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MEASUREMENTS OF ORIENTATION IN A DISCRETIZED SPACE BY FOURIER TRANSFORM : AUTOMATIC INVESTIGATION OF FIBER ORIENTATION IN A REINFORCED CONCRETE

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ABSTRACT

Usual algorithms implemented on many automatic analyzers to establish the roses of directions are too sensitive to digitization, which can lead to biased results. With usual methods indeed, measurements are conducted at the local 3 x 3 pixel scale. Moreover at that local scale, only 0°, ± 26.5°, ± 45°, ± 63.5° and 92° directions can be selected. As measurements are performed at the scale of the whole image (256 x 256 or 512 x 512 pixels), the incidence of digitization artefacts is considerably decreased. In such a manner it appears that the (Fast) Fourier Transform (FFT) algorithm, whose procedures are described, is a well suited method to give an actual estimate of orientation. Moreover, depending on the accuracy required, a larger number of orientations can be investigated and without any bias. Automatic length measurements are done at a local 3 x 3 pixel scale. The direct use of the FFT can only contribute to reduce the error of length measurements. The examples given in this paper are concerning a civil engineering material: global fiber arrangement was quantified in a concrete reinforced with metallic glass ribbons.

Key words: orientation, digitization, automatic image analysis, rose of directions, Fourier image transform.

INTRODUCTION

It is difficult to achieve correct measurements of orientation of lines in the discretized space defined by the square frame of many automatic image analyzers. Firstly, the Fourier image transform, as a method to quantify orientations, is compared to a computerized usual rose of direction method, in order to show how both are sensitive to digitization artefacts. Secondly, it is shown how the use of the fast Fourier image transform can characterize quickly the global fiber orientation in a fiber reinforced concrete, and how such a morphological information is useful for the civil engineer.

ROSE OF DIRECTIONS AND DIGITIZATION ARTEFACTS

The rose of direction measurement is usually defined in continuous space as the $L_2(X, \alpha)d\alpha$ function. It indicates in polar coordinates the length of the contours of an object X, oriented following the direction range [α, $\alpha \pm d\alpha$], (Coster & Chermant, 1989; Serra, 1982). However, for example, the digitization of an actual line oriented at 14° (dashed line) on a square grid of an automatic image analyzer does not conserve the actual orientation at the pixel scale (Fig. 1), as already mentioned by Chaix and Grillon (1996). This line is then constituted of sequences of 3 pixels oriented at 0° and 3 pixels oriented at 26.5° : so that virtual 0° orientations are taken into account due to the digitization artefacts. To reveal these virtual orientations, one can shift image A, one pixel on the left but also one on the right and the intersect both translated images. All digitized orientations which are not in a 0° direction are not recovered, but only 0° digitized orientations, at least 3 pixels long, are pointed out by a remaining pixel at least. In doing so, working at a 3 x 3 pixel scale, one builds an usual automatic rose of direction algorithm.

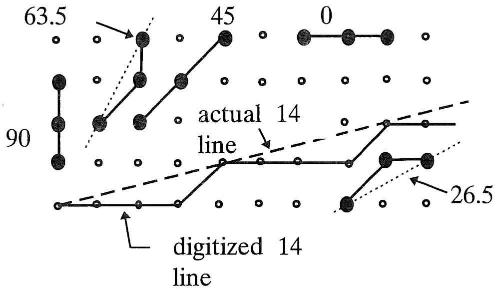

Fig. 1. Discrete square grid, with oriented structural elements defined at the 3 x 3 pixel scale (in black), and digitization artefacts for an actual line oriented at 14°.

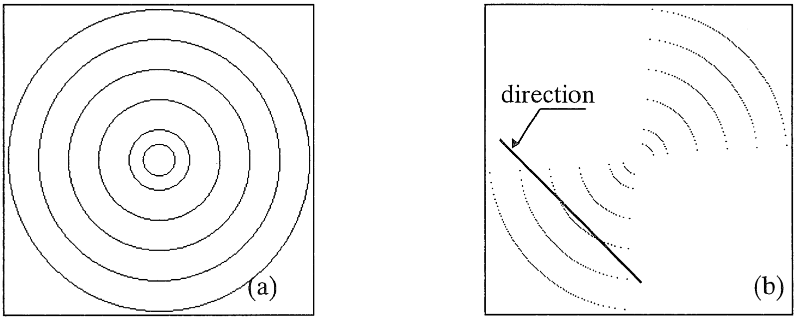

Fig. 2. Chopped portions of digitized circles (a) detected by the usual automatic rose of directions in a 135° direction as orientations are measured at the 3 x 3 pixel scale (b).

This shift-intersection operation can be repeated in the 0°, 26.5°, 45°, 63.5°, 90°, 116.5°, 135°, and 153.5° directions defined in an 8 connexity system. In doing so unexpected 135° orientations (Fig. 2b) have been found in circles, whose diameters are 26, 50, 100, 150, 200 and 250 pixels (Fig. 2a).

The detected discretized circle portions appear chopped in small 135° short segments or isolated pixels which are far from actual 135° tangent lines (Fig. 2b). The number of pixels which should represent the actual 135° direction are then overestimated and the resulting usual rose of directions, automatically calculated, is correct in the digitized space but is biased with regard to reality. Moreover, due to the pixel neighbourhood configuration, such an usual rose of direction technique will be inappropriate if more intermediate directions, different from 0°, ± 26.5°, ± 45°, ± 63.5° and 90° are to be easily quantified.

FOURIER TRANSFORM OF AN IMAGE

On the opposite the Fast Fourier Transform (FFT) should overcome the artefacts due to digitization as it works on the whole image size. The discretized Fourier transform, *X(u,v)*, for *u,v = 0,...., N-1* (*N* corresponding to the image width given by a number of pixels), of a grey level image defined by a bi-dimensional function, *x(k,l)*, is a complex image [Eq.1] :

$$X(u,v)=\frac{1}{N}\sum_{k,l=0}^{N-1}x(k,l)\times e^{-\frac{2i\pi}{N}\times(uk+vl)} \qquad (1)$$

The resulting Fourier spectrum, defined in the frequency domain, of figure 2a is shown in figure 3a. In order to detect a 135° orientation, the inverse Fourier transform (Fig. 3b) is operated using the convolution product *y(k,l)* [Eq. 2], with a symmetrical centered rectangular mask *H(u,v)*, oriented at 45°, (Fig. 3a) :

$$y(k,l)=\frac{1}{N}\sum_{u,v=0}^{N-1}X(u,v)\times H(u,v)\times e^{\frac{2i\pi}{N}\times(uk+vl)} \qquad (2)$$

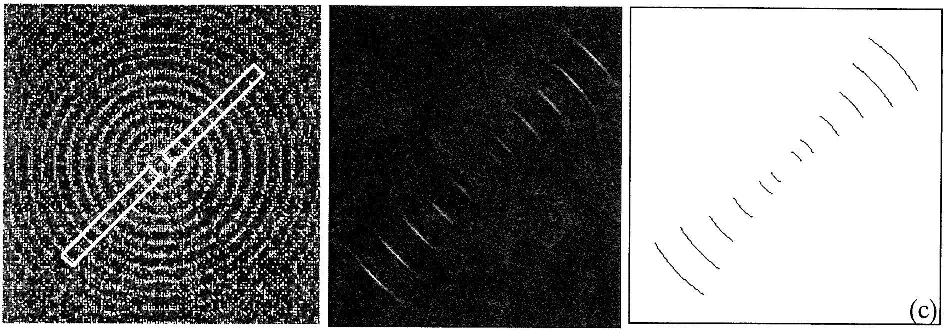

Fig. 3. Illustration of the Fast Fourier Transform algorithm : a) Fourier spectrum and the 45° mask drawn in white ; b) inverse Fourier transform calculated in the 45° mask ; c) the resulting detected continuous portions of circles in a direction close to 135°.

This mask excludes the central image part: this ensures that low frequencies common to all directions are not taken into account. The mask width is manually adjusted, depending on the required accuracy in orientation. The whitest traces in figure 3b materialize the portions of the circles close to the 135° direction. They are then thresholded and intersected with the initial image (cf. Fig. 2a). Thus, long continuous portions of circles close to the 135° direction are selected (Fig. 3c) as one would have intended to do it by a manual process, quite independently on the digitization artefacts, (Gonzalez et al., 1994 ; Redon et al., 1998).

COMMENTS ON THE PRECISION OF AUTOMATIC LENGTH MEASUREMENTS

Either with the FFT or with the usual automatic rose of direction method, automatic length measurements are performed at the pixel scale. Thus length depends on the digitization artefacts anyway. However, as various local 3 pixel orientations are indexed in a same oriented longer portion of line, the Fourier transform length measurements are less misleading, even if it does not deliver exactly an actual length as defined in the corresponding real continuous domain.

However, as compared to the usual rose of direction method firstly described, the investigation of narrow angular sectors, such as 5°, 10°, etc..., is now easily achievable as the FFT operates at the scale of the whole image. Using the FFT algorithm, very precise rose of directions which, for example, evidences the actual isotropy of the circular structure of figure 2a, can be obtained with a limited bias as compared to reality.

INVESTIGATION OF FIBER ORIENTATION IN A REINFORCED CONCRETE

The Fourier transform has been applied every 10° to quantify accurately the fiber orientation in a concrete reinforced by amorphous cast iron ribbons. With two orthogonal series of 2D projected X-ray images of 10 x 10 x 1.5 cm^3 concrete slices (Fig. 4), it is possible to appreciate the global 3D arrangement of the fibers in the hardened volume of concrete.

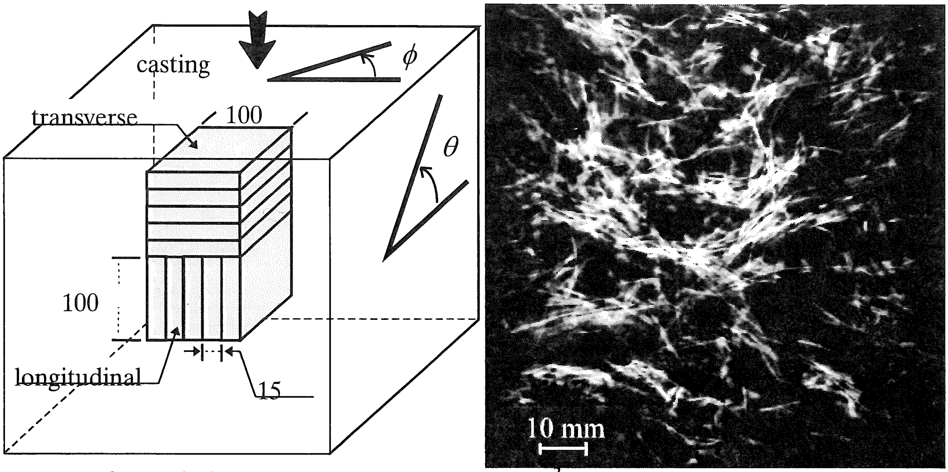

Fig. 4. Scheme of the position of the 10 x 10 x 1.5 cm^3 reinforced concrete slices in a cast fiber reinforced concrete block and X-ray image of a longitudinal FRC slice with large air voids, in black, surrounded by the fibers, in white.

The observed spatial distribution of the fibers is characteristic of a transverse isotropy. The material has a revolution axis, corresponding to its casting axis, (Granju & Ringot, 1989; Redon et al., 1997 a). Indeed, the fiber distribution is isotropic on transverse sections which are perpendicular to the casting axis of the concrete (Fig. 5a). The slight anisotropy observed around $\phi = 15°$ is not significant as the measurements have been conducted on five FRC slices only. However, only a few measurements on five longitudinal FRC slices have revealed that most of the fibers are aligned in quite horizontal directions, orthogonal to the casting axis (Fig. 5b). These "planes of fibers" range between $\theta = 0°$ and $\pm 30°$ angles.

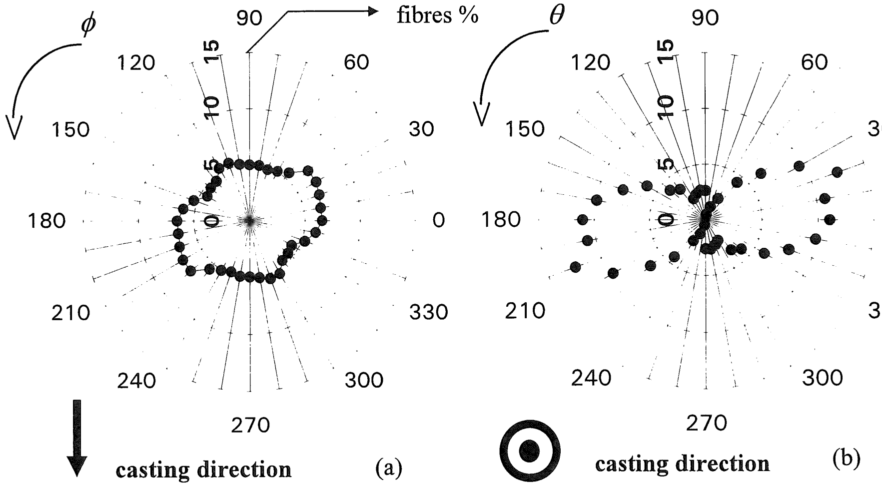

Fig. 5. Orientation of the amorphous cast iron fibers in the hardened concrete : a) in transverse slices (angle ϕ) ; b) in longitudinal slices (angle θ).

MECHANICAL CONSEQUENCES OF THE FIBER ARRANGEMENT

The origin of the transverse isotropic arrangement of the fibers is obvious. Indeed, during the casting, fibers are subjected to gravity forces of the above concrete. This gravity effect is also enhanced by the vibration, by the ribbon shape of these metallic glass fibers, $30 \times 1.6 \times 0.03$ mm^3 in size, and by an increase of workability (Debicki, 1988; Rossi et al., 1989). As a consequence, these fibers act as barriers, preventing air extraction during the vibration of the fresh mix. The small air bubbles coalesce when they meet a ribbon and form large horizontal pores, as it can be seen particularly on X-ray images (cf. Fig. 4).

This explains why the compression strength of such a FRC is lower than those of ordinary concrete elaborated with the same constituents (Redon, 1997; Redon et al., 1996). Under uniaxial compression, this anisotropic fiber distribution also induces a strong anisotropic damage process (Rossi et al., 1989; Redon et al., 1997 b). Concrete/fiber debonding is favored when compression is directed following the "planes of fibers", whereas damage is delayed by a microcrack bridging process as compression is applied perpendicular to these planes. On the opposite, in tension, the fibers should be oriented along the axis of tension.

CONCLUSION

The advantages of the Fourier image transform have been evidenced as this method allows to quantify orientations automatically without being sensitive to digitization artefacts. This method offers the advantage to work within a fast algorithm, which gives access to the quantification of a large number of orientations. At the 3 x 3 pixel scale, only orientations following the 8 orientations of the square frame could have been evidenced. However, for both methods, length measurements are difficult to achieve as anyway they have to be conducted at the pixel level.

However, through the civil engineering example presented in this paper, it is evidenced and characterized that a fast and automatic treatment of orientations has reveled a material anisotropy, from few parameters and measurements. Such an information is of prime importance for the civil engineer who is interested in the consequences of the casting procedure of the fiber reinforced concrete on its mechanical properties.

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REFERENCES

Chaix JM, Grillon F. On the rose of directions measurements on the discrete grid of an automatic image analyser. J Microsc 1996; 184: 208-213.

Coster M, Chermant JL. Précis d'analyse d'images. 2nd edition, Les Presses du CNRS, 1989.

Debicki G. Contribution à l'étude du rôle de fibres dispersées anisotropiquement dans le mortier de ciment sur les lois de comportement, les critères de résistance et la fissuration du matériau. Thèse de Doctorat ès Sciences, University of Lyon I, 1988.

Gonzalez LM, Cumbrera F, Sanchez-Bajo F, Pajares A. Measurement of fiber orientation in short-fiber composites. Acta Metall Mater 1994; 42 : 689-694.

Granju JL, Ringot E. Amorphous iron fiber reinforced concretes and mortars, comparaison of the fiber arrangement. Acta Stereol 1989; 8 : 579-584.

Redon C. Morphologie et comportement mécanique de bétons renforcés par des fibres de fonte amorphe. Thèse de Doctorat of the University of Caen, 1997.

Redon C, Chermant JL, Quenec'h JL. Characterization of the macroporosity of concretes using an automatic image analysis. Proc. Intl. Symp. on Brittle Matrix Composites 5, BMC 5, Brandt AM, Li VC, and Marshall IH, Warsaw, Oct. 13-15th 1997 a; pp 291-299.

Redon C, Chermant L, Chermant JL. A mechanical damage model based on the measurement of microcrack orientation in concrete by Fourier transform. Acta Stereol 1997; 16 : 287-292.

Redon C, Quenec'h JL, Chermant L, Chermant JL. Influence of superplasticizer and metallic glass ribbons on the macroporosity and the compressive strength in concrete. Acta Stereol 1996; 15 : 233 -239.

Redon C, Chermant L, Chermant JL, Coster M. Assesment of fibre orientation in reinforced concrete, using Fourier image transform, J Microsc 1998; in press.

Rossi P, Harrouche N, Le Maou F. Comportement mécanique des bétons de fibres métalliques utilisés dans les structures en béton armé et précontraint. Ann ITBTP 1989; 479 bis : 165-183.

Serra J. Image Analysis and Mathematical Morphology. Academic Press, 1982.

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