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AN ANALYSIS OF USING THE METHOD OF TWO-DIMENSIONAL DIGITAL IMAGE CORRELATION IN GLASS COLUMN RESEARCH

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The study of glass multilayer columns made of ordinary glass using triplexing technology. The main disadvantage of using ordinary glass is the fragile nature of its destruction, it breaks instantly. To avoid this effect, triplexing technology is used: the glass is joined in several layers with an EVASAFE polymer film (Bridgestone, Japan), after which the columns were heated to a temperature of 130 °C and kept for 30 minutes. The film material is an elastomer (a polymer with highly elastic properties in a wide temperature range). This allowed restraining parts of fragments of glass structures, making them plastic inside the bonding plane, increased their reliability, prevented the instantaneous opening of cracks in the depth of the section.

A method for studying multilayer glass columns for central-axial compression using the method of two-dimensional digital image correlation is developed. Two series of prototypes were manufactured and tested. The tests were performed on a hydraulic press.

The model of the destruction of glass columns of different cross-section is investigated and described. The accuracy of the digital image correlation method using two-dimensional correlation for glass centrally compressed columns is estimated. The results of the digital image correlation method with the results of measurements of absolute deformations by mechanical devices are compared. Based on the analysis of the results, the dependences of relative deformations ε on the applied load N were determined using the digital image correlation method. The dependences of relative deformations ε on normal stresses σ=N/A and dependences of relative deformations ε on the outer glass surfaces on the applied load N are determined

Keywords: digital image correlation, multilayer glass column, triplex, sheet glass

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1. Introduction

Due to the development of such new architectural styles as deconstructivism and hi-tech [1], materials that convey an architectural design only through the shape are increasingly used in construction. It is usually solid concrete, light and delicate metal, as well as glass, without which futurism is now impossible to imagine. The role of glass in the modern realities of construction changes into something more than the usual enclosure.

On the other hand, there is a problem in glass research, since such material is characterized by the statistical strength theory and fragile destruction; the first characteristic complicates the prediction of the critical load, the second, in turn, makes it impossible to use traditional methods of structural research, because of the possible damage to the devices placed on the prototype, so we have to resort to optical research methods.

The method of digital image correlation (hereinafter DIC) is one of the most common methods of optical design research. This method is used in Ukraine to study reinforced concrete and metal structures [2–4]; this method is used abroad to discover both the dynamic effects [5] and physical indicators of athletes [6].

Given all the above, these studies are relevant today and have great potential for practical application in the future in the world.

2. Literature review and problem statement

The digital image correlation method is an optical research method, based on the comparison of digital images of the body surface before and after deformation. As a result, absolute deformation values are obtained. Measurement occurs by tracking the movements of points on the visible surface of the body [7].

This method together with mechanical devices was used to measure the deformations in a number of studies of glass structures [8, 9], in particular plates. The DIC method was successfully performed in the study, but some important parameters were not specified in the processing of the results, including the scale of correlation, which is one of the mandatory parameters according to the recommendations given in [10, 11] and grayscale for the analysis of relative deformations.

According to the recommendations [11], when preparing the test sample for deformation measurement by the DIC method, it is necessary to pay attention to the following: lighting, quality of application of the speckle surface, characteristics of the photo camera (matrix size, protective filters), characteristics of optics (focal length). Taking into account the above parameters, it can be stated that the DIC method for deformation measurement is very sensitive to the influence of external factors that determine the quality of the image and the clarity of the speckle surface, especially noise. An attempt to influence precisely the factors of image quality using templates was made in experimental studies of DIC parameters [12]. The authors use the chamotte board principle to obtain maximum image information for the DIC method. No such optimization was used in this experiment, and no such improvements have been made in previous experiments with glass samples [8, 9]. As the software works better when applying grayscale, therefore, maximum image information was obtained for the DIC method.

One of the important qualities of glass is the nature of the distribution of the physical and mechanical properties of the material. For glass, the Weibull distribution is used, and more detailed parameters are described in papers of the distribution nature of the glass strength characteristics [13]. The form of this distribution may depend on a curve graph that takes into account the influence of probability theory. That is, it is not possible to guarantee the exact strength of glass, but this does not prevent it from being used in construction [14].

The study of glass columns was conducted using two-dimensional correlation, but still there is a question concerning the sufficiency of such a method to obtain accurate deformation results, provided that the column is deformed in the process of compression along three axes. For some types of samples, it is sufficient to simply ensure that the design of the element is working. In our case, the main element was a centrally compressed column. The experiments comparing two different types of correlation have already been performed [15], in this paper the sensitivity of the DIC to the rotation of the metal plate in the plane was tested and showed a rather poor result for the two-dimensional correlation.

Based on many research institutes, the DIC method is used for concrete research [16] and for full-scale structures in inaccessible locations when using additional equipment [17].

Therefore, to date, no rules or methods for determining the deformation parameters of glass columns using DIC have been identified. This area is poorly studied because glass is a fragile material. The research itself is quite dangerous, as the destruction occurs instantly.

The question remains whether two-dimensional DIC is sufficient to obtain accurate results of deformations, provided that the column is deformed in the process of compression along three axes. The research used the experience of applying the method of DIC for other types of structures – glass, metal and concrete [2–17].

3. The aim and objectives of the study

The aim of this study was to determine the deformation parameters of glass columns and verify the reliability of the results using the two-dimensional method of DIC, to determine whether the use of two-dimensional correlation was sufficient to study compression columns, selected hardware and software settings.

To achieve the aim, the following objectives were set:

– to study the glass multilayer columns for central-axial compression with recording deformations by the DIC method and clock-type indicators;

– to determine dependencies and factors influencing the results of the study of glass columns for the central-axial compression using the DIC method, taking into account the indications of clock-type mechanical indicators.

4. Materials and methods for the experimental study of glass columns using the digital image correlation method

Glass columns of two series of types CS-4 and CS-5 were tested. The experimental samples were made using triplexing technology of non-hardened M4 glass. EVASAFE polymer film (Bridgestone, Japan) was used to bond the layers of non-hardened glass. The characteristics of the glass columns of each series and materials are given in Table 1.

Table 1

Characteristics of prototypes

Series	Type of columns	Section, mm	Height, mm	Thickness of one layer of glass, mm	Characteristics of glass		
					Glass type	Compressive strength, MPa	Specific weight, kg/m^3
4	CS-4.1 CS-4.2	70×100	1,000	10	M4	700	2,500
5	CS-5.1 CS-5.2	35×100	1,000	10	M4	700	2,500

Two series of glass columns differ only in cross-sectional dimensions. The first series of columns with section 70×100 mm (Fig. 1, *a*); the second series is 35×100 mm (Fig. 1, *b*).

The glass columns were tested for central compression with pivotally secured supports. The samples were tested on a PG-250 hydraulic press. The load was applied in steps of 25 kN until destruction.

In addition to the DIC method, mechanical devices – Aistov's PAO-67 deflectometers and mechanical extensometers, which consisted of hourly type indicators with a scale division of 0.001 mm and two chips placed apart from each other at a distance of 200 mm, connected by a stainless steel rod, were used to record movements and absolute deformations of the samples.

Optical observation was performed using a Canon 60d SLR digital camera with the following characteristics:

– pixel size – 4.3 microns;

– matrix size –22.3×14.9 mm;

– lens – Canon Zoom Lens EF-S 18-55 mm f/3.5-5.6 IS STM.

To use the DIC method, the speckle surface was arranged by applying white paint on one of the faces of the column over which black paint was sprayed [7].

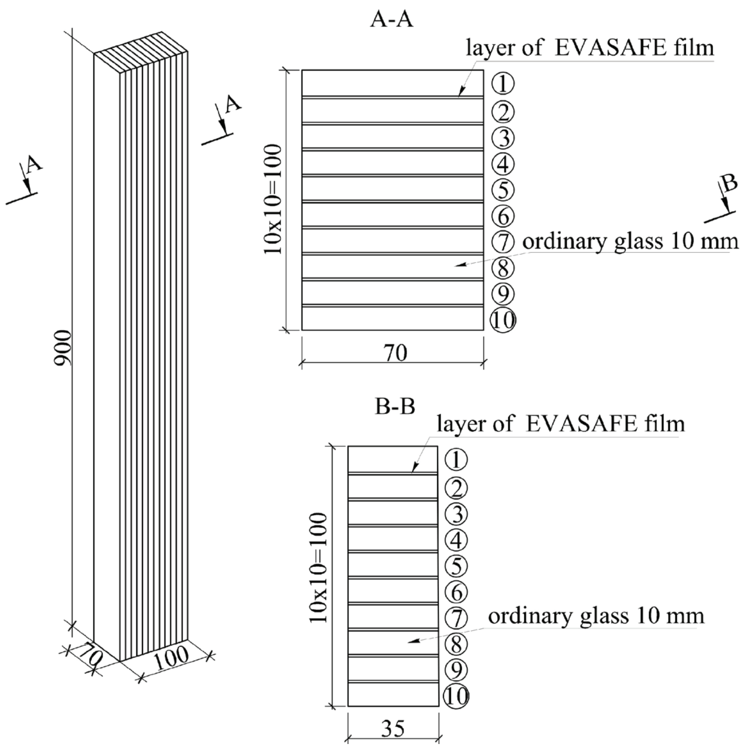


Fig. 1. Columns of series: *a* – CS-4; *b* – CS-5

The sample was placed in metal supports in the form of "boots" [18], which provided swivel work of the sample. The general view of the test stand is shown in Fig. 2. The layout of devices on the column is shown in Fig. 3.

Fig. 2. General view of the test stand: 1 – research element; 2 – speckle surface for deformation measurement using the DIC method; 3 – hinged supports in the form of metal "boots"; 4 – digital camera; 5 – mechanical extensometer; 6 – Aistov's PAO-67 deflectometer

At each stage of the study, a photograph of the speckle surface was taken and the readings of mechanical devices were recorded. Mechanical devices were removed from the column when the first visible cracks appeared or when the load reached 80 % of the predicted destruction value. The process of the speckle surface photographing continued until the end of the experiment.

The white balance was set by default as this parameter could be corrected later.

As the specialized software used grayscale to analyze relative deformations using a photo editor, the image settings change from color scale to gray one.

The relative deformation was then analyzed using the GOM Correlate program. Before starting the general analysis, it was important to bring the image data to a 1:1 scale and select the parameters for correlation. Guidelines and recommendations were used for this purpose [19]. Next, two types of elements were created for research according to the recommendations: the first is a plane element that considered deformations on a given plane (it was created to reflect the nature of deformation on the plane), the second one is a point element, a fixed-size facet with a fixed pixel binding. Between the two such point elements, a DIC extensometer was placed, which actually duplicated the mechanical extensometers described above, which were placed on the extreme surfaces of the column. The appearance and layout of these elements are shown in Fig. 4.

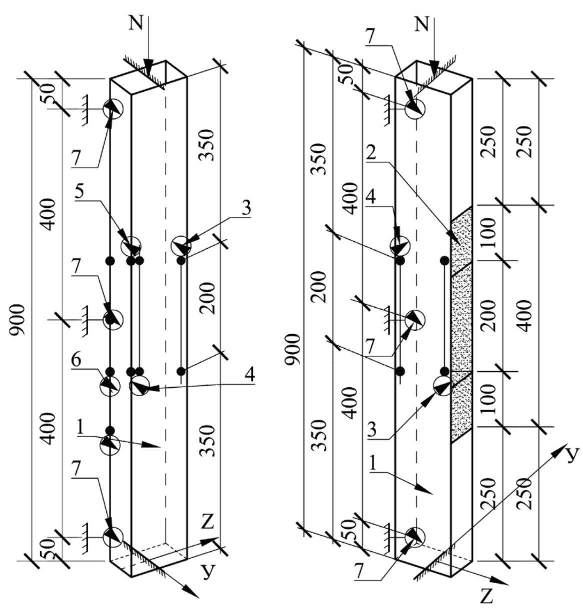


Fig. 3. Layout of devices: 1 – test column; 2 – speckle surface for deformation measurement using the DIC method; 3 – ME-1 mechanical extensometer; 4 – ME-2 mechanical extensometer; 5 – ME-3 mechanical extensometer; 6 – ME-4 mechanical extensometer; 7 – Aistov's PAO-67 deflectometer

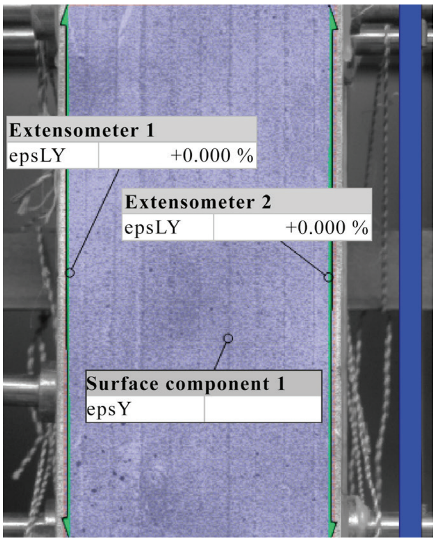
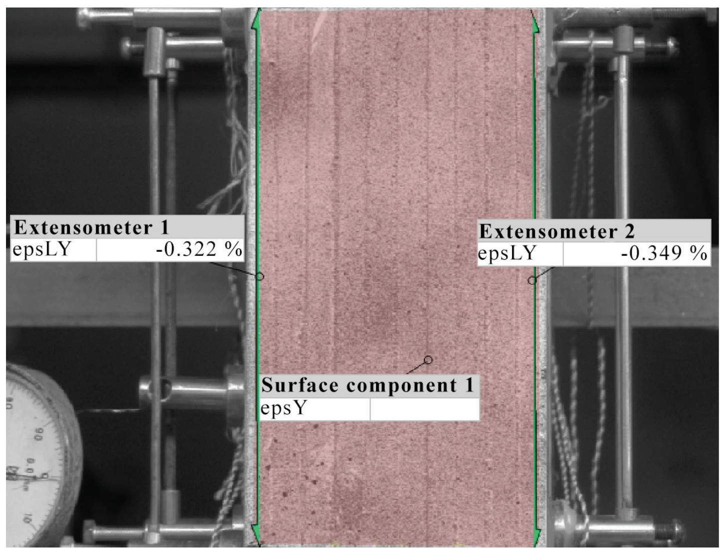


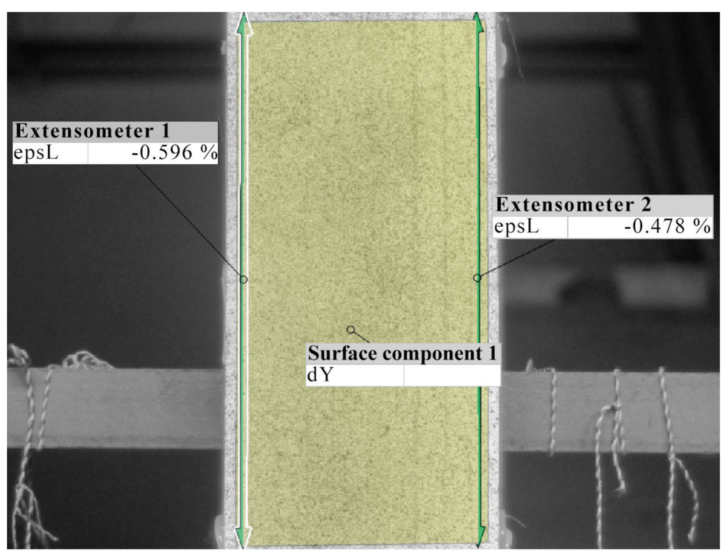
Fig. 4. Layout of the plane element and extensometer 1 and 2 in the GOM Correlate program

a *b*

Fig. 5. Nature of destruction of columns of the 4th series: *a* – CS-4.1 column; *b* – CS-4.2 column



a



b

Fig. 6. Comparison of gradients of isofields of relative deformations for columns: *a* – CS-4.1; *b* – CS-4.2

Using the constructed digital image correlation extensometer, the analysis of relative deformations and comparison of the obtained results with the readings of mechanical extensometers were performed.

5. Results of studies of glass multilayer columns for central-axial compression using the method of two-dimensional digital image correlation

5. 1. Columns CS-4.1 and CS-4.2

The columns of the type CS-4.1 and CS-4.2 with a cross section of 70×100 mm collapsed at different loads as during testing the CS-4.2 column, the plywood gasket in the supporting metal "boot" was damaged, which created additional eccentricity. The CS-4.1 column collapsed at a load $N_{cr4.1}$=985 kN and the CS-4.2 column – at $N_{cr4.2}$=705 kN, respectively. The nature of the destruction is shown in Fig. 5. The columns of this series had a bend in two planes, most of which occurred in a plane perpendicular to the layers of glass.

During the processing of the results obtained with the help of DIC, the fact of the eccentricity occurrence for the CS-4.2 column is perfectly reflected in the isofields of structure deformation in the vertical direction (Fig. 6).

According to the results of the study, a graph of the dependence of the relative deformations on the magnitude of the applied load for mechanical extensometers, located on the extreme layers of glass, was constructed. For the CS-4.1 column in Fig. 7, for the CS-4.2 column in Fig. 8.

According to the results of the experiment, relative deformations were determined using the DIC method and graphs for extensometer 1 and 2 were constructed (Fig. 9, 10).

Comparison of the results of relative deformations obtained by two methods of measuring the deformations of columns is shown in Fig. 11, 12.

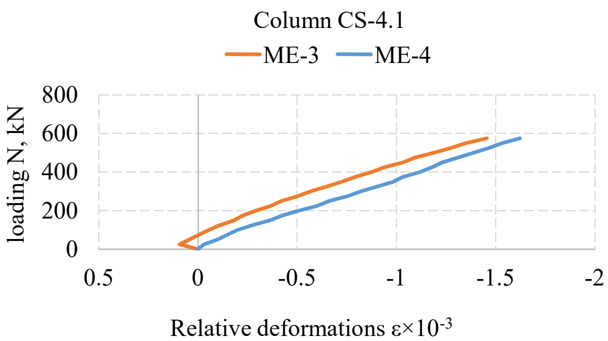


Fig. 7. Graph of the dependence of relative deformations ε on the outer glass surfaces on applied load *N* for the CS-4.1 column

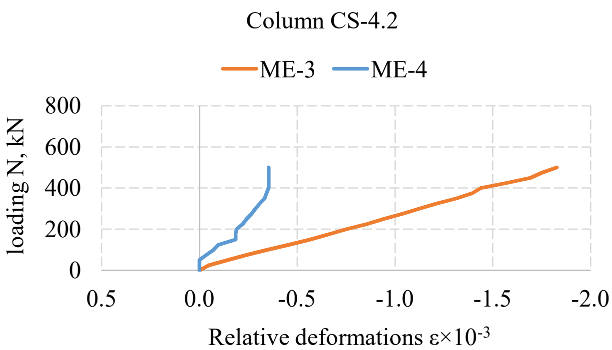


Fig. 8. Graph of the dependence of relative deformations ε on the outer glass surfaces on applied load *N* for the CS-4.2 column

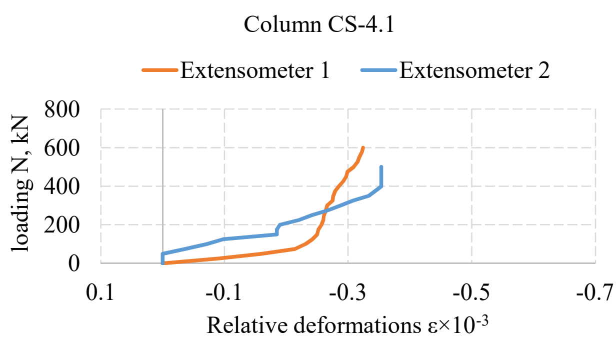


Fig. 9. Graph of the dependence of relative deformations ε on applied load *N* when using DIC for the CS-4.1 column

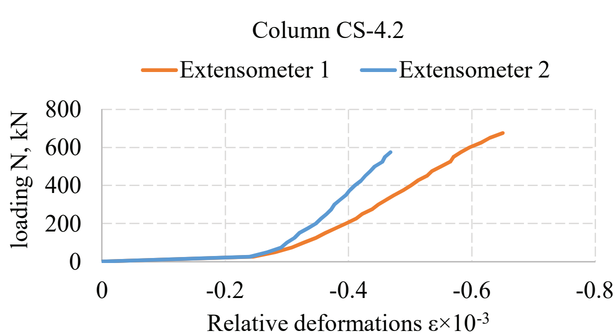


Fig. 10. Graph of the dependence of relative deformations ε on applied load *N* when using DIC for the CS-4.2 column

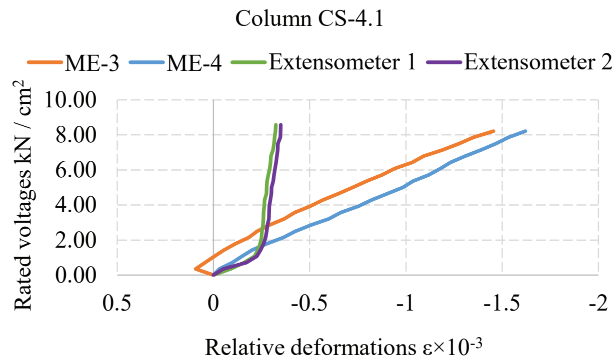


Fig. 11. Combined graph of the dependence of relative deformations ε on rated stress σ=N/A, for the CS-4.1 column

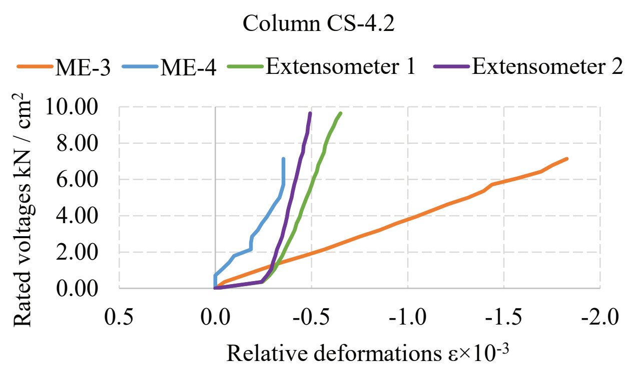


Fig. 12. Combined graph of the dependence of relative deformations ε on rated stress σ=N/A, for the CS-4.2 column

5. 2. Columns CS-5.1 and CS-5.2

Columns of type CS-5.1 and CS-5.2 with a cross-section of 35×100 mm were destroyed at the same loads and with the same nature of destruction (Fig. 13).

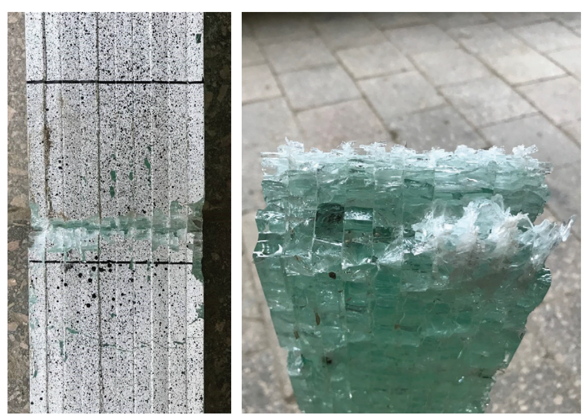


Fig. 13. Nature of destruction of CS-5.1 and CS-5.2 columns

The CS-5.1 column collapsed at a load of $N_{r5.1}$=300 kN, the CS-5.2 column – at a load of $N_{r5.2}$=302.5 kN.

According to the results of the studies, the graphs of the dependence of the relative deformation on the applied load according to the mechanical extensometer readings were constructed for the CS-5.1 column (Fig. 14) and CS-5.2 column (Fig. 15).

The same graphs are constructed for the extensometer 1 and 2 for the CS-5.1 (Fig. 16) and CS-5.2 columns (Fig. 17).

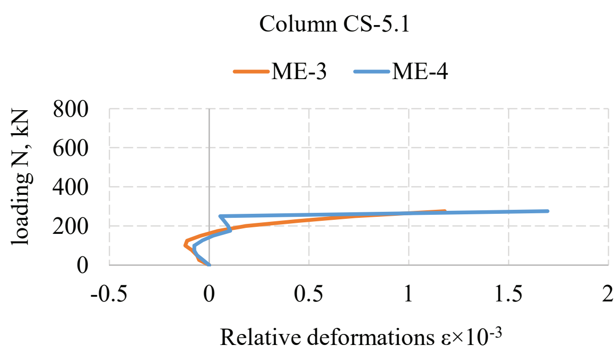


Fig. 14. Graph of the dependence of relative deformations ε on the outer glass surfaces on applied load *N* for the CS-5.1 column

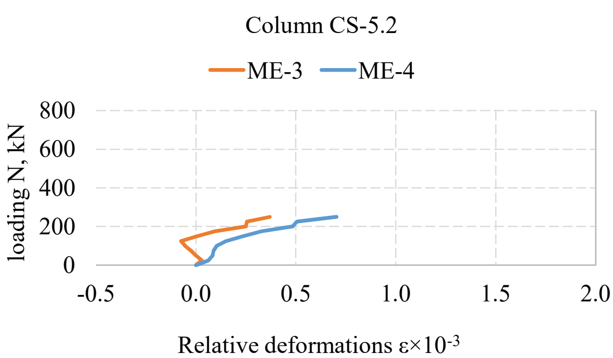


Fig. 15. Graph of the dependence of relative deformations ε on the outer glass surfaces on applied load *N* for the CS-5.2 column

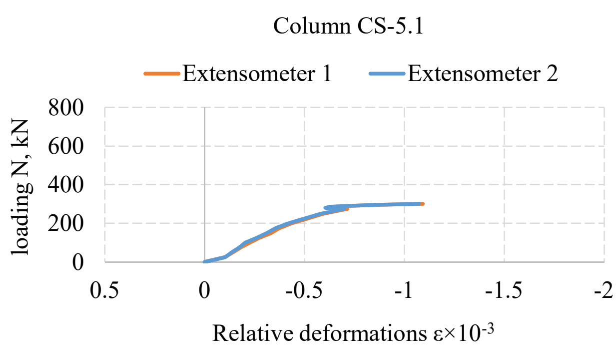


Fig. 16. Graph of the dependence of relative deformations ε on applied load *N* when using DIC for the CS-5.1 column

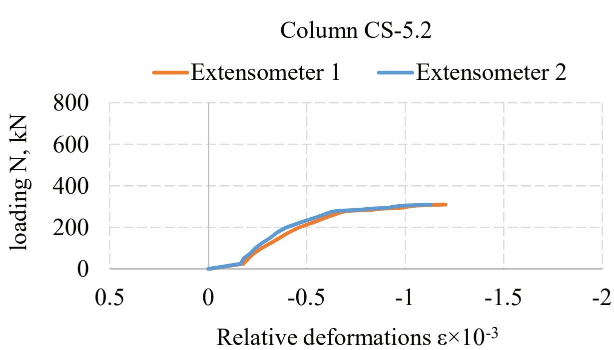


Fig. 17. Graph of the dependence of relative deformations ε on applied load *N* when using DIC for the CS-5.2 column

A combined graph of the dependence of relative deformations ε on rated stress σ=*N*/*A* was constructed for the CS-5.1 (Fig. 18) and CS-5.2 columns (Fig. 19).

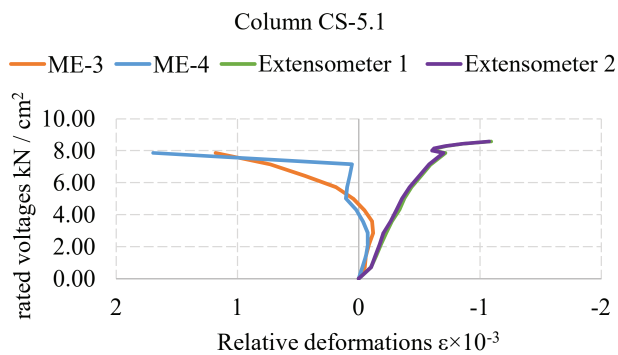


Fig. 18. Combined graph of the dependence of relative deformations ε on rated stress σ=*N*/*A*, for the CS-5.1 column

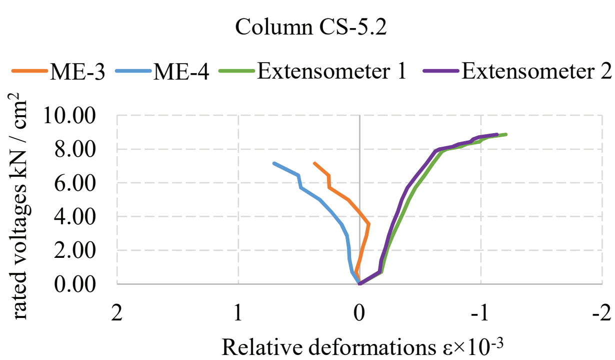


Fig. 19. Combined graph of the dependence of relative deformations ε on rated stress σ=*N*/*A*, for the CS-5.2 column

As can be seen from the graphs in Fig. 18, 19, the readings of mechanical devices and the results obtained by the DIC method differed in the nature of deformations.

6. Discussion of the results of using the method of two-dimensional digital image correlation in the study of glass columns

According to the results of studies and comparisons of graphs of relative deformations, depending on the applied load, it can be stated that the above-described method of using two-dimensional image correlation is not effective in the study of glass columns for central-axial compression (Fig. 7–19). There are many reasons for this, first of all, the type of correlation. Perhaps, in this case of the research, the three-dimensional image correlation will be much more successfully performed. Another important element is the optimization of software for further processing of images, correlation is the relationship between phenomena and quantities, which, in turn, depend on a number of other important mathematical factors, and now the available version of the software does not allow influencing these factors.

The advantages of using the correlation method according to these experiments can be attributed to the flexibility of presentation of results and a large amount of stored information, since in the future there is a much greater prospect for processing not only relative deformations, but also other deformation characteristics of the studied element. Another advantage is the convenience of presenting information – visual perception is much more pleasant to the observer. The duration of the correlation is also worth noting, it continued even when the mechanical devices were put out of operation.

As we can see from the graph in Fig. 11, there is a visible difference in the readings of the devices of the two different measurement methods. For the CS-4.1 column, according to the readings of mechanical devices, the relative deformations grew uniformly throughout the experiment, in contrast to the values obtained with DIC, which grew uniformly to a load N=100 kN, but after that the relative deformations have no longer increased so rapidly.

The readings of mechanical extensometers for the CS-4.2 column differ from those of the CS-4.1 column. The reason for this was the eccentricity mentioned above. The values of the ME-4 are of this nature for the same reason. The nature of the dependence of relative deformations for the ME-3 device remained unchanged, but its deformation values for this device increased. For the readings obtained by the DIC method, the eccentricity was reflected in only a small difference in the readings. As for the previous column, the difference in the readings of devices of the two methods is noticeable and inevitable.

Analyzing the results of the destruction of columns of two series of different sections, the difference in the nature of the destruction of these elements is worth noting. You can visually notice the difference at the stress concentration point (the break point of the column), for both types of samples it is different – for CS-4.1 and CS-4.2 columns, the concentration has a diagonal distribution across all glass layers of the column, even in the presence of eccentricity; for CS-5.1 and CS-5.2 columns – this is a straight line. It can be stated that in the columns with the larger cross-section, each layer collapsed alternately with the change of stress concentration along the height, although for the observer, the moment of destruction occurred in an extremely short period of time, and in the columns of the smaller cross-section – destruction of all layers occurred simultaneously.

Another important feature is the readings of devices on the CS-5.1 and CS-5.2 columns. It should be noted that the DIC method is not sufficiently accurate, but the nature of relative deformations always coincides with the character on mechanical devices. Taking this into account, it can be stated that glass structures do not have large cross-sections, but rather cross-sections with undeveloped faces in the direction from the plane are subjected to another kind of influence and work similar to bending structures. That is, glass elements that work on central compression also perceive other factors of influence.

According to the results obtained, it can be argued that the two-dimensional DIC is not sufficient to obtain accurate results of deformations of glass columns. Therefore, in the future it is necessary to study glass columns using three-dimensional digital image correlation.

7. Conclusions

1. Studies of glass columns for central-axial compression revealed the presence of additional influences of a certain order that affect the operation and nature of the destruction of multilayer glass columns. The method of digital image correlation has proved to be a convenient optical method, but because of photo-fixation in one plane it is inefficient to use it as a reference method for studying glass columns. Comparative analysis of this method with mechanical devices revealed no dependencies that could be described by simple mathematical functions, which complicates further processing of the results of this method. The reasons for such inaccuracies in the results are the following factors: insufficient use of two-dimensional correlation in studies of such elements as glass columns; imperfection of the analysis and its optimization.

2. The method of digital image correlation is not new, but the prospects for its further study and implementation in many fields of research are quite realistic, but with the need to further study in different scenarios. In the columns of a larger cross-section, each layer collapsed alternately with the change of the stress concentration in height, although for the observer, the moment of destruction occurred in an extremely short period of time, and in the columns of a smaller cross-section, the destruction of all layers occurred simultaneously. The use of two-dimensional correlation in the study of glass columns for compression is not possible, because the columns are deformed in the direction of the three axes in space. For the study, it is necessary to use three-dimensional DIC.

References

1. Hyatt, P., Hyatt, J. (2004). Great Glass Buildings: 50 Modern Classics. Images Publishing, 240.
2. Kovalchyk, Y. I. (2012). Possibilities for the use of the method of digital image correlation to study the building structures. Zbirnyk naukovykh prats (haluzeve mashynobuduvannia, budivnytstvo), 5 (35), 92–100.
3. Koval, P. M., Ivanytskyi, Ya. L., Kovalchyk, Ya. I., Molkov, Yu. V. (2013). Doslidzhennia napruzheno-deformovanoho stanu betonnykh zrazkiv metodom tsyfrovoi koreliatsiyi zobrazhen. Avtomobilni dorohy i dorozhne budivnytstvo, 89, 185–192. Available at: http://nbuv.gov.ua/UJRN/adidb_2013_89_27
4. Maksymenko, O. P., Ivanyts'kyi, Y. L., Hvozdyuk, M. M. (2015). Evaluation of the Stiffness of a Composite–Metal Joint by the Method of Digital Image Correlation. Materials Science, 50 (6), 817–823. doi: https://doi.org/10.1007/s11003-015-9788-x
5. Ngeljaratan, L., Moustafa, M. (2017). Digital Image Correlation for Dynamic Shake Table Test Measurements. 7th International Conference on Advances in Experimental Structural Engineering. Available at: https://www.researchgate.net/publication/326016564_Digital_Image_Correlation_for_Dynamic_Shake_Table_Test_Measurements
6. Blenkinsopp, R., Harland, A., Price, D., Lucas, T., Roberts, J. (2012). A Method to Measure Dynamic Dorsal Foot Surface Shape and Deformation During Linear Running Using Digital Image Correlation. Procedia Engineering, 34, 266–271. doi: https://doi.org/10.1016/j.proeng.2012.04.046

7. Schreier, H., Orteu, J.-J., Sutton, M. A. (2009). Image correlation for shape, motion and deformation measurements: basic concepts, theory and applications. Springer. doi: https://doi.org/10.1007/978-0-387-78747-3
8. Demchyna, B. H., Cherevko, M. V. (2015). Doslidzhennia mitsnosti ta deformatyvnosti sklianykh balok z vertykalnym rozmishchenniam shariv. Visnyk Natsionalnoho universytetu «Lvivska politekhnika». Teoriya i praktyka budivnytstva, 823, 113–116.
9. Osadchuk, T., Demchyna, B. (2017). Strain measurement of laminated glass plates using digital image correlation. Komunalne hospodarstvo mist. Seriya: Tekhnichni nauky ta arkhitektura, 134, 153–163.
10. GOM Correlate Profesional V8 SR1 Manual Basic. GOM mbH. Available at: http://213.8.45.88/PDF/gom_correlate_prof_basic_v8.pdf
11. Jones, E. M. C., Iadicola, M. A. (Eds.) (2018). A Good Practices Guide for Digital Image Correlation. International Digital Image Correlation Society. doi: https://doi.org/10.32720/idics/gpg.ed1
12. Bomarito, G. F., Hochhalter, J. D., Ruggles, T. J., Cannon, A. H. (2017). Increasing accuracy and precision of digital image correlation through pattern optimization. Optics and Lasers in Engineering, 91, 73–85. doi: https://doi.org/10.1016/j.optlaseng.2016.11.005
13. Datsiou, K. C., Overend, M. (2018). Weibull parameter estimation and goodness-of-fit for glass strength data. Structural Safety, 73, 29–41. doi: https://doi.org/10.1016/j.strusafe.2018.02.002
14. Haldimann, M., Luible, A., Overend, M. (2008). Structural use of glass. IABSE, 215.
15. Sutton, M. A., Yan, J. H., Tiwari, V., Schreier, H. W., Orteu, J. J. (2008). The effect of out-of-plane motion on 2D and 3D digital image correlation measurements. Optics and Lasers in Engineering, 46 (10), 746–757. doi: https://doi.org/10.1016/j.optlaseng.2008.05.005
16. Lee, J., Kim, E., Gwon, S., Cho, S., Sim, S.-H. (2019). Uniaxial Static Stress Estimation for Concrete Structures Using Digital Image Correlation. Sensors, 19 (2), 319. doi: https://doi.org/10.3390/s19020319
17. Catt, S., Fick, B., Hoskins, M., Praski, J., Baqersad, J. (2019). Development of a Semi-autonomous Drone for Structural Health Monitoring of Structures Using Digital Image Correlation (DIC). Proceedings of the 36th IMAC, A Conference and Exposition on Structural Dynamics, 49–57. doi: https://doi.org/10.1007/978-3-319-74476-6_7
18. Demchyna, B. H., Surmai, M. I., Tkach, R. O. (2018). Pat. No. 134878 UA. Sposib vyprobuvannia sklianoi kolony. No. u201812746; declareted: 21.12.2018; published: 10.06.2019, Bul. No. 11.
19. Ab Ghani, A. F., Ali, M. B., DharMalingam, S., Mahmud, J. (2016). Digital Image Correlation (DIC) Technique in Measuring Strain Using Opensource Platform Ncorr. Journal of Advanced Research in Applied Mechanic, 26 (1), 10–21. Available at: https://www.researchgate.net/publication/309463775_Digital_Image_Correlation_DIC_Technique_in_Measuring_Strain_Using_Opensource_Platform_Ncorr
20. Demchyna, B., Surmai, M., Tkach, R. (2019). The experimental study of glass multilayer columns using digital image correlation. Archives of Materials Science and Engineering, 1 (96), 32–41. doi: https://doi.org/10.5604/01.3001.0013.1990