Stress and strain analysis of a material with Digital Image Correlation method (DIC)

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Preface

This bachelor thesis has been written at the Department of Mechanical and Marine Engineering at Western University of Applied Sciences (WNUAS) in the "???" program.

Several people have contributed academically, practically and with support to this bachelor thesis. We would therefore firstly like to thank our supervisors Professor Ragnar Gjengedal and Professor Ørjan Fyllingen for their time, valuable knowledge and support throughout the entire process.

Furthermore, we would like to thank Professor Harald Moen for his big help, specially regarding the laboratory. Finally, as we are exchange students of the Erasmus+ program, we would like to thank Jan Ove Rogde Mjånes for making us feel at home and having cared about us at every moment.

Abstract

This document offers an overview of the potentialities and limitations of digital image correlation (DIC) as a technique for measuring displacements and strain in biomechanical applications. As DIC involves a high degree of computation, and of operator-dependent decisions, reliability of displacement and strain measurements by means of DIC cannot be taken for granted. This review includes many tests as well as the study of many different factors and variables that can affect the reliability of the results obtained through the testing.

Problems involving methods used are addressed as well as possible or existing solutions, as well as variations of the method tha can lead to better results in terms of optimization or cheapening. Topics addressed include: speckle pattern and its acquisition, analysis of relative error and a theoretical approach not only to the software but to the classic strain test.

The obtained results are compared to measuremnets obtained through different methods. Limitations of the method are discussed as well as repeatability and the possibility of new sources of error when taking our method to an industrial approach. In order to provide an overview accessible to many scientists not necessarily mathematical based, this document intentionally does not include details of the complicated mathematical methods used by the software the thesis is based on.

1. Introduction

Digital image correlation (DIC) is an optical technique that measures displacements and strain by studying images of a sample under tension in 2D or 3D. Correlation theories for the measurement of alterations in data were first applied to digital images in 1975 . DIC was introduced in the early of 80s, with the first system developed at the University of South Carolina [1].

This project consists of a system capable of measuring the stress and deformation of a specimen during a tensile test with images taken by a camera.

The objective is to analyze the deformation at all times in the whole specimen to detect the most critical point, i.e. the spot that will fail in the specimen due to stress. This is interesting because it can be predicted when and how the specimen is going to reach the fail. This can be of great use in almost any time of industry machinery, as it will give a lot of information of when and where replacements need to be made to ensure the correct behaviour of machinery. It can also lead to changes or reinforcements being made to it so it can last longer and therefore improve the efficiency in production.

In general, the traditional measurement system with the contact displacement/strain gauges is more suitable for small and uniform strain deformation of the loaded sample due to its high sensitivity and ease of manufacture. However, in the context of practical engineering, few loaded samples are subjected to strict uniform deformation, and heterogeneous deformation is more common. In this case, the strain gauge located at discrete points may be difficult to characterize regarding the region of concern. In order to address this issue and avoid the damage to the sample itself, the need for the full-field noncontact approaches is more urgent. After decades of development of noncontact measurement technology, many full-field detection methods based on optical pattern recognition coe into beings, such as holographic interference, electronic speckle pattern, speckle photography, and digital image correlation (DIC) [2], which is the topic of this thesis. DIC has many outstanding advantages, such as relatively simple preparations of the measuring system and the lower requirement to the experimental environment.

This technique can be used for a wide range of applications in material research and component testing to analyze the static and dynamic behaviors of specimens. The full field strain map generated by the DIC algorithm is commonly used to replace strain gauges.

Figure 1 schematically describes the process carried out throughout the project to obtain the stress and deformation of a sample.

2.1 Theoretical approach

2.1.1. Tensile testing and material behaviour theory

If an object is subjected to an external force, it deforms. To know how much it deforms and the stress to which it is subjected, tensile testing is carried out. In that test, a specimen is subjected to a tension until failure. The traditional method to measure these variables is an extensometer.

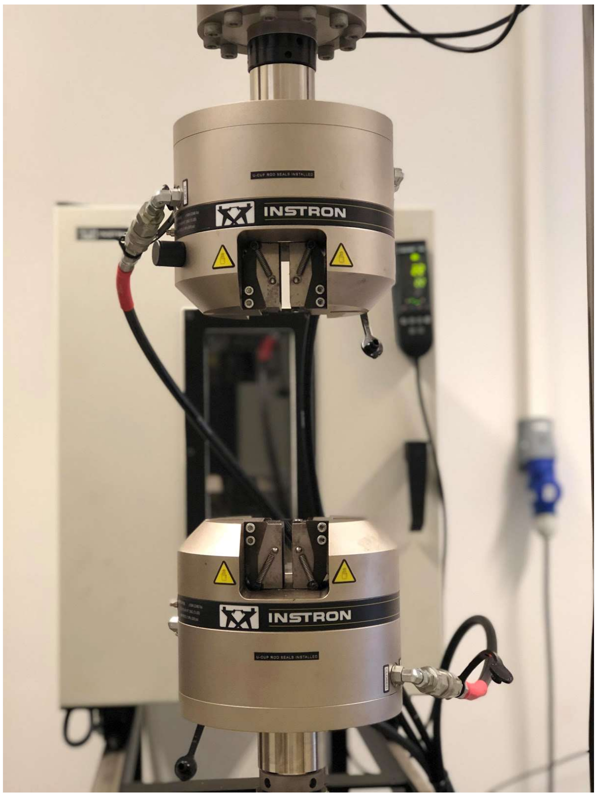


Figure 2: Tensile machine

The elongation measurement is used to calculate the engineering_strain, ε, using the following equation: The strain ε indicates the relative length change of an element.

$$\varepsilon = \frac{L - L_0}{L_0} = \frac{\Delta L}{L_0} \tag{1}$$

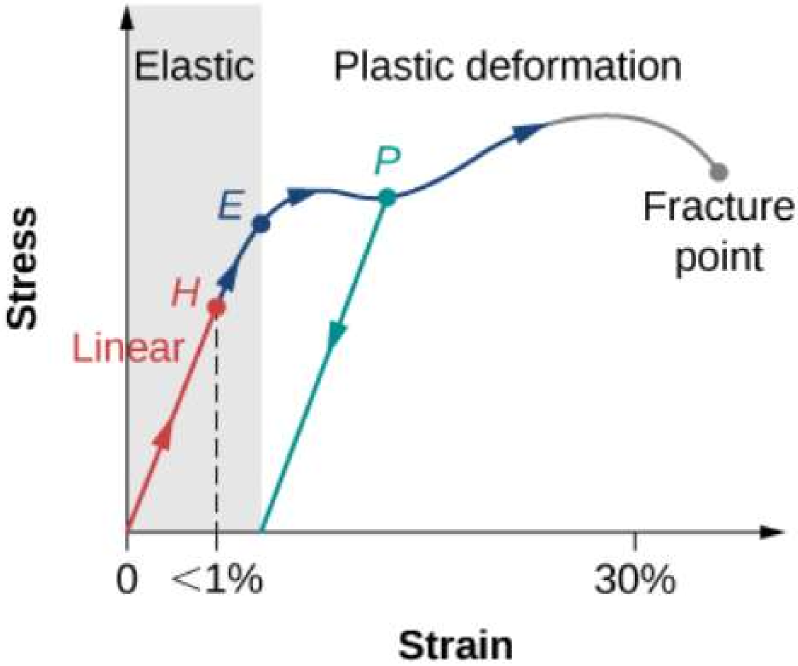


Figure 5: *Stress-strain deformation graphic showing elastic and plastic deformation stages* [4]

A material is in its elastic zone if it is able to regain its initial size and shape when stress ends. When the stress is less than the proportionality limit, the stress is proportional to the strain.

Young's modulus (E) [4] is defined by the constant that linearly relates the stress (σ) and deformation (ε) when the material is in the elastic zone:

$$E=\frac{\sigma}{\varepsilon}=\frac{F}{A}\cdot\frac{L_0}{\Delta L}\rightarrow\varepsilon=\frac{\sigma}{E} \qquad (2)$$

Here F is the applied force, A is the transversal area, L_0 the initial length and ΔL the variation of the length.

A material exhibits a plastic behavior when the tension is greater than the elastic limit. In the plastic region, the object does not recover initial size or shape when the tension ends, but acquires a permanent deformation.

In addition to this, when a material is deforming in the plastic region it no longer behaves as the young modulus' equation will predict. For this region Hollomon's method has to be applied to get an accurate prediction.

$$\sigma=\sigma_0*\varepsilon^m \qquad (3)$$

This comparison is performed dividing the reference image into many subsets. Then, the software searchs, for each deformed picture taken, a matching subset that maximizes their correlation in gray scale values.

In the project, it will just be analysed the effects of the stress in x and y dimensions, i.e. two dimensions. That is why the designed specimen with the graphic tool Inventor has a non significant thickness. The material that will be used for the experiment is steel.

Throughout the study, different specimen shapes will be used. For initial trials, the shape is inspired by the usual cylindrical specimen used in the traction test, but plain. In order for the specimen to be properly caught by the machine, the ends must have a minimum length of 25 millimeters. For this reason, the shape has been designed so that the ends measure 45 millimeters, thus ensuring that the specimen is well fixed. This initial form is ideal to start experimenting with the DIC method because the extensometer is able to perfectly measure the deformation, in order to accurately contrast the results.

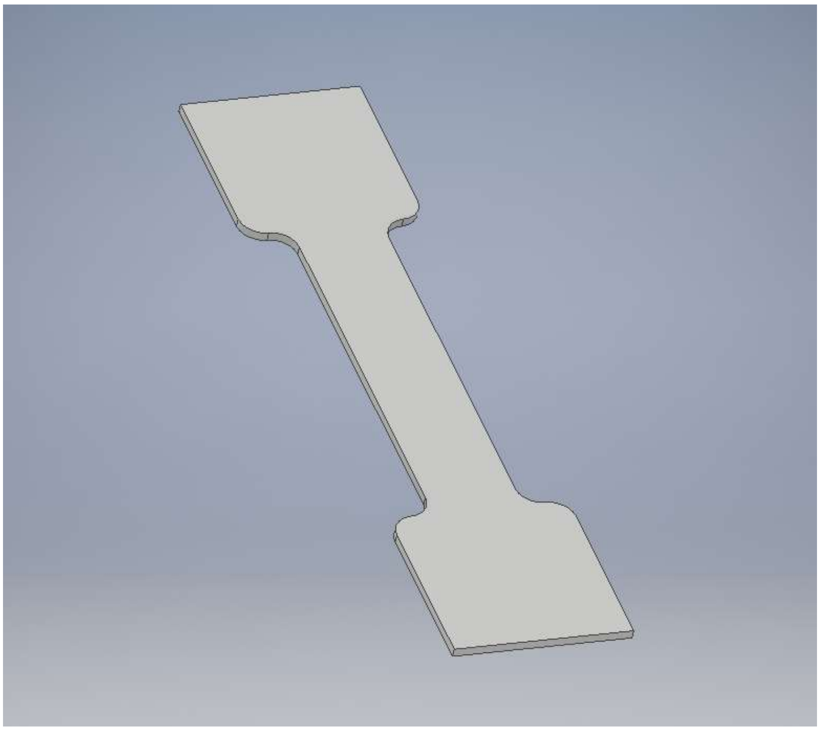


Figure 7*: First specimen designed with Inventor*

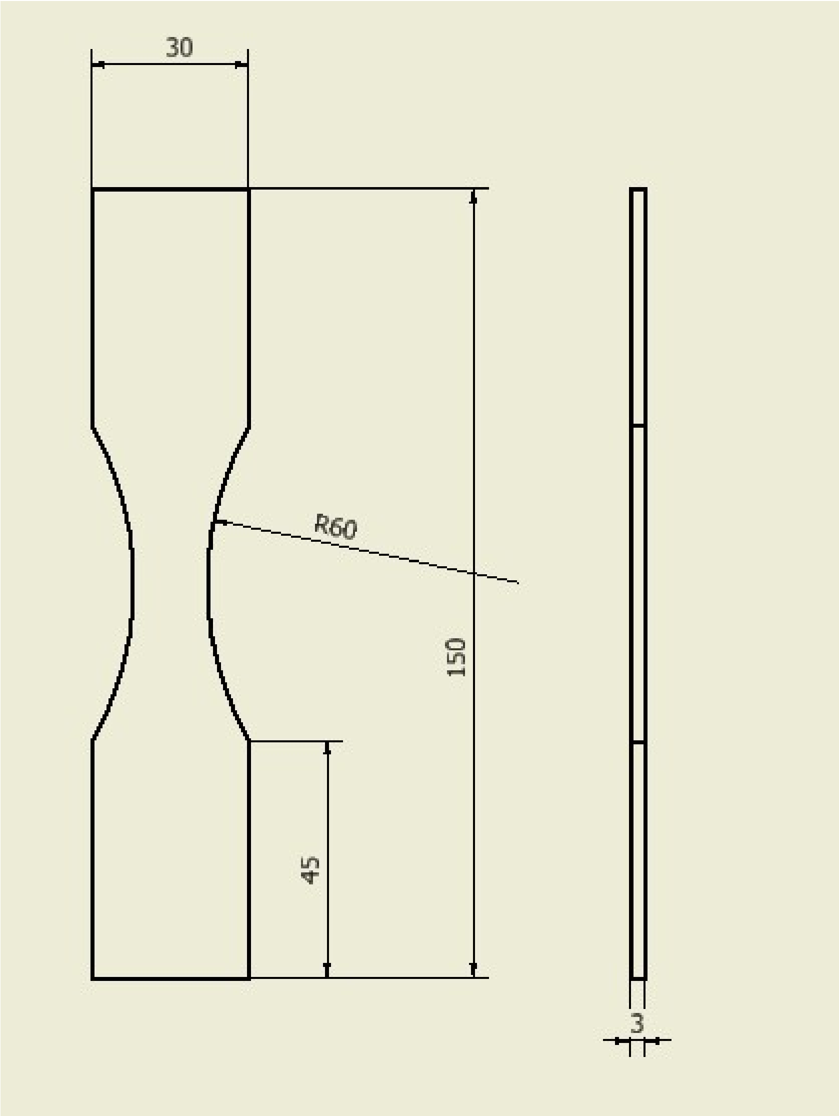


Figure 9: *AutoCAD Drawing of the second specimen*

Once the repeatability of the method has been verified with the initial specimen, the next step is to perform the experiment with an hourglass-shaped sample. It is very difficult to measure the strain in this type of test specimen with a common strain gauge, where there is a small, curved section. This is where the DIC method becomes really useful.

The goal is to measure the maximum stress, and this occurs in the smallest section, located just in the curved part.

Longer computation time	Shorter computation time
Better detection of local effects	Worse detection of local effects

Elements which you do not include when creating the surface component:

- Fixtures
- Backgrounds
- Edges of the measuring object
- Contour jumps

2.2. Scientific method

2.2.1. Set-up requirements

- Sample surface should be flat when measuring only two dimensions.
- The optical axis of the camera lens must form ninety degrees (perpendicularity) with the sample surface.
- The light source must be smooth, stable and constant throughout the entire experiment.
- A possible appearance of shadows on the sample surface must be avoided at every moment.
- It may be necessary to use a tripod to guarantee the accuracy of the camera position for the duration of the test.

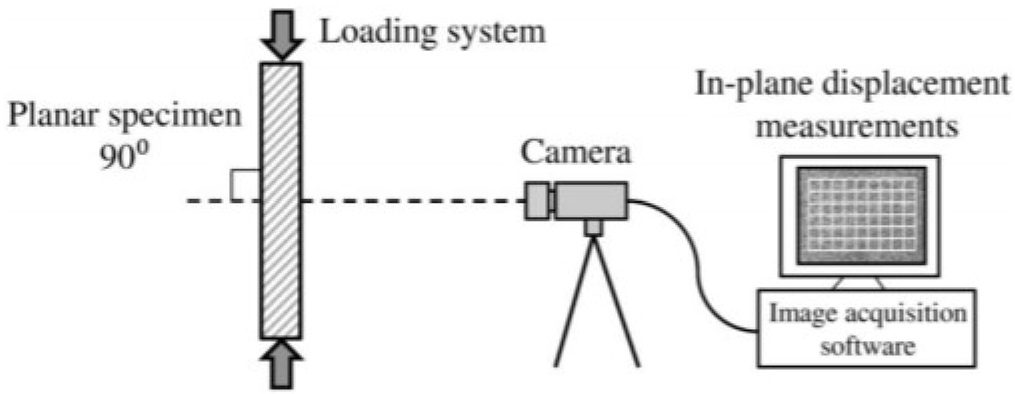


Figure 10: *Sketch of the set-up carried out in the laboratory* [7]

- The size of the speck should be a minimum of 3 pixels to avoid noise, but less than 7 pixels to achieve a high density of data points to analyze. The size in millimeters depends on the length of the sample and the resolution of the camera, and can be calculated with the following formula:

$$\text{Size}=\frac{\text{Sample length}}{\text{Camera resolution}}\cdot[3,7]\text{px per speck} \quad (4)$$

- The speckle must have a good grayscale contrast in order to avoid possible mistakes.
- Regardless of environmental conditions, the pattern must remain adhered to the piece throughout the test, that is, be constant and stable.
- The pattern should have a mottled density of 50%.

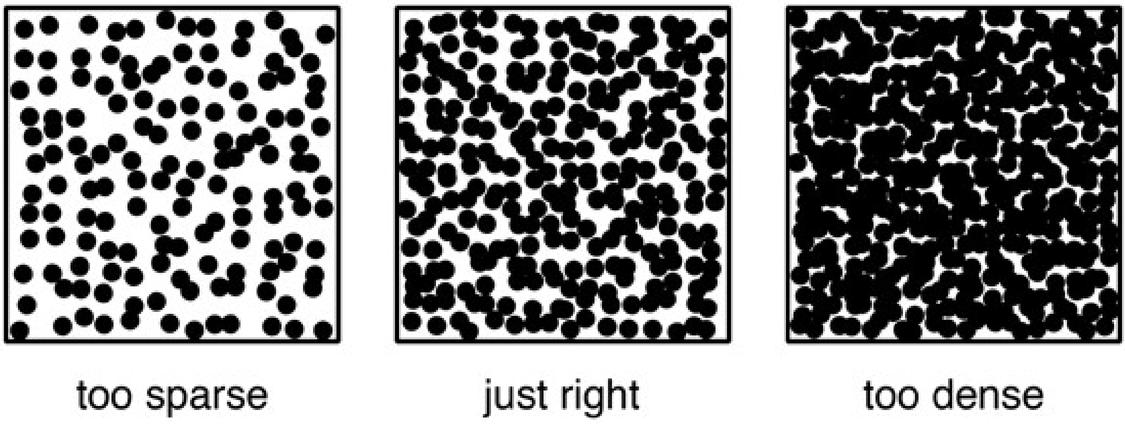


Figure 12: *Comparison between speckle patterns with different density* [8]

2.2.3. Speckle patterning methods

There are many ways to create this artificial pattern, but the main and most used are paint, inks and dyes and powder particles. The last two methods are typically used with materials too elastic where painting does not adhere, or wet surfaces.

As this project uses steel as the material, painting has been chosen as the method. Painted stain patterns are widely used because the paint is compatible with most engineering materials, and high-quality patterns can be achieved quickly by spraying the paint onto the surface. Black or white paint is usually used because they are the ones that achieve the most contrast. Specifically, the use of a light-colored swatch is preferred or, failing that, white paint as a background and black as the mottled pattern because black paint maintains a better contrast over white paint.

If the sample is subjected to large deformation tests, it is recommended to paint the sample 24 to 48 hours before [9]. This is because as the paint dries, it hardens and loses its adherence with the sample.

of values, there are 2^8=256 possible cases (from 0 to 255). This value is assigned to a pixel depending on the intensity of the light reflected by the surface of the specimen.

As there are hundreds of thousands of pixels in an image, depending on the resolution, the repeatability is ensured. So, to deal with this problem, the image is divided into subsets. The purpose is to get subsets with totally different combinations of dots, so that all of them are distinctive.

Subsequently, two successive images are compared by taking a subset of the undeformed image (i.e. the reference image) and looking for it in the deformed image. The search is carried out in the areas near the location of the subset in the reference image. This guarantees that the correlation found is correct, since the double condition is achieved: similarity of pixels and proximity between the initial and deformed subset. Although it is quite easy for a person to identify movement in successive images, it is difficult to translate this action into a mathematical algorithm, and that is why there are many different and successful methods of doing this.

In GOM Correlate, this comparison can be achieved with interpolation features such as different subpixel interpolations, e.g. bilinear interpolation, bicubic interpolation or spline interpolation that provide the corresponding maximum of similarity in the subpixel area.

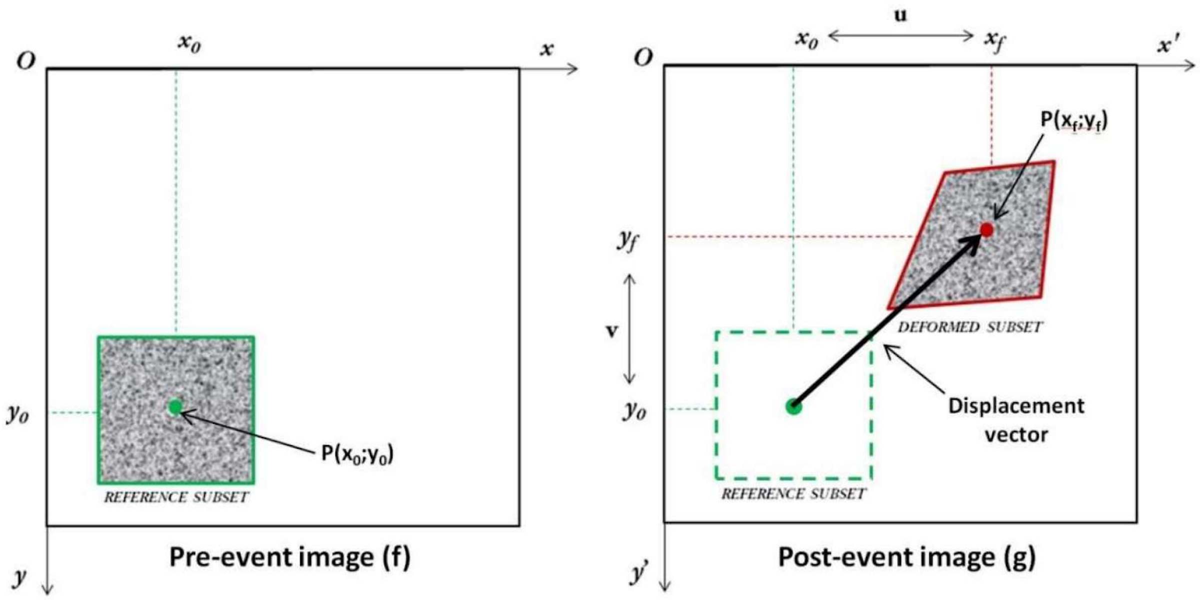


Figure 14: Search of the displacement vector [11]

Once the deformed subset has been identified, the software defines a displacement vector to quantify the subset movement.

The displacement vector has as its origin the center of the initial subset P(x0; y0), and as its end the center of the deformed subset P(xf; yf). This vector is the average of the pixel displacements of the subset.

To calculate displacements in the x and y directions, the displacement vector is projected in them:

$$\text{Displacement in the x direction: } u = x_f - x_0 \quad (4)$$

The software chosen to carry out the synchronization of the images is LabView. In this way, it is possible to choose how often a photograph is taken, and save them in chronological order in the desired folder on the computer.

In Figure 16 there is a scheme of the program elements and their functions:

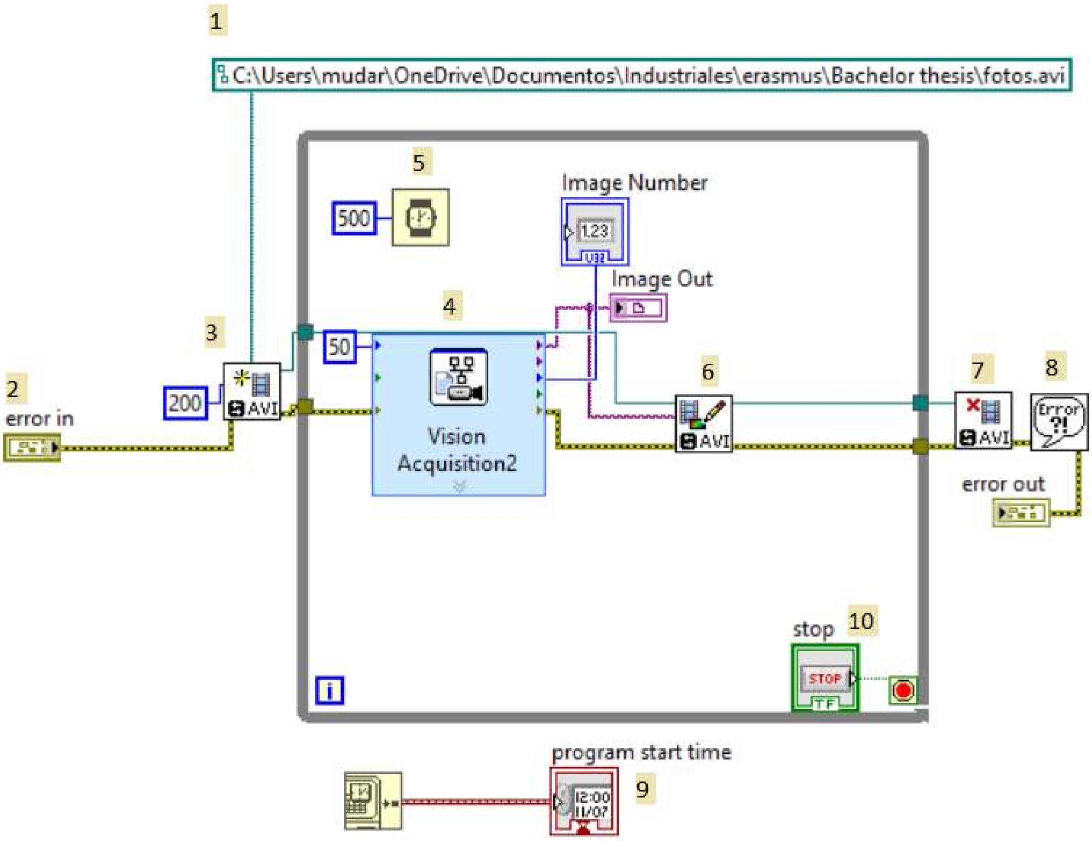


Figure 16: *LabView program*

1. Path where the images taken in order are saved.
2. Error cluster, recomendable but not mandatory.
3. Initialization block to capture the images.
4. Principal function: here the camera, the size of the images and the way to capture them is chosen (an unique image or repeatedly).
5. Interval controller: in this case, an image is taken every 500 milliseconds.
6. The image is saved in a file.
7. The program indicates that the file has been created and closes it.
8. The program output gives an error message in that case.
9. This is a program star time indicator to ensure a common time frame between the images and the data processed by the tensile machine software.
10. A stop button to be pressed when the testing is over.

In this program, there is still no way to start taking the pictures at the same time as the test starts automatically, to synchronize the data obtained by the tensile machine software with the one obtained by the DIC method. This has to be done manually.

Figure 17: Example of *Typical aberrant measurements sometimes occur in a local approach.*

Source: Development of a Global Digital Image Correrlation Approach for fast High-Resolution Displacement Measurements, by Univeristy of Montreal

2.3.2 Sub-Pixel interpolation

To perform the optimization required by the pattern matching, image functions and their derivatives need to be interpolated, therefore making a continuous objective function. The fastest (and therefore the most simple) would be the zero-order model, which interpolates in the borders of pixels to find the position of the subpixel peak, this method, even though fast, can lead to significant sources of error. The larger the order of interpolation eoud obviously reduce the error, however, the exact quantification of these errors is very complicated and depends on the intensity variations specific to the surface pattern, noise etc.

2.3.3 Image Noise

During the processing of images random oscillations of grey scales exist, mainly in the surroundings of the speckles, this phenomenon is referred to as image noise. This uncertainty in the image is of great importance in the measuring process as it doesn't only affect the sensitivity of the measurements but it has a great importance also in the subpixel interpolation mentioned above.
A decrease in the resolution of the smartphone camera was caused by the need to use the zoom tool, because it was physically impossible to bring the mobile closer to the sample. When analyzing the images with the software, the dots were not captured well, so the camera type had to be changed to a digital one. Digital cameras have optical zoom that maintain image quality.

In order to analyze the quality, a photo of each pattern has been imported into the GOM correlate software. This software has a tool that examines the quality of the pattern on a scale from red to green: the greener the result, the better. A guidance can be the number of points analyzed: the higher it is, the more data the software analyzes and therefore the better the results obtained with the study.

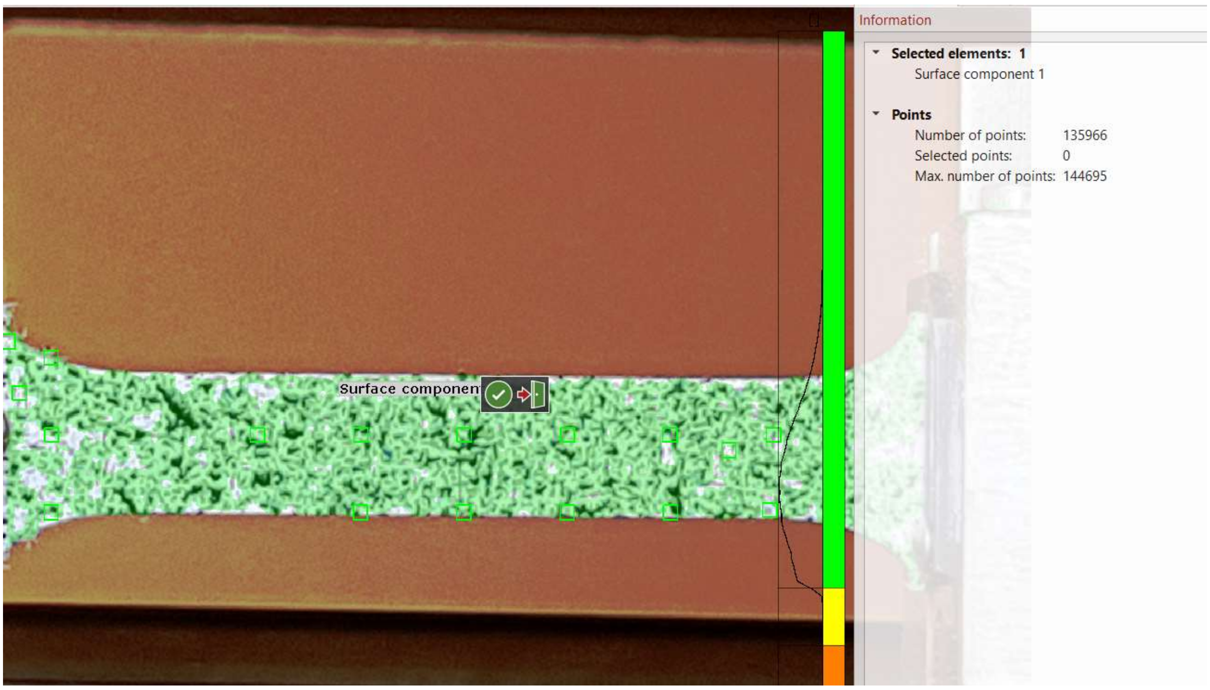


Figure 20: *Toothbrush pattern analysis*

The toothbrush pattern analysis shows that although there is a large part of the surface in green, there are areas whose points could not be interpreted by the software. Ideally, thecprogram should capture all the surface in order to analyze it in its entirety.

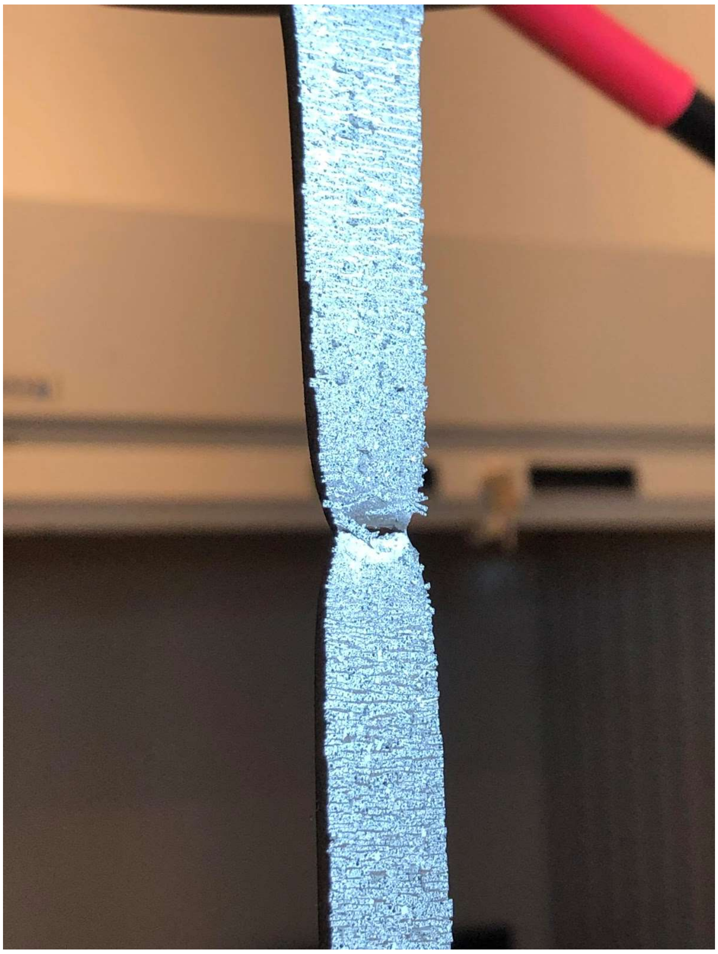


Figure 22: *The specimen after the tensile test with the white paint broken.*

As mentioned in the previous chapter, the white paint broke. After this, the possibility of spraying the pattern directly onto the metal surface was tried out, as it is shown in Figure 25, giving good enough quality in the surface component generated by the software.

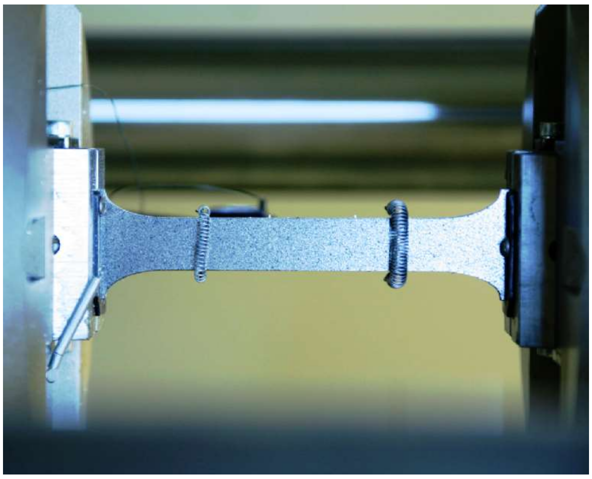


Figure 25: *Specimen with the extensometer attached*

- **First correct test: report**

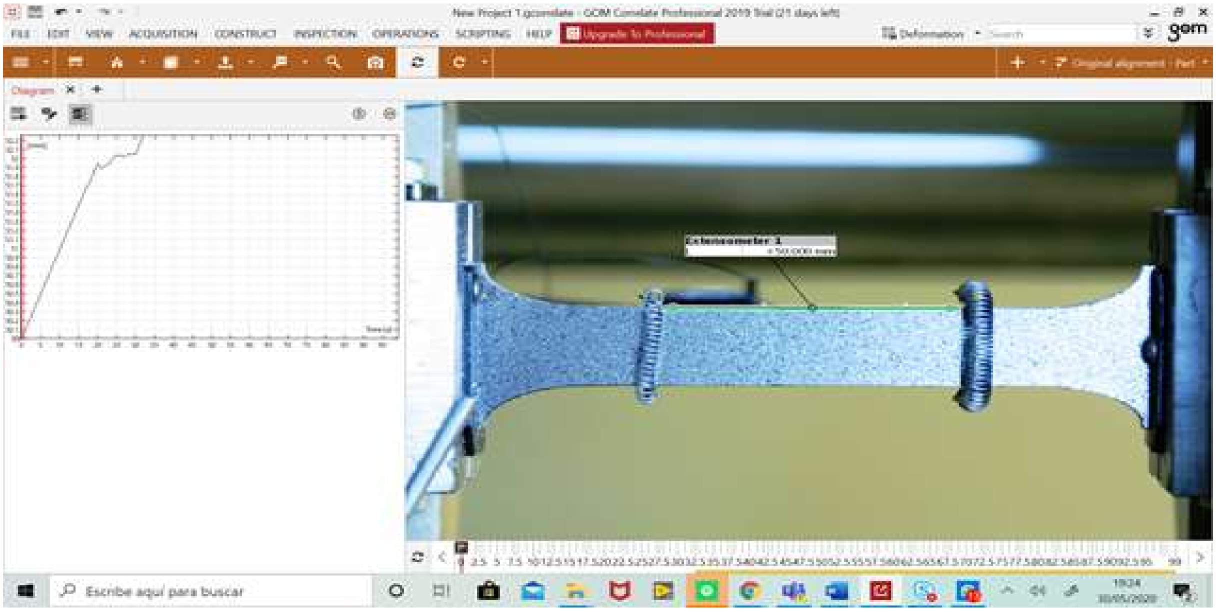


Figure 26: *First test: Stage 0, extensometer shows L=50mm*

The first successful test has been carried out with medium resolution, demonstrating that this quality is sufficient to obtain consistent results. In this test, an additional measurement was taken with a strain gauge in order to check the results obtained with the DIC software.

The specimen has only been tested in the area (surface component 1) in between both springs of the extensometer as if a bigger area is tested these two elements (which don't appear in the photo because this is the last stage) produce errors in the calculation the software performs when measuring strain. On the top left corner of the image a graph of this technical strain plotted against the distance from the start of the section 1, which in our 2D approach is a black line.

This graph is quite symmetrical and the values make sense as to the central points of the specimen having the highest strain percentage, however there is at least one value which differs from the overall continuity of the results. This value which is at the mark of 38 mm shows a steep peak in the decrease in the strain which doesn't correspond to what is expected. This value is most probably an error which may be caused by an area of the speckle pattern not being clearly defined and the facets having unclear boundaries.

The results can be compared with the extensometer data by joining both in a common graph, as it can be seen in Figure 29:

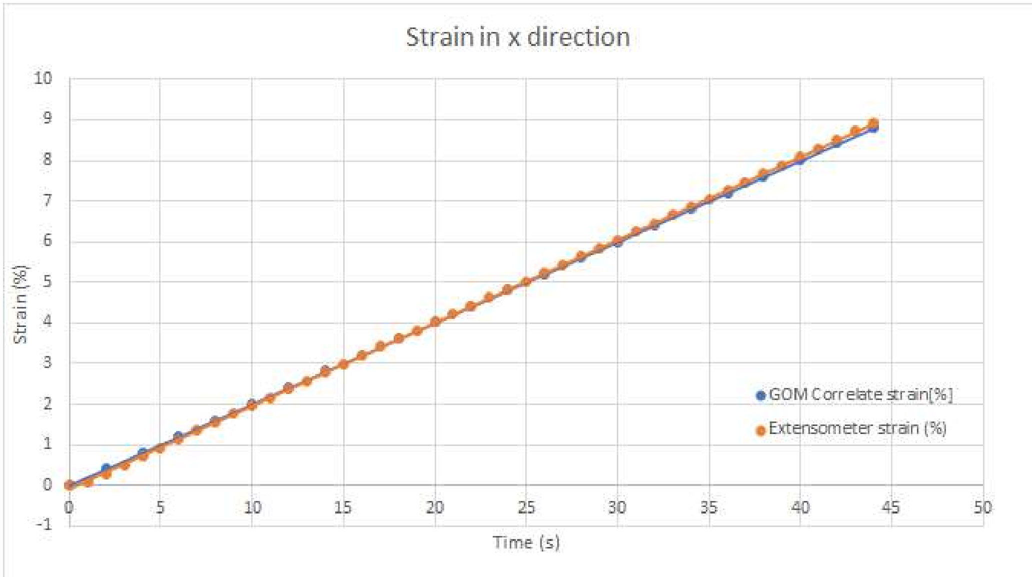


Figure 29: *Comparison of extensometer and DIC software results*

The strain obtained with the DIC software, in blue, is almost coincident with the one obtained with the extensometer, in orange.

It i even more interesting to compare the stress-strain curve, as it is shown in Figure 30.

Where L_0 is the extensometer length and L the DIC software length at every period of time.

By contrasting the data obtained with the extensometer, it can be concluded that the DIC method offers accurate results. The small differences found between both methods may be due to the following reasons:

- The virtual extensometer created with DIC software requires the user to specify the start and end points and the distance between them. This step results in errors, as the user chooses the points inaccurately. Although the distance of the extensometer could be defined in a very clear way, in the photographs taken in the test this is less obvious because the springs used to fix the extensometer to the specimen cover the initial and final part of the extensometer much of the time. In some images, the ends of the extensometer are clearly seen, while in others only the springs are seen and the user has to assume that these ends are located somewhere on the spring. These both situations are shown in the following images:

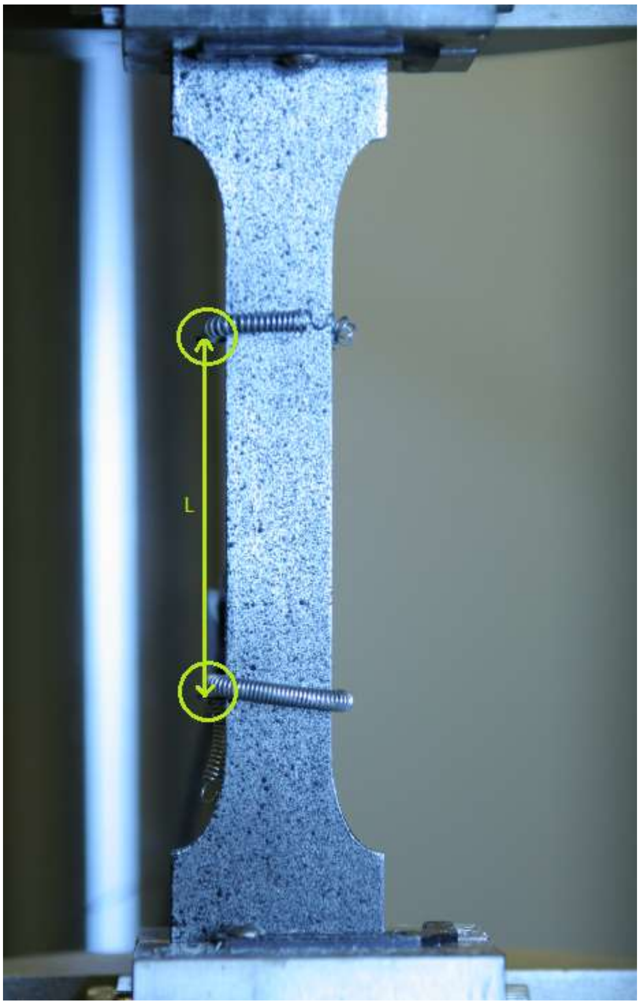


Figure 32: *Ends of the extensometer clearly defined*

extensometer shows very small values, which although they are negligible cause a relative error of 100% because the DIC method gives null values of deformation.

3.3. Image acquisition: camera self-heating

A recurring problem when acquiring images is the distorsion, which largely depends on the camera lens. This is due to the camera self-heating: it becomes hot when it is used for a long time, and causes the deformation of the lens.

In most cameras, the internal temperature increases for one or two hours until the thermal equilibrium is found. This self-heating produces a darker current noise and thermal expansion of various supports to connect the camera sensor, causing a slight additional movement of the sensor current and the subsequent expansion and translation of the image.

If the test requires a long period of time, these effects cannot be ignored and the camera must be preheated before startinf¡g. This aspect has been the subject of numerous studies, where it has been determined that the image distorsion causes a 70–230 με strain error in the DIC measurement [14].

The test carried out in the project lasts approximately three minutes. It can be considered that it is a short test, so the self-heating camera effects can be initially ignored. This is a very specific situation, and it should not be forgotten that in tests whose duration is longer this can cause errors.

To reduce measurement errors, it is necessary to eliminate the human factor as much as possible. Therefore, a fundamental improvement is to synchronize the start of the tensile test with the start of taking pictures without having to depend on a person pressing the button. This can be done by somehow synchronizing the software that controls the tension machine with LabView. At the moment, this has not been achieved, making it a good field of development.

On the other hand, by now the system is able to analyze only the deformation in two dimensions. Given that for many applications it is necessary to know the state of deformation of the three dimensions of a sample, another possibility of improvement would be to achieve these measurements with the DIC method. This is when the only eligible option between the two software that have been selected in the project is GOM Correlate, since Ncorr does not allow the development of this tool. For this application it would be necessary to acquire a second camera, so that both cameras take photographs at the same time from different perspectives in order to capture deformation in the third dimension. Another option would be to acquire or design a device made up of a set of mirrors, where different points of view can be captured with the same camera. These two setups are shown in the following photographs:

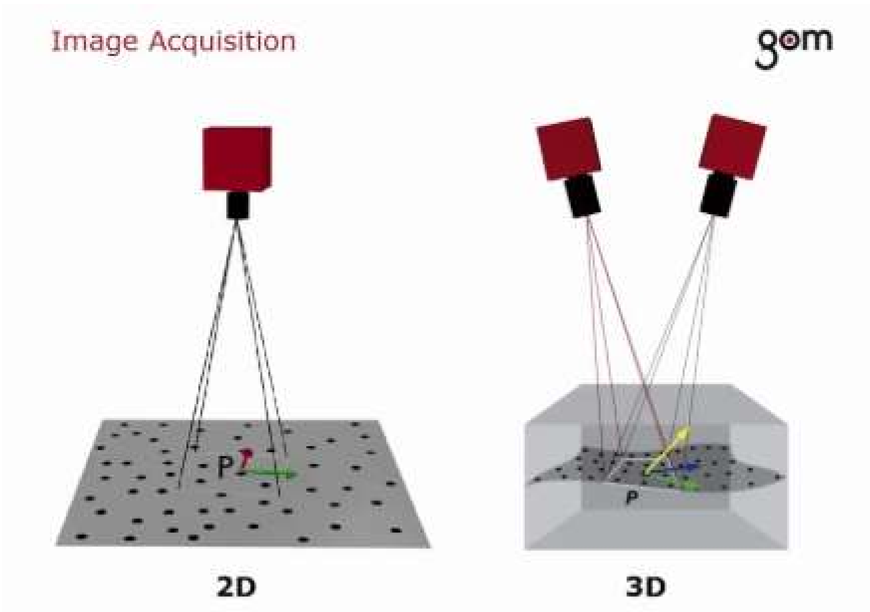


Figure 34: *Differences between 2D and 3D method with two cameras* [15]

existing ones to work with them. This is of great use to the industry as it facilitates the search of the optimal shape for any use a company may need to produce by speeding up the trial-error process. This PRO version has a far wider range of conditions that can be applied to our experiments. Firstly alignments can be modifyed as well as the local coordinate systems to help to in obtaining simpler and clearer results. Furthermore it includes on option to download the external conditions our test is carried out in, these include material tested, vibrations that the specimen may be subject to or even climatic conditions such as temperature, pressure and humidity.

4.4. Critical resolution

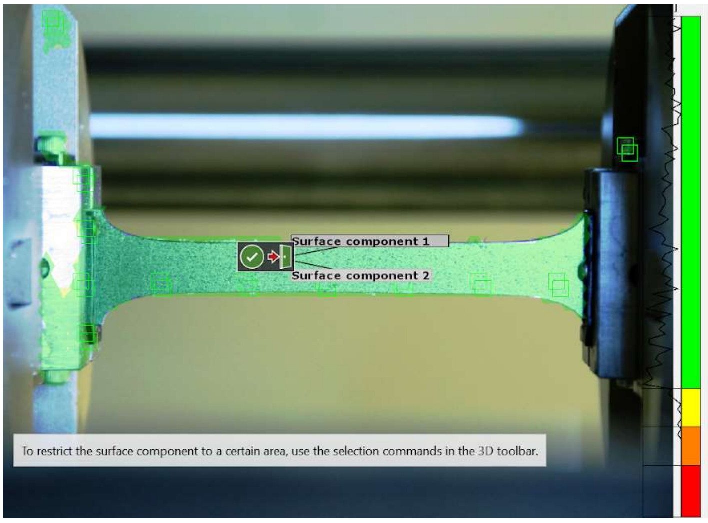
The frequency with which photographs are taken varies depending on the type of test and the material. If changes occur rapidly in the material, high frequency is required; on the other hand, if the changes appear more slowly, it is enough to take a photo per second

On the other hand, the frequency depends on the picture resolution. Higher resolution implies that the speed of capture of photographs decreases, so if it is necessary to take pictures quite often, the resolution of the pictures has to be decreased. In addition, the higher the resolution, the more memory each photo will occupy.

Furthermore, memory is sometimes a limited resource, so it is advisable to search for the exact resolution to have sufficient quality so that the analysis of photographs using the software provides accurate results.

To analyze the decrease in the ability of the software to analyze the images as the resolution decreased it is interesting to decrease the resolution gradually to observe how the software behaves.

ACTUAL IMAGE Resolution: 1152x1728 pixels (high resolution)



Even though the non-acceptable areas increase slightly (yellow and orange), the great majority of our surface component is still good enough to carry out our test with GOM Correlate. The white areas, where the software is not able to calculate the strain, are increasing slightly.

3. Low resolution

Figure 39: *Low resolution example of the* test

In this image, the undetected areas by the software have increased a lot. Even though the most critical section is still covered by a good enough pattern the rest of the specimen will not be measured to an acceptable degree of accuracy. This results in this image's quality not being good enough to get reliable results on our surface component.

4.5. Reproducibility

Once correct and accurate results have been obtained, the next step is to check if the method is reproducible. This implies that the method can be repeated an indefinite number of times and each time a precise result is reached.

To demonstrate such reproducibility, three tests have been carried out with successful results. In the following graphs, it can be noticed how the stress-strain curve obtained by the digital image correlation method is practically coincident with the one of the extensometer.

Fluctuations between results are due to the factors developed when talking about the relative error in previous chapter of the report.

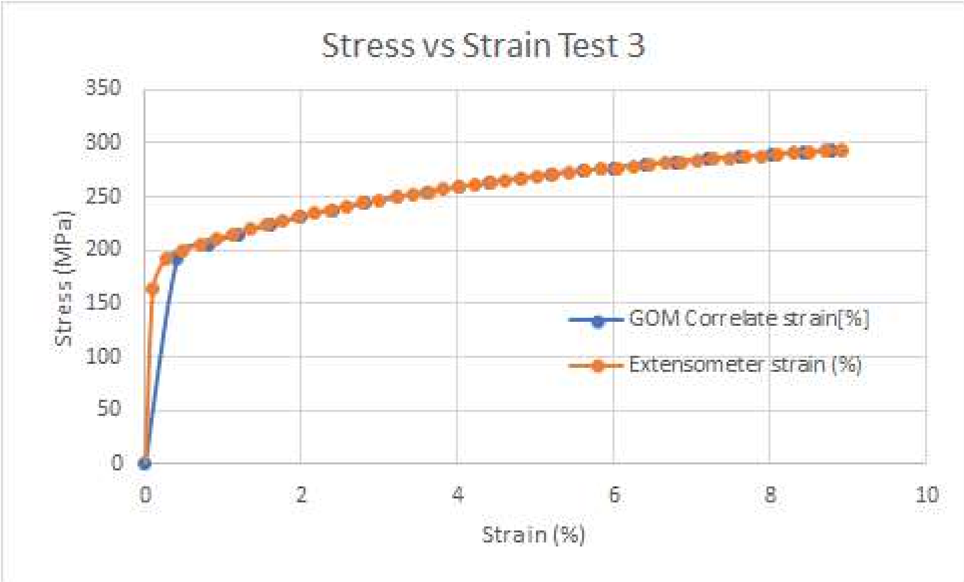


Figure 42: *Comparison between extensometer and GOM Correlate deformation in Test 3*

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