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Improved extended digital image correlation for crack tip deformation measurement

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ABSTRACT

The objective is to find an appropriate shape function which can enhance the performance of Extended Digital Image Correlation (X-DIC). This paper presents an improved X-DIC methodology to measure the discontinuous deformation across the crack. After simplifying the shape function of crack tip element based on the linear elastic fracture mechanics, non-rectangular subset is proposed to eliminate the effect of the crack width on the measurement accuracy. Then, the work verifies the performance of improved X-DIC by measuring the deformation of a specimen with a mode I crack. Experimental results show that the proposed method is effective at improving the measurement accuracy and enhancing the computational efficiency of X-DIC. In the end, the thesis provides a practical application of improved X-DIC to crack tip deformation measurement.

1. Introduction

Digital image correlation (DIC) method is a rapidly developing photomechanical technique with advantages including sufficient sensitivity, full-field and non-contact measurement, simple system setup, potential for use in both large and small viewing fields and avoidance of interferometric fringe treatment, etc. As such, it has been fertile ground for research on experimental mechanics [1,2], and attracted the attention of both researchers and practitioners with backgrounds in the mechanics of solids, applied physics, mechanical engineering and materials science [3–6]. During the past three decades, DIC has not only been widely used in solving different types of applied science and engineering problems. In addition, it brought about improvements in design and measurement practices.

DIC was applied in solving fracture mechanics problems initially [7]. With the development of finite element method (FEM), the unified work of FEM and DIC has been accomplished. Extended digital image correlation (X-DIC) is also proposed, considering the difficulty of measuring the displacement field near the discontinuous region with conventional DIC method [8]. However, in previous research, the displacement approximation of X-FEM was taken as the shape function of X-DIC, extending its application scope to measurement of the discontinuous deformation field, without any modification. It is noteworthy that systematic errors resulted from undermatched subset shape functions would affect the meaurement accuracy of DIC [9]. To investigate and employ an appropriate shape function is instrumental in enhancing the performance of X-DIC. Study by Chen et al. investigates the error distribution of X-DIC and develops single-element X-DIC with higher accuracy [10,11].

In this paper, after introducing the principle of X-DIC, the shape function of X-DIC is investigated and improved. A complementary experiment confirms the performance of improved X-DIC. In the end, the thesis provides a practical application of improved X-DIC to crack tip deformation measurement.

2. Improved X-DIC method

2.1. Measurement procedure of improved X-DIC

The measurement procedure of improved X-DIC is the same as that of single-element X-DIC [10]. Both the reference image and the deformed image with discretization of the region of interest (ROI) are employed in the improved X-DIC method. Fig. 1 shows an example of discretization of ROI in the reference image.

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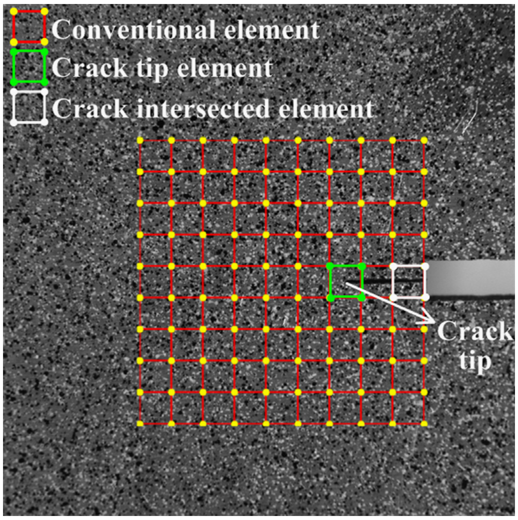

Fig. 1. Discretization of ROI in the reference image.

Single-element correlation scheme is selected to perform the correlation process. $f(x, y)$ is the gray level value at coordinate (x, y) of the reference element, and $g(x^*, y^*)$ is the gray level value at coordinate (x^*, y^*) of the deformed element. Any point whose coordinate is (x, y) in the reference image is related to the deformed image by the deformation kinematic relationship

$$\begin{cases} x^* = x + u(x,y) \\ y^* = y + v(x,y) \end{cases} \tag{1}$$

where u and v represent the horizontal displacement and the vertical displacement, respectively.

The correlation coefficient is a quantitative measurement of the strength of relationship between the reference element and the deformed element. The frequently used correlation coefficient can be written as [12]:

$$C = \frac{\sum f(x,y) \times g(x + u_{shape}(x,y), y + v_{shape}(x,y))}{\sqrt{\sum f^2(x,y) \times \sum g^2(x + u_{shape}(x,y), y + v_{shape}(x,y))}}. \tag{2}$$

where $u_{shape}(x, y)$ and $v_{shape}(x, y)$ are shape functions of improved X-DIC (detailed introduction in the next section) used to describe the displacement field of the reference element. The maximum value of C indicates that $u_{shape}(x, y)$ and $v_{shape}(x, y)$ can be considered the actual displacement field of the reference element. In this case, Newton–Raphson iteration method is used to solve the displacement field. Consequently, the displacement field of the ROI is obtained by interpolating the nodal displacements. Based on small deformation assumption, the strain field of the ROI can be calculated from the following equations:

$$\begin{cases} \varepsilon_x = \frac{\partial u(x,y)}{\partial x} \\ \varepsilon_y = \frac{\partial v(x,y)}{\partial y} \\ \gamma_{xy} = \frac{\partial u(x,y)}{\partial y} + \frac{\partial v(x,y)}{\partial x} \end{cases} \tag{3}$$

where ε_x, ε_y and γ_{xy} stand for the strain components.

2.2. Shape function of improved X-DIC

The expression of shape function affects the performance of X-DIC to some extent. On this ground, this section deals with how the shape function is analyzed and simplified to improve the performance of X-DIC. The displacement approximation of X-FEM is selected as the shape function of X-DIC, which could be expressed as [13]

$$\begin{cases} \left.\begin{aligned} u(x,y) &= \sum_{i=1}^{4} N_i a_i \\ v(x,y) &= \sum_{i=1}^{4} N_i d_i \end{aligned}\right\} \text{ for conventional element} \\ \left.\begin{aligned} u(x,y) &= \sum_{i=1}^{4} N_i [a_i + H(x) b_i] \\ v(x,y) &= \sum_{i=1}^{4} N_i [d_i + H(x) e_i] \end{aligned}\right\} \text{ for crack intersected element} \\ \left.\begin{aligned} u(x,y) &= \sum_{i=1}^{4} N_i [a_i + \sum_{l=1}^{4} B_i^l(r,\theta) c_i^l] \\ v(x,y) &= \sum_{i=1}^{4} N_i [d_i + \sum_{l=1}^{4} B_i^l(r,\theta) k_i^l] \end{aligned}\right\} \text{ for crack tip element} \end{cases} \tag{4}$$

where i stands for the node number, N_i is the shape function of 4-node quadrilateral element in FEM, a_i and d_i are the generalized displacement vector of the nodes, b_i and e_i are the enriched degrees of freedom of the nodes on the crack intersected element, c_i^l and k_i^l are the enriched degrees of freedom of the nodes on the crack tip element. $H(x)$ is the Heaviside function, which equals 1 on one side of the crack and equals -1 on the other side. $B_i^l(r,\theta)$ is the enrichment function of the crack tip. It is expressed in the local coordinate system as

$$[B_l^l(r,\theta)] = \left[\sqrt{r}\sin\frac{\theta}{2}, \sqrt{r}\cos\frac{\theta}{2}, \sqrt{r}\sin\frac{\theta}{2}\sin\theta, \sqrt{r}\cos\frac{\theta}{2}\sin\theta\right] \tag{5}$$

where r and θ are the polar coordinates in the local crack tip coordinate system.

The shape function for conventional element used in improved X-DIC is the same as the one introduced in the authors' previous work [11,14]. In addition, core area method is used in the measurement. Each conventional element in Fig. 1 is taken as the core area (area surrounding the center point of the subset with a smaller size). Reference subset with the displacement approximation of conventional element is used to track its corresponding location in the deformed image. The measured deformation of the core area is taken as the reliable test result.

For crack intersected element, Eq. (4) show that the expression of the shape function above and below the crack are the same as that for the conventional element. Moreover, when using crack intersected element, the sub-pixel interpolation scheme performed near the crack may produce more errors because of the

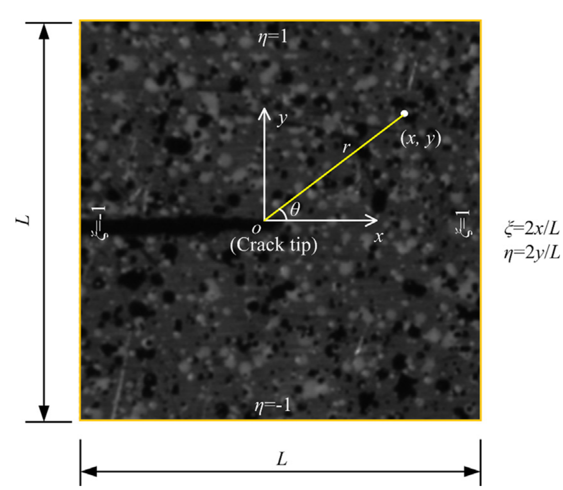

Fig. 2. The crack tip element.