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INVESTIGATION OF STRESS-STRAIN PARAMETERS IN RC BEAMS USING DIC

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The article discusses the assessment of the state of reinforced concrete beams using the digital image correlation method and submicron indicators. Bending elements are the most widely used in reinforced concrete structures, so the ability to accurately evaluate and use new methods that simplify the labor intensity of the process and increase the accuracy of measuring deformations and load-bearing capacity is extremely important. The purpose of the study is to evaluate both experimental and theoretical investigations of the deformation and load-bearing capacity of a reinforced concrete beam under load. As a result of the study, the values of the deformation were determined. Comparative graphs were constructed for the submicron sensor values, digital correlation results, and theoretical values obtained by the finite element method using the "LIRA" software package. The constructed diagrams show good convergence, with experimental and theoretical results values differing from theoretical ones by no more than 5 %.

Keywords: reinforced concrete beam, digital image correlation method, damage, strains, defects, modelling.

Introduction

Structural elements experience deformations and defects under loading (Mykhalevskyi, N. A., 2023), which over time can lead to changes in their stress-strain state. To ensure the safety and durability of such structures, continuous monitoring of their technical condition is necessary. One of the most effective methods for assessing deformation processes (Sjölander, A., 2023) is Digital Image Correlation (DIC) – a non-contact technology that enables highly accurate tracking of even the smallest changes in material structure.

This method is based on the analysis of digital images of an object before and after the application of loads. The surface of the structure is coated with a special high-contrast speckle pattern, allowing the software to recognize even the smallest displacements of points during deformation (Blikharskyy, Y., 2024). As a result, a comprehensive stress distribution map can be obtained, helping to identify risk zones before visible damage occurs. In DIC studies, parameters such as speckle position and size are used to characterize the images.

Neglecting the influence of these parameters can lead to significant discrepancies between the computed DIC results for simulated and real values. This may also cause conflicting results, as described in more detail in the Cui`s work (Cui, 2024).

Materials and method

The construction industry is continuously evolving, focusing on economic efficiency, environmental safety, and structural durability. One of the key aspects of ensuring the reliability of buildings and structures is the accurate assessment of their stress-strain state, particularly under variable loads and external influences. This is especially relevant for critical structures such as bridges and high-rise buildings, where improper assessment can lead to severe consequences. Among the various methods for monitoring structural condition, Digital Image Correlation (DIC) has garnered significant attention (Ulzurrun S. D., 2023). DIC is based on digital image analysis of an object before and after deformation.

The experimental study of a reinforced concrete beam using non-contact sensors enables precise measurements of stress, strain, and deflections. In this study, microtech sensors with a resolution of 1×10^{-4} mm and an error margin of less than 13 microns were used. The surface of the tested structure was pre-treated with a special high-contrast speckle pattern, which serves as a marker for tracking even the slightest changes in the material structure. With DIC, it is possible to obtain a detailed stress distribution map, identify weak points in the structure, and predict potential damage before it actually occurs. This significantly enhances safety levels and reduces repair costs. Additionally, the method allows for real-time monitoring of material behavior under operational conditions without requiring dismantling or halting the structure's function. One of the key advantages of DIC is its versatility. In his study, (Dongyang, 2020) described the method's effective application for investigating reinforced concrete, steel, and composite structures, including displacement analysis, failure detection, and other mechanical characteristics. Furthermore, an experimental study (Meiramov, 2025) examined the correlation between crack propagation and deflection in reinforced concrete beams. The application of this method is particularly crucial in modern research aimed at improving the strength and durability of construction materials. Thus, Digital Image Correlation is a powerful tool in modern structural engineering. It not only enables precise structural condition assessment but also facilitates future behavior predictions, contributing to enhanced safety and efficient resource utilization. Studies by Yuan (Yuan, 2021) and H. Cruz, (Cruz, 2019) have demonstrated that analyzing beam behavior requires a comprehensive approach, including simultaneous experimental and theoretical research as well as finite element modeling. Numerical models typically show good agreement with experimental data, confirming their high accuracy. These models have also proven effective in predicting deflections and the ultimate load-bearing capacity of reinforced concrete beams with high precision. Research findings presented by R. Perera (Perera, 2023) on the behavior of reinforced concrete beams highlight the significance of numerical models in predicting beam deformations. Overall, a comprehensive approach combining theoretical and experimental studies provides the most accurate results for strength and deformation analysis. The objective of this research is to conduct experimental studies on reinforced concrete beams using Digital Image Correlation and strain sensors, as well as to compare the results with theoretical calculations and finite element modeling. Another key task is to perform an in-depth analysis of the obtained data to verify the reliability of both theoretical and experimental methods. At the first stage of the study, experimental measurements were carried out using strain sensors and Digital Image Correlation, which helped minimize errors and validate the efficiency of the experimental research methods. The general view of the test specimen, with dimensions of 2100×200×100 mm, is shown in Fig. 1.

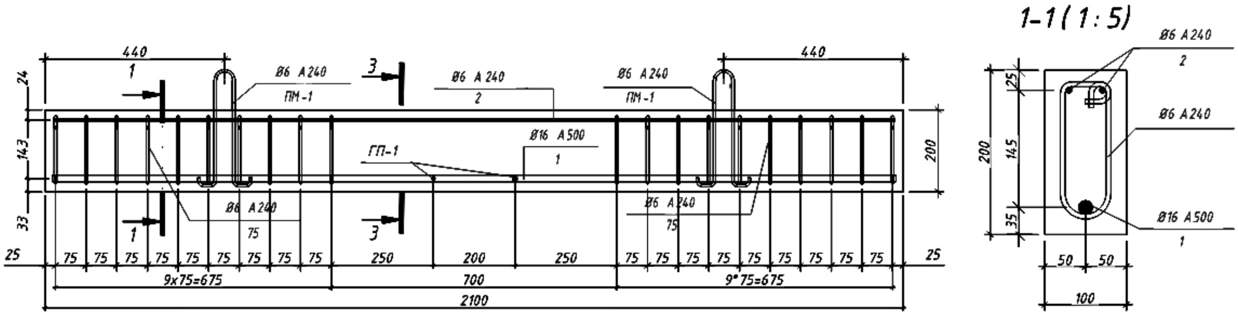

Fig. 1. Formwork drawing of the reinforced concrete beam

Experimental Implementation

To ensure precise measurements, Digital Image Correlation (DIC) was applied to one side of the beam, while the other side was equipped with non-contact micro-indicators. This comparative method allows for the accurate utilization of both techniques and facilitates a detailed analysis of the reinforced concrete structure's behavior. It also enables the comparison of deformations obtained using these two methods and helps assess the effectiveness of the integrated approach. The loading was applied as two concentrated forces at one-third of the beam's span, with a distance of 630 mm between them.

Each load increment was increased in 10 % steps of the estimated load-bearing capacity, with stabilization intervals for measurement accuracy. A hydraulic jack and a distribution traverse were used to apply the loads.

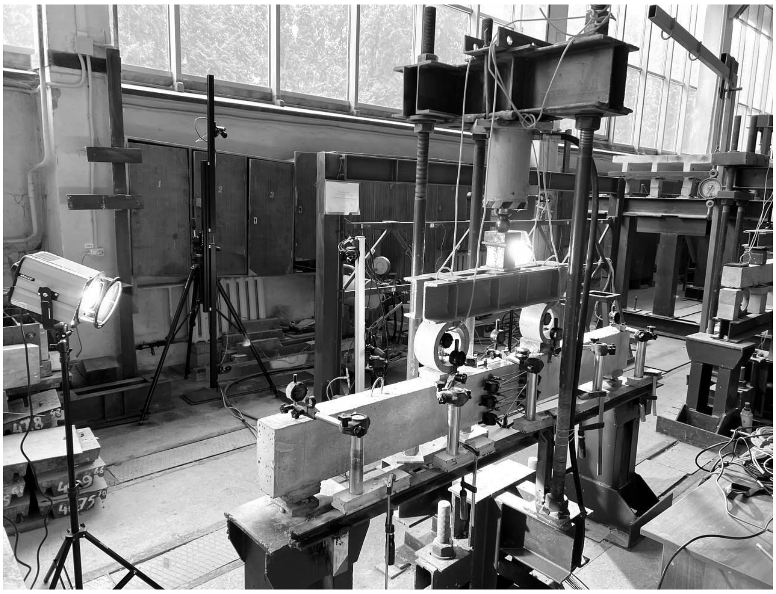

Fig. 2. General view of the experimental RC beam

The measurements taken from the beam surface using micro-indicators were transmitted to a PC via Bluetooth, allowing the experiment to continue until the beam's physical failure. Data was recorded at 1-second intervals. To measure the stress in the most compressed concrete fiber, two micro-indicators were used. For reinforcement stress measurement, a sensor mounted on mechanical fasteners was employed. A total of five sensors were installed along the beam's height. The first sensor was positioned 20 mm from the top surface, while the remaining sensors were spaced at 30 mm intervals. The beam deflection was measured using three sensors: one located at mid-span, two at the load application points, and two additional sensors positioned above the supports.

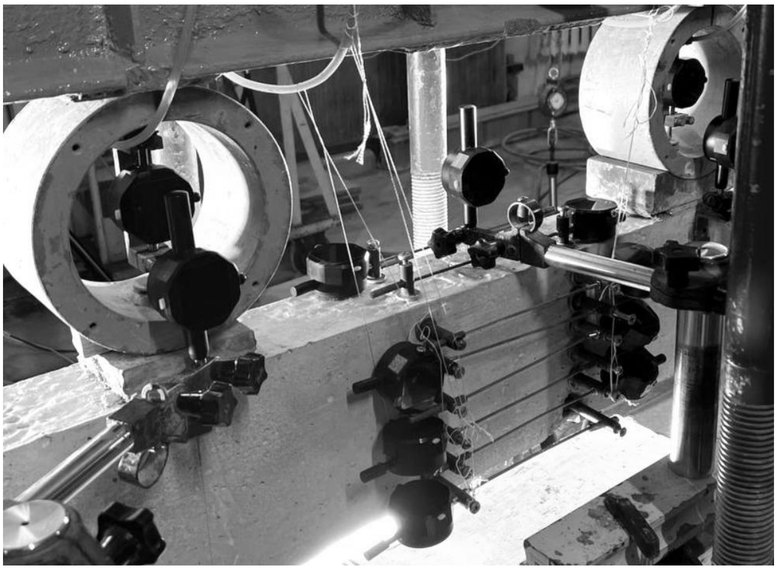

Fig. 3. General view of the placement of micro-indicators

To apply the Digital Image Correlation method for the experimental study of the reinforced concrete beam, the sample required special preparation. The surface was first cleaned and sanded using an angle grinder. Afterward, the concrete surface was dusted off with a compressor and cleaned with a surface cleaner. A thin layer of non-elastic white matte paint was applied to the surface of the reinforced concrete beam. Once the white background dried, black speckles of a defined size were applied to the surface of the reinforced concrete beam using a special roller (Fig. 4).

Fig. 4. General view of the prepared surface

To ensure accurate results obtained using the Digital Image Correlation method, in addition to preparing the sample surface and applying the characteristic pattern, proper lighting and camera settings must be ensured. The obtained values are then transferred to the software using the VIC-2D-7 program.

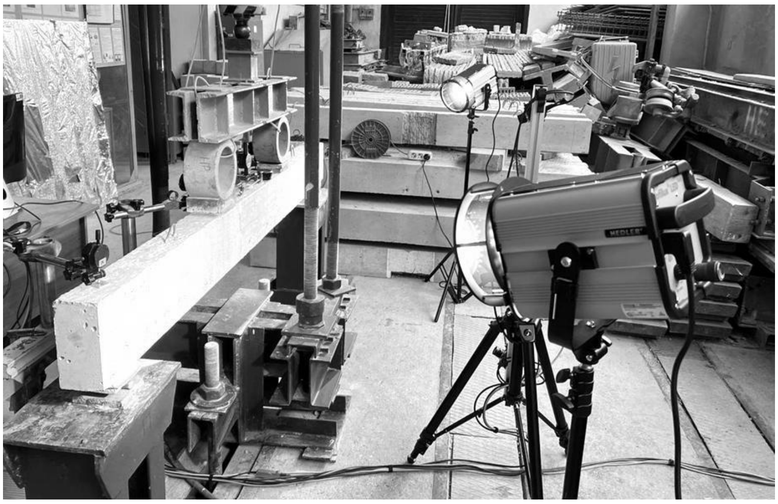

Fig. 5. General view of the reinforced concrete beam from the side of the Digital Image Correlation

The specialized software assigns a value of "255" to the black color and "0" to the white color. A camera and lighting system was set up to obtain high-quality images without shadows and reflections. Two cameras were positioned 600 mm apart, covering the pure bending zone, while two additional cameras were placed at distances that allowed data to be captured from the entire surface of the reinforced concrete beam. During the test, a series of images was recorded, with each frame capturing the state of the sample before and after loading. The obtained images are imported into the VIC-2D program, where preprocessing is performed: the analysis area is defined, and correlation parameters are set. The program uses correlation algorithms to track changes in the position and shape of the markers in the images by comparing each frame to the initial state. As a result, a displacement and deformation field are obtained, which can be visualized in the form of graphs. The data is exported for further analysis or comparison with calculation models. Afterward, the obtained data is analyzed to determine the maximum stresses, deformation distribution, and the localization of possible failure zones. VIC-2D allows for exporting the results as numerical tables or graphical reports for further use in calculations and modeling. This method is non-contact and highly accurate, making it effective for studying the mechanical behavior of materials under various loading conditions. The images are the result of Digital Image Correlation (DIC) in the VIC-2D program, showing a deformation field map with a color gradient, where different shades correspond to stress and displacement levels (Fig. 6).

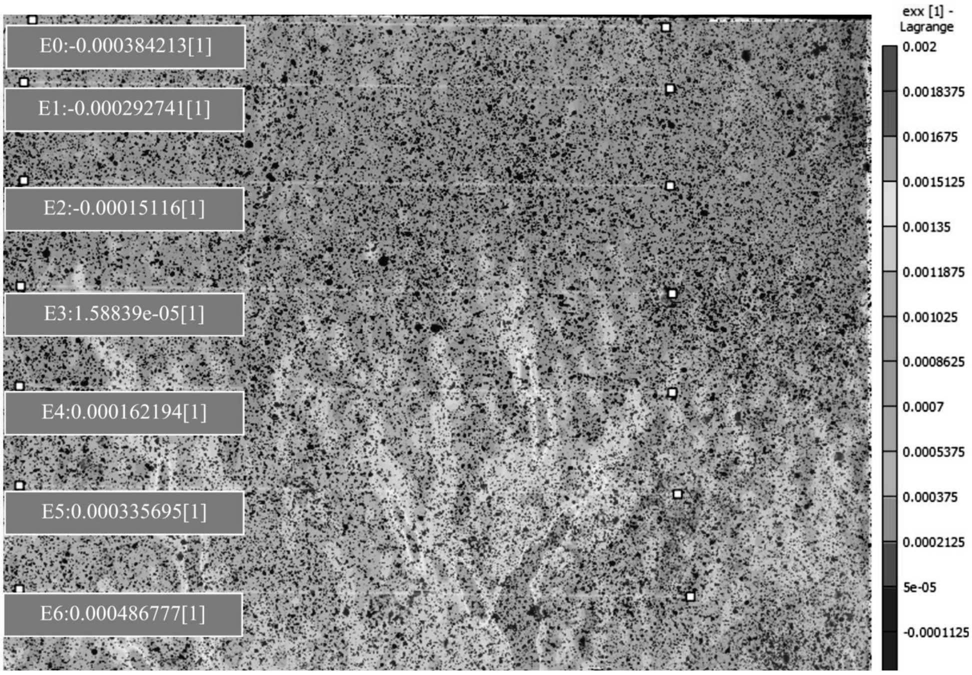

Fig. 6. Deformation map in VIC software

The deformation map shows stress at a certain stage of loading, with red zones indicating maximum deformations and blue and purple areas representing less deformed regions. Black markers with numerical values show local deformation values at selected points. At the bottom, inclined red-yellow stripes are visible, indicating local concentration of deformations, which may suggest the formation of cracks or plastic deformation zones in the material. The speckle pattern (black and white dots) in the background serves as markers for the correlation algorithm, which tracks their displacement under load.

Finite element modeling

To verify the experimental data, a theoretical study was conducted, which included calculating the stress-strain state of the reinforced concrete beam according to the regulations of DBN B.2.6-98:2009 and Eurocode 2, as well as numerical modeling using the finite element method (Mykhalevskyi, N. A., 2023) with the specialized software package LIRA-SAPR (Deineka, V., 2024). An analysis of the obtained results was performed to compare the theoretical and experimental data, allowing the accuracy of the calculation methods and their correspondence to real operational conditions to be assessed. The finite element model was built using volumetric finite elements (FE) No. 236, which account for the nonlinear behavior of concrete. In all models, the concrete class C35/45 was determined based on the testing of prism, cube, and cylindrical specimens. The program takes into account the characteristic strength of concrete. The nonlinear behavior of concrete was described using the 25th exponential deformation law. To simulate the behavior of the reinforcement cage, finite elements No. 210, which are physically nonlinear universal spatial FEs, were used. The nonlinear properties of the reinforcement were described using a 14th piecewise-linear deformation function. The values of the ultimate strains, Young's modulus, and yield strength of the reinforcement were taken according to the determined physical-mechanical parameters for steel class A500C (working reinforcement: compressed and stretched) and A240C, as determined by the R-100 testing machine.

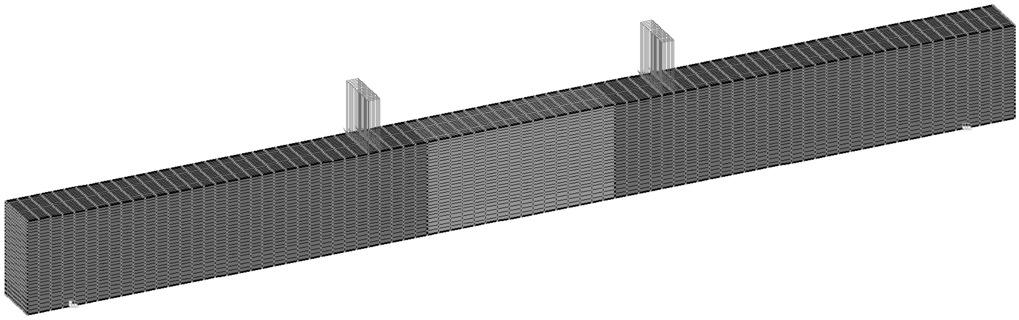

Fig. 7. General view of the computational model of the control beam

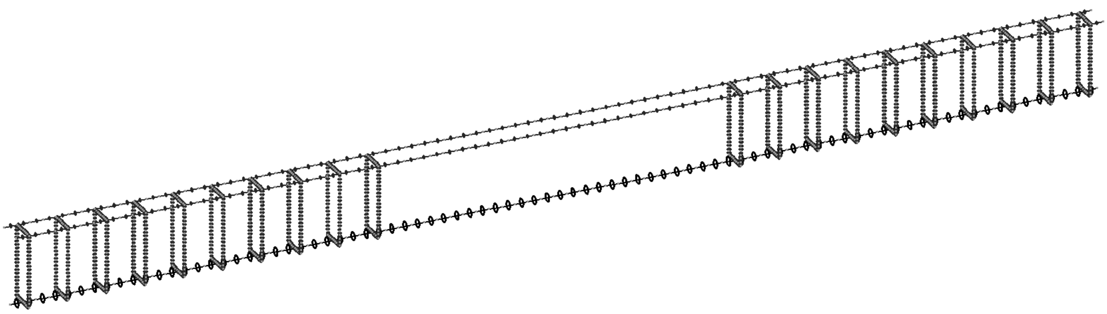

Fig. 8. General view of the computational model of the reinforcement cage of the beam

The applied load of *Fu* = 2.7 kN at points located at 1/3 and 2/3 of the span of the beam is key to understanding the stress-strain state under the applied load. In the comparison of theoretical and experimental results, deformation and displacement data obtained through finite element modeling (FEM) in LIRA-SAPR are compared with experimental data from both the digital image correlation (DIC) method and microindicators.

This comparison is critical for evaluating the accuracy of the theoretical model and identifying any discrepancies between the theoretical and actual deformation values. By utilizing the finite element method (FEM) in LIRA-SAPR, deformations of the compressed concrete zone, deformations of the reinforced stretching zone, and beam deflections were determined. Comparative graphs were constructed to align the theoretical values with the experimental data, offering insights into how well the theoretical predictions match the physical behavior observed in the experiments.

The overall goal of this analysis is to refine the predictive capabilities of the theoretical models and assess the real-world behavior of reinforced concrete beams under load. The validation process helps ensure the reliability of the calculations and supports further structural analysis and design optimization.

Results and discussion

This section presents the results of theoretical studies and experimental tests with a detailed comparative analysis and discussion. The comprehensive approach used in this study allowed for verification of the obtained data and confirmation of the validity of the methods applied. Theoretical and experimental investigations yielded the following results: the deflection values of the test sample and the complete deformation field of the concrete. The results are presented graphically in the form of dependencies: "M-$\varepsilon_{concr} \times 10^{-5}$" (bending moment relative to the deformation of the most compressed concrete zone), "M-$\varepsilon_{rebar} \times 10^{-5}$" (bending moment relative to the deformation of the reinforcement), "M-f" (bending moment relative to the deflection), as shown in Fig. 9–11.

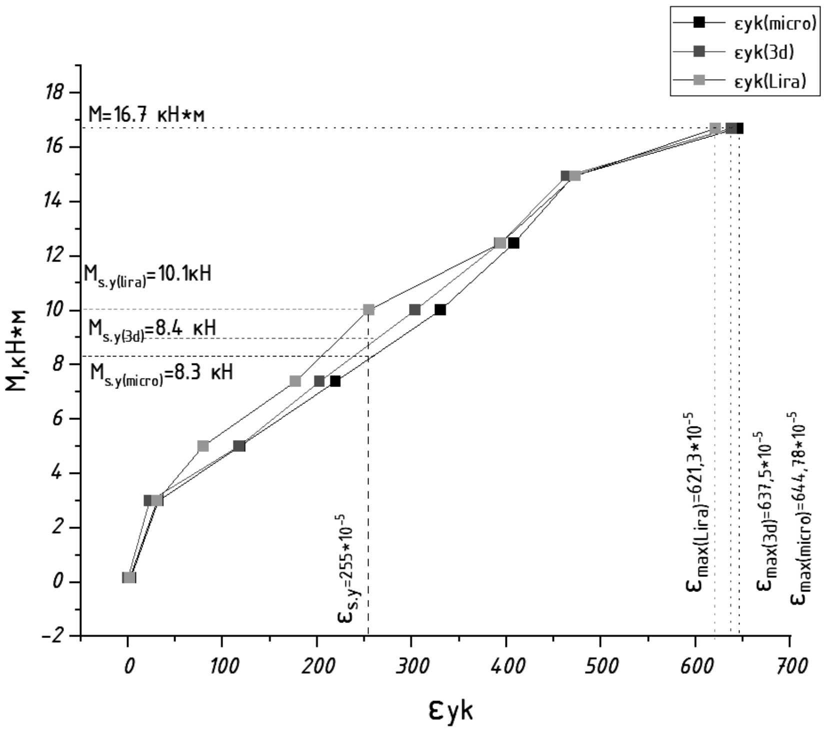

Fig. 9. Comparative graph of reinforcement deformations

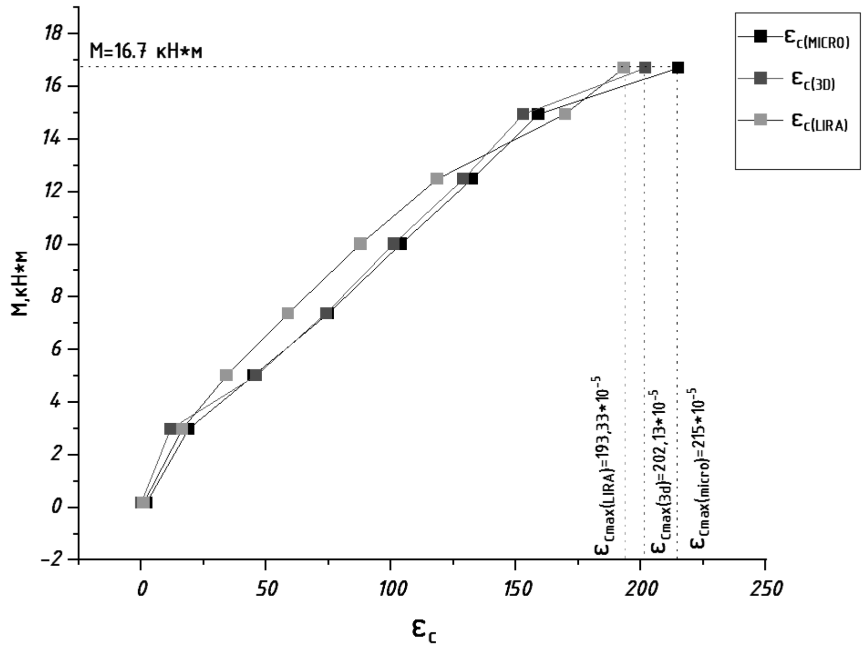

Fig. 10. Comparative graph of the deformations of the compressed concrete zone

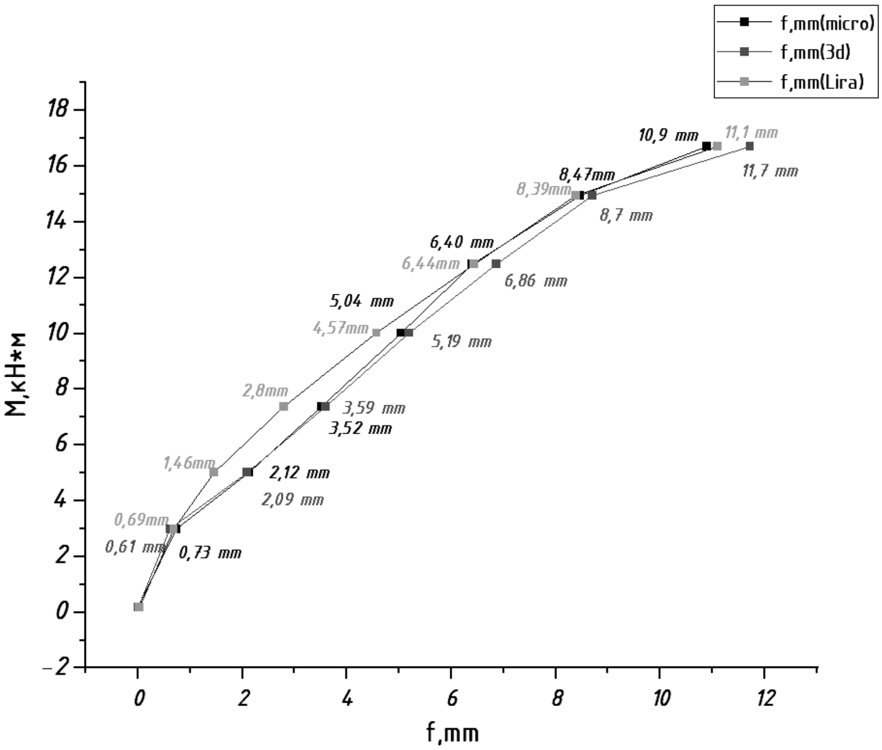

Fig. 11. Comparative graph of deflections

According to the obtained data from the graphs, the convergence of deflections and deformations between the theoretical results and experimental data has been analyzed. Fig. 9 shows the comparative graph of the deformation of the stretched reinforcement. These results are also shown in Table 1. The results of deformation values for the compressed concrete zone and deflections are presented in Table 2 and Table 3. For the micro-indicators, at $M_{s,y(micro)}$ = 8.3 kN·m, the deformation of the stretched reinforcement reaches the yield point $\varepsilon_{s,y}$ = $255 \cdot 10^{-5}$ which corresponds to the point of loss of bearing capacity. After this deformation, there is an increase in the deformation of both the compressed and stretched zones.

The image correlation method detects the yield point at $M_{s,y(3d)}$ = 8.4 kN·m, while the theoretical value obtained using the LIRA SAPR software is $M_{s,y(LIRA)}$ = 10.1 кН·м. The theoretical value of the loss of bearing capacity is slightly higher than the experimental data, which may indicate that the model accounts for certain idealizations or does not consider some real factors such as material heterogeneity or local defects. At a loading of M_{ult} = 16ю7 kN·m, the following maximum values were recorded for analysis: $\varepsilon_{s,y\ max(LIRA)}$ = $621.3 \cdot 10^{-5}$, $\varepsilon_{s,y\ max(3d)}$ = $637.5 \cdot 10^{-5}$ = $637.5 \cdot 10^{-5}$, $\varepsilon_{s,y\ max(mirco)}$ = $644.88 \cdot 10^{-5}$. The difference between the LIRA SAPR and digital image correlation methods is 2.61 %. The difference between the digital image correlation and micro-indicators is 1.15 %. The difference between the LIRA SAPR and micro-indicators reaches 3.81 %. The identification of discrepancies between theoretical and experimental values highlights the importance of combining different approaches to obtain a more accurate assessment of the structure's behavior under real conditions. At M_{ult} = 16.7 kN·m, the experimental sample loses its bearing capacity due to the brittle failure of the compressed concrete zone (Fig. 12). The obtained maximum values for the most compressed fiber of concrete are as follows: $\varepsilon_{c,\ max(LIRA)}$ = $193.3 \cdot 10^{-5}$, $\varepsilon_{c,\ max(3d)}$ = $202.1 \cdot 10^{-5}$, $\varepsilon_{c\ max(mirco)}$ = $215 \cdot 10^{-5}$. The discrepancy between the maximum values of the compressed fiber is on average about 6.72 %. The discrepancy between the deformations of the stretched reinforcement and the compressed concrete fiber is small, indicating a good convergence between the results of the different methods. This suggests that despite some discrepancies with the theoretical calculations, the image correlation and micro-indicator methods yield results that reflect the real loading conditions, confirming the accuracy and reliability of these methods.

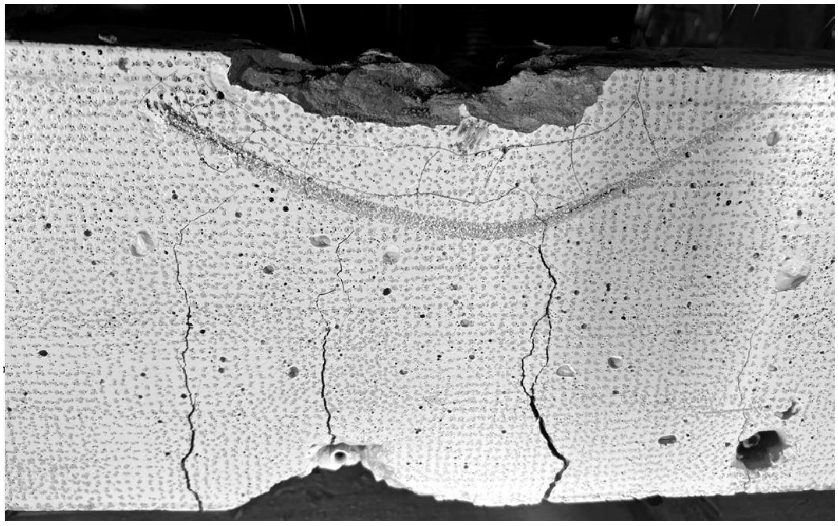

Fig. 12. Concrete failure of the most compressed fiber

The graph shown in Fig. 11 demonstrates the relationship between the bending moment *M*, kN·m, and deflection f, mm. Experimental data obtained using the image correlation method show a tendency to underestimate deflections compared to micro-indicators, which may be due to the specifics of the image processing algorithm. The obtained results indicate an acceptable level of convergence between numerical and experimental modeling. The main factors contributing to discrepancies are the sensitivity of the digital image correlation method to lighting conditions and surface texture. The error within 3 % indicates sufficient accuracy and reliability of the reinforced concrete specimen's performance.

Table 1

Comparative table of reinforcement deformations

M, кN·m	ε_{yk} (micro)	ε_{yk} (3d)	ε_{yk} (Lira)
0.17583	3.09	0.157	2
2.98917	31.93	22.7064	30.46
5.01125	118.45	117.359	79.46
7.385	219.39	202.316	176.79
10.0225	330.63	303.711	254.67
12.48417	407.88	393.316	393.9
14.94583	470.71	463.74	472.65
16.70417	644.78	637.516	621.1

Table 2

Comparative table of deformations in the compressed zone of concrete

M, кN·m	ε_{ck} (micro)	ε_{ck} (3d)	ε_{ck} (Lira)
0.17583	2.10526	0.0186	0.98
2.98917	19	11.8208	16.53
5.01125	45	46	34.17
7.385	75	74	58.83
10.0225	104	101	87.88
12.48417	132.5	129	118.5
14.94583	159	153	169.6
16.70417	215	202	193.33

Table 3

Comparative table of deflections

M, кN·m	*f,* mm (micro)	*f,* mm (3d)	f, mm (Lira)
0.17583	0	0.00698	0.03
2.98917	0.736	0.61181	0.69
5.01125	2.125	2.09639	1.46
7.385	3.52	3.598	2.8
10.0225	5.045	5.19948	4.57
12.48417	6.404	6.8653	6.44
14.94583	8.473	8.70506	8.39
16.70417	10.892	11.7261	11.1

Conclusions

The study includes an analysis of the stress-strain state of reinforced concrete beams. Experimental data were obtained using Digital Image Correlation (DIC) technology and non-contact micron measuring devices. The theoretical part of the study included comparative calculations and finite element modeling using the "LIRA" software. The deformation and deflection diagrams had similar shapes and characteristics, with deviations between numerical values around 5 %. Based on the obtained values and analysis of the theoretical data, it can be concluded that this comprehensive method for determining deformations and displacements allows for more accurate and less labor-intensive experimental data acquisition.

Prospects for Future Research

The prospects for further research may focus on several important aspects: studying how different types of damage affect the strength and deformability of beams under load. Analyzing at which load levels damaged beams begin to exhibit critical deformations or failure, which will help improve methods for predicting their behavior under real operating conditions. Investigating the influence of damage type on failure mechanisms, how different types of damage alter stress distribution, and how this affects the overall strength of the structure.

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ДОСЛІДЖЕННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ В ЗАЛІЗОБЕТОННИХ БАЛКАХ ЗА ДОПОМОГОЮ МЕТОДУ ЦИФРОВОЇ КОРЕЛЯЦІЇ

Наведено аналіз напружено-деформованого стану залізобетонних балок за допомогою методу цифрової кореляції зображень та мікроіндикаторів. Елементи на згин найпоширеніші в залізобетонних конструкціях, тому можливість точно оцінювати і використовувати нові методи, які зменшують трудомісткість процесу та підвищують точність вимірювання деформацій та несучої здатності, надзвичайно важлива. Метою дослідження є оцінювання як експериментальних, так і теоретичних досліджень деформацій та несучої здатності залізобетонної балки під навантаженням. Експериментальні дослідження здійснено за допомогою мікроіндикаторів та методу цифрової кореляції зображень. У результаті дослідження визначено значення деформації в стиснутій зоні бетону, напруження в арматурі та значення прогину. Побудовано порівняльні графіки для значень мікроіндикаторів, результатів цифрової кореляції та теоретичних значень, отриманих методом скінченних елементів за допомогою програмного забезпечення "LIRA". Побудовані діаграми показують хорошу збіжність; експериментальні та теоретичні результати для стиснутої зони бетону та розтягнутої арматури містяться у межах похибки до 7 %, а значення прогину відрізняються від теоретичних не більше ніж на 5 %. Отже, оцінка впливу методу за допомогою цифрової кореляції зображень та мікроіндикаторів демонструє високу точність у визначенні деформацій залізобетонних балок. Можна зробити висновок, що цей метод надає достовірну інформацію для оцінювання дійсної роботи елементів та напружено-деформованого стану, підвищує точність визначення значень. Зокрема, результати експериментальних досліджень підтверджують, що цей підхід дає змогу ефективно моніторити стан конструкцій, навіть на ранніх етапах їх експлуатації. Подальші дослідження можуть передбачати вивчення поведінки інших типів залізобетонних конструкцій під навантаженнями різних видів.

Ключові слова: залізобетонна балка, метод цифрової кореляціїї зображень, пошкодження, деформації, дефекти, моделювання.