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# STRAIN ANALYSIS OF SPECIMENS SUBJECT TO TENSILE TEST USING OPEN-SOURCE DIGITAL IMAGE CORRELATION SYSTEMS

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**Abstract.** Typically, strain is measured in standardized mechanical tests, usually using extensometers. Since the use of extensometers requires contact with the specimen, the placement of the extensometer and test conditions need to be carefully prepared to ensure correct and accurate measurements. An alternative method that has been explored in deformation analysis is Digital Image Correlation (DIC), which is a technique that analyzes deformation without contact with the specimen and involves simpler procedures than those required in measurements using extensometers. There are currently some free and open-source Digital Image Correlation software available. However, the documentation for these applications often lacks validation data that demonstrates the reliability of the measurements. Thus, the results produced by these systems have reduced credibility, making their use unsuitable for deformation measurement, particularly in mechanical testing performed in research laboratories. In this context, this work aims to evaluate some open-source Digital Image Correlation applications. The purpose is to investigate the ability of these systems to accurately determine the deformation of specimens ASTM D638, subjected to tensile testing. The results obtained with the Digital Image Correlation applications were compared with those obtained with extensometers to assess the accuracy of the measurements. It concluded that, with a good speckle pattern, the DIC software can obtain strain measurements very similar to those obtained by the extensometer. The results obtained using the open-source DIC software deviated less than 10% from those obtained from experimental tests using the extensometer.

**Keywords:** Digital Image Correlation (DIC), Strain measurement, non-contact measurement, Digital measurement

## 1. INTRODUCTION

The analysis and characterization of deformations are activities that allow an understanding of the behavior of a material when suffering the action of a load. In this way, it is possible to select the most suitable material for the desired application. Traditionally, these analyses are based on methods that use accelerometers and strain gauges installed on the object under study to measure the deformation during standardized tests (Baqersad *et al.*, 2017). However, these techniques have some characteristics that can difficult their application, such as the complexity related to the assembly of the equipment and the ability to perform measurements only in the region where the measuring system is mounted. Additionally, the electrical connections necessary for data transmission can make it difficult to use the traditional approaches in situations where the specimen is under rotation (Baqersad *et al.*, 2017).

Among the alternative methods for measuring deformation, one of the techniques that has been highlighted is the Digital Image Correlation (DIC). In general terms, the deformation measurement technique using DIC consists of processing a series of images captured during the deformation process of the object of interest. The pixels of the reference image (without deformation) and the image of the already deformed body are mapped. Then, the coordinate of each element is used to calculate the deformation fields and generate the displacement vector from the difference in the position of the initial and final sub-region (Pan, 2011). This technique has advantages over traditional techniques, such as no interference with the integrity of the object since there is no physical contact with the object of interest. In addition, the technique is flexible, can be applied in experiments of different natures, and has low cost and complexity (de Deus Filho *et al.*, 2022).

As discussed by (Belloni *et al.*, 2019; de Deus Filho *et al.*, 2022), there are already some commercial solutions for DIC on the market such as GOM, Vic-2D, MatchID, and Lavision, to mention a few. Although these solutions have most of the requirements needed by users of this type of technology because they are comprehensive tools from the application point of view, some functionalities often incorporated in the product are not always necessary for the end user, but they participate in the cost of the software. In addition, these solutions usually do not allow access to the software source code, which may prevent customization of certain aspects. Alternatively, there are also open-source solutions, developed on open platforms, which can be used and customized by the user according to their specific needs. Among the open-source solutions, it is worth mentioning py2DIC (Belloni *et al.*, 2019),  $\mu$ DIC (Olufsen *et al.*, 2020), and iCorrVision (de Deus Filho *et al.*, 2022). py2DIC is a free open-source software developed at the Geodesy and Geomatics Division of the Sapienza University of Rome, for 2D-DIC analysis. The algorithm for digital image correlation was implemented in Python and the program can calculate the displacement and deformation of samples subjected to mechanical stress (Belloni *et al.*, 2018). The software has a simplified graphical user interface (GUI), which facilitates its use.  $\mu$ DIC provides a set of routines for 2D-DIC analysis ranging from image import to post-processing of the results. Each of the routines has been written in a way that allows the use of the components independently (Olufsen *et al.*, 2020). iCorrVision is the most recent open-source DIC application among those addressed in this paper. In addition to including the full set of basic functionalities to perform digital processing of 2D-DIC images, this application also has a complete GUI, with functionalities including image capture (de Deus Filho *et al.*, 2022).

Despite the large number of open-source software for digital image correlation, some of these applications do not have adequate documentation regarding the use of the system or the reliability of the measurements. In these conditions, in addition to the difficulty of the correct configuration of the system, the lack of validation data of the measurements reduces the credibility of the application regarding the accuracy and uncertainty of the results. In this work, it is evaluated some open-source digital image correlation applications available, developed on free platforms. The reliability of the results found using the application will be confronted with the results obtained in the laboratory using conventional strain gauge measurement techniques to evaluate the accuracy of the measurements.

## 2. METHODOLOGY

### 2.1 Theoretical foundation on DIC and open-source software selection

Digital Image Correlation, or simply DIC, is a method of analyzing deformation through images, where an algorithm will correlate different images in order to obtain a deformation value (Pan, 2011). To do this, the software selects a square reference subset in the image before deformation, which had a certain variation in particle intensity. After that, through a criterion and some calculations, the algorithm finds a deformed subset in the image after deformation, which had the highest possible particle similarity in relation to the reference subset of the original image (Pan, 2011). With this, it is possible to calculate the difference between the two subsets and, consequently, generate a displacement vector (Pan, 2011). This process is carried out for several reference subsets, so that the entire deformed surface is analyzed. Therefore, the DIC method does not require a complex apparatus.

In traditional methods, such as extensometers, the use of complex equipment, such as wires, sensors and supports, as well as direct contact with the specimen, is practically a rule (Baqersad *et al.*, 2017). Thus, it often becomes difficult or even impossible to use these methods for certain experiments, such as in rotating systems (Baqersad *et al.*, 2017). In the DIC method, basically all that is needed is a camera, good lighting, and the application of a speckle pattern on the

specimen so that the DIC software can perform the calculations, which makes this technique possible to apply in a much wider range of experiments (de Deus Filho *et al.*, 2022).

The criteria to select the DIC software to be analyzed in this paper was based on two main aspects. First, the application should be developed on an open platform. From the applications considered, only open-source software based on the Python programming language was analyzed. The Python language presents an attractive simplicity for various purposes (Bogdanchikov *et al.*, 2013), such as DIC, but does not fall behind in terms of functionality and usage options, which is increasingly leading to the use of this language in different areas (Srinath, 2017). In addition, open-source software provides greater accessibility, since its codes are usually made available free of charge, which makes it possible to use by a wider range of users.

The second selection criteria is based on the documentation available. In this sense, the software should present some kind of documentation, such as a manual and/or an article related, presenting its main functionalities. This aspect was considered because the results obtained by the author, present in the documentation would facilitate the understanding of the main aspects of each software.

Given these aspects, three candidates were selected: iCorrVision-2D, py2DIC, and  $\mu$ DIC. All these software have the characteristics already mentioned. However, the  $\mu$ DIC software was not able to generate the data referring to the results in the form of files, only graphical data, which would not allow the comparison. py2DIC, according to the author, presents the results files, but it was not possible to use the software due to some incompatibilities of Python library versions. On the other hand, the iCorrVision-2D software did not present any incompatibility, in addition to being capable of generating all the outputs necessary to analyze the data and compare with those obtained by the extensometer. Therefore, this was the software chosen for this work.

The iCorrVision-2D is a DIC software developed at Fluminense Federal University, Brazil, and NOVA University Lisbon, Portugal and, as already mentioned, the software is open-source and based on the Python programming language. However, unlike the two others selected softwares, as well as most others open-source softwares available on the market, iCorrVision-2D has all the tools necessary for a complete deformation study included in a single environment (de Deus Filho *et al.*, 2022), making it easier to use and optimizing the time required for an analysis, since all available resources follow the same usage methodology. These resources are available in the form of modules, that is, executable files, and they are: (1) image acquisition module, (2) correlation module, where DIC will be performed, and (3) post-processing module, where data will be processed and presented in the form of figures and *.dat* files (de Deus Filho *et al.*, 2022). And these characteristics only support the choice of this software for this work.

## 2.2 Experimental validation

For this work, the results obtained from experimental tests were used to validate the software. This test was carried out in accordance with the ASTM D638 standard (ASTM D638, 2006), and the equipment used is shown in Figure 1. The machine was configured with a deformation speed of 2 mm/min, and a final deformation of 0.5 mm, which was measured with an extensometer. A black screen was placed on the backplane of the specimen, as shown in Figure 2, which provides a good contrast with the specimen, something fundamental for the DIC.



Figure 1. Tensile test equipment.



Figure 2. Machine with the specimen and the black background.

The specimen used in each experiment was printed in PLA plastic by a Creality Ender-3 S1 Pro 3D printer, with a 0.4 mm nozzle, and a density of 100%. The dimensions of the specimen follow the ASTM D638 standard.

The specimens were printed without any painting, however, for the proper functioning of the DIC, it was necessary to apply a speckle pattern to the specimen, which will function as a carrier of deformation information (Dong & Pan, 2017). This speckle pattern must follow some criteria, such as good contrast, randomness, and isotropy of the speckles (Dong & Pan, 2017). In this way, there are some variables involved in the realization of each speckle pattern which are the density of spots, the size of each spot, and the method used for marking (Dong & Pan, 2017). Normally, this pattern is applied using black or gray spray paint but, in this work, the pattern was applied using an ordinary brush. In this way, the four specimens were marked with different types of speckle patterns, as shown in Figure 3.

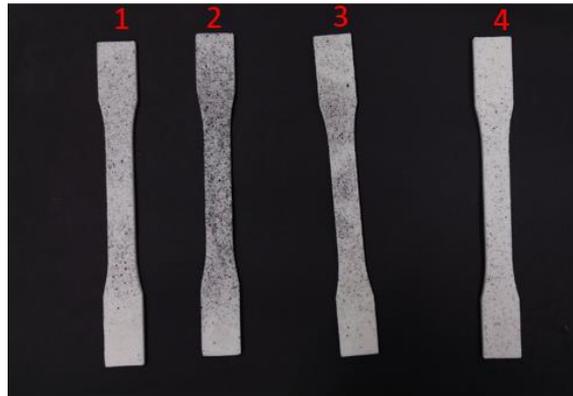


Figure 3. Specimens with speckle patterns.

In specimen 4, the speckle pattern was applied to guarantee low density, with a predominance of white regions, and punctual black spots, while in specimen 2, a high density of particles was sought. Specimens 1 and 3 are presented as a middle ground between the two already mentioned. However, unlike specimens 2 and 4, the isotropy was intentionally disrespected, and there are regions where the distances between each spot were not uniform, resulting in different particle densities along the specimen. In specimen 1, the isotropy was a little impaired, while in specimen 3, the alteration was more intense.

To acquire the images, a smartphone camera with a resolution of 1920x1080 pixels and a frame rate of 30 fps was used. Figure 4 presents the complete apparatus of the traction test carried out.



Figure 4. Complete test setup.

### 2.3 Software evaluation

In the tensile test, the extensometer will be used to measure the deformation of the specimen at each instant of time. The deformation can be calculated by Eq. 1.

$$\varepsilon = \frac{\Delta L}{L_0} \quad (1)$$

where  $[\varepsilon]$  is the strain,  $[\Delta L]$  is the change in length, and  $[L_0]$  is the initial length of the analyzed area. To compare the extensometer measurements using the iCorrVision-2D software, it was necessary to use the correlation module, where parameters such as the size of the reference subset and the desired subset are defined. Furthermore, the Region of Interest (ROI), which is where the image correlation will effectively occur, must be defined. For this, the principle of Saint-Venant (Toupin, 1965) will be used, which allows analyzing the properties of a specimen, such as its deformation, from a region sufficiently distant from the points where the forces are applied, where the stresses and strains are practically uniform. Therefore, for the test addressed in this article, the ROI was defined as a region close to the center of each specimen, as shown in Figure 5.

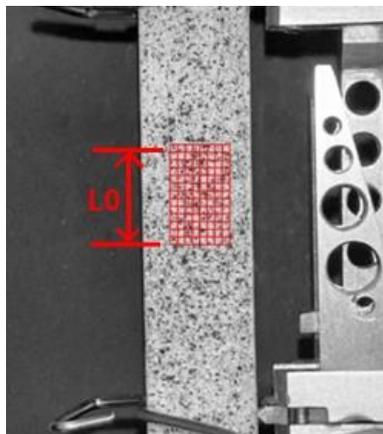


Figure 5. Region of Interest (ROI).

Thus, it is expected to obtain a ROI strain similar to the strain measured by the extensometer.

The videos of the tests acquired by the camera must be separated into frames and then, used in the correlation module, without any previous image treatment, such as the application of filters. However, considering the duration of the tests, as well as the frame rate of the camera, an amount of about 1500 frames or more would be generated, which would not be feasible for the application of the DIC method, as it would require many hours of processing, making the use of the software uninteresting. In view of this, only a few frames were selected from each test, more precisely, one frame every ten frames, ensuring a reduction in processing time, but still with enough images for the software to function.

In addition, the software was also evaluated regarding the total processing time, that is, the time spent on the correlation and the post-processing of each test performed. Another important issue to be studied was the usability of the software, the ability to customize parameters, resources, *etc.*

### 3. RESULTS

With the data collected from each experimental test, the frames referring to every test were processed by the correlation module and, later, by the post-processing module of the iCorrVision software, as shown in Figure 6 and Figure 7. From this, the times spent during the processing of each module were recorded, and the results are shown in Table 1. The longest test was number 2, which can be explained by the greater number of frames to be analyzed.



Figure 6. Correlation module.

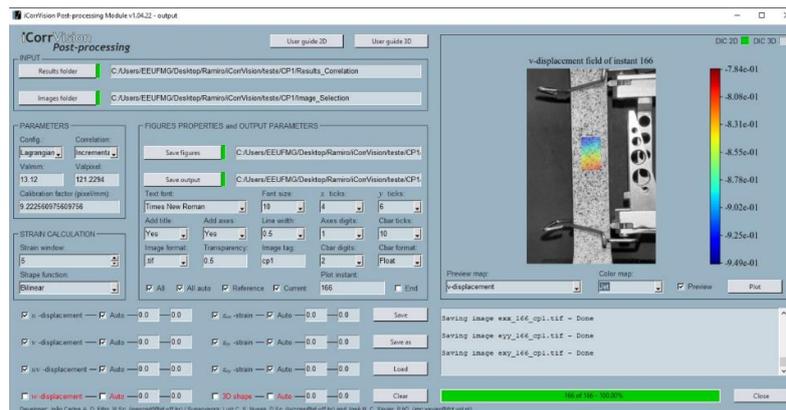


Figure 7. Post-processing module.

Table 1. Processing time of each test regarding the number of frames

Test	Number of frames	Time (s)
1	166	32min40s
2	199	39min42s
3	157	29min14s
4	157	26min37s

The iCorrVision-2D also showed good robustness. In fact, as seen in Figure 6, it is possible to define several parameters for the correlation process, such as the pixel size in millimeters, the filter used, the size of the subsets, the configuration to be used, be it Lagrangian, Eulerian, *etc.* This is presented to the user through a graphical user interface (GUI), making the customization process more intuitive. In addition, the author provides an instruction manual, with the step-by-step of each stage of the process.

### 3.1 Experimental results

During the tensile tests, the extensometer was responsible for measuring the variation in the length of the specimen, so it was possible to use Eq. 1 to calculate the deformation for each instant of time. Considering that the initial length of the analyzed area for all test specimens was 50 mm, and the total length variation should be 0.5 mm, the strain evolution over time for the four tests is presented in Figure 8. Since all specimens were manufactured using the same material, the results were similar. The experimental results were used to evaluate the quality of the results obtained using DIC, employing iCorrVison software.

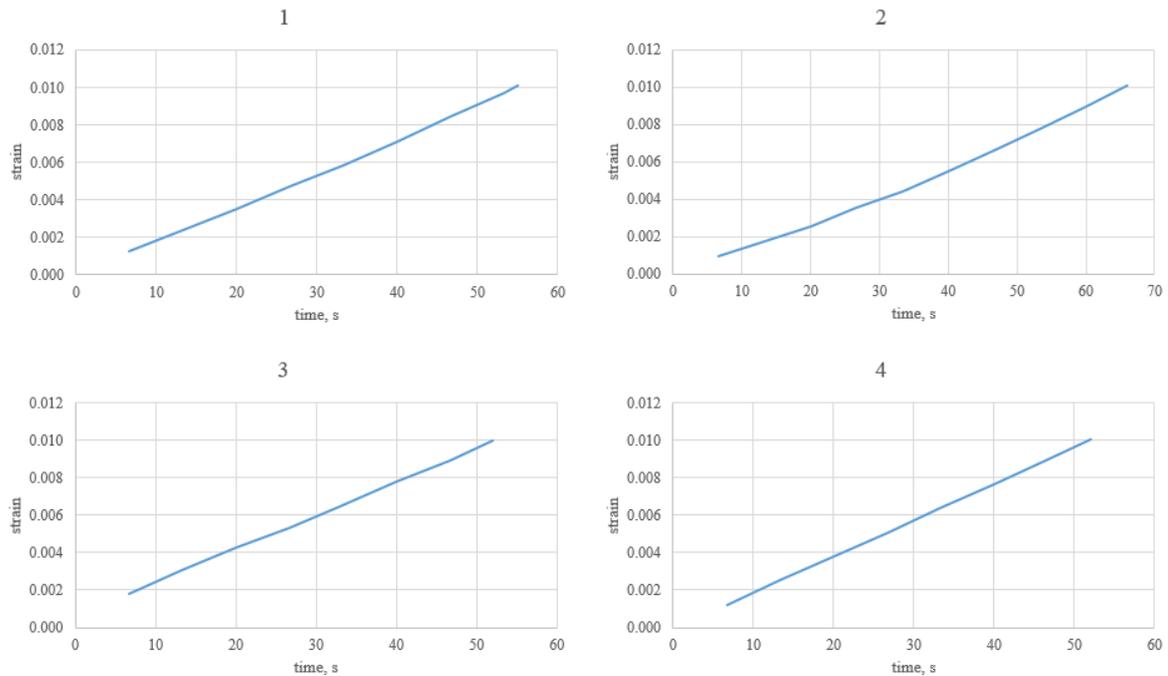


Figure 8. Strain evolution over time for tests 1, 2, 3, and 4.

### 3.2 DIC results using iCorrVision software

After using the iCorrVision software, the post-processing module generates several outputs containing information about the deformations verified by image correlation, both in *.dat* file format and in the form of figures with deformation maps. In these figures is presented a graphical representation of the content present in the *.dat* files. Figure 9 shows the strain map on the vertical axis of specimen 2. Since the inferior holding grip is static and only the superior grip moves during the test, the maximum strain registered during the test is located in the superior part of the ROI.

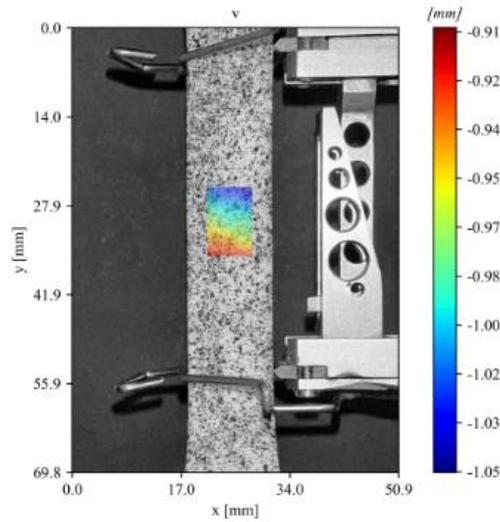


Figure 9. Strain map for specimen 2.

Using the data provided by iCorrVision software it was possible to use Eq. 1 to calculate the total deformation of the specimen. In this case,  $[L_0]$  represents the length of the defined ROI and the length variation  $[\Delta L]$  was obtained from the software output data files. Figure 10 shows a comparison between the stress-strain curves measured using the extensometer and calculated using the data provided by the software for specimens 2 and 4.

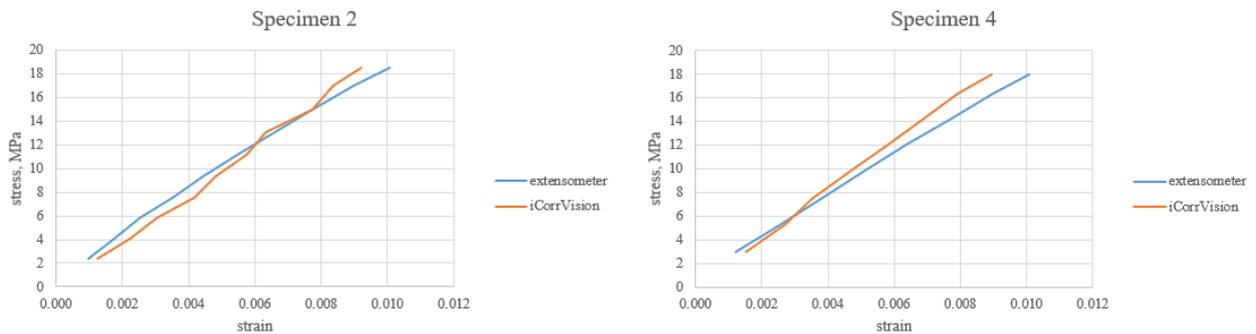


Figure 10. Stress-strain comparison for specimens 2 and 4.

In Figure 10, it is possible to notice a similarity in the stress-strain curves measured by the software and by the extensometer. Figure 11 presents a comparison between the strain measured using the data from the iCorrVision software and the strain measured using the extensometer. The best results were achieved for the tests 2 and 4 presenting close measures between both methods. Specimen 2 was marked with a denser speckle pattern and most of data points are within the deviation range of  $\pm 10\%$ . Specimen 4, despite being marked with a less dense speckle pattern, showed similar results. Thus, in most of the points studied in these two cases, the variations in measurements made by the DIC software in relation to the extensometer are around 4%, with a few points showing variations of around 11%.

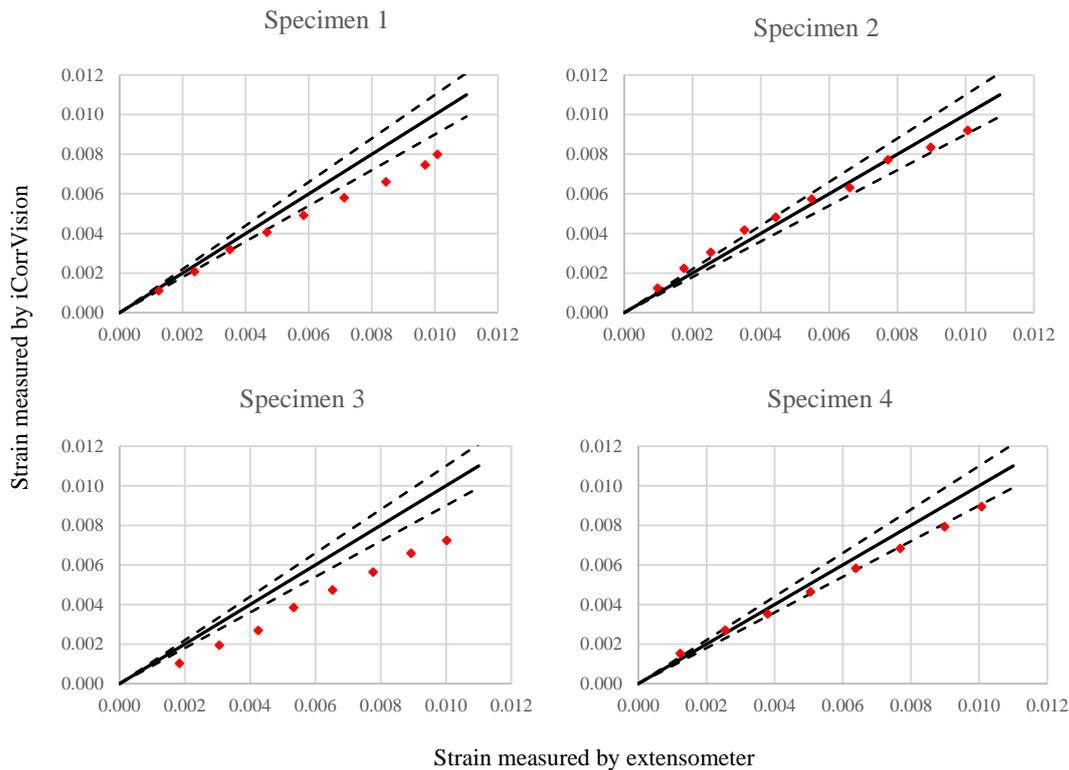


Figure 11. Comparison between the strain measured by the DIC software and by extensometer.

In test 1, where isotropy was slightly impaired, until close to half of the test, the DIC software was able to follow the measurements of the extensometer quite satisfactorily, however, in the other half, the measurements diverged, with the software marking values lower than those of the extensometer. Finally, in test 3, where the speckle pattern was applied with less care, as can be seen in Figure 3, the values diverged throughout the entire experiment, with no point even close to the values obtained using the extensometer. Thus, these two cases presented variations of 10% to 40% in the most divergent measurements.

#### 4. CONCLUSION

The use of the Digital Image Correlation software to determine the deformation of a specimen submitted to a tensile test has been shown to be efficient and viable. The set of functionalities provided with iCorrVision software proved to be sufficient to perform reliable measurements using DIC technique. The documentation provided was enough to use all the main functionalities of the software.

The pattern of particles applied over the specimens proved to be determinant in the quality of the results. A good level of contrast, with a well-defined isotropy, without regions filled in more than others, without directionality in the applied pattern, is fundamental to achieving reliable results. Following these requirements, in this work, it was possible to accomplish results of deformation that deviate less than 10% from those obtained by using the extensometer, even with such a small deformation of 0.5 mm.

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