This paper reports the development and verification of a new procedure for formation of a complete stress-strain curve of concrete with a downward region of strain by using a digital image correlation method. A new technique to build spectle patterns on the surface of concrete is described. That makes it possible to accurately enough reproduce the spectle patterns on the surface of concrete and perform a high-quality analysis of strains involving digital image correlation. The advantages of this research technique have been established when predicting the formation of internal cracks in concrete followed by their propagation. In addition, using the digital image correlation methodology makes it possible to obtain strains of the entire studied plane of the sample at each stage of loading. This procedure provides an opportunity to investigate a change in strains and the movement of individual points or areas when studying concrete surfaces. That is a relevant issue as it enables more detailed diagnostics of existing reinforced concrete structures. To check the accuracy of this procedure application, a mechanical gauge with an accuracy of 0.001 mm was additionally installed. 2 high-speed monochrome CCD cameras with different lenses were used in determining concrete strains involving the digital image correlation technique. The deformations were controlled with a period of time every 250 ms. The load was controlled by an additional third camera with a speed of 50 frames/second. The result of the experimental study is the formed full concrete destruction diagram with a downward region of strain. The deviation of the results of strains based on the mechanical gauge with an accuracy of 0.001 mm with a base of 200 mm from those acquired by the digital image correlation procedure was mainly up to 10 %, which confirms the reliability of the results. The results of this work allow a more accurate calculation of reinforced concrete structures in the practice of design, inspection, or reinforcement of existing structures

Keywords: digital image correlation, stress-strain curve, concrete, spectle patterns

UDC 624.012

DOI: 10.15587/1729-4061.2021.234131

FORMATION OF A COMPLETE STRESS-STRAIN CURVE OF CONCRETE USING DIGITAL IMAGE CORELLATION

Yaroslav Blikharskyy
Corresponding author
PhD, Associate Professor
Department of Highways and Bridges*
E-mail: yaroslav.z.blikharskyy@lpnu.ua

Andrii Pavliv
Doctor of Architecture Sciences, Associate Professor
Department of Design and Architecture Fundamentals*

*Lviv Polytechnic National University
S. Bandery str., 12, Lviv, Ukraine, 79013

Received date 22.03.2021
Accepted date 13.05.2021
Published date 30.06.2021

How to Cite: *Blikharskyy, Y., Pavliv, A. (2021). Formation of a complete stress-strain curve of concrete using digital image corellation. Eastern-European Journal of Enterprise Technologies, 3 (7 (111)), 37–44. doi: https://doi.org/10.15587/1729-4061.2021.234131*

1. Introduction

Reinforced concrete structures are among the most common in the world. A significant body of research tackles reinforced concrete structures. Paper [1] reports the calculation of non-center-compressed reinforced concrete elements. It is based on the use in the calculations of predictable curvature when reaching the boundary deformations of concrete compression and the reinforcement yield strength. A theoretical complete concrete destruction curve is used to calculate reinforced concrete retaining walls [2]. It is actual to use the concrete stress limit for the calculation of reinforced concrete frames [3] and reinforced concrete buttresses [4] since the basis for calculating such structures is a deformation model based on the nonlinear curves of concrete destruction. Paper [5] reports a theoretical calculation of reinforced concrete structures of the round, rectangular, and T cross-sections. The calculation was carried out according to the deformation model with embedded theoretical nonlinear curves of concrete destruction. For the experimental studies of reinforced concrete beams with pre-strained working reinforcement [6, 7], the limit deformation and concrete stress are relevant, since this is one of the criteria for such structures in terms of exhaustion of their bearing capacity. The use of downward concrete deformation curve is relevant for the calculation of reinforced concrete structures damaged during operation [8, 9]. To determine the bearing capacity of damaged reinforced concrete columns at different cross-sections and the percentage of damage, a complete concrete destruction curve is required [10, 11]. Given the complexity and heterogeneous properties of reinforced concrete [12], the calculation of damaged structures is more difficult compared to damaged metal structures [13]. That is why experimental concrete tests are important for calculating damaged structures. Determining the characteristics of concrete in full is relevant for composite concrete structures. Work [14] reports the use of a theoretical concrete curve for bending concrete structures reinforced with composite bars. The rational design of the cross-section of composite reinforced concrete span structures of bridges [15] employs the theoretical values of concrete stress limit. For a more accurate calculation of reinforcement of reinforced concrete columns using reinforced concrete [16] or composite concrete [17] clips, one must take into consideration the full characteristics of concrete. The authors of the cited works applied theoretical normative data. One of the modern methods of reinforcement is the use of carbon fiber [18] and carbon tape [19]. The carbon destruction curve is linear, similar to steel, but the destruction of concrete is nonlinear and depends on the mixture, composition, strength, etc. Therefore, to calculate the strengthening of such structures, experimental characteristics of concrete are important. That could make it possible to predict the reliability of such structures [20]. The above works confirm that the use of a full concrete curve is a relevant issue and requires new ways to define these characteristics. In particular, devising new methods of experimental testing is a relevant task.

According to current regulatory documents [21, 22], reinforced concrete structures are calculated on the basis of a deformation model. Underlying the calculation of the bearing capacity of reinforced concrete structures is a nonlinear deformation model that employs a nonlinear curve of concrete destruction σ-ε and a two-line curve of reinforcement σ-ε, and is built on the iteration method. This method essentially implies that at each stage of iterative calculation the values of relative average deformations of the stretched concrete fiber $\varepsilon_{c(2)}$ are determined according to the predefined amount of deformations of the compressed concrete fiber $\varepsilon_{c(1)}$.

In equilibrium equations [21, 22], the value of the moment or longitudinal force is selected so that the equilibrium conditions are met [21, 22]. When the predefined calculation accuracy is achieved at the assigned amount of deformations, the calculation is terminated; the corresponding value of the moment or longitudinal force is determined from the equilibrium equations. Next, at the predefined value of compressed fiber $\varepsilon_{c(1)}$, they are increased by the value $\Delta\varepsilon_{c(1)}$, and the calculation is repeated until the condition $\varepsilon_{c(1)\geq}\varepsilon_{cu1}$ is met. Terminating the calculation marks that the compressed fiber reached the concrete deformation limit, which is one of the conditions for exhaustion of bearing capacity. After completion of the calculation, the deformations of the compressed and stretched concrete fiber, as well as the main reinforcement, were obtained.

The calculation according to the deformation model makes it possible to more accurately estimate such structures but there is an issue related to building a complete curve of concrete destruction with a downward line, which is an important and relevant issue. To construct a stress-strain curve, concrete prisms are used with an aspect ratio of 1:4. The difficulty in constructing such a curve is the fact that a sample undergoes a sudden destruction when, during the test, the maximum deformations $\varepsilon_{c(1)}$ are reached. Especially for higher strength concrete.

Constructing a full stress-strain curve of concrete started in the 1970s [23]. In particular, in work [24], specially prepared cylinders were used to build a complete destruction curve. To build the curve, strain gauges with accuracy of 0.001 mm were used, as well as a specially designed setup. However, this method requires additional costs to prepare the experiment. In addition, monitoring the readouts of displacement changes to determine deformations is quite difficult.

That is why the issue of devising new methods for testing and building a curve of concrete destruction is relevant; it could allow for a more accurate calculation of reinforced concrete structures.

2. Literature review and problem statement

A significant number of works tackled the construction of a complete stress-strain curve for steel [25–27]. In particular, paper [25] reported the results from a standard test of steel with an imitation of corrosion damage. However, that procedure does not make it possible to identify a change in the deformations for the entire sample. In [26], this issue was resolved by an additional analysis using a finite-element method. However, that does not allow for an analysis based on experimental results. The solution to this issue is presented in paper [27]. A procedure for analyzing steel stretching involving construction of a stress-strain curve using digital image correlation was used. However, the cited studies solve the task of building a curve for steel elements. The difficulty in constructing a complete curve of concrete destruction is a sudden destruction after reaching maximum stress and maximum values of deformations.

The study of the formation of a complete "stress-strain" diagram of concrete is presented in the paper [28]. To determine the strains, LVDT sensors with an accuracy of 0.001 mm and a specially prepared insert were used. The advantage of such sensors is remote registration of deformations. However, this technique requires expensive sensors and specially prepared equipment.

The option of overcoming the problem related to building a concrete curve using standard moving sensors is presented in work [29]. The concrete prisms of class C50/60 were tested on two different presses under a severe load mode. The first part of the research was carried out at a specially prepared installation Instron 8806. This experimental setup is equipped with a highly rigid frame, which assures precise alignment, and sensors for constant load control. The press uses advanced devices for digital control and load sensors, which make it possible to build a complete curve of concrete destruction.

However, all those techniques require specially prepared complex high-cost testing machines for such tests. In addition, those procedures do not make it possible to obtain the distribution of stresses over the entire surface of concrete. Therefore, it is important to find new ways to build a complete stress-strain curve for concrete samples.

With the development of technology, a new technique to control deformations appeared, namely a digital image correlation procedure [30, 31]. In general, the digital image correlation (DIC) method can be described as optical measurement with digital image processing and numerical calculations. To use this method, one needs a high-speed camera with a high-quality digital matrix and randomly arranged spectle patterns, black against a light background, or white against black, for analysis. The base of the programs is a complex algorithm, which determines the movement of areas with high accuracy. The camera and the quality of spectle pattern application exert the greatest impact on accuracy.

The digital image correlation (DIC) method is commonly used in the study of the stressed-strained state of building structures, in particular, it is widely applied in the mechanics of destruction of steel structures [32, 33]. Paper [34] report the use of a digital correlation procedure for bending reinforced concrete structures. However, no physical-mechanical characteristics of concrete were investigated. Specific tests involving the digital image correlation procedure were proposed by the authors of work [35]. The characteristics of crack propagation in concrete samples were investigated based on different software tools. However, using the digital correlation procedure to determine the physical and mechanical characteristics of concrete was not studied in detail.

All this suggests that it is advisable to conduct a study into the construction of a full stress-strain curve of concrete. It is especially important to solve the task of building a downward section of concrete deformation involving a procedure for digital image correlation. That could make it possible to investigate more accurately and in detail the physical and mechanical characteristics of concrete for the calculation of structures.

3. The aim and objectives of the study

The purpose of this study is to form a complete stress-strain curve of concrete with a downward section by using a digital image correlation methodology. That would make it possible to practically use the nonlinear curve in the theoretical calculation of reinforced concrete constructions according to the deformation model.

To accomplish the aim, the following tasks have been set:

– to investigate the longitudinal and transverse strains of concrete using a digital image correlation methodology and determine the possibilities of its use;

– to perform an experimental study involving the formation of a complete stress-strain curve of concrete and determine the accuracy of the procedure of digital image correlation.

4. The study materials and methods

4 cubes with dimensions of 100×100×100 mm and 3 prisms with dimensions of 100×100×400 mm were fabricated. The research was carried out by an experimental method. 2 cameras were used to determine deformations using a procedure of digital image correlation. Namely, the monochromatic cameras “Grasshopper 3” by Flir (Canada) with the Computar F25/2.8 lens and with the Canon EF 70-200MM F/2.8 L IS III USM lens were used (Fig. 1).

Fig. 1. General view of the cameras “Grasshopper 3” by Flir

The specifications of the cameras are given in Table 1.

Table 1

Specifications of the “Grasshopper 3” cameras by Flir (Canada)

Title	Characteristic
Model name	GS3-U3-91S6M-C
Analog-digital converter	14-bit
Color	Mono
Frame rate	9
Megapixel	9.1
Pixel size	3.69
Resolution	3,376×2,704
Sensor type	CCD
Exposure range	0.040 ms до 32 s

The specifications of the camera were checked using specially made dies with different pixel sizes. The specifications fully correspond to those claimed by the manufacturer (Fig. 2).

Fig. 2. Checking the specifications of the camera

The procedure of digital image correlation requires the creation of spectle patterns on the examined surface in order to register deformations.

There are various ways to create spectle patterns. The most popular are spraying with an aerosol spray or applying by using specially made rollers with needles of a suitable diameter or dies. Aerosol application is quite difficult when executing the exact sizes of spectle patterns while special rollers with needles or dies are quite expensive and also have disadvantages during application.

Work [36] proposes a technique for applying spectle patterns on a metal surface. This method implies preliminary printing on paper of spectle patterns of the necessary configuration using a laser printer. After that, the surface of paper is applied to the metal surface and heated. Next, the spectle patterns are transferred from paper to the surface of steel.

This technique gave us the idea to devise a procedure to apply spectle patterns to the surface of concrete.

The essence of the proposed procedure for creating spectle patterns is as follows. The surface of concrete is preliminarily polished to the maximum leveling of the surface using grinders and stone for grinding (Fig. 3).

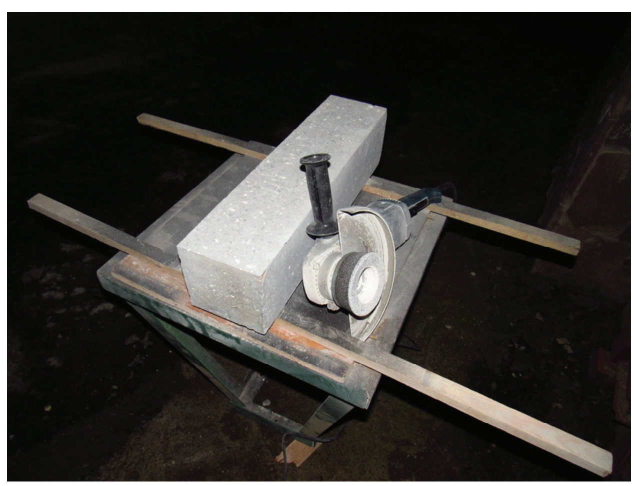


Fig. 3. Leveling the surface of the concrete of the examined prism

After that, the concrete surface is cleaned with solvent (Fig. 4).

Fig. 4. Cleaning the surface of the concrete of experimental prisms with a solvent

At the next stage, spectle patterns are printed on paper using a laser printer and attached to the surface of concrete. After that, the upper surface of paper is thoroughly impregnated with acetone (Fig. 5); the surface of the paper is leveled on the concrete. An important point is the impregnation time; the procedure must be carried out quickly since the acetone could start to dissolve the spectle patterns: they would become blurred at the surface of the concrete. Our result is shown in Fig. 6.

The result of this procedure application is the uniform contrast spectle patterns with ideal dimensions of the required configuration.

The first stage was to test concrete cubes with pre-applied black spectle patterns of different configurations. The purpose of this test was to determine the optimal dimensions of spectle patterns for the further processing of the image. It was preliminary planned to make spectle patterns with a diameter of 0.5 mm, with a density of 70 %, and a variation of 75 (Fig. 7).

a

b

Fig. 5. Creation of spectle patterns at the surface of concrete: *a* – the process of impregnation of printed spectle patterns at the surface; *b* – the alignment of spectle patterns at the surface

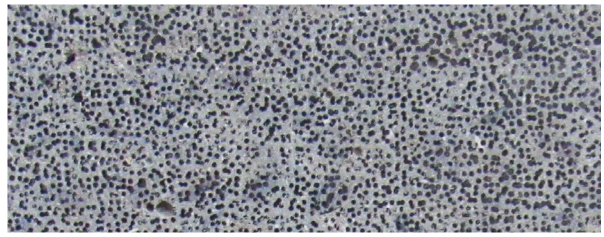


Fig. 6. The result of applying spectle patterns on the surface of concrete

After testing the cubes the size of 100×100×100 mm, it was established that the strength was $f_{cm,cube}$=63.8 MPa, which corresponds to the class of concrete C50/60. In addition, the diameter of the spectle patterns for the planned site to be examined (100×400 mm) in the concrete prisms was taken to equal 1 mm with a density of 70 % and a variation coefficient of 75 %.

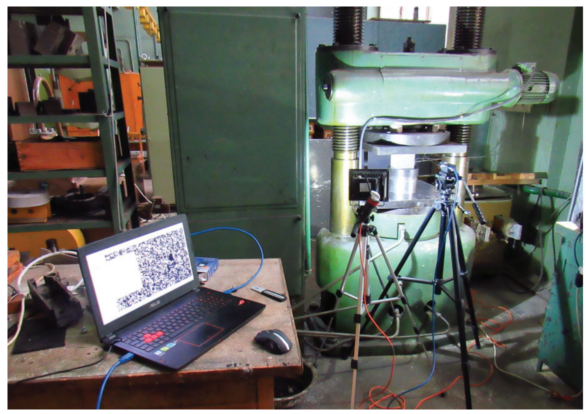


Fig. 7. Testing concrete cubes the size of 150×150×150 mm

Concrete prisms of 100×100×400 mm were tested at a hydraulic press with a maximum load of 2500 kN (Fig. 8). Deformations Strains were controlled over a period of every 250 ms. Since the press machine cannot record the load in time, an additional third camera with a frame rate of 50 frames/sec was used to register the load.

To control and check strains using the procedure of digital image correlation, a mechanical gauge with an accuracy of 0.001 mm was additionally installed on the prism. The base of the indicator was 200 mm.

Fig. 8. Experimental setup: 1 – LED lighting; 2 – camera with Computar F25/2.8 lens; 3 – camera with Canon EF 70-200MM F/2.8 L IS III USM lens; 4 – a load monitoring camera; 5 – a laptop for recording images; 6 – a laptop to record load; 7 – examined sample (camera 2 view)

Strains for image correlation were recorded by 2 cameras at a speed of 250 ms. 2 LED lamps were used for lighting.

VIC-2D software was used to process digital images in order to determine concrete strains. The VIC 2D software was developed by Correlated Solutions. The software employs an algorithm for analyzing the spectle patterns, which makes it possible to determine relative movements.

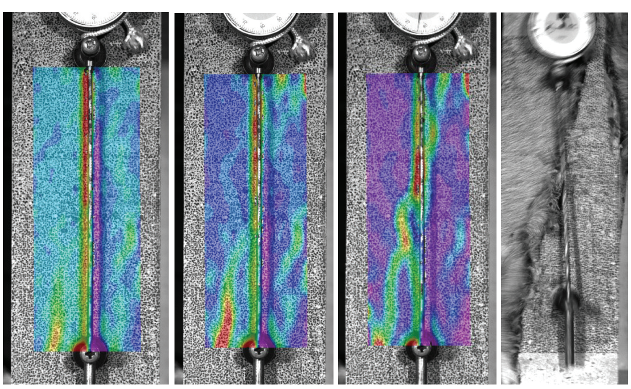
5. Building a complete stress-strain curve of concrete with a descending branch line, using the procedure of digital image correlation

5. 1. Investigating longitudinal and transverse deformations of concrete according to the procedure of digital image correlation

The image correlation method provides a possibility to determine strains on the full surface of the examined sample.

When analyzing transverse strains of the prism, it is possible to detect the appearance of an internal crack of the sample before it emerges outside. This allows the detection of cracks at a time when cracks are not yet possible to register visually (Fig. 9).

The collapse of the prism made from the C50/60 class of concrete occurred suddenly, with the propagation of the internal crack outside the sample, which is characteristic of such classes. Owing to the use of a high-speed camera and photographic registration each 250 ms, it was possible to record the moment of destruction of the sample (Fig. 9, *d*).

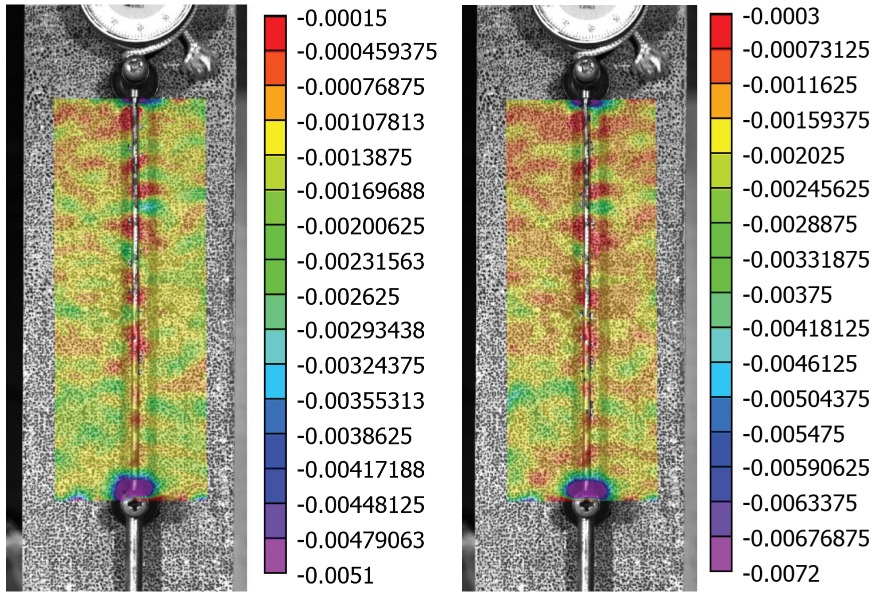


a *b* *c* *d*

Fig. 9. The nature of crack formation, acquired by using the digital image correlation procedure: *a* — under a stress of 41.5 MPa; *b* — under a stress of 42 MPa; *c* — under a stress of 43 MPa; *d* — at the time of destruction

In the same way, the procedure makes it possible to determine vertical strains of the sample, in each region (Fig. 10).

This makes it possible to investigate the nature of strains showing their distribution over the entire surface of the sample, which is impossible standard procedures.



a *b*

Fig. 10. Distribution of vertical strains in the sample: *a* — under a stress of 40.5 MPa; *b* — under a stress of 44.0 MPa

5. 2. Experimental study on the formation of a complete stress-strain curve of concrete according to the devised methodology

To form a complete load "stress-strains" curve of concrete, the video recording of loading was split into images of 4 frames/second. Thus, it was possible to synchronize the load with the strains acquired by the method of digital image correlation and those obtained using a mechanical gauge with an accuracy of 0.001 mm with a base of 200 mm.

The stress-strain curve for the concrete prism of class C50/60 is shown in Fig. 11. Virtual extensometers were installed in the software within the middle of the sample and on the base of 200 mm in order to determine relative deformations strains by the digital image correlation methodology.

As a result, based on the proposed methodology, a complete curve of concrete destruction was built without the use of specially adapted equipment. Note the values from the gauge (Fig. 1) and the values obtained from digital image correlation (DIC_Lense_Canon and DIC_Lense_Computar) have deviations within a tolerance limit while the nature of the curve corresponds to the rated values in normative documents.

When using a Canon EF 70-200MM F/2.8 L IS III USM (DIC_Lense_Canon) lens, some deviations at 25...35 MPa are noticeable. This is because the scale of the explored area with a Canon lens is 3 times larger than that for the Computar F25/2.8, so one needs to use spectle patterns of a much smaller size. However, this spectacle size is sufficient for the Computar F25/2.8 lens for a given examined area.

The comparison of stress deviation results obtained using a mechanical gauge and image correlation with different lenses is illustrated in Table 2.

That is, the deviation of the values of relative strains obtained from the mechanical gauge and by the procedure of digital image correlation under a stress of 44.5 MPa was in the range of 10–11 %, and under a maximum stress of 44.875 MPa in the range of up to 15 %.

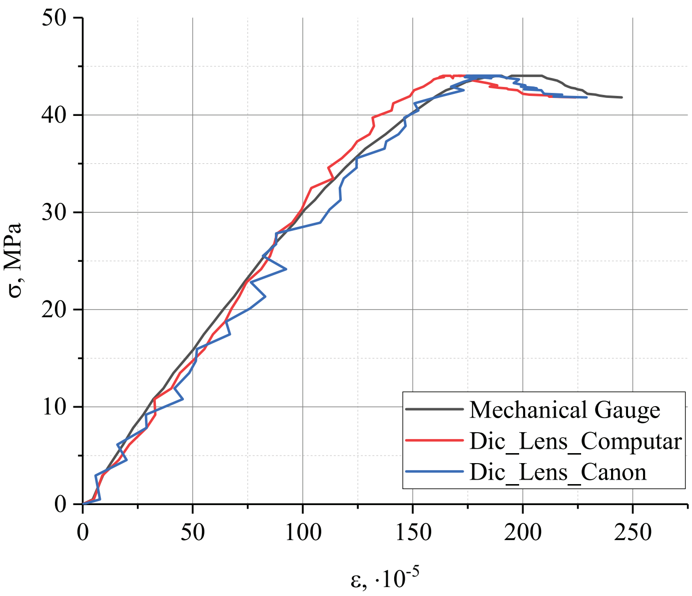


Fig. 11. Complete curve of concrete destruction, the sample of C50/60 class

Table 2

Comparison of changes in strains based on a mechanical gauge and digital image correlation

Stress, MPa	Strains, $\times 10^{-5}$			Deviation relative to the mechanical gauge, Computar lens, %	Deviation relative to the mechanical gauge, Canon lens, %
	Mechanical gauge, the base of 200 mm	Digital image correlation, Computar lens	Digital image correlation, Canon lens		
12.1	36.7	40.32	41.72	9.88	13.68
19.1	59.6	64.73	65.14	8.55	9.23
26.0	82.6	85.16	81.89	3.14	0.82
31.9	105.5	101.4	117.2	3.89	11.09
38.0	133	124.73	137.97	6.24	3.71
42.0	156	141.14	150.81	9.5	3.3
44.5	178.9	159.56	176.69	10.81	1.23
44.875	201.8	171.87	177.65	14.84	11.98

6. Discussion of results of studying concrete samples using the procedure of digital image correlation

The result of this work is the devised methodology for creating spectle patterns for digital image correlation. The procedure involves the gradual dissolution of spectle patterns printed on paper to the concrete surface using acetone. This technique makes it possible to effectively create spectle patterns of various configurations (Fig. 6). Based on the results of tests (Table 2), the devised procedure makes it possible to analyze the digital image correlation in order to determine strains with an accuracy of 3 % to 10 %.

According to the devised methodology, it is possible to predict the formation of cracks (Fig. 9), since the procedure of digital image correlation yields the transverse movement of all points of the plane. A significant advantage is the ability to analyze the places of formation of internal cracks, which is impossible to determine visually. The result of this research is a formation of complete "stress-strains" curve of concrete obtained by means of digital image correlation when using a press machine not adapted for this purpose (Fig. 11). That makes it possible to test concrete samples without the cost of retrofitting the test equipment. The result of this study is the derived value of strain along the descending branch line of the stress-strain curve for concrete samples. This procedure makes it possible to perform the calculation of reinforced concrete constructions by using preliminary experimental tests of concrete and introducing to the calculation a nonlinear curve, with more reliable accuracy. Similarly, based on the "stress-strain" curve, it is possible to obtain more reliable coefficients for the 5th order polynomial to improve the accuracy of calculation. In addition, based a given procedure, we established ultimate stresses on the descending branch line σ_{cu1}=42.48 MPa, as well as ultimate strain ε_{cu1}=0.00229. It is these parameters and nonlinear curves that are included in the current norms for the calculation of reinforced concrete constructions [21, 22]. We obtained these results by using high-speed monochrome cameras and a recording with speed of 250 ms.

Experimental strain data were obtained based on mechanical gauge values and the procedure of digital image correlation. The results of deviation of these data are mainly in the range of up to 10 %. That makes it possible to assert the reliability results in this work and the possibility of applying this procedure. The advantage of this procedure over existing ones is the possibility to determine the strains of a concrete sample contact-free, as well as multiple use. Existing procedures employ, to determine the strains, by using LVDT sensors [30] or strain gages [31]. When tested with LVDT sensors [30], there is a risk of damaging them due to the sudden destruction of concrete; strain gages [31] are disposable. In addition, this technique does not require a specially designed expensive equipment for testing, unlike [29]. Existing procedures make it possible to acquire curves but do not provide for an opportunity to predict cracks and determine the strains over the entire surface of the sample.

Thus, the procedure of digital image correlation makes it possible, when studying concrete and reinforced concrete samples, at any stage of loading, to determine strains throughout the plane or in any of the areas of interest. At the same time, it is possible to determine movements of both individual points and the estimated strains between points or throughout the plane. According to the results of our research, there is a high reliability of our findings in comparison with mechanical devices, which allows us to recommend a given procedure to examine such structures.

However, there are certain disadvantages when using the proposed method in practice. In particular, it is necessary to choose the right dimensions of the spectle patterns, as well as a lens. When using a Computar lens, the results convergence was in the range of up to 10–11 %; with a Canon lens, it was up to 15 % (Table 2). This is because the size of 1-mm diameter spectle patterns is too large for the Canon lens. It is also important not to have direct natural light on the camera lens. Another drawback is access from the camera to the examined object. Sensors can be installed directly on a prism. Cameras can record images at a certain distance, so there should be no foreign objects between the camera and the examined sample. Limitations when applying the digital image correlation method to determine deformations are the dimensions of examined samples. Flir's Grasshopper 3 cameras (Canada) with Computar F25/2.8 lens used in this work make it possible to measure deformations for

400×400 mm samples. These are the maximum dimensions, which are enough to determine the relative deformations of concrete with an accuracy of 0.1 μm.

Taking into consideration the positive results of our study, it is planned to continue improving the use of the digital image correlation procedure and advance the research. In future studies, it is planned to improve the calculation technique to determine the width of crack opening at each stage of loading. In addition, it is planned to improve a given procedure for using real-size reinforced concrete beams in experimental tests.

7. Conclusions

1. The transverse and longitudinal strains of concrete were obtained at each stage of loading. Unlike existing methods, the proposed procedure makes it possible to determine strains over the entire plane of the sample. That makes it possible to investigate a change in the strains and the movement of individual points or areas when studying concrete surfaces. This, in turn, makes it possible to explore the places and the nature of crack formation for practical application. In particular, when examining existing structures, it is possible to register the places of future crack origination and the strains of individual areas.

2. At this works presented a result of formation a complete stress-strain curve of concrete with a descending branch line using the procedure of digital image correlation. The deviation between the values of relative deformations obtained from a micro indicator and those based on the devised procedure of digital image correlation under a stress of 44.5 MPa was in the range of up to 10–11 %, and under a maximum stress of 44.875 MPa in the range of up to 15 %. This allows us to assert the possibility of using the devised procedure for testing concrete samples.

References

1. Bambura, A. M., Dorogova, O. V., Sazonova, I. R., Bogdan, V. M. (2018). Calculations of the eccentriccompressed slender reinforced concrete members applying an “effective” curvature method. Nauka ta budivnytstvo, 3, 10–20.
2. Mergos, P. E., Mantoglou, F. (2019). Optimum design of reinforced concrete retaining walls with the flower pollination algorithm. Structural and Multidisciplinary Optimization, 61 (2), 575–585. doi: https://doi.org/10.1007/s00158-019-02380-x
3. Martins, A. M. B., Simões, L. M. C., Negrão, J. H. J. O., Lopes, A. V. (2019). Sensitivity analysis and optimum design of reinforced concrete frames according to Eurocode 2. Engineering Optimization, 52 (12), 2011–2032. doi: https://doi.org/10.1080/0305215x.2019.1693554
4. Tahsin Öztürk, H., Dede, T., Türker, E. (2020). Optimum design of reinforced concrete counterfort retaining walls using TLBO, Jaya algorithm. Structures, 25, 285–296. doi: https://doi.org/10.1016/j.istruc.2020.03.020
5. Pavlikov, A., Harkava, O., Kochkarev, D. (2019). Calculation of reinforced concrete members strength by new concept. Proceedings of the fib Symposium 2019: Concrete - Innovations in Materials, Design and Structures, 820–827.
6. Bobalo, T., Blikharskyy, Y., Kopiika, N., Volynets, M. (2021). Influence of the Percentage of Reinforcement on the Compressive Forces Loss in Pre-stressed RC Beams Strengthened with a Package of Steel Bars. Proceedings of EcoComfort 2020, 53–62. doi: https://doi.org/10.1007/978-3-030-57340-9_7
7. Kovalchuk, B., Blikharskyy, Y., Selejdak, J., Blikharskyy, Z. (2020). Strength of Reinforced Concrete Beams Strengthened Under Loading with Additional Reinforcement with Different Levels of its Pre-tension. Proceedings of EcoComfort 2020, 227–236. doi: https://doi.org/10.1007/978-3-030-57340-9_28
8. Kotes, P., Strieska, M., Brodnan, M. (2018). Sensitive analysis of calculation of corrosion rate according to standard approach. IOP Conference Series: Materials Science and Engineering, 385, 012031. doi: https://doi.org/10.1088/1757-899x/385/1/012031
9. Koteš, P., Strieška, M., Brodňan, M. (2018). Long-time measurements of reinforcement due to air pollution corrosion on reinforced girder bridge. 18th International Multidisciplinary Scientific GeoConference SGEM 2018, 18 (4.2), 515–521. doi: https://doi.org/10.5593/sgem2018/4.2/s19.067
10. Klymenko, Y., Kos, Z., Grynyova, I., Maksiuta, O. (2020). Operation of Damaged H-Shaped Columns. Proceedings of EcoComfort 2020, 192–201. doi: https://doi.org/10.1007/978-3-030-57340-9_24
11. Kos, Ž., Klimenko, Y. (2019). The development of prediction model for failure force of damaged reinforced-concrete slender columns. Tehnički vjesnik, 26 (6), 1635–1641. doi: https://doi.org/10.17559/tv-20181219093612
12. Blikharskyy, Y., Kopiika, N., Selejdak, J. (2020). Non-uniform corrosion of steel rebar and its influence on reinforced concrete elements` reliability. Production Engineering Archives, 26 (2), 67–72. doi: https://doi.org/10.30657/pea.2020.26.14
13. Selejdak, J., Urbański, M., Winiarski, M. (2018). Assessment of a steel bridge corrosion degree. E3S Web of Conferences, 49, 00098. doi: https://doi.org/10.1051/e3sconf/20184900098
14. Vatulia, G., Berestianskaya, S., Opanasenko, E., Berestianskaya, A. (2017). Substantiation of concrete core rational parameters for bending composite structures. MATEC Web of Conferences, 107, 00044. doi: https://doi.org/10.1051/matecconf/201710700044
15. Vatulia, G. L., Lobiak, O. V., Deryzemlia, S. V., Verevicheva, M. A., Orel, Y. F. (2019). Rationalization of cross-sections of the composite reinforced concrete span structure of bridges with a monolithic reinforced concrete roadway slab. IOP Conference Series: Materials Science and Engineering, 664, 012014. doi: https://doi.org/10.1088/1757-899x/664/1/012014
16. Khmil, R., Tytarenko, R., Blikharskyy, Y., Vegera, P. (2020). The Probabilistic Calculation Model of RC Beams, Strengthened by RC Jacket. Proceedings of EcoComfort 2020, 182–191. doi: https://doi.org/10.1007/978-3-030-57340-9_23
17. Mansour, W., Tayeh, B. A. (2020). Shear Behaviour of RC Beams Strengthened by Various Ultrahigh Performance Fibre-Reinforced Concrete Systems. Advances in Civil Engineering, 2020, 1–18. doi: https://doi.org/10.1155/2020/2139054

18. Koteš, P., Vavruš, M., Jošt, J., Prokop, J. (2020). Strengthening of Concrete Column by Using the Wrapper Layer of Fibre Reinforced Concrete. Materials, 13 (23), 5432. doi: https://doi.org/10.3390/ma13235432
19. Brózda, K., Selejdak, J. (2018). The computational analysis of the crack width of beams reinforced with CFRP and steel bars. MATEC Web of Conferences, 183, 02003. doi: https://doi.org/10.1051/matecconf/201818302003
20. Ye Khmil, R., Yu Tytarenko, R., Blikharskyy, Y. Z., Vegera, P. I. (2021). Improvement of the method of probability evaluation of the failure-free operation of reinforced concrete beams strengthened under load. IOP Conference Series: Materials Science and Engineering, 1021, 012014. doi: https://doi.org/10.1088/1757-899x/1021/1/012014
21. DBN V.2.6-98:2009. Konstruktsiyi budynkiv i sporud. Betonni ta zalizobetonni konstruktsiyi. Osnovni polozhennia (2011). Kyiv: Minrehionbud Ukrainy, 72.
22. Eurocode EN 1990:2002. Basis of structural design. Brussels: European Committee for Standardization (CEN).
23. Popovics, S. (1973). A numerical approach to the complete stress-strain curve of concrete. Cement and Concrete Research, 3 (5), 583–599. doi: https://doi.org/10.1016/0008-8846(73)90096-3
24. Barnard, P. R. (1964). Researches into the complete stress-strain curve for concrete. Magazine of Concrete Research, 16 (49), 203–210. doi: https://doi.org/10.1680/macr.1964.16.49.203
25. Lipiński, T. (2017). Roughness of 1.0721 steel after corrosion tests in 20% NaCl. Production Engineering Archives, 15 (15), 27–30. doi: https://doi.org/10.30657/pea.2017.15.07
26. Kweon, H. D., Kim, J. W., Song, O., Oh, D. (2021). Determination of true stress-strain curve of type 304 and 316 stainless steels using a typical tensile test and finite element analysis. Nuclear Engineering and Technology, 53 (2), 647–656. doi: https://doi.org/10.1016/j.net.2020.07.014
27. Zhang, Q., Mol'kov, Y. V., Sobko, Y. M., Blikhars'kyi, Y. Z., Khmil', R. E. (2015). Determination of the Mechanical Characteristics and Specific Fracture Energy of Thermally Hardened Reinforcement. Materials Science, 50 (6), 824–829. doi: https://doi.org/10.1007/s11003-015-9789-9
28. Watanabe, K., Niwa, J., Yokota, H., Iwanami, M. (2004). Experimental Study on Stress-Strain Curve of Concrete Considering Localized Failure in Compression. Journal of Advanced Concrete Technology, 2 (3), 395–407. doi: https://doi.org/10.3151/jact.2.395
29. Dohojda, M., Babych, Y., Filipchuk, S. V., Savitskiy, V. V. (2019). Research of deformative properties of concrete class C50/60 taking into account the descending branch of deformation. Resource-saving materials, structures, buildings and structures, 37, 175–183. doi: https://doi.org/10.31713/budres.v0i37.325
30. Lavatelli, A., Turrisi, S., Zappa, E. (2018). A motion blur compensation algorithm for 2D DIC measurements of deformable bodies. Measurement Science and Technology, 30 (2), 025401. doi: https://doi.org/10.1088/1361-6501/aaf31a
31. Zappa, E., Hasheminejad, N. (2017). Digital Image Correlation Technique in Dynamic Applications on Deformable Targets. Experimental Techniques, 41 (4), 377–387. doi: https://doi.org/10.1007/s40799-017-0184-3
32. Mai, B. V., Pham, C. H., Hancock, G. J., Nguyen, G. D. (2019). Block shear strength and behaviour of cold-reduced G450 steel bolted connections using DIC. Journal of Constructional Steel Research, 157, 151–160. doi: https://doi.org/10.1016/j.jcsr.2018.11.025
33. Tung, S.-H., Shih, M.-H., Kuo, J.-C. (2010). Application of digital image correlation for anisotropic plastic deformation during tension testing. Optics and Lasers in Engineering, 48 (5), 636–641. doi: https://doi.org/10.1016/j.optlaseng.2009.09.011
34. Fayyad, T. M., Lees, J. M. (2014). Application of Digital Image Correlation to Reinforced Concrete Fracture. Procedia Materials Science, 3, 1585–1590. doi: https://doi.org/10.1016/j.mspro.2014.06.256
35. Skarżyński, Ł., Kozicki, J., Tejchman, J. (2013). Application of DIC Technique to Concrete—Study on Objectivity of Measured Surface Displacements. Experimental Mechanics, 53 (9), 1545–1559. doi: https://doi.org/10.1007/s11340-013-9781-y
36. Gualtieri, S. (2012). Novel technique for DIC speckle pattern optimization and generation. Politecnico Di Milano, 127.