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An Image Based Method for Characterising the Mechanical Behaviours of Fabrics. Part I: The Measurement of In-plane Tensile Behaviour

Abstract
The characterisation of fabric mechanical properties including tensile, bending, shearing, compressing and fracture was investigated by an image based method. In this paper, an in-plane strain-stress measurement system was built using the Kawabata Evaluation System (KES) attached to a set of image digitalisation and analysis modules. The trajectory tracking method based on image analysis was used to calculate the displacement and distortion of reference points printed on a fabric surface under a certain load, so as to determine the displacement and strain distribution field of the specimen. The two-dimensional displacement distribution field and related parameters were used to define the in-plane deformation of fabrics instead of the traditional one-dimensional strain-stress curve. The relationship between strain values determined by the Kawabata Evaluation System and those obtained by the image-based method was analysed, and the experimental results show that the image-based method is effective and simple to characterise both the global and local strains two dimensionally.

Key words: *fabrics, mechanical properties,image-based method, displacement, shape deformation, Kawabata Evaluation System.*

Introduction

Understanding of the mechanical behaviour of materials is very important for scientists to investigate the nature of materials. Scientists usually use a strain-stress curve or a polar diagram to describe a mechanical response under a certain load [2 - 4, 6]; however, the measurement of local strain variation and anisotropy seems to be difficult when using this simple direct contact method. With the development of digital techniques, image analysis is becoming extremely popular in experimental measurement and industry quality control. This may also be due to the large availability of low-cost, easy- to-use hardware and software facilities for digital image acquisition, recording and processing. So it is possible for us to apply image analysis to determine the two-dimensional or three-dimensional local deformation of materials accurately and easily.

In the last decade, some researchers have proposed successful non-contacting optical techniques based on image correlation techniques [7 - 10]. They have been applied to the measurement of displacements and strains. The technique utilises two similarly speckled images, which were captured by a solid state video camera, to represent the states of the object before and after deformation. By utilising the concept of image correlation, it can calculate the displacement of each speckle. The computer vision aided technique has the advantages of a simple system and direct image sensing of 2D/3D surface change during stretching, bending or other related deformation, and thus full 2D/3D field strain distribution of a sample surface could be extracted instead of traditional one dimensional strain curve recoding.

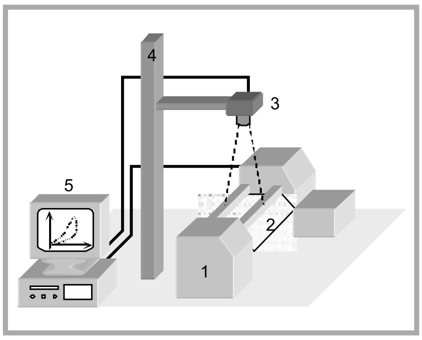

Figure 1. *Schematic of image capturing system for in-plane tensile measurement; 1) KES-FB1, 2) specimen, 3 digital camera, 4) stage, 5) computer.*

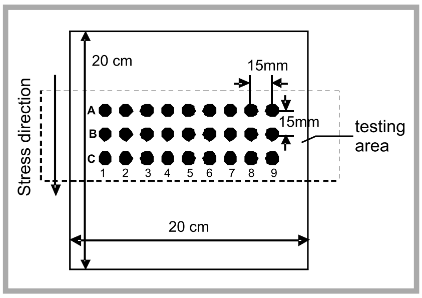

Figure 2. *Reference points printed on the specimen surface.*

However, few papers related to the application of image analysis on the characterisation of fabric mechanical properties including stretching, bending, shearing and other related deformations could be found in this area till now. Since the measurement of strain and stress has always been an important and classical factor in the evaluation of fabric properties and experimental stress analysis, more research needs to be focused on this topic by introducing new testing techniques and concepts, which would facilitate scientists in investigating the essential mechanism of textile materials.

In this paper, we present a testing method based on image analysis techniques to determine the tensile behaviour of fabrics. Firstly, we established a digital dynamic image system to capture the image sequences of testing specimens during tension, and develop a set of image analysis algorithms to calculate the strain distribution field in different directions. The experimental result shows that our method can characterize the two dimensional tensile behaviour of fabrics reliably and accurately.

Methodology

System set-up

Figure 1 shows a schematic of a typical setup for a two-dimensional image capturing system. As shown in Figure 1, a single digital camera (Nikon D70) is

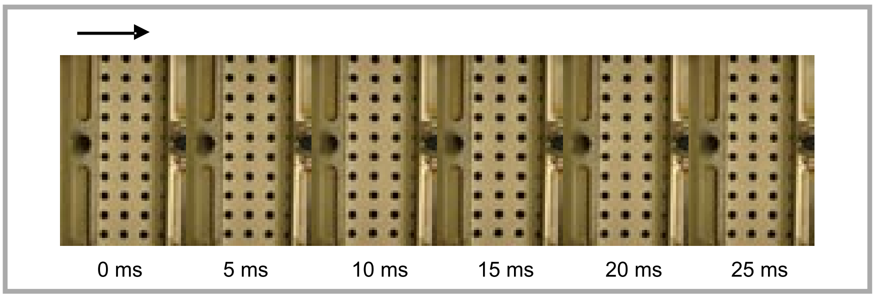

Figure 3. *Image series captured during tension.*

mounted on the stage of a KES-FB1 (tensile measurement); the optical axis of the camera lens is approximately perpendicular to the surface of the test specimen. The specimen is assumed to be deformed in the plane of the object's surface, with out-of-plane motion small enough to be neglected. The digital camera dynamically captures individual digital image sequences of the object's surface at a certain shutter speed during the stretching process. The initial image is referred to as the "un-deformed image" and each of the subsequent images will be denoted as "deformed images".

Sample preparation

All specimens are cut into 20 × 20 cm squares, and 9 × 3 cm circular disks are printed in dark color on a white or light colour fabric as reference points, as shown in Figure 2. The diameter of each disk is 6 mm and the distance between two disk centers is 15 mm; good contrast is achieved by selecting a dark colour and white background. It is an effective way to simplify the image analysis algorithm by using reference points printed on the specimen. Other pattern styles (such as natural texture) can also be selected to be reference points. According to practical measurement, the texture matching algorithm is complex relatively; here we only introduce the simplest image correlation technique based on this kind of reference point.

Deformation measurement by using image analysis method

The specimen is mounted flatly on the stage of the KES-FB1 using two chucks first, and then image digitalisation of the specimen surface is triggered by the startup of the KES-FB1.

Image Digitalisation

Image sequences of the specimen under tension are recorded from the beginning to the end of stretch. After that all images are transferred onto a computer and analysed to calculate the displacement of reference points (disk centre) and the shape transformation of disks in each frame. The visual 2D movement of the specimen surface could be easily characterised by using photographs taken at different times, as shown in Figure 3.

Boundary detection of an ellipse disk

The Laplacian-Gaussian edge detection algorithm is applied to identify the boundary of dark ellipse disks. The image pixels of dark ellipse disks have lower gray values than other pixels of other objects, so a certain threshold t_0 can be determined to distinguish the reference points from an image background based firstly on its histogram. Let $f(x, y)$ denote the image of the fabric surface, and

$$LoG(x, y, \sigma) = \frac{1}{\pi\sigma^4}\left(1 - \frac{x^2 + y^2}{2\sigma^2}\right) \cdot e^{-\frac{x^2+y^2}{2\sigma^2}}$$

be a Laplacian-Gaussian filter, where σ is the spread of the Gaussian filter and controls the degree of smoothing. The boundary enhanced image of $f(x, y)$ with $LoG(x, y, \sigma)$ can be expressed by the equation

$$g(x, y) = f(x, y) \circ LoG(x, y, \sigma)$$

where $\circ$ is used to indicate the convolution of two functions. And since the two chucks and some incomplete disks appear in the images, it is also necessary to erase them by just cropping the sub-image of the effective testing region as shown in Figure 4.

Parameter estimation of an ellipse disk

Since in the Cartesian coordinate system, both circular disks and ellipse disks can be represented parametrically by a 5-parameter ellipse cell (x_0, y_0, a, b, θ), where (x_0, y_0) is the center, θ is the tilt of the ellipse, a and b are the major and minor axes, respectively. Let $P(x, y)$ be the boundary point of the ellipse disk, and n:

$$\frac{(x\cos\theta + y\sin\theta - x_0)^2}{a^2} + \frac{(-x\sin\theta + y\cos\theta - y_0)^2}{b^2} = 1$$

Then, we estimate the 5 parameters of each ellipse disk printed on the specimen surface by using a simple ellipse identification method [1, 4]. To simplify the ellipse detection algorithm, the center of the ellipse (x_0, y_0) can be initially estimated by using the mass centre:

$$x_0 = \frac{\sum_{i=1}^{n} x_i}{n}, \quad y_0 = \frac{\sum_{i=1}^{n} y_i}{n}$$

and (x_i, y_i) are boundary points. The major axis a and minor axis b can easily be determined by the maximum and minimum length of the segment series passing through (x_0, y_0). θ is equal to the angle (in degrees) between the x-axis and the minor axis of the ellipse. The eccentricity of an ellipse is calculated by using

$$e = \sqrt{1 - \frac{b^2}{a^2}},$$

and this parameter isused to describe the shape deformation.

Displacements and shape deformation measurement

Supposing (x_{0i}, y_{0i}, a_i, b_i, θ_i) are the parameters of one ellipse disk on the specimen surface before deformation, (x'_{0i}, y'_{0i}, a'_i, b'_i, θ'_i) is the i image of the same point during deformation, then the displacement of its centre along the x direction could/can be easily calculated by $u_i = (x'_{0i} - x_{0i}) \cdot S_x$, and the displacement of its center along y direction being. $v_i = (y'_{0i} - y_{0i}) \cdot S_y$, where S_x, S_y is the resolution (mm/pixel) of the digital camera the along x and y directions separately, as shown in Figure 4.a. Shape deformation of an ellipse is expressed by $\eta = e'_i / e_i \times 100\%$. The anisotropy of fabric

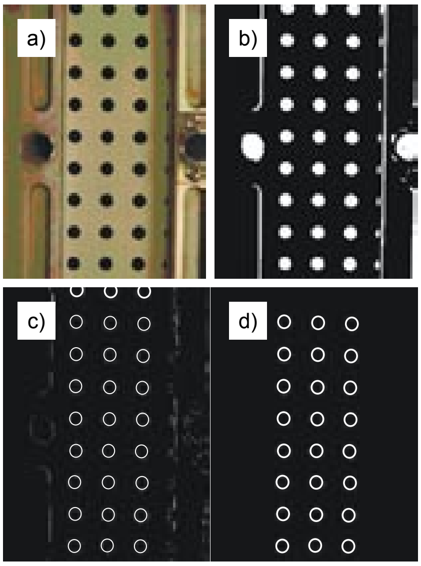

Figure 4. *Images of boundary detection; a) original image, b) binary image ($f(x, y) > t_0$), c) boundary image g(x, y), d) boundary image of ellipse disks only.*

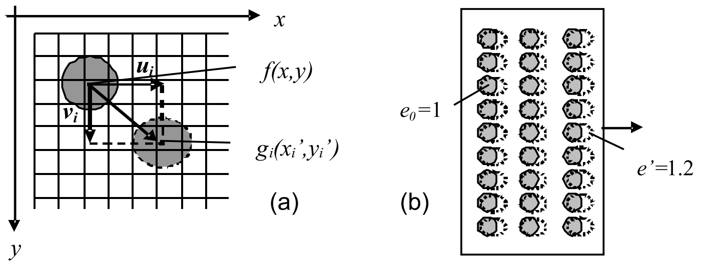

Figure 5. *Displacement and shape deformation measurement.*

Table 1. *Basic fabric properties tested with use a KES; LT - linearity of tensile load - extention curve, WT - tensile energy per unit area, RT - tensile resilent, EMT - extensibility.*

Fabric ID	Thickness, mm	Weight, g/m²	Direction	Tensile properties			
				LT	WT	RT	EMT
P	0.68	4.68	Warp	0.803	2.70	54.55	5.48
			Weft	0.877	3.14	50.00	5.84
T	0.86	8.07	Warp	0.765	3.43	37.14	7.32
			Weft	0.601	2.70	52.73	7.32
R	0.72	5.10	Warp	0.800	3.92	41.25	6.80
			Weft	0.929	3.82	44.87	6.72

tensile behaviour can be determined by the comparison of displacement and deformation in different directions.

Figure 5 shows the displacement and shape deformation measurement.

Experiments and results

In this paper, three kinds of fabrics were tested by using this method with the following specifications: white/plain/cotton/(P), green/twill/cotton/(T), and white/plain/ramie/(R), all these samples were cut into 20 cm × 20 cm squares, and the mechanical properties of the these, which were tested using KES, are listed in Table 1.

Figure 6 shows the relationship between strain and stress during tension, and since the strain is determined by the one dimensional displacement of the sliding base holding testing sample, the two dimensional local displacement of sample surface points can not be calculated and analysed using this method. The anisotropy of fabric tensile properties also can not be characterised based on this one-dimensional testing method.

Since the stress-strain curves show that the three samples have very similar tensile behaviour, sample P was chosen to describe the measurement of 2D displacement and passion ratio in the following steps. In Figure 8, we measured the real-time displacements of three reference points A, B, C during tension along its stress direction. Since the positions of A, B, C are different, the slopes of their displacement curves are not equivalent, and the slope of A is smaller than B, and the slope of B is smaller than C. It shows that the displacement increases as the location of surface points are far from the gripping position. The relationship between the displacement u_i of surface points and its distance d_i from gripping points could/can be expressed by following equation: $u_i = \varepsilon \cdot d_i + D$, where ε is the average strain in per cent at a certain stress and D is a constant. From Figure 7, the average strain in per cent under maximum load is calculated, ε = 5.38%, and the value is very close to ε_k = 5.48%, measured using KES. It proves that the strain measurement based on image analysis is as reliable and accurate as the traditional testing method.

In Figure 9, the real-time displacements of nine surface points vertical to their stress direction were measured during tension. It was easily found that the displacement field of these points shows the anisotropy of testing materials. Point 5 has almost no vertical deformation, which is located on the central line along the stress direction; however, other points located away from the central line have an obvious, large vertical displacement. And the vertical displacements of symmetrical points, such as point 1 and 9 are very close.

In Figure 10, we compared the passion ratio of three surface points located at different distances along the stress direction from the gripping points, and found that the passion ratio at point A is bigger than point B and C. It proves that the passion ratio is not distributed uniformly; it should be a function depending on its position. The same comparisons are made among nine surface points located symmetrically at the side of the central line the along stress direction, as presented in Figure 11. It shows that the passion ratio is also related to its distance to the central line. According to these observations, we could/can formulate a surface deformation model based on the experimental results and also could validate traditional theoretical mechanical models of textile materials much more conveniently.

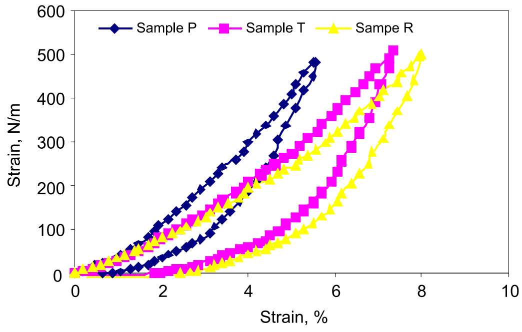

Figure 6. *Strain-stress curves of the three samples.*

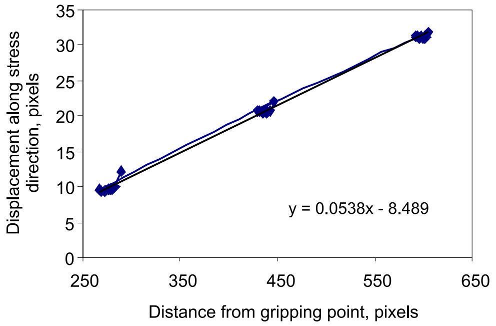

Figure 7. *Strain calculation.*

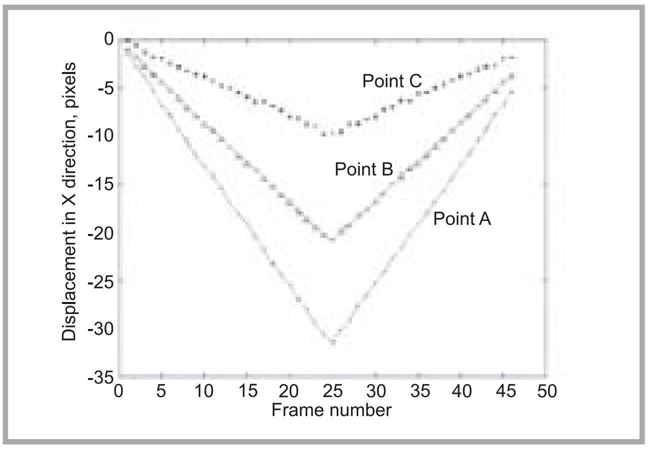

Figure 8. Displacement along stress direction (pixels).

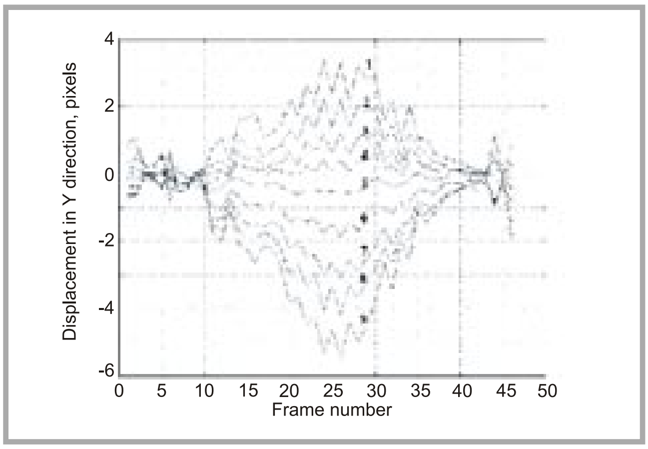

Figure 9. Displacement in vertical direction (pixels).

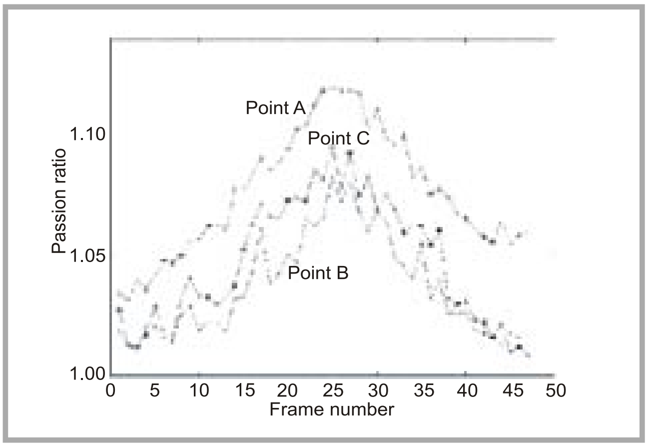

Figure 10. Passion ratio along stress direction.

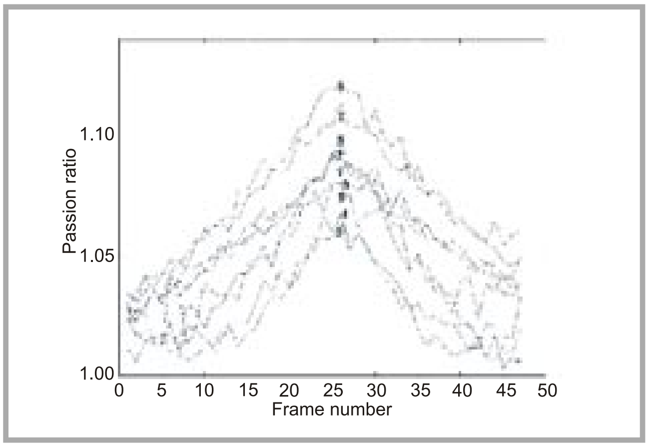

Figure 11. Passion ratio in vertical direction.

Conclusion

The image-based methodology used in this paper can display the real time movement of reference points visually printed on a fabric surface and directly calculate the real time displacement of these reference points. Hence, it is convenient to apply this method to evaluate two dimensional mechanical behaviour under a certain in-plane tension. From our experimental results, we found that the image-based strain value is consistent with the KES strain value, and image-based techniques used for tensile analysis have the advantage of being effective and stable. Both the deformation along the stress direction and vertical to its stress direction can be measured simultaneously; however, it can not be characterised by using traditional one-dimensional strain testing method. For fabrics which have the nature of non-uniform strain and stress distribution under a certain load, it is necessary to characterise the anisotropy property for a better understanding of the mechanical behaviour of materials. In our research, we provide an effective tool to study the correlationship between these behaviours and material structures or properties, so as to predict and simulate the mechanical behaviour under a certain load. Further work will focus on how to evaluate the bending and shearing behaviour of materials by using image analysis methods, as well as how to develop image-based particle tracking methods depending only on the natural texture of fabrics.

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