of the model more severely, estimates large data more precisely, and accounts for the sample size in the penalty formula. Hence the specification with the minimum value of the information criterion (AIC or BIC) will be considered optimal, reflecting a compromise between the accuracy of the data description and the complexity of the model.

In Table 1, the information indicators of the selected model specification (5) are compared with (6) calculation formulas SP 360.1325800, as well as with formulas FIB Model code 2010 and RILEM TC 162-TDF. As can be seen, all 4 metrics have the lowest value for the selected specification (5).

Table 1

Quality indicators of the regression equation

Equation	MSE	MAPE	AIC	BIC
(5)	6110.08	26.78 %	500.19	657.57
(6)	7506.72	28 %	511.72	669.11
СП 360.1325800	30528.81	47 %	590.28	757.35
FIB Model code 2010	56070.45	57 %	624.32	811.49
RILEM TC 162-TDF	24092.38	42 %	577.02	750.69

The accuracy of the proposed methods for calculating the strength of I-UHPC beams under the action of transverse forces was assessed by comparing the theoretical and experimental values of destructive loads based on a sample of data obtained from the relevant published experimental studies [7, 13, 32, 36, 37, 42–50]. The values of destructive loads are identified as follows:

$$Q_{\text{per}} = Q_{b,\text{per}} + Q_{f,\text{per}} + Q_{sw},$$

where $Q_{b,\text{per}}$ and $Q_{f,\text{per}}$ are the contributions of concrete and fibers based on (3) and (4).

Tables 2–4 provide a comparative assessment of the accuracy of the suggested regression and standard calculation methods. At the same time, beams with no fiber reinforcement are calculated according to the formulas of SP 63.13330, ACI 318M and Eurocode 2, and beams with fiber reinforcement are calculated according to the formulas of SP 360.1325800, designed for steel-fiber structures, and according to the formulas FIB Model code 2010 and RILEM TC 162-TDF for UHPC structures.

Table 2

Comparison of the experimental Q_{exp} and theoretical Q_{calc} values of the strength of UHPC-beams *with no fiber and transverse rod reinforcement*

Indicator	Calculation method			
	Regression	SP 63.13330	ACI 318M	EC 2
Mean deviation in % $\left(\frac{Q_{exp} - Q_{calc}}{Q_{exp}}\right) \cdot 100$	17	40	29	21
Mean value of the ratio Q_{exp}/Q_{calc}	1.03	1.45	1.34	1.2
Coefficient of the ratio variation Q_{exp}/Q_{calc}	0.22	0.43	0.44	0.56

Table 3

Comparison of the experimental Q_{exp} and theoretical Q_{calc} values of the strength of UHPC beams with fibers and with no *transverse rod reinforcement*

Indicator	Calculation method			
	Regression	SP 360.1325800	FIB Model code 2010	RILEM TC 162-TDF
Mean deviation in % $\left(\frac{Q_{exp} - Q_{calc}}{Q_{exp}}\right) \cdot 100$	26	47	57	42
Mean value of the ratio Q_{exp}/Q_{calc}	1	2.46	2.76	1.85
Coefficient of the ratio variation Q_{exp}/Q_{calc}	0.29	0.64	0.42	0.41

Table 4

Comparison of the experimental Q_{exp} and theoretical Q_{calc} values of the strength of UHPC beams with fibers and with no *transverse rod reinforcement*

Indicator	Calculation method			
	Regression	SP 360.1325800	FIB Model code 2010	RILEM TC 162-TDF
Mean deviation in % $\left(\frac{Q_{exp} - Q_{calc}}{Q_{exp}}\right) \cdot 100$	28	37	39	39
Mean value of the ratio Q_{exp}/Q_{calc}	1.19	1.71	1.76	1.81
Coefficient of the ratio variation Q_{exp}/Q_{calc}	0.33	0.44	0.43	0.38

The highest accuracy of the regression model is achieved in the absence of fiber and transverse core reinforcement of beams: the average difference between the experimental and theoretical values in this case is 17%. While calculating beams with fibers and clamps, the error is expected to increase, reaching 28%. As can be seen, the average value of the ratio Q_{exp}/Q_{calc} was 1.19, i.e. the deviation is formed towards the margin.

Discussion and Conclusion. The results presented by the obtained regression models indicate the possibility of calculating the contribution of concrete and fibers to the resistance of the UHPC beams to transverse forces. The assessment of the quality and reliability of the models is confirmed by using a set of metrics and comparing them with alternatives. The calculation based on the developed regressions improves the convergence of theoretical and experimental results by up to 2.4 times compared to the formulas of norms. The synthesis of statistical methods and artificial intelligence tools opens up avenues for further improvement of methods for calculating building structures, particularly in cases of tasks which are difficult to formalize where designing traditional analytical solutions is challenging.

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