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DIGITAL IMAGE CORRELATION APPLICATION TO STRUCTURAL INTEGRITY ASSESSMENT

PRIMENA KORELACIJE DIGITALNIH SLIKA NA PROCENU INTEGRITETA KONSTRUKCIJA

Originalni naučni rad / Original scientific paper
UDK /UDC:

Rad primljen / Paper received: 24.11.2023

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Keywords
- digital image correlation
- structural integrity
- crack
- welded joints

Ključne reči
- korelacija digitalnih slika
- integritet konstrukcija
- prslina
- zavareni spojevi

Abstract

Digital image correlation represents a useful, efficient, and widely applied method of non-contact strain and displacement measuring in various types of structures. It is often combined with other means of integrity assessment, such as the finite element method and the use of fracture mechanics parameters. This paper presents a short overview of digital image correlation in various fields including mechanical and civil engineering, biomedicine, and some other, more 'exotic' examples. Additionally, some of the examples shown here perfectly illustrate the applicability of this method to cases where high levels of detail and accuracy are necessary in order to measure strain.

Izvod

Korelacija digitalnih slika predstavlja korisnu, efikasnu i veoma rasprostranjenu metodu beskontaktnog merenja pomeranja i deformacija različitih vrsta konstrukcija. Često se koristi u kombinaciji sa drugim načinima ocene integriteta, poput metode konačnih elemenata i primene parametara mehanike loma. U ovom radu je dat kratak pregled primene ove metode u različitim oblastima, uključujući mašinstvo, građevinarstvo, biomedicina, a i neki 'egzotični' primeri. Takođe su prikazani primeri koji na najbolji način ilustruju primenljivost ove metode na slučajeve koji zahtevaju veoma precizan i detaljan pristup merenju deformacija.

INTRODUCTION

Digital image correlation (DIC), a method used for non-contact strain measuring, began developing during the late eighties of the last century. Some of the first papers on the topic are given in /1-3/. Research presented in /2/ thoroughly describes the principles and numerical procedures of the method. Using a console with a concentrated force at its free end as an example demonstrates the possibility of applying DIC in order to obtain the total displacement field for a planar object. Namely, the method is based on numerical correlation of 'small surfaces' in a non-deformed and in a deformed body. To achieve this, it is first necessary to apply an irregular pattern to the measured surface, more often than not in the form of black dots on a white surface. Based on this pattern, it is possible to determine the positions of 'small surfaces' before and after deformation. Another important part of this method is the post-processing of data, which is also described here, using ARAMIS® software /4/, since it is one of the most widely used systems for DIC.

ISSUES RELATED TO DIC DEVELOPMENT

In this section we provide a more detailed description of how the basic principles of DIC were developed and improved over time. A number of papers dealing with various problems will be used to illustrate this. As mentioned previously, the most common way of processing data obtained by DIC is by using the ARAMIS® software which provides a standard method that can be applied to numerous problems, instead of approaching each problem individually, /4/. This system can be applied to both two- and three-dimensional problems, as demonstrated in /5/. Due to this, the range of applications of this method has increased considerably over the last few decades, along with the rapid development of computer technologies. However, these new applications also reveal some drawbacks of the DIC method /6, 7/ mostly related to poor accuracy, which was closely related to the calibration of the equipment, the size of 'small surfaces' and subset shape functions. Issues were also caused by inadequate lighting which could decrease accuracy and reliability of results by up to 10 times, /7/.

An example of an attempt to solve this problem is given in /8/, and involved an improvised calibration method, using strain gauges placed on a plate with holes. The plate did not have a black and white pattern - instead, the authors relied on the roughness of its metal surface as the source of 'small surfaces'. This innovative method represented an important step in the right direction when it comes to the calibration of DIC cameras, which greatly improved ever since.

EXAMPLES OF DIC APPLICATION

Numerous examples have confirmed that DIC can be applied to any practical problem, regardless of the material in question (concrete, metal, tissues, clay, wood …), which also represents a great advantage of this method /9-12/. Stress analysis of aluminium sheets connected by adhesives was analysed in /13/ by combining DIC with numerical simulations via FEM, with both methods showing exceptional agreement in terms of results. Such an example of a report is shown in Fig. 1. Paper /14/ further emphasizes the universal application of DIC to different materials, by using it to analyse the behaviour of rubber materials. It was even used to investigate the behaviour of safety belts during crash simulations, of particular interest due to the fact that it represents a factor that cannot be observed under controlled conditions, as opposed to tensile tests /15/. Digital image correlation was able to record all different load cases, as well as friction and instability simultaneously, whereas numerical simulations would require a much more complex approach in order to properly simulate all these factors.

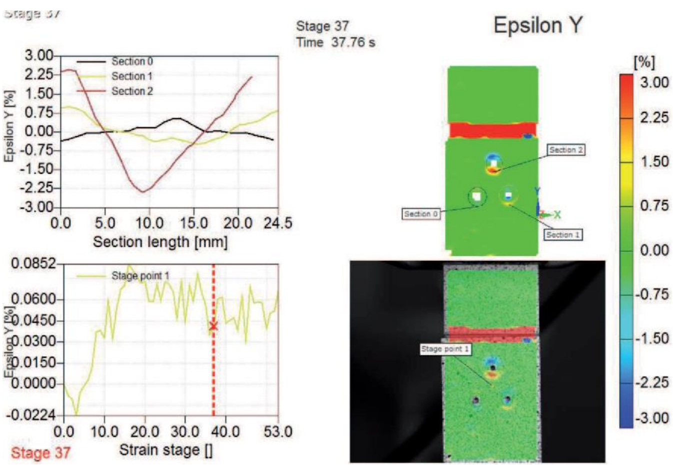

Figure1. Measurement report from the DIC system of the hybrid adhesive bonded/riveted joint with type (1+2) rivets layout - relative elongation in cross sections around rivets, /13/.

Digital image correlation is also invaluable in monitoring crack growth in various structures, as can be seen in /16-19/. Research in these papers involved, among other things, the mutual influence of multiple cracks, as determined by numerical, experimental and analytical means, as well as the improvement of measuring accuracy by assigning each pixel a coefficient (depending on its quality, e.g., edge pixels are considered to be of low quality). In this way, the overall accuracy of the method in the vicinity of the defect was significantly increased /17/, as can be seen in Fig. 2.

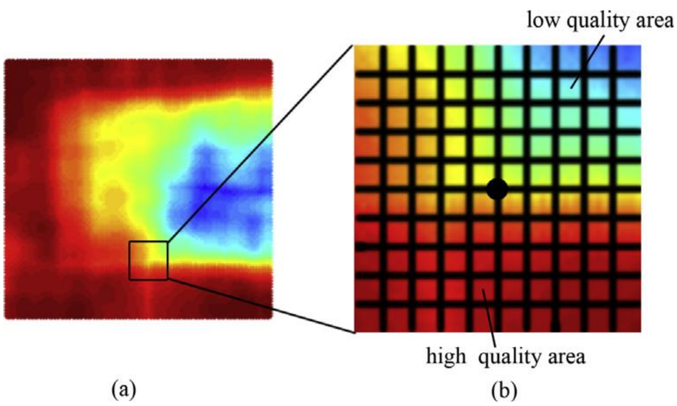

Figure 2. a) Pixel qualities of an image with damaged area; b) a subset with different quality pixels near the damaged area /17/.

These improvements allowed the possibility of accurate measuring the deformation in metals and composites in cases of impact loading, /20, 21/.

DIC APPLICATION ON THE LOCAL LEVEL

This section deals with various DIC-related research performed at the University of Belgrade, Faculty of Mechanical Engineering, many of which were performed by the authors of this paper. This became possible after the Department of Strength of Structures acquired the DIC system ARAMIS® /4/. The main focus here was strain measurement and determination of the stress state in pressure vessels, as can be seen in /22, 23/. The first paper analyses a valve casing subjected to internal pressure, with the aim to obtain the total stress/strain state in order to determine how the design of the valve could be further improved. The second paper analysed a bifurcated pipe with complex geometry. In this case, DIC was the only available method for determining the stress concentration in pipe welded joints, providing accurate results, even in zones of significant geometry discontinuity and high stress gradients. More on this can be found in /24, 25/. A previous alternative was to use strain gauges along the specimens, which was not sufficiently accurate in the case of very small characteristic regions, e.g., the heat affected zone. In such cases, non-contact methods such as DIC, can be the only reliable way to determine stresses and strains with sufficient accuracy.

These advantages of the DIC method resulted in a number of papers involving the tensile behaviour of welded joints, along with determining the mechanical properties for each individual welded joint region. More on this can be found in /26/. In addition to welded joints, the method was applied to biomaterials, mainly dental implants /27, 28/. Most of this work is related to deformation occurring when the said implants are subjected to light, and DIC provided a very accurate means of measuring small deformation and providing insight into its distribution within the implant /29/. Similar research was conducted on lock compression plates made of titanium alloys, in order to determine critical locations where stress concentration is the highest, thus allowing the authors to accurately assume where cracks would initiate. In this way, DIC provided a reliable basis for numerical simulation of fatigue crack growth in LCPs, which is always a relevant topic in the biomedical field, /30, 31/.

INTEGRITY ASSESSMENT OF WELDED JOINTS USING DIC

Use of DIC to determine stress/strain fields in welded joints is of particular interest, as it can reliably pinpoint locations of stress concentrations, which can considerably decrease the load-bearing capacity of these structures. Welded joints are critical due to geometry and heterogeneity, and these factors are both considered in research shown in this section in more detail compared to the previous overview.

One of the earliest works by the authors /25/ involving the use of DIC in strain measuring is related to stress concentration in welded joints. The welded joint in question is overmatched, i.e., the weld metal strength is significantly larger than the parent material. The goal is to determine how these differences in mechanical properties affect the stress distribution in various welded joint regions. Use of DIC in this case also helped the authors determine that there were no noticeable defects in the welded joint itself. The same authors also measured/calculated local stresses and strains in /26/, during the tensile tests of welded joint specimens. The main focus this time was on the difference in stresses in the root and facial sides of the weld. In both cases, the results were obtained by using virtual strain gauges, representing another useful feature of the digital image correlation method. One of the obtained results is shown in Fig. 3.

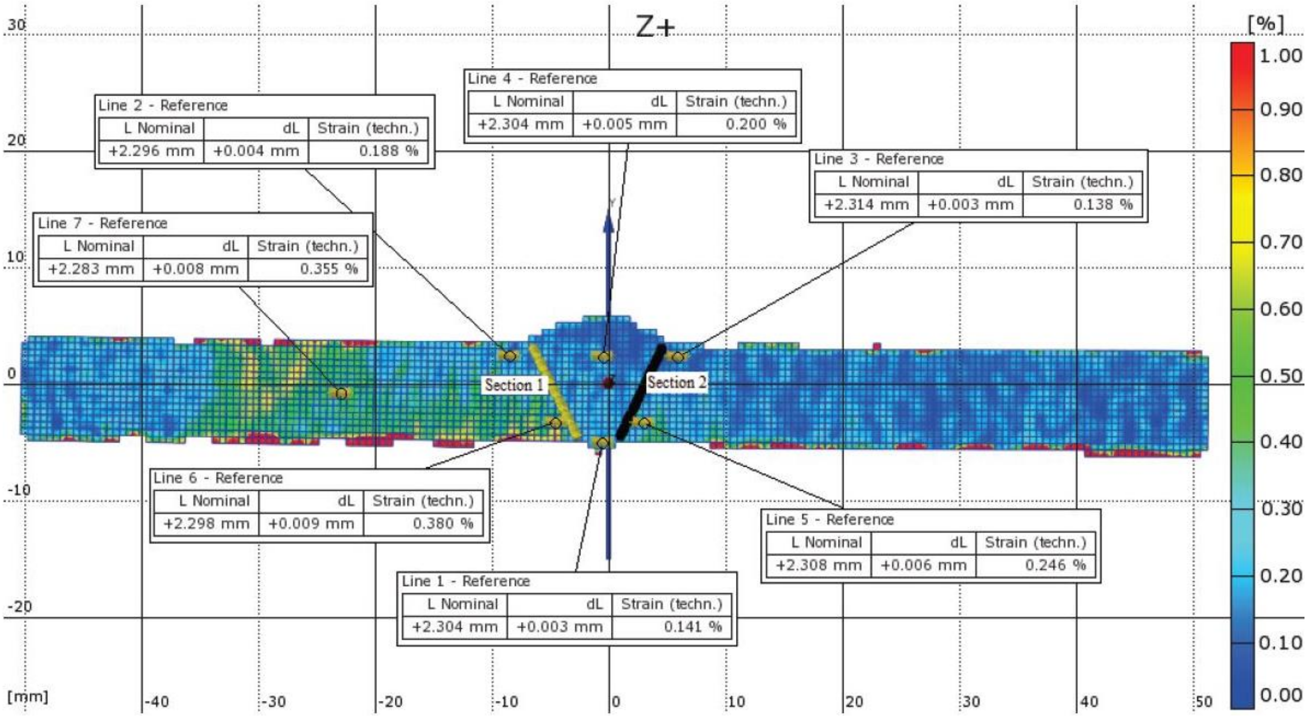

Figure 3. Strain distribution in a welded joint specimen during tensile testing as obtained by ARAMIS (Milošević et al. /25/).

Previous papers have also demonstrated the possibility of determining the mechanical properties of each welded joint region, which can be useful in replacing experiments. Milošević et al. /32, 33/ further investigated this possibility by constructing the true stress-strain curve for ARMOX 500T steel, based on results obtained by DIC and FEM simulations performed by using ABAQUS®. The former was used to obtain a base for validation of numerical simulation of the tensile test using the latter. This provided a sufficiently accurate stress-strain curve that had shown good agreement with experimental results. This methodology was further validated by introducing analytical tools, as shown in /35/. One of the results obtained using this approach is shown in Fig. 4, showing the dependence between strain and displacement at certain measuring locations in the welded joint.

This methodology also introduced the stress concentration factor into the process, thus improving the accuracy of determining the stresses and strains. This approach is also applicable to undermatched welded joints (the weld metal is 'weaker' than the parent material, as can also be seen in the work of Younis et al. /36/, which involved the determining of stress-strain curves for Niomol 490K steel, a very different material compared to the previously mentioned Armox 500T. In this case, DIC itself was sufficient for the curves, although it is generally better to validate the results in one or more ways, including those described earlier in this section.

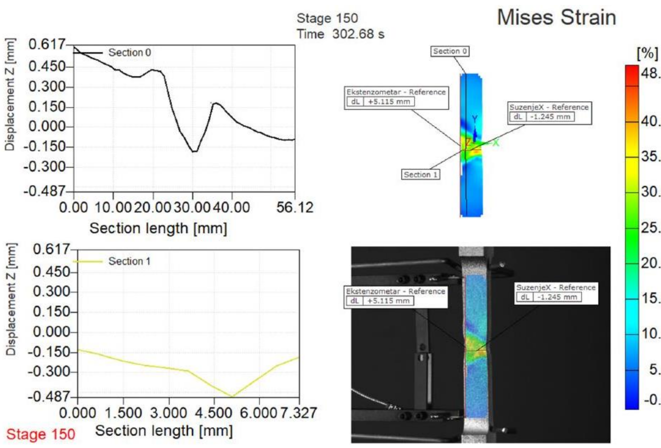

Figure 4. Strain and displacement measurement results obtained via ARAMIS®, Milošević et al. /34/.

INTEGRITY ASSESSMENT OF WELDED JOINTS WITH MULTIPLE DEFECTS

Application of DIC was proven particularly effective during the tensile testing of welded joints with multiple defects, /34, 35/. The obtained results were used to validate finite element models. This work involved determining the mechanical properties of each individual welded joint region, with a special focus on the heat affected zone, in order to improve numerical models. Comparison of strain distribution and magnitudes (Fig. 5) obtained by FEM and DIC provided sufficiently accurate mechanical properties of the HAZ.

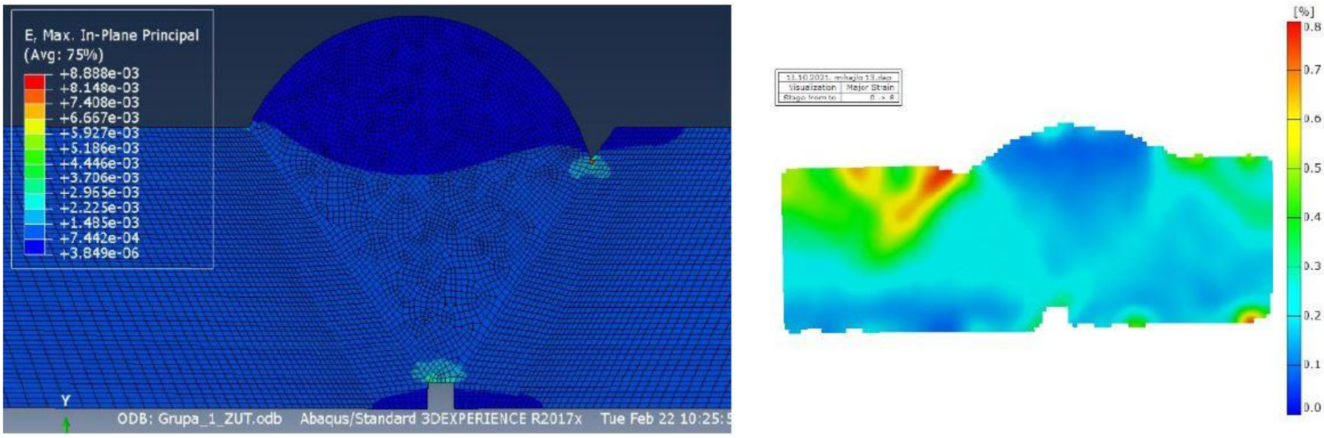

Figure 5. Comparison of strain results obtained by FEM and DIC, /34/.

CONCLUSION

The presented papers demonstrate the use of digital image correlation, using ARAMIS® software, often combined with the FEM, to assess structural integrity. These studies have shown how strain and displacements caused by uniaxial tension can affect the integrity of various structures, with a particular focus on the welded joints. The method was proven particularly effective to determine the stress/strain distribution on a local level, with exceptional accuracy. DIC also provided valuable input data for numerical simulations, while also being useful as a means of validating numerical results.

These advantages of the DIC will be used in analysing of more complex cases, mainly ones involving welded joints with different combinations of multiple defects. The ability to accurately determine the stress/strain distribution and magnitudes in various welded joint regions will be very useful in achieving this goal. By combining DIC with the FEM approach, it will also be possible to lower the necessity for physical experiments, thus saving considerable time and resources.

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