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METHODOLOGY FOR THE APPLICATION OF THE DIGITAL IMAGE CORRELATION (DIC) FOR INVESTIGATING RC BEAMS

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The article discusses the improvement of the digital image correlation (DIC) method for analyzing deformations in RC beams, specifically focusing on the importance of zero-strain verification. This step is critical for ensuring high measurement accuracy, as it helps identify and minimize systematic and random errors. Before starting the research, system calibration is conducted, which includes the assessment of background noise and stability that influence the results. The study shows that proper sample preparation, pattern creation, and control of external factors allow for obtaining reliable data. The application of DIC enables remote monitoring of cracks and evaluation of the stress-strain state of structures. It has been established that this method is useful not only for scientific experiments but also in practical engineering, contributing to the increased reliability of structures.

Key words: Digital image correlation (DIC), RC beam, deformation, zero-strain, stressed-deformed state, measurement accuracy.

Introduction

In the study of structural deformations under external loads, several common data collection methods are employed. Traditionally, contact methods such as strain measurement are used, where mechanical sensors or strain gauges measure stresses and deformations. However, these methods have limitations–they depend on the quality of sensor attachment, are sensitive to external influences, and may introduce additional errors due to physical contact with the structure. The lack of a complete picture of deformation distribution across the entire surface of the structure often makes these methods insufficiently accurate.

With the development of non-contact technologies, new tools for more precise deformation analysis have emerged, among which the digital image correlation (DIC) method plays a significant role. This innovative method uses surface image analysis of the structure during its deformation under load. A key advantage of this method is the ability to obtain three-dimensional information about the deformation distribution without physical intervention in the structure, thus avoiding errors associated with contact methods.

The DIC method is already being actively used in scientific research and engineering practice due to its high accuracy and capability to analyze large areas of structures in real-time. Its use allows for a detailed study of structural behavior under load, which is critical for ensuring their reliability and safety.

However, despite its clear advantages, improving this method remains an important task. Enhancing DIC accuracy and developing new image processing algorithms could significantly increase its efficiency. Further optimization of this method will reduce analysis errors, shorten data processing time, and expand its application in modern construction and engineering practices.

The aim of this article is to improve the digital image correlation (DIC) method to enhance the accuracy of deformation studies in structures under load, with an emphasis on optimizing its application in engineering practice.

The methods for determining deformations in RC structures can be divided into destructive and non-destructive methods (Rahim et al., 2020). Non-destructive methods (Katam et al., 2023) focus on the inspection, testing of construction materials, and examining the material composition without causing damage. Non-destructive methods are widely used both in scientific research (Vavilov, 2014) and in practical engineering (Hola and Schabowicz, 2010).

Using non-destructive methods, one can measure indicators such as modulus of elasticity, surface hardness, strength, density, water absorption, depth and propagation of cracks, and the placement of reinforcement. These methods show high effectiveness in assessing RC structures subjected to corrosion (Zou et al., 2013)

In research (Ongpeng, 2018), a qualitative and detailed comparative analysis of various non-destructive methods for monitoring RC structures is presented. The study also highlights the effectiveness of digital image correlation (DIC) alongside ultrasonic, thermographic, and acoustic emission methods.

Accurate measurement of material deformations is crucial for determining the stress-strain state of structures, and traditional methods are being replaced by more advanced techniques involving automation and computerization (Cintron and Saouma, 2008).

Deformations are measured as a percentage change in length relative to the initial value by comparing a reference image to deformed images (Kopiika et al., 2022). These results are then used to calculate physical and mechanical characteristics, such as Young's modulus and Poisson's ratio, and to develop a real stress-strain diagram for the structure (Kopiika et al., 2022).

DIC is an optical method based on mathematical correlation analysis of digital images of an object in different stress-strain states. The DIC algorithm involves continuous digital camera imaging, capturing surface deformations, enabling real-time evaluation of physical parameters. Key principles and image processing approaches are discussed in several sources (Niezrecki et al., 2018).

For the DIC method, a speckle pattern of points is applied depending on the camera resolution and the distance from the surface. Numerical methods and software are used to analyze these patterns, constructing a deformation and stress distribution map. Each deformed image is assigned a unique pattern distribution compared to the initial image.

The position of each image subset is tracked throughout the deformation process, with pixel subsets represented as matrices of natural numbers. White pixels equal “0,” black pixels “100,” and gray pixels range between “0...100.” Each subset contains several gray points, forming different correlation regions (Blikharskyy et al., 2022).

The pattern parameters are essential, as they determine the accuracy of displacement calculations. The key requirements for the pattern include isotropy, 50–70 % surface coverage, high contrast, and randomness (Hu et al., 2021). A group of researchers (Passieux et al., 2012) focused their work on optimizing the DIC method, specifically to reduce the impact of external factors such as temperature, noise, lighting, sample size changes, wind, dust, and pattern inaccuracies.

The method is also effective for analyzing failure and crack formation in materials, as noted in other works (Valle et al., 2015) and DIC can be used to construct a full field of deformations in the crack zone.

Several works (Spellman et al., 2017) have also focused on modeling the behavior of composite and cementitious materials commonly used to strengthen RC structures (Funari and Verre, 2021). Additionally, DIC allows remote monitoring of cracking on the surface, making it effective for determining the ultimate state of structures. This method is highly effective for practical engineering tasks in technical supervision and provides accurate predictions of the residual structural service life (Cruz et al., 2019).

A unique advantage of DIC, aside from studying flat surfaces, is its capability for 3D modeling of structural characteristics and behavior under external loads (Yamaguchi, 2000).

Materials and methods

To obtain deformation results, the method of digital image correlation (DIC) was improved and applied to the study of RC beams with geometric dimensions of 2100×200×100 mm. The method was used to investigate both a 350×200 mm section of concrete and a 200 mm length of reinforcement. Deformation measurements were carried out using a special speckle pattern created according to the recommendations and requirements for the studied area. As described earlier, the software requires two colors to track the movement of individual matrices, taking into account all errors and corrections. Before the test, the samples were prepared by grinding uneven surfaces of the concrete, cleaning off dust, and brushing the reinforcement (see Fig. 1).

Fig. 1. The process of leveling and cleaning the surface of concrete and reinforcement

The next step in preparation was to create a uniform black or white background for the pattern. White background with black speckles was used for the concrete, while black background with white speckles was used for the reinforcement. The black background for the reinforcement was created using matte aerosol paint (see Fig. 2), and after it dried, a pattern of white speckles was applied using an airbrush (see Fig. 3).

The optimal speckle diameter of 0.2–0.4 mm was determined based on the pixel count of the camera and the distance to the study area. A lime-based paint was used for the white background on the concrete, providing more accurate results due to its absorption into the surface rather than forming an elastic film. The paint was applied with a roller in two layers: the first thinner and the second thicker (see Fig. 2). The speckle pattern of black dots was applied to the concrete using a controlled splatter technique with stiff brush bristles and a needle, along with water-based black ink as the coloring agent (see Fig. 4). The optimal speckle diameter on the concrete was calculated to be 0.3–0.7 mm. The applied speckle pattern for the DIC method is shown on the concrete (see Fig. 5) and on the reinforcement (see Fig. 6).

Fig. 2. Application of a white background on concrete (left) and a black background on reinforcement (right)

Fig. 3. Application of speckles on the reinforcement using an airbrush

Fig. 4. Application of speckles on concrete using the spraying method

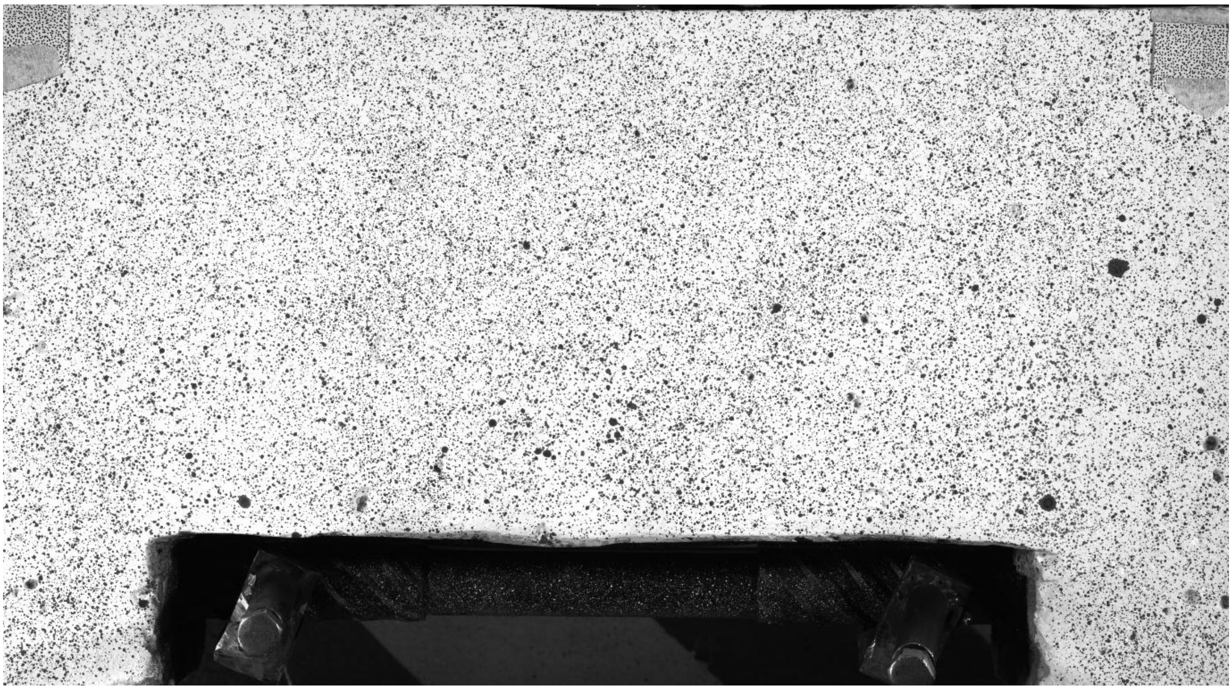

Fig. 5. Applied speckles on concrete

Fig. 6. Applied speckles on reinforcement

For the study and determination of deformations in the tensioned thermally-strengthened reinforcement and concrete within the pure bending zone across the entire height of the cross-section, two monochromatic “Grasshopper 3” cameras from Flir (Canada) equipped with Computar F25/2.8 lenses were used. The first stage of testing with the use of cameras began with mounting them on a tripod in the designed position and adjusting the parameters. The overall setup of the cameras is shown in Fig. 7.

Fig. 7. Overall view of the camera arrangement for image capture

The camera for photographing the concrete section was installed perpendicularly at a distance of 700 mm from the surface of the sample (see Fig. 8). The lens aperture was set to 1/5.6 units to achieve optimal image sharpness and contrast between the background and the speckles. The camera for determining the deformations of the tensioned reinforcement was positioned perpendicularly at a distance of 400 mm with an aperture of 1/4 units (see Fig. 9).

Fig. 8. Camera for capturing images of concrete deformation

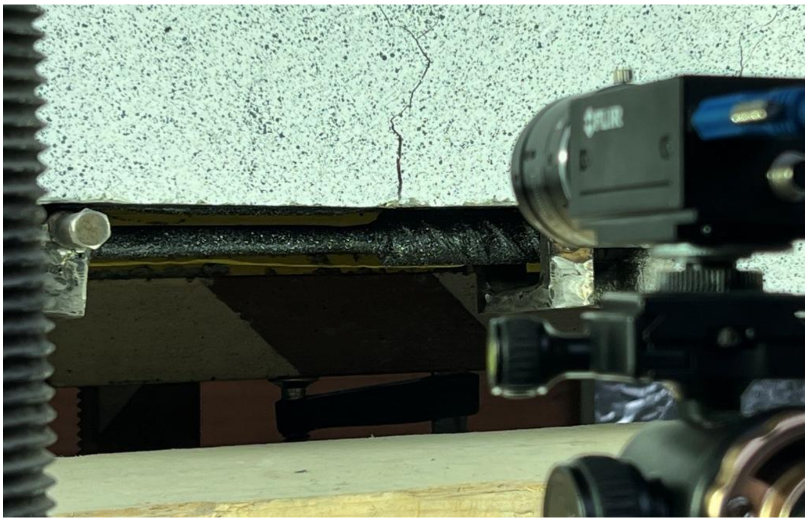

Fig. 9 Overall view of the camera that captured images of the stretched thermally strengthenedworking reinforcement

After focusing, the aperture values were reset to the specified settings described above. The camera setup procedure was carried out using the Fly Capture software provided by the camera manufacturer. Adjustments were made to the gamma, exposure, shutter speed, and other parameters. This procedure was necessary to optimize the settings under the existing lighting conditions to ensure high contrast and clarity of the speckles and the background (see Fig. 10).

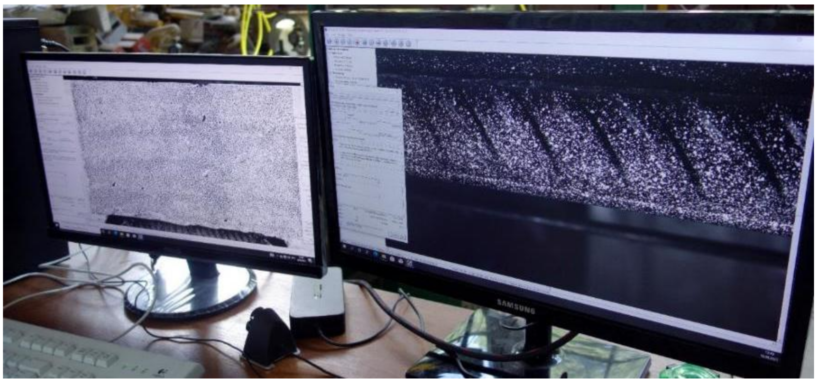

Fig. 10. Adjusting the focus of the cameras for image capture

Both cameras (for concrete and reinforcement) simultaneously recorded images at intervals of 100 ms each, utilizing camera buffering to maintain the image registration speed. After testing the sample, the images were processed using the specialized Vic-2D software, and the corresponding deformations and results for analysis were obtained (Klym and Blikharskyy, 2024).

Before the experiment, an advanced zero-strain verification was conducted, which is a crucial step for ensuring the quality of research using the digital image correlation (DIC) method. This approach allows for an evaluation of background noise levels and system stability before the actual testing, a critical aspect for ensuring high accuracy in research results.

The primary goal of the zero-strain verification is to detect and minimize both systematic and random measurement errors. This verification ensures high accuracy and reliability of experimental data while preventing misinterpretation of results.

Before sample testing, the DIC system is calibrated and adjusted according to the experiment's requirements, ensuring stable lighting conditions and sample fixation to avoid any external influences on the measurements. The next step involves recording a series of static images of the test sample without applying any load. This helps assess the system's noise level and verify its stability. It is recommended to capture images for 1-2 minutes at the same frame rate that will be used during the actual test.

The captured images are then loaded into Vic-2D software for analysis. After analysis, the deformations between the first and last images are compared, which should be zero if the system is working correctly. If there are deviations, both spatial and temporal standard deviations must be calculated.

The standard deviation calculation helps determine the noise level in the system. Spatial standard deviation measures how quantitative output indicators (QOIs) vary from one pixel to another in static images. If the images are stable, the difference between pixels will be minimal. Temporal standard deviation measures how QOIs change over time for the same pixel in a series of images. If the system is stable, these changes will also be minimal.

After calculating the standard deviation, the results are assessed. If the noise level (standard deviation) meets the experiment's requirements, testing continues. If the noise exceeds permissible limits, further adjustments are necessary, such as reducing environmental influences, adjusting lighting conditions, stabilizing the camera, and improving sample fixation.

Zero-strain verification is a critical step for ensuring measurement accuracy. It helps identify and eliminate any systematic errors before the experiment begins. Minimizing noise improves the accuracy and reliability of the data, while ensuring system stability prevents erroneous interpretation of research results.

Results and discussions

The study aimed to optimize the application of Digital Image Correlation (DIC) for assessing the stress-strain behavior of RC beams, a critical component in the evaluation of structural performance under load. DIC, a non-contact, optical method, has gained prominence for its ability to capture and analyze surface deformations with high precision. The results of this research are significant not only for academic inquiry but also for practical engineering applications, where accuracy in assessing material behavior is paramount.

One of the primary outcomes of the study was the verification of DIC's accuracy in measuring deformations in both concrete and steel reinforcement. Through advanced zero-strain verification, the experiment ensured that systematic and random errors were minimized. This procedure was crucial as it allowed the researchers to identify and account for any background noise that could potentially distort the measurement data.

Before the tests began, the calibration of the DIC system under consistent lighting conditions and stable sample fixation played an integral role in guaranteeing the accuracy of the results. The use of high-resolution cameras combined with the precise application of speckle patterns on both the concrete surface and reinforcement provided the necessary detail to track deformations effectively. The cameras captured images at intervals of 100 milliseconds, allowing for real-time deformation analysis. This approach was particularly effective for detecting minor deformations, which are critical for understanding the stress distribution across RC beams.

The research demonstrated that the DIC method could accurately capture deformations in both concrete and reinforcement, especially in areas subjected to pure bending. For concrete, the speckle pattern applied using a controlled splatter technique ensured high contrast and sharpness, crucial for tracking surface deformations under stress. Similarly, the reinforcement speckle pattern, applied using an airbrush, provided clear visibility of the reinforcement's behavior during loading.

The results indicated that the deformation patterns observed in both materials were consistent with theoretical models. The method effectively identified critical zones where cracking and failure were likely to occur, thereby validating DIC as a reliable tool for structural health monitoring. The ability to track deformation across the entire surface of the RC beams provided insights into the distribution of stress, allowing for a more comprehensive understanding of the structural behavior under load.

The study's zero-strain verification process highlighted its importance in ensuring measurement reliability. By capturing static images of the test samples before loading and comparing the deformation between initial and final states, the system's stability and noise levels were rigorously assessed. The low levels of spatial and temporal standard deviations confirmed that the DIC system was functioning optimally, with minimal noise interfering with the data. This step was critical in validating the experimental results and ensuring the accuracy of the strain measurements.

The findings of this study have substantial implications for practical engineering. The DIC method, with its ability to provide precise, real-time deformation data without physical contact, presents a significant advancement over traditional methods such as strain gauges. In real-world applications, particularly in the monitoring of RC beams in bridges and buildings, DIC offers a non-invasive solution that can improve the accuracy of structural health monitoring.

For instance, the ability to detect early-stage cracking and stress concentration zones allows engineers to take preventive measures before structural failures occur. This is particularly relevant for infrastructure subjected to cyclic loads or environmental factors such as corrosion. The study's application of DIC to monitor the stress-strain state of both concrete and reinforcement underlines its value in diagnosing and predicting the service life of RC structures, making it a highly effective tool in ensuring long-term structural safety.

Despite its effectiveness, the study acknowledges certain challenges in applying the DIC method. External factors such as lighting conditions, temperature fluctuations, and dust can affect the accuracy of the measurements. To mitigate these influences, the experiment employed controlled environmental conditions, but future research should focus on developing algorithms capable of compensating for these variables in uncontrolled environments.

Moreover, improvements in software algorithms for image processing could further enhance the precision of the DIC method. Reducing data processing time without compromising accuracy would make the method more accessible for routine structural assessments in the field. Integrating DIC with other non-destructive evaluation techniques, such as acoustic emission or thermography, could also provide a more comprehensive understanding of structural integrity.

The ability of the DIC method to perform 3D modeling of structural deformations is a major advantage, especially in complex structures where stress distribution is not uniform. This feature can be particularly useful in the analysis of RC beams with irregular cross-sections or varying material properties. Furthermore, DIC's remote monitoring capabilities make it suitable for long-term structural health monitoring, reducing the need for frequent manual inspections.

The study’s results contribute to the broader understanding of how DIC can be applied beyond laboratory conditions, offering valuable insights for its integration into routine structural health monitoring systems. This method's potential for continuous, real-time monitoring could significantly improve the safety and maintenance strategies of infrastructure, reducing the risk of catastrophic failures due to undetected damage.

One notable aspect in the practical application of Digital Image Correlation (DIC) is the influence of environmental conditions on the accuracy of the measurements. While the controlled laboratory environment of this study ensured minimal interference, real-world applications often face external challenges, such as variable lighting, temperature fluctuations, vibrations, and even environmental debris like dust or rain. Each of these factors can introduce noise into the measurement process, potentially compromising the integrity of the data collected. For instance, fluctuating light conditions, especially in outdoor settings, can reduce the contrast of the speckle patterns on the concrete and reinforcement surfaces, making it more difficult for the system to accurately track the deformations. In this study, the speckle pattern was optimized for high contrast under controlled lighting. However, in practical applications, further development is needed to create speckle patterns that remain visible and clear under varying light conditions. One solution could be the use of more advanced camera sensors or image processing algorithms that can dynamically adjust to lighting changes without affecting the accuracy of the results.

Similarly, temperature variations can affect both the material properties of the RC beams and the accuracy of the DIC measurements. Materials expand or contract in response to temperature changes, and this thermal strain may be incorrectly interpreted by the DIC system as mechanical deformation. Therefore, future studies could benefit from integrating temperature sensors alongside the DIC system to account for thermal effects. This would allow for more precise differentiation between thermal and mechanical strain, leading to even more reliable data in field conditions.

The application of DIC in the analysis of RC beams also has significant implications for the design and construction phases of engineering projects. By providing accurate and detailed data on how RC beams behave under load, DIC can inform better design choices, particularly in critical structures such as high-rise buildings, bridges, and industrial facilities where the failure of even a single beam can have catastrophic consequences. The ability of DIC to capture real-time deformation data also allows for immediate feedback during the construction process. For example, DIC could be used to monitor the performance of RC beams as they are installed, ensuring that they meet the design specifications and perform as expected under load. Any deviations from expected behavior could be identified and corrected during construction, potentially saving time and reducing the need for costly repairs or reinforcements later on.

Additionally, DIC can be used to validate design models and simulations by providing empirical data that can be compared against predicted performance. This validation process is critical in ensuring that the theoretical models used in the design phase accurately reflect real-world behavior, thereby improving the safety and reliability of structures.

While DIC has been successfully applied in laboratory settings and for small-to-medium scale structures, one of the challenges moving forward is scaling the technology for use on larger infrastructure projects. The current study focused on RC beams with specific geometric dimensions, but applying DIC to entire buildings or bridges would require careful consideration of several factors, including camera positioning, resolution, and data processing capabilities. For large-scale applications, multiple high-resolution cameras would likely need to be synchronized to capture different parts of the structure simultaneously. This introduces challenges in data integration, as the deformation data from each camera must be combined into a coherent whole without losing accuracy.

Advances in computer vision and data processing algorithms will be essential to overcome these challenges, enabling the seamless stitching together of data from multiple sources. Furthermore, the storage and processing of large volumes of data collected by DIC systems present another obstacle. Capturing high-resolution images at short intervals, as demonstrated in the study, can generate significant amounts of data, which must be processed in real-time to provide actionable insights. Future research should explore more efficient data compression and processing techniques to make DIC more scalable for use in large infrastructure projects.

The results of this study point to several areas where further development of DIC technology could enhance its capabilities. One such area is the automation of the system calibration and setup process. In the current study, the calibration of the DIC system required careful manual adjustment of the cameras, lighting, and speckle patterns to ensure accurate results. Automating this process could reduce the time and expertise required to set up DIC systems, making the technology more accessible for routine use in construction and engineering.

Another area for development is the improvement of DIC algorithms to better handle dynamic loading conditions. While the study focused on static or quasi-static loads, many real-world structures are subject to dynamic loads, such as those caused by wind, traffic, or seismic activity. Enhancing DIC algorithms to accurately capture deformations under dynamic loading would extend its application to a broader range of engineering challenges, particularly in regions prone to natural disasters.

Conclusions

Based on the review of non-destructive testing methods, it can be concluded that digital image correlation (DIC) methods hold immense potential for diagnosing, monitoring, and controlling the condition of construction structures and materials. The implementation of modern deformation research techniques, particularly DIC, allows for a structured and detailed description of the stress-strain state in real-time.

The proposed technique of applying a background and speckle patterns on the surface of concrete and reinforcement ensures high image clarity and contrast. This enables precise real-time deformation capture, reflected in the accuracy of the research results. Additionally, determining the optimal spot diameter and fine-tuning camera settings (positioning, focus, aperture) provide a detailed picture of the deformation processes in the test samples.

Zero-strain verification is a critical step in preparing for mechanical testing using the DIC method. This procedure ensures high accuracy and reliability of results, essential for successful scientific research.

The proposed improvements to the DIC methodology have significantly enhanced measurement accuracy, making this method applicable not only in scientific research but also in practical engineering tasks. It is suitable for monitoring the condition of construction structures subjected to loads, corrosion, and damage.

The research has demonstrated the effectiveness of Digital Image Correlation (DIC) in accurately measuring deformations in RC beams, providing detailed insights into the stress-strain behavior of both concrete and reinforcement. Through zero-strain verification and precise application of speckle patterns, the study ensured high accuracy in the results, confirming DIC’s suitability for both scientific research and practical engineering applications.

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МЕТОДИКА ЗАСТОСУВАННЯ ЦИФРОВОЇ КОРЕЛЯЦІЇ ЗОБРАЖЕНЬ (ЦКЗ) ДЛЯ ДОСЛІДЖЕННЯ ЗАЛІЗОБЕТОННИХ БАЛОК

У статті розглянуто вдосконалення методу цифрової кореляції зображень (ЦКЗ) для аналізу деформацій залізобетонних конструкцій під впливом навантажень. Традиційні контактні методи, такі як тензометрія, незважаючи на їх точність, мають обмеження через фізичний контакт, що може призвести до похибок у вимірюваннях. Вдосконалений метод ЦКЗ дає змогу забезпечити точні вимірювання без фізичного втручання, що особливо важливо під час дослідження залізобетонних балок. Перед випробуванням здійснено перевірку на нульову деформацію, що є важливим етапом для оцінки фонових шумів і стабільності системи вимірювання. Ця перевірка дала змогу мінімізувати як систематичні, так і випадкові похибки у вимірюваннях. Система ЦКЗ була налаштована згідно із вимогами експерименту для уникнення зовнішніх впливів на результати, включаючи стабільне освітлення та фіксацію зразків. Основні етапи дослідження передбачали підготовку зразків залізобетонних балок, що складалося зі шліфування й очищення поверхонь, а також створення спеціального візерунка: білого фону з чорними крапками на бетоні й чорного фону з білими крапками на арматурі. Встановлення оптимальних діаметрів крапок критично важливе для точного аналізу деформацій. Результати дослідження показали, що вдосконалений метод ЦКЗ забезпечує високу точність фіксації деформацій як бетону, так і арматури, даючи змогу ефективно виявляти критичні зони тріщиноутворення та прогнозувати залишковий ресурс конструкцій. Запропоновані вдосконалення істотно підвищують точність і надійність вимірювань, роблячи ЦКЗ перспективним для інженерної практики та наукових досліджень. Отримані результати відкривають нові можливості для моніторингу стану залізобетонних конструкцій, які зазнають навантажень і корозії, що сприятиме забезпеченню їхньої надійності та довговічності в реальних умовах експлуатації.

Ключові слова: цифрова кореляція зображень (ЦКЗ), залізобетонна балка, деформації, нульова деформація, напружено-деформований стан, точність вимірювання.