

# Physical Imaging of Bone Sequential Light Microscopy Observations

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**Résumé** — We propose to evaluate the precision of Digital Image Correlation applied to sequential light microscopy observations of fracturing human Haversian cortical bone. The displacement field on the surface of 3D samples is tracked using a cross-correlation formulation. Due to the potential high number of sequential observations, this study focuses on evaluating displacements at a given growth step obtained by direct comparison of the studied step and the undeformed initial state or by iterative comparisons of successive pairs of observations.

**Mots clés** — digital image correlation, imaging, fracture, toughness, contact, bone.

## 1 Introduction

The experimental setting monitors and characterises micro cracks in bone by successive light microscopy observations of the surface of human Haversian cortical bone millimetric 3D samples. The subsequent construction of a mechanical model is made possible by measuring mathematically compatible displacements that become the essential boundary conditions of a finite element model [1]. The displacements are measured using a zero-centered normalised cross-correlation formulation that suppresses differences in average luminosity and contrast between the reference and the deformed observations [2, 3, 4, 5] :

$$C^k = 1 - \frac{\sum_{i \in (\Omega_c^k, \omega_c^k)} (f(\mathbf{X}_i) - \bar{f}_{\Omega_c^k}) (g(\mathbf{x}_i) - \bar{g}_{\omega_c^k})}{\sqrt{\sum_{i \in \Omega_c^k} (f(\mathbf{X}_i) - \bar{f}_{\Omega_c^k})^2} \sqrt{\sum_{i \in \omega_c^k} (g(\mathbf{x}_i) - \bar{g}_{\omega_c^k})^2}} \quad (1)$$

where  $\mathbf{X}_i$  and  $\mathbf{x}_i$  are the pixel/subpixel coordinates of a point  $i$  in the reference picture  $S_0$  and the deformed picture  $S_n$  respectively.  $f$  and  $g$  are the grey-level of pixel/subpixel  $i$  in  $S_0$  and  $S_n$  respectively.  $\bar{f}_{\Omega_c^k}$  and  $\bar{g}_{\omega_c^k}$  are the average grey-levels on the correlation domain in  $S_0$  and  $S_n$  respectively.

Because such experiments generate numerous successive observations, this study focuses on two alternative procedures where the method is applied either directly between an initial and the considered observations or gradually between successive pairs of images.

## 2 Methodology

The displacements are evaluated at a given crack growth step either by direct comparison of the studied step and the undeformed initial state or by iterative comparisons of successive pairs of observations. The cross-correlation formulation is applied for the correlation between grey-level intensities [6] where the subpixel precision is achieved by means of a gradient-based descent algorithm [2] that is reliable for large grey-level discontinuities and using full optimisation [7, 8, 2, 4, 5]. In each correlation domain centered around a studied points, the local displacement field is most commonly assumed bilinear on the sample surface [9, 10, 2, 3], which supposes that the local deformations are homogeneous. Because bone is an heterogeneous material, a domain partitioning algorithm is necessary and coupled to the digital image correlation.

In the gradual correlation procedure, two cases are studied. In one case, the deformation gradient between a first and second images determines the analogous domain between this first pair of images ; this domain is used to calculate the correlation between the following pair of images composed of the second and third images. In the other case, the correlation between the second and third images is calculated in

the same manner as between the first pair of images by using a circular correlation domain of predefined radius in the second image. Additionally the precision of the procedures is assessed in images generated or “simulated” by controlled uniform deformations and compared when applied to “experimental” observations.

### 3 Results

In order to compare the accuracy between cross-correlation methods, three indicators are calculated. The first indicator is the evolution of the coefficient of correlation is first studied in the frame of direct and gradual analysis for a series of images. The second indicator is the average difference in displacements calculated by cross-correlation methods and visual measurements. The third indicator is the “error map” of the normalised difference in displacement calculated by cross-correlation methods and visual measurements. - In the case of the analysis of four consecutive crack growth step, the reference average difference in displacements calculated by cross-correlation methods and visual measurements varies from 0.29 and 0.85 percent for direct and gradual correlation in “simulated” images. The average difference in displacements calculated by cross-correlation methods and visual measurements in experimental images varies from 3.8 and 3.7 percent for direct and gradual correlation. The error maps are shown in Fig 1

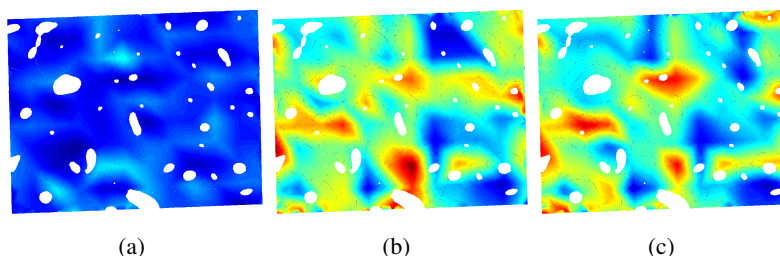


FIG. 1 – Maps of normalised displacement error in “simulated” images for (a) direct cross-correlation, (b) gradual cross-correlation retaining the deformed domain of correlation, (c) a gradual cross-correlation where the correlation domain in the first image is set circular.

### Références

- [1] E. Budyn, T. Hoc. *Analysis of micro fracture in human Haversian cortical bone under transverse tension using Extended Physical Imaging*, International Journal for Numerical Methods in Engineering, 82(8), page 940-page 965, 2009.
- [2] P. Doumalin, M. Bornert, J. Crépin. *Characterization of the strain distribution in heterogeneous materials*, Méc Ind, 4, page 607-page 617, 2003.
- [3] J. Zhang, G. Jin, S. Ma, L. Meng. *Application of an improved subpixel registration algorithm on digital speckle correlation measurement*, Optics and Laser Technology, 35, page 533-page 54, 2003.
- [4] N. Lenoir, M. Bornert, J. Desrues, P. Bésuelle, G. Viggiani. *Volumetric Digital Image Correlation Applied to X-ray Microtomography Images from Triaxial Compression Tests on Argillaceous Rock*, Strain, 43, page 193-page 205, 2007.
- [5] A. Germaneau, P. Doumalin, J. C. Dupré. *Full 3D measurement of Strain Field by Scattered Light for Analysis of Structures*, Experimental Mechanics, 47, page 523-page 532, 2007.
- [6] M. A. Sutton, W. Wolters, W. J. Peters, W. F. Ranson, S. R. McNeill. *Determination of displacements using an improved digital image correlation*, Image and Vision Computing, 1, page 133-page 139, 1983.
- [7] W. H. Peters, W. F. Ranson, J. F. Kalthoff, S. R. Winkler. *A study of dynamic near-crack-tip fracture parameters by digital image analysis*, Journal de Physique, Colloque C5, page 631-page 638, 1985.
- [8] S. R. McNeill, W. H. Peters, M. A. Sutton. *Estimation of stress intensity factor by digital image correlation*, Engineering Fracture Mechanics, 28, page 101-page 112, 1987.
- [9] T. C. Chu, W. F. Ranson, M. A. Sutton, W. H. Peters. *Applications of Digital-Image-Correlation Techniques to Experimental Mechanics*, Experimental Mechanics, 25(3), page 232-page 244, 1985.
- [10] H. A. Bruck, S. R. McNeill, M. A. Sutton, Peters III, W. H. *Digital Image Correlation Using Newton-Raphson Method of Partial Differential Correction*, Experimental Mechanics, 29(3), page 261-page 267, 1989.