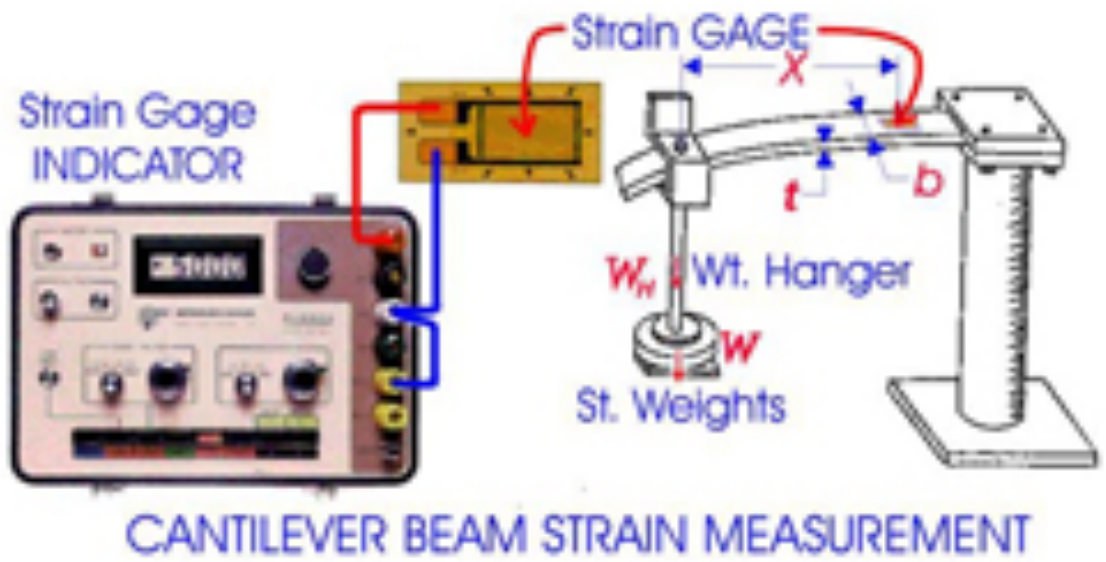
Optical Metrology

Lecture 8: Measurement of Strain by Digital Image Correlation

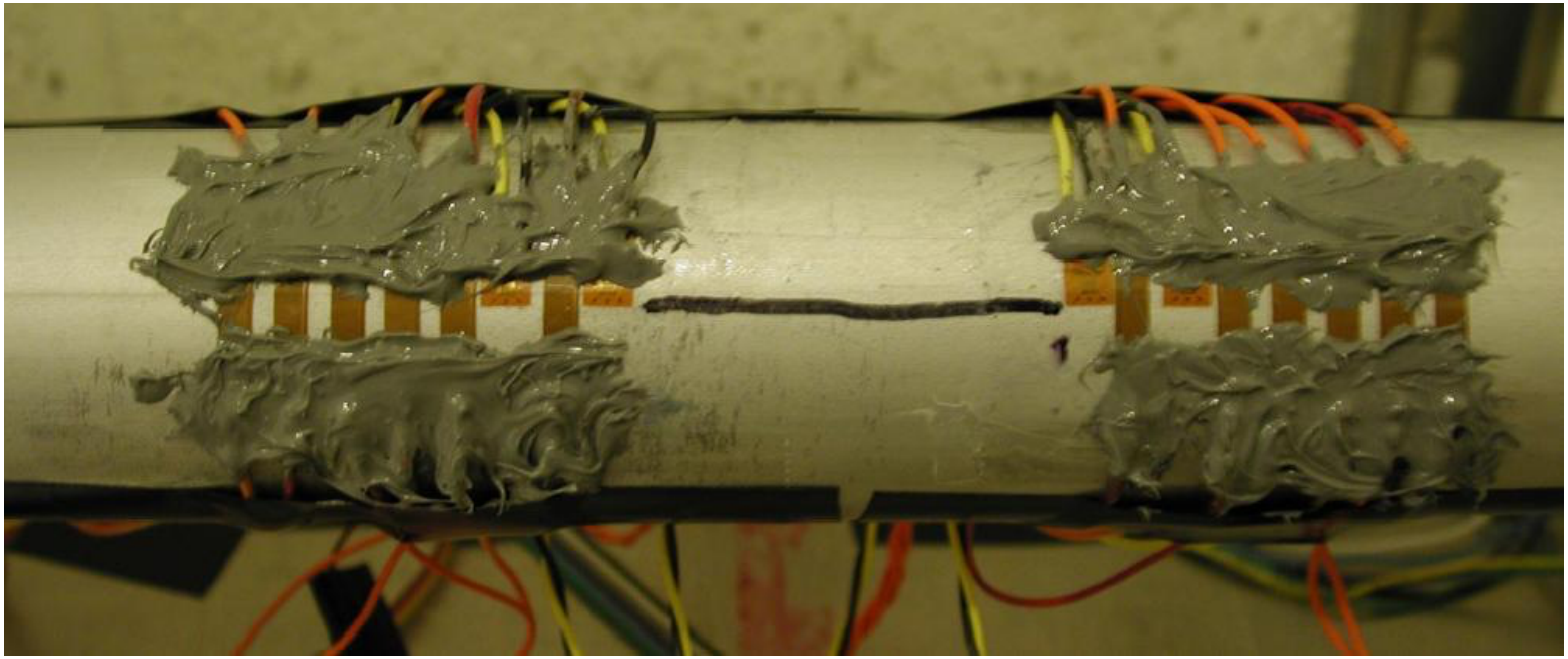
Measurement of strain

- Strain measurements are important in mechanical sciences.
- A strain in any material can be defined as the coefficient of the change in length and the initial length.
- Strains are involved in many important material properties and parameters (i.e. Stress-Strain Curve, Young's Modulus, Poisson's Ratio, etc.).



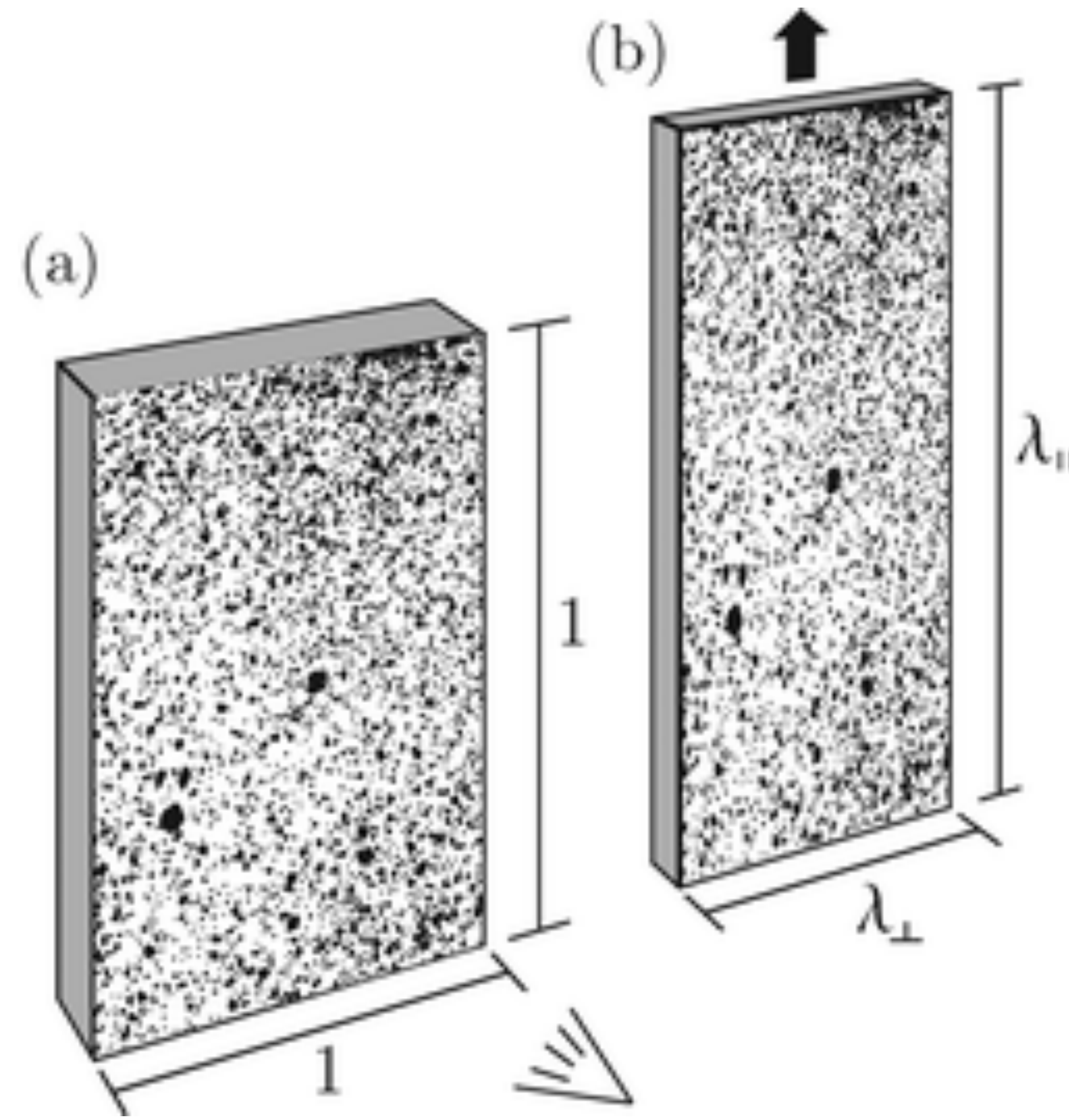
Measurement of strain

Strain gauge is a good solution, but too cumbersome for 2D strain maps. Not practical!



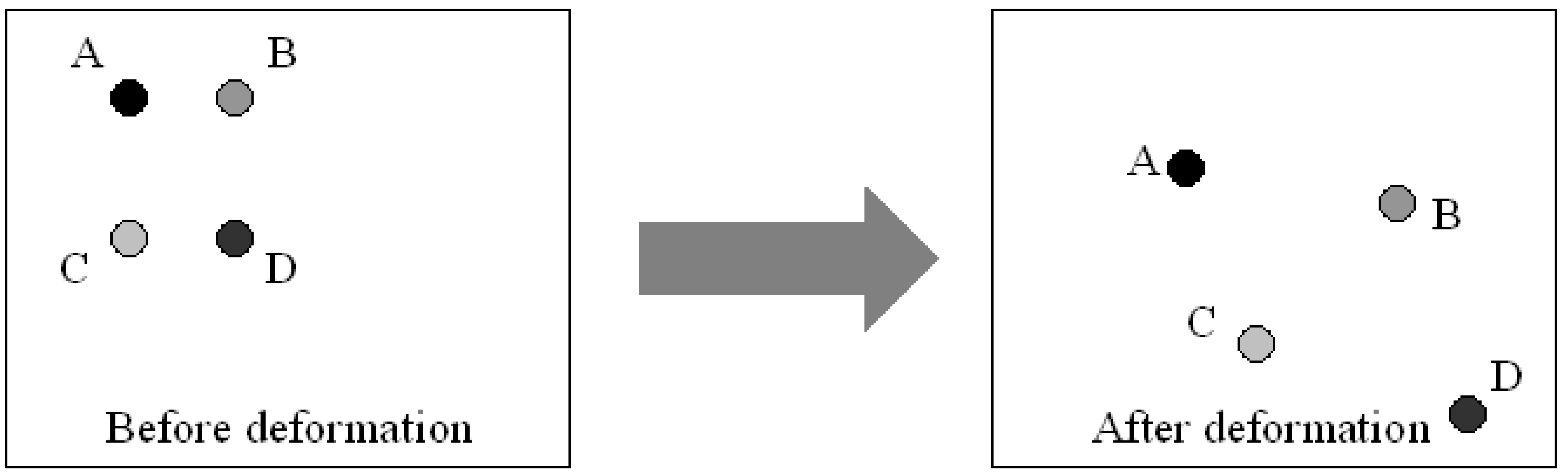
Digital Image Correlation

- Is an optical method that uses a mathematical correlation analysis to examine digital image data taken while samples are in mechanical tests.
- Capture consecutive images with a digital camera during the deformation period to evaluate the change in surface characteristics and understand the behavior of the specimen while is subject to incremental loads.
- To apply this method, the specimen needs to be prepared by the application of a random dot pattern (speckle pattern) to its surface.



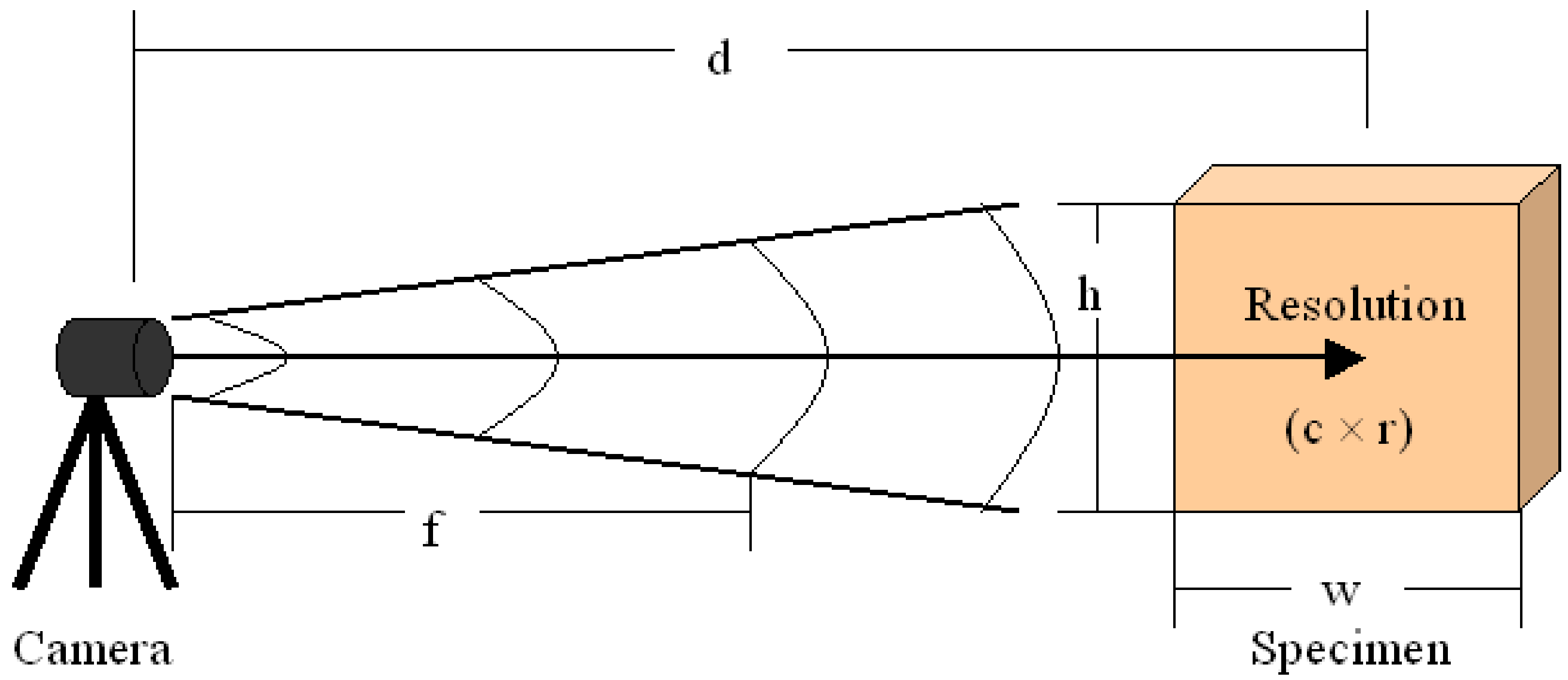
The Technique

- This technique starts with a picture before loading (reference image) and then a series of pictures are taken during the deformation process (deformed images).
- All the deformed images show a different random dot pattern relative to the initial non-deformed reference image.
- With computer software these differences between patterns can be calculated by correlating all the pixels of the reference image and any deformed image, and a strain distribution map can be created.



The Setup

- Optimal results depend on image resolution, width and height of specimen, distance between camera and specimen, focal length and speckle pattern.

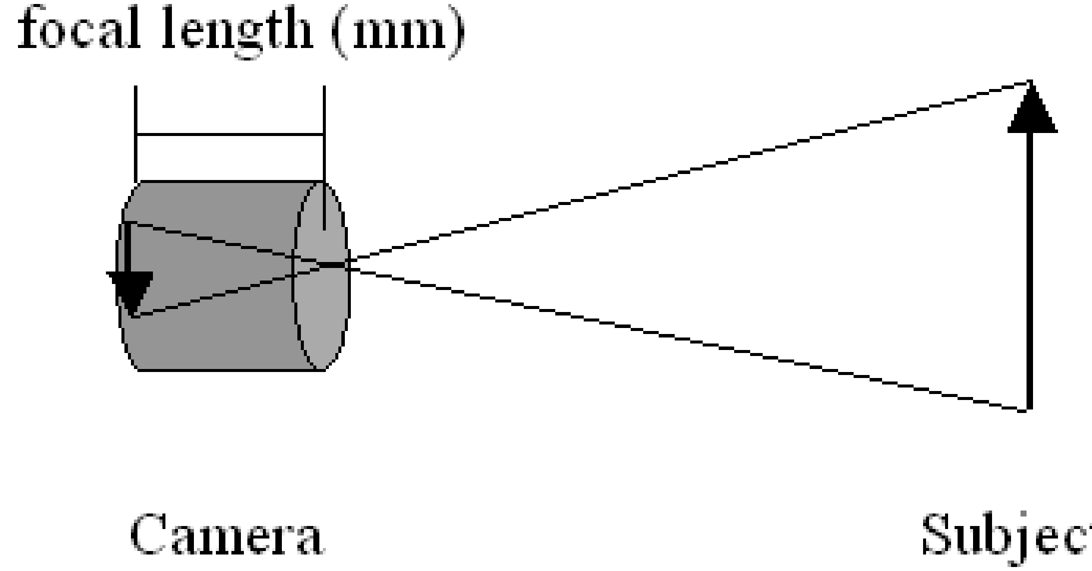


Focal Length and Distance between Camera and Specimen

It is important to determine adequate distance and lens.

The three categories are wide-angle lens (focal length < 35 mm), normal lens (35 mm < focal length < 55 mm) and telephoto lens (focal length > 55 mm).

The higher the focal length, the closer the image is going to be registered in the digital camera.



Distortion Effects

- The distortion can be defined as the lens defect that produces an imperfect image. Distortion effects can appear when the lens is zoomed. Zoom lenses at their maximum wide-angle (28 mm) or telephoto (> 80 mm) setting can be affected by barrel or pincushion distortions, respectively.
- To avoid distortion effects, the images need to be centralized.

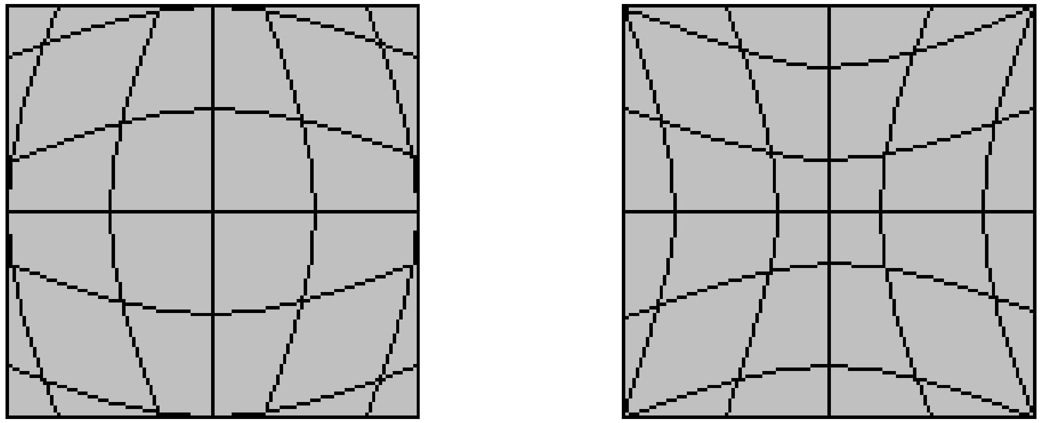
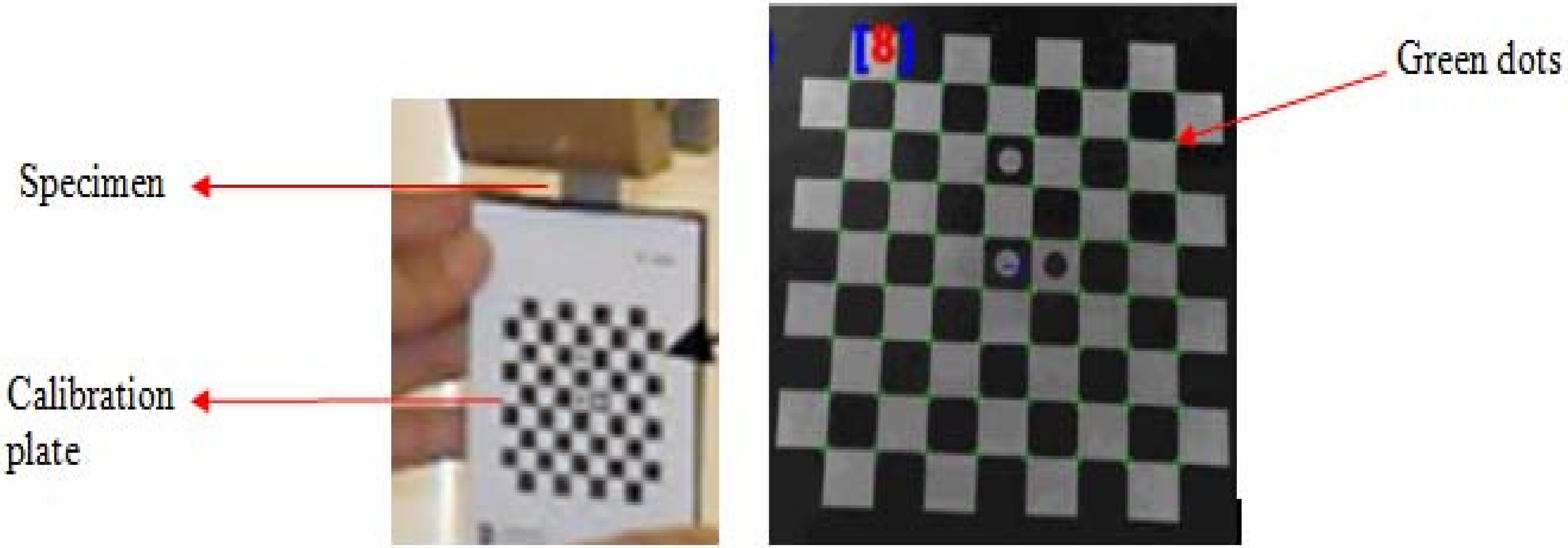


Figure 1.8: Barrel (left) and pincushion (right) distortion.

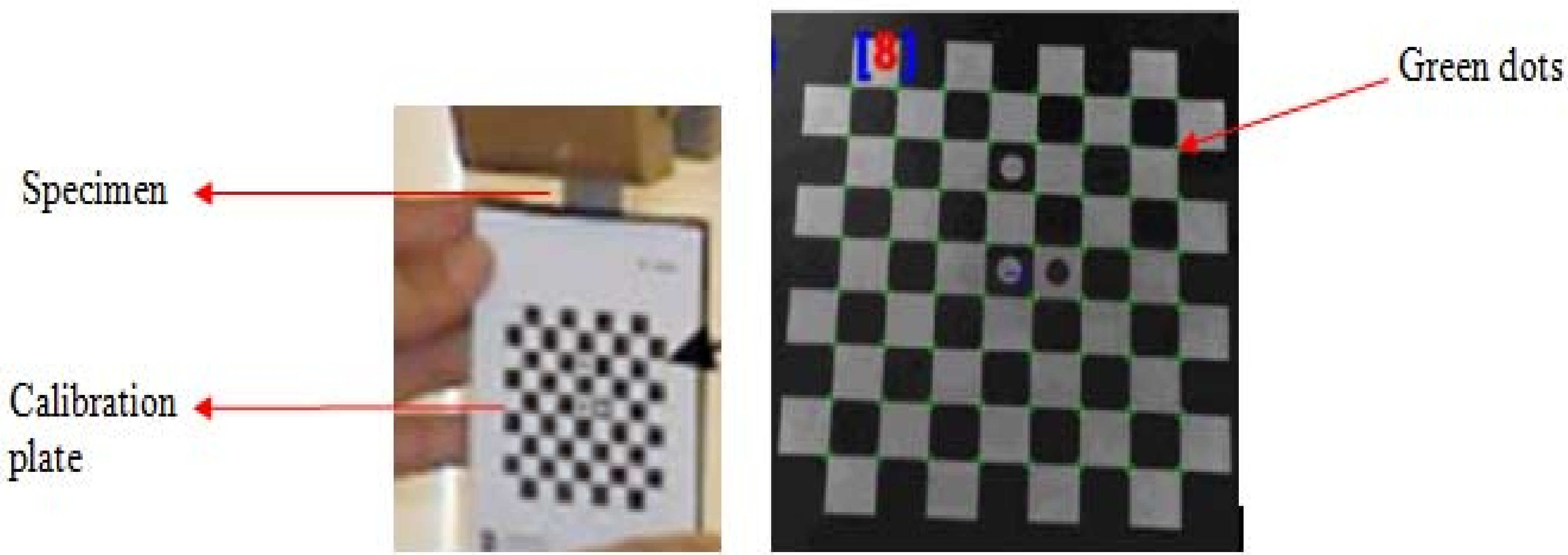
Camera Calibration

- Calibrating the DIC system is a key process to ensure that the measured results are accurate.
- DIC calibration gives the information to relate the ideal model of camera to the actual physical device and to determine the position and orientation of the camera with respect to a world reference system.
- This information includes two kinds of parameters, intrinsic parameters and extrinsic parameters.



Camera Calibration

- The intrinsic parameters indicate the internal geometric and optical characteristics of the camera, such as focal length of the lenses, distortions of the lenses, and the positions between the lenses and CCD image device.
- The extrinsic parameters indicate the external geometric relation between the camera and the specimen, such as rotation matrix and translation vector.
- The calibration plate should be placed in the same plane as that of the CCD chip of the camera and at a same distance as that of the specimen or in front of the specimen as shown below.



Speckle Pattern

- The specimen surface to be studied must have a random dot pattern.
- The speckle pattern is essential, because it permits the software to be able to identify and calculate the displacements with accuracy.
- To obtain accurate results with the digital image correlation it is important to get an adequate speckle pattern.
- An adequate speckle pattern must have a considerable quantity of black speckles with different shapes and sizes.
- The effectiveness of the speckle pattern can be determined by the quantity of pixels per black speckle. A good speckle pattern must have small black speckles (10 pixels), medium black speckles (20 pixels) and large black speckles (30 pixels).

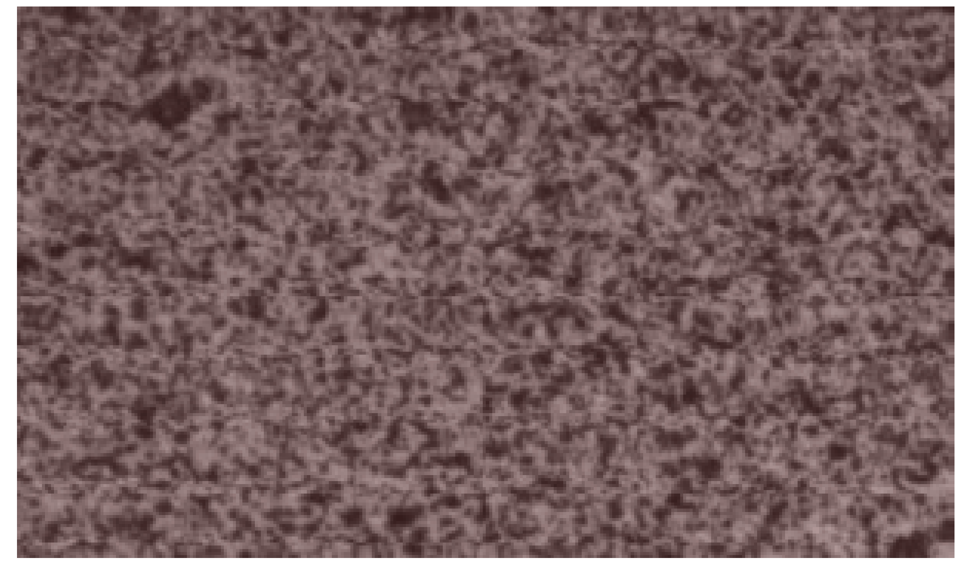


Figure 1.9: A good speckle pattern

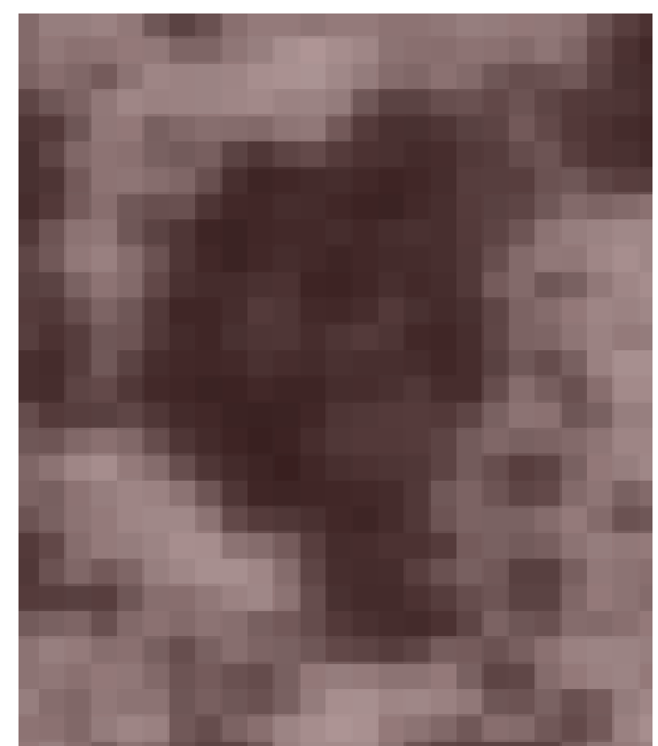
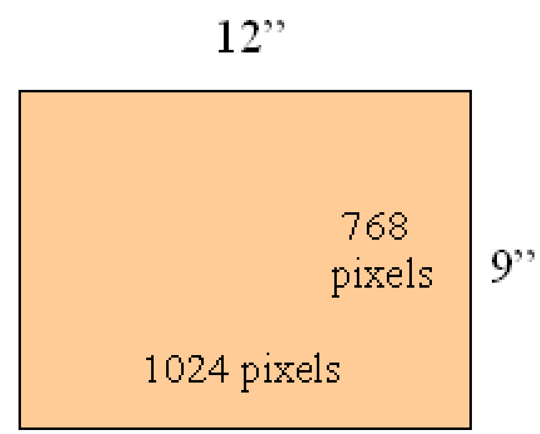


Figure 1.10: A medium black speckle zoomed. The black speckle has approximately 15 pixels wide and 20 pixels high.

Speckle Pattern

Speckle dot size

$$\zeta = p \times \varsigma$$



$$\varsigma_w = \frac{w}{c} = \frac{12}{1024} = 0.012\, {}^{inch}\!/_{pixel} \qquad \varsigma_h = \frac{h}{r} = \frac{9}{768} = 0.012\, {}^{inch}\!/_{pixel}$$

Small → $\zeta = p \times \varsigma = 10 pixels \times 0.012\, {}^{inch}\!/_{pixel} = 0.12 inch$

Medium → $\zeta = p \times \varsigma = 20 pixels \times 0.012\, {}^{inch}\!/_{pixel} = 0.24 inch$

Large → $\zeta = p \times \varsigma = 30 pxels \times 0.012\, {}^{inch}\!/_{pixel} = 0.36 inch$

The Theory

Calculate the average gray scale intensity over the subset in the reference image and deformed image and compare them. Eq. 1 shows the basic form of the cross-correlation term using the two consecutive images.

$$c(u,v) = \sum_i \sum_j L_1(r_i, s_j) L_2(r_i + u_L, s_j + v_L) \qquad (1)$$

$$u_L = u + \frac{\partial u}{\partial r} \cdot (r_L - r_C) + \frac{\partial u}{\partial s} \cdot (s_L - s_C) \qquad (2)$$

$$v_L = v + \frac{\partial v}{\partial r} \cdot (r_L - r_C) + \frac{\partial v}{\partial s} \cdot (s_L - s_C) \qquad (3)$$

Here, u and v are the in-plane displacements of the center points of a subset located at (r_C, s_C), and uL and vL are the displacements of an arbitrary point (r_L, s_L) in the subset. L_1 represents the intensity of subset pixels in the reference image. L_2 represents the intensity of pixel in the deformed image. Solving for the variables u and v gives the in-plane deformation in the x direction and y direction, respectively.

The Theory

A more accurate approach is the normalized correlation equation.

$$C(u,v) = \frac{\sum_i \sum_j L_1(r_i, s_j).L_2(r_i + u_L, s_j + v_L)}{\sqrt{\sum_i \sum_j L^2{}_1(r_i, s_j) \sum_i \sum_j \; L_2{}^2(r_i + u_L, s_j + v_L)}} \qquad (4)$$

In the Equation (4) the normalized correlation coefficient C (u, v) reaches its maximum at one. The in-plane displacements can be determined by identifying a subset around a point at one position in the reference image and comparing it to the subset around a point in the deformed image having the same intensity distribution.

The Theory

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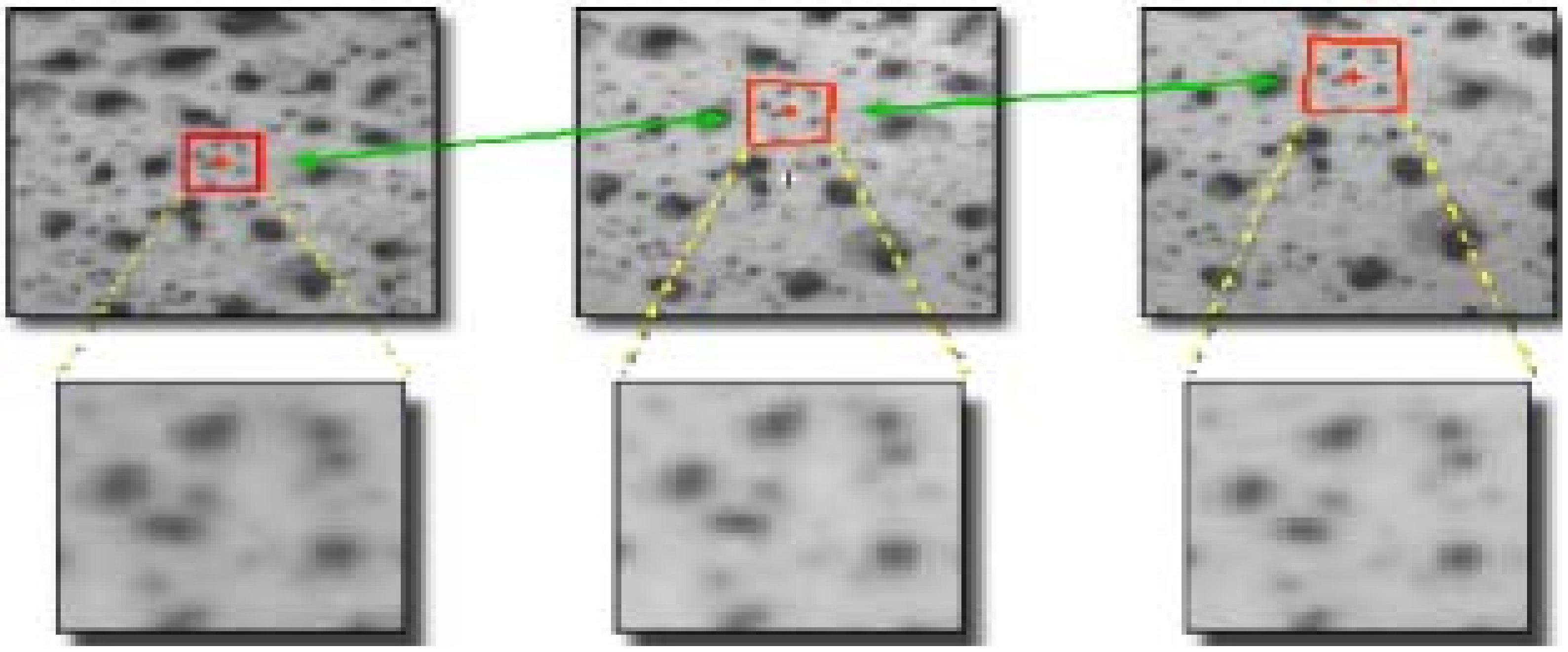

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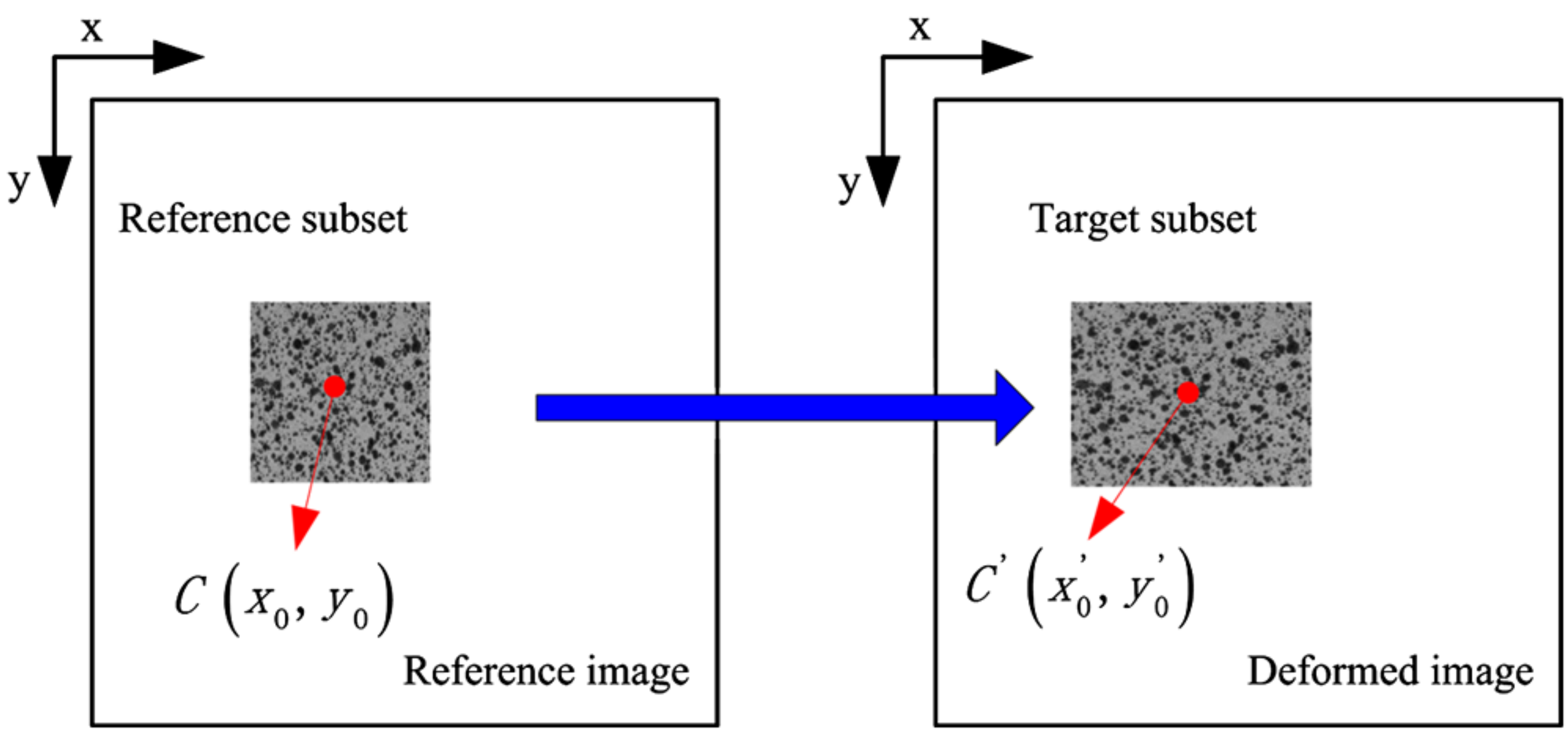

The Theory

Most sophisticated algorithms optimize correlation results with illumination compensation and affine transformations.

$$G_t(x_t,y_t) = g_0 + g_1 G(x_t,y_t)$$

and

$$x_1 = a_0 + a_1 x + a_2 y + a_3 xy$$
$$y_1 = a_4 + a_5 x + a_6 y + a_7 xy$$

Within the correlation algorithm the difference

$$\sum (G_t(x_t,y_t) - G(x,y))^2$$

of these patterns is minimized.

By varying the illumination parameters

(g_0 , g_1)

and the parameters of the affine transformation

$(a_0,\ldots,a_7)$

a matching accuracy of better than 0.01 pixel can be achieved.

http://www.dantecdynamics.com/measurement-principles-of-dic

The Theory

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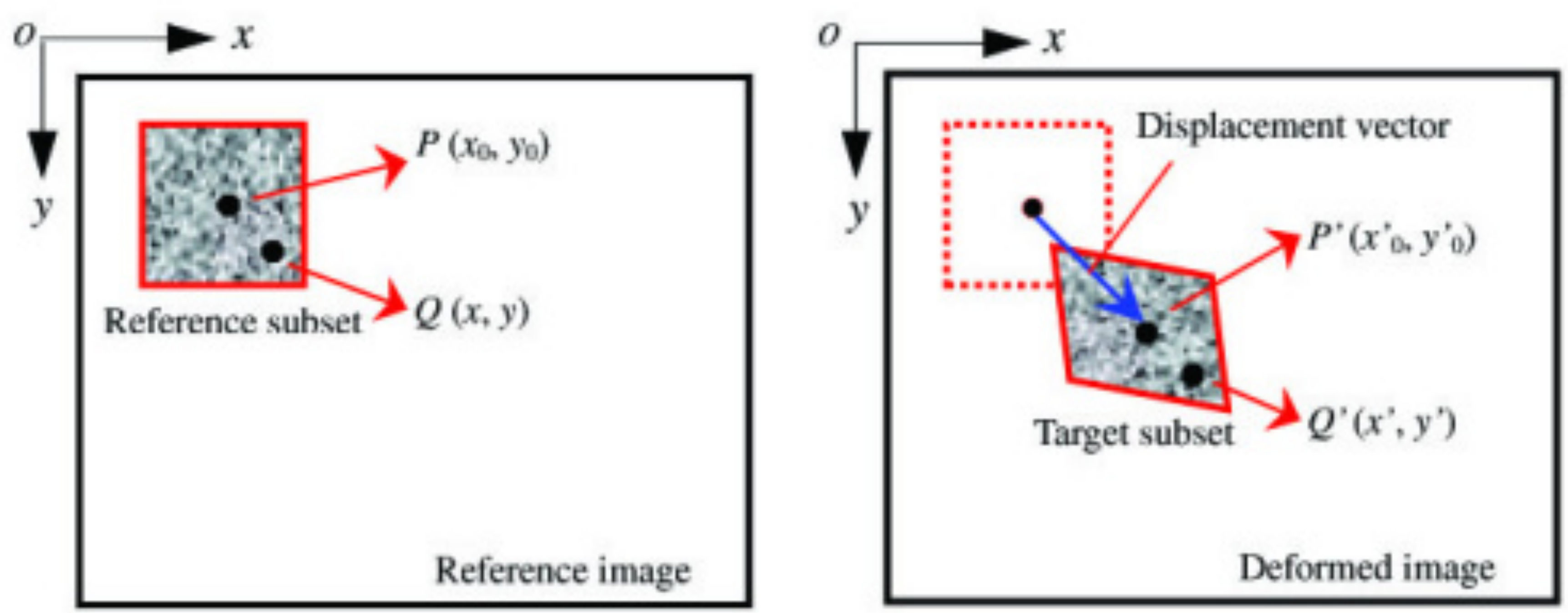


The Theory

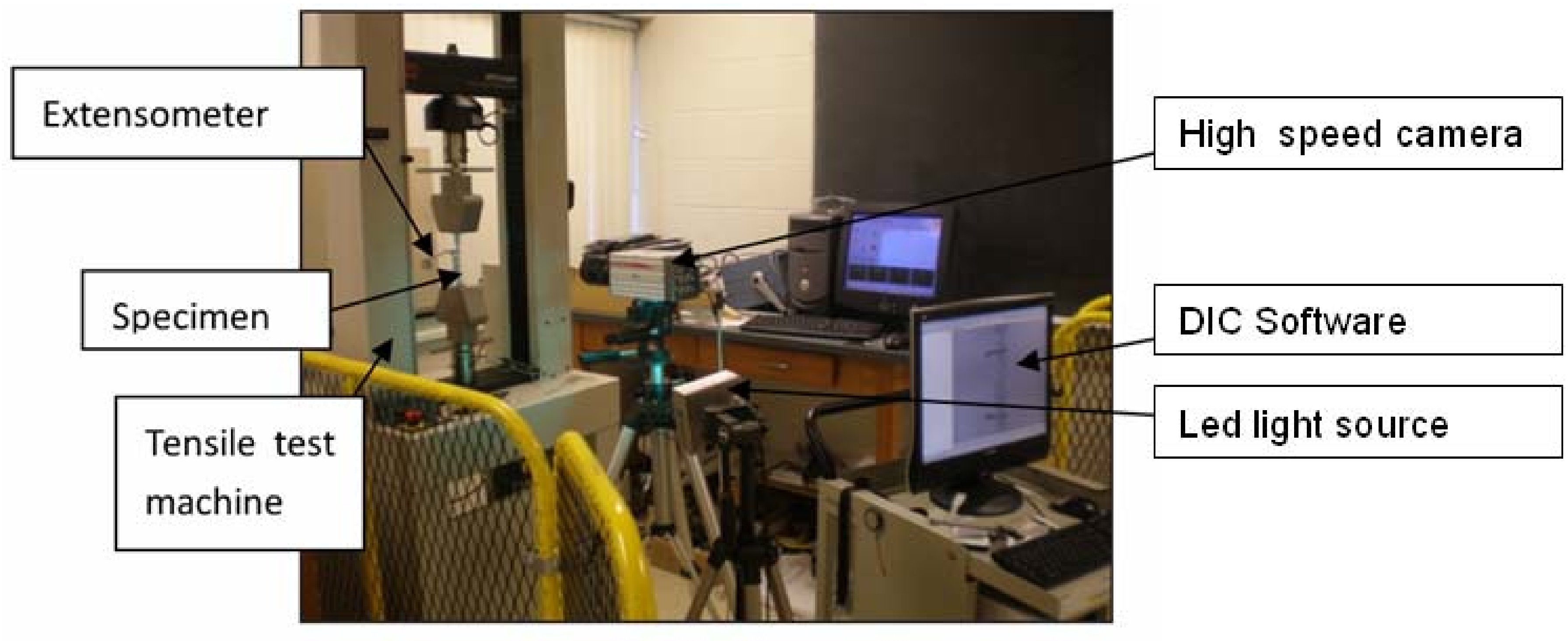
- Like a strain gauge is zeroed to an "undeformed" condition and then used as reference, the first image is used as reference.
- DIC provides experimental data that is directly comparable to Finite Element simulations.
- Triangulation between two cameras is used to determine location in z-direction.

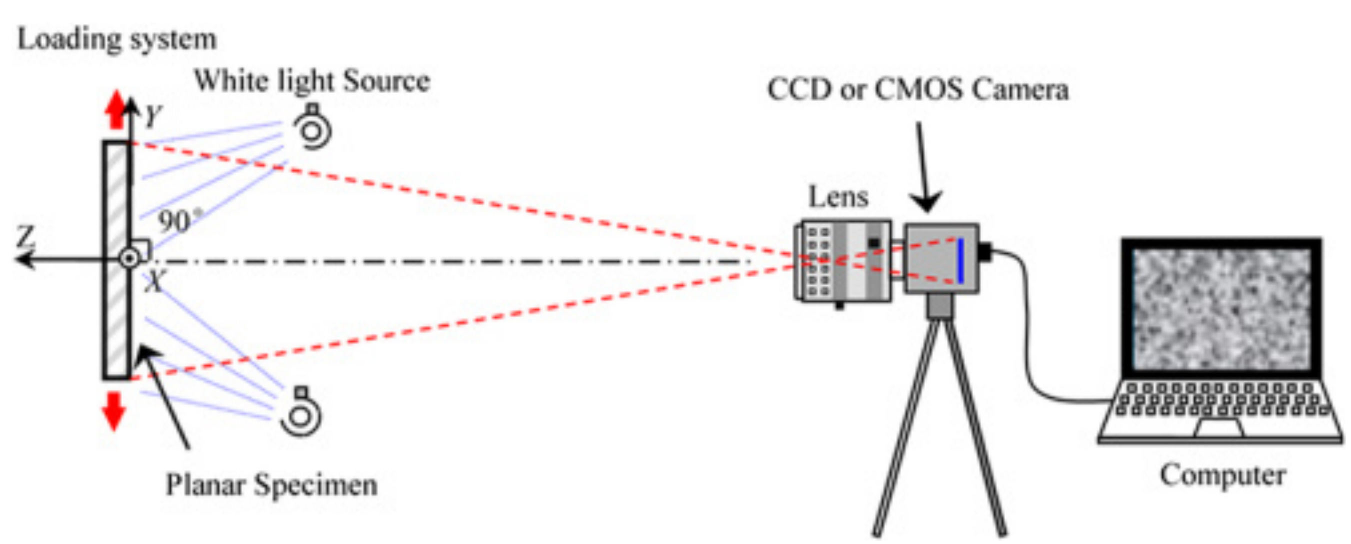
Experimental setup

Figure 2.2: Applying speckle pattern.

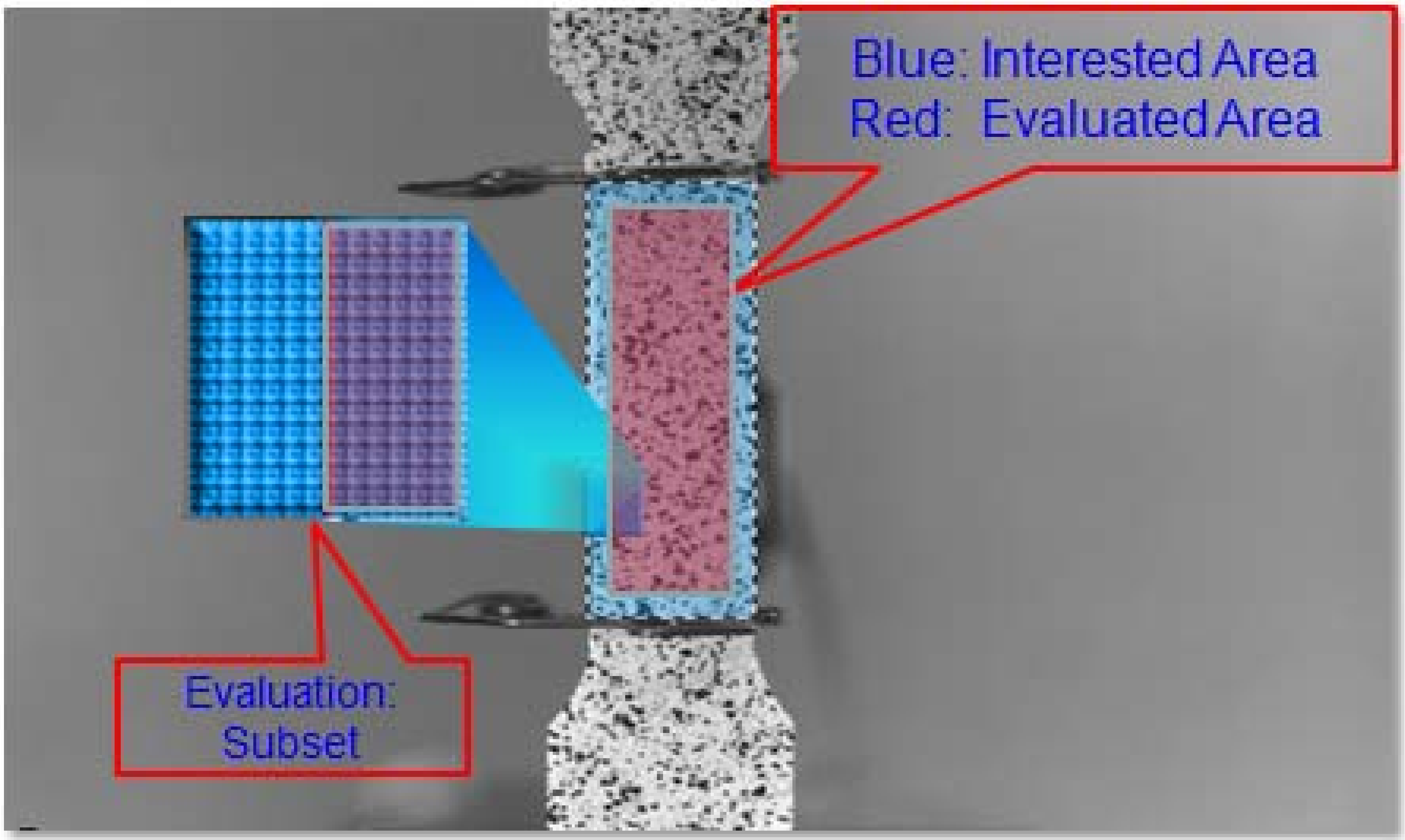
Figure 2.3: Measuring of the black speckles length.

Experimental setup





Experimental setup



Experimental setup

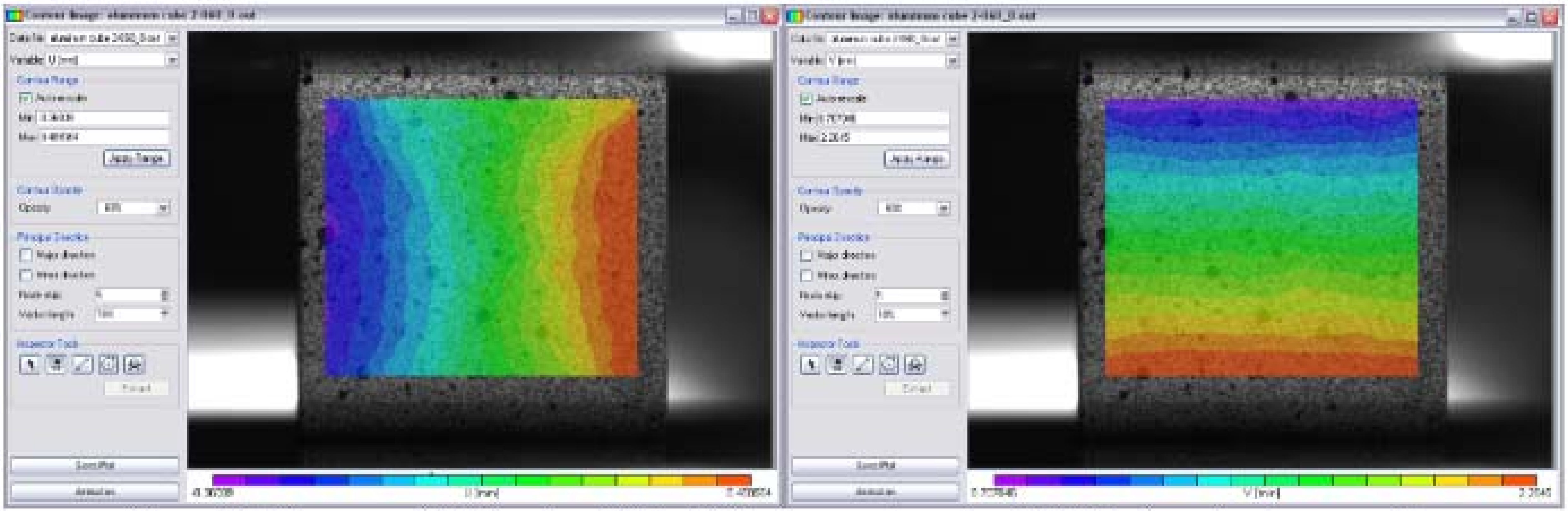


Figure 3.1: Transversal (left) and axial (right) displacement map in a 1×1×1 inches aluminum sample.

Experimental setup

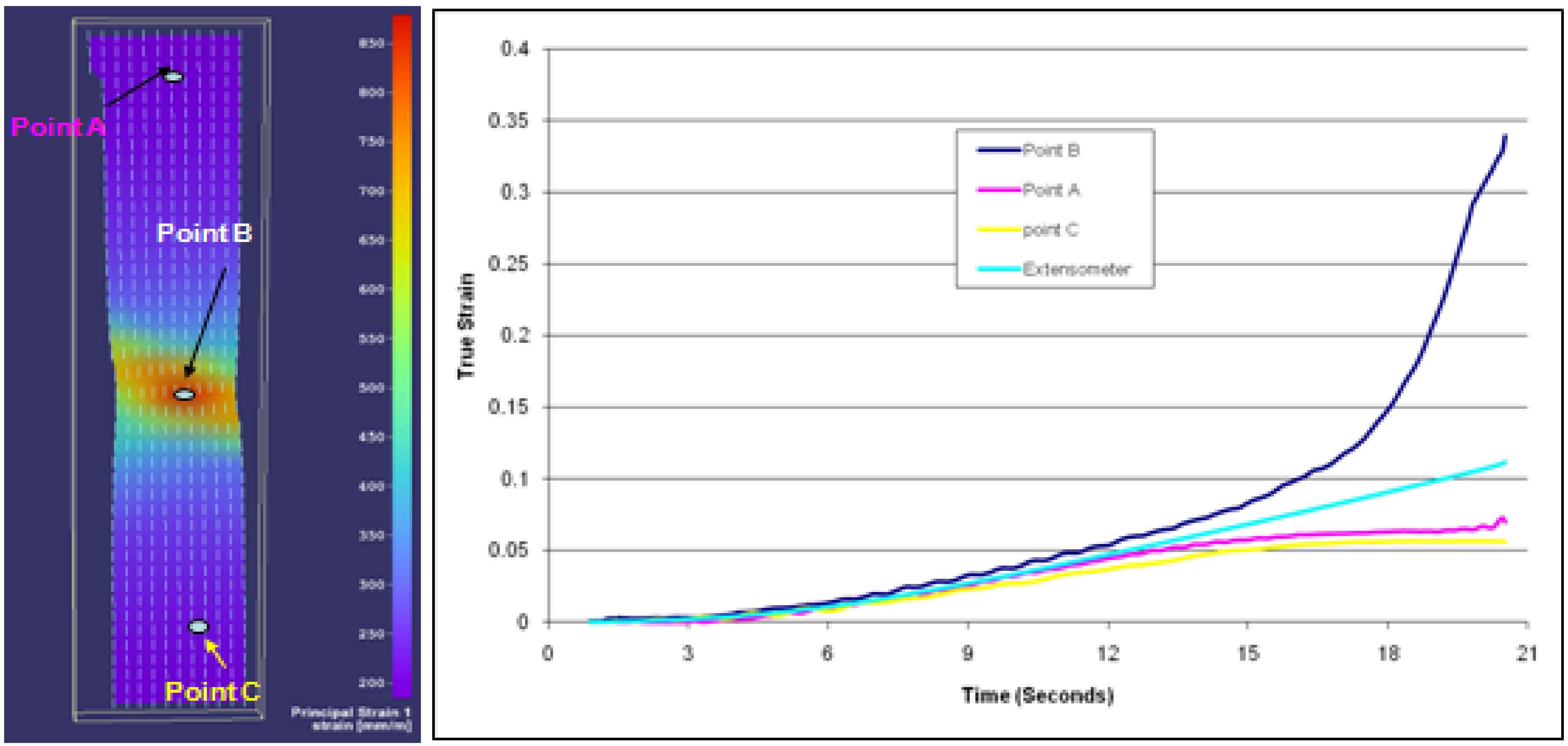


Fig. 6 Strain-time profile of DP600 with DIC and extensometer

DIC overview

Advantages

- Non-contact measurement.
- Rich-data, over 10000 points in surface.
- Analysis is done in post processing.
- Provides information for shape, position, displacement, and strain.
- Calibration technique ensures high accuracy.
- Not affected by rigid body motion.

Disadvantages

- Cannot measure existing damage.
- Must have a clear line of sight by camera.

Software

- Open source Python package SPAM - Software for the Practical Analysis of Materials https://ttk.gricad-pages.univ-grenoble-alpes.fr/spam/intro.html
- Open source 2D-DIC Matlab. http://www.ncorr.com/
- Improved Digital Image Correlation (DIC), Elizabeth Jones. http://www.mathworks.com/matlabcentral/fileexchange/43073-improved-digital-image-correlation--dic-
- 2D and 3D DIC. Correlated solutions. http://www.correlatedsolutions.com/

(Optional) activity

- Analyze two data-sets with the Improved Digital Image Correlation (DIC) toolbox.
  - Dataset 1: An experimental data set used for illustration in the DIC toolbox.
  - Dataset 2: Simulation data of ideal strain.