Crack tip detection and SIF evaluation using DIC and High-speed photography

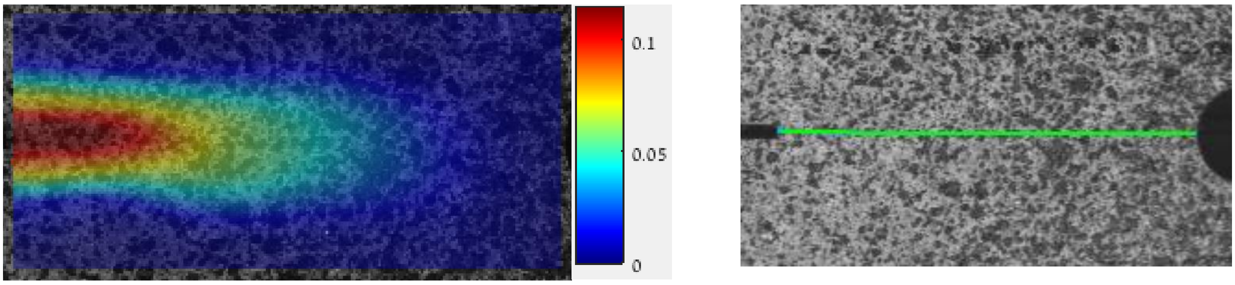
The rapid manner of the dynamic fracture experiments which takes place under 200µs demands a quick data extraction method. This is fulfilled by a high-speed camera that could capture up to 8×10^6 frames per second. 180 images are capture from each experiments with frame rates varying from 0.8×10^6 to 1.5×10^6 having a resolution of 924x768. High-speed camera is set up for every experiments by modifying the frame rate, focus, lighting, exposure and the domain of interest on the specimen to attain high accuracy and to encapsulated maximum possible crack path. The extracted images are used to evaluate the full field displacement and strain by applying the DIC.

Displacement and strain fields of the specimen during the fracture are used to examine the crack path and the stress field. Crack path and SIF are the key parameters used to characterize the fracture, since the crack path describes the trail of damage and SIF represents the stress field. Crack tip of an instance during the fracture isn't easy to detect with naked eyes due to the sharpness of the brittle crack. Certain tools are developed by using image processing to detect the crack tip and to evaluate the SIF under mode I fracture.

The developed program to detect the crack tip, compares the displacement field with an ideal mode-I displacement field in a domain, then uses a minimum error criterion to find the crack tip. SIF of this particular location is the SIF of that instance of the fracture. High level of noise is an obstacle at this stage. To overcome this issue, a Fourier series based filter is used on the displacement field from the DIC for better accuracy. The crack tip detection and the SIF evaluation of an instance is carried out in two steps.

i. *Crack path detection from the DIC of a frame*

Crack tip is explored on a pre-defined path instead of scanning a large area to find the crack tip easily and accurately. The pre-defined path is the crack path and it taken from the discontinuity generated during the crack propagation. The crack path is recognized from the strain field of a developed crack (Figure 5a). Due to the mode I nature of the fracture and the horizontal crack propagation, the displacement component u_y and the strain e_{yy} are taken for the comparison.



a) b)

Figure 1. Crack path extraction from the DIC. a) e_{yy} from DIC. b) crack path of the specimen.

ii. *Evaluating the crack tip location and SIF.*

The crack tip is scanned along the crack path using the displacement field from the DIC. The experimental displacement field at an instance is compared with the analytical displacement field developed using the linear elastic model. The analytical displacement field u_y, is considered as the superposition of the rigid body motion (u_{y0}) and the power series (Eq.1). The relative displacement field $u_y - u_{y0}$, contains the contour and amplitude of the displacement fields separately. So, the mapping of each terms with the experimental displacement returns the corresponding amplitudes (K_i). The overall best overlap or least error corresponds to the crack tip and the amplitudes K_i are the SIF of that particular instance.

$$u_y = u_{y0} + \sum_{i=1}^{n} \frac{K_i f}{2G} \left(-\alpha_1 r_1^{i/2} \sin\left(\frac{i\theta_1}{2}\right) + h_i r_2^{i/2} \sin\left(\frac{i\theta_2}{2}\right) \right) = u_{y0} + \sum_{i=1}^{n} \frac{K_i f}{2G} F(x,y,c) \qquad (1)$$

$$Where,\ K_i = SIF\ of\ each\,term, r_i = \sqrt{x^2 + \alpha_i y^2},\ \ \theta_i = \tan^{-1}\left(\frac{\alpha_i y}{x}\right),\ \ i = [1, 2],\ \ (x, y)\varepsilon \in \Re^2$$

$$\alpha_1 = \sqrt{1 - \left(\frac{c}{c_l}\right)^2},\ \ \alpha_2 = \sqrt{1 - \left(\frac{c}{c_s}\right)^2},\ \ f = \frac{1 + \alpha_1^{\ 2}}{4\alpha_1\alpha_2 - (1 + \alpha_2^{\ 2})^2},\ \ h_1 = \frac{2\alpha_1}{(1 + \alpha_2^{\ 2})},\ \ h_2 = \frac{1 + \alpha_2^{\ 2}}{2\alpha_2}$$

$$c_l = \sqrt{\frac{k+1}{k-1}\frac{\mu}{\rho}},\ \ c_s = \sqrt{\frac{\mu}{\rho}},\ \ c = crack\ \ propagation\ velocity$$

$$v = Poisson's\ ratio,\ \ \mu = Shear\ modulus,\ \ \rho = density$$

Similar comparison of the displacement fields to obtain the SIF is a modified form of the method proposed by Roux and Francois[42]. Roux and Francois introduced a way to consider the overall displacement (or stress) field as a superposition of multiple fields. They considered 8 basis fields including the rigid body motion and multiple fracture modes. Using this approach, SIF of multiple modes and coefficients in the power series expression could be evaluated.

Since the number of terms in the displacement expression increases the analysis time, the terms are reduced by examining the data from the numerical analysis. Although, the accuracy increases with the number of terms, the process become unstable and sensitive to the noise. Finite element analysis of a similar system with Hopkinson bar is carried out with a striker velocity of 19.6m/s. Displacement of a domain near the crack is taken for the analysis when the mode I crack is fully developed. As shown in Figure 2, the accuracy of SIF and the error has saturated with two terms in the displacement expression. First two terms of the displacement power series expression are taken as shown in Figure 2.

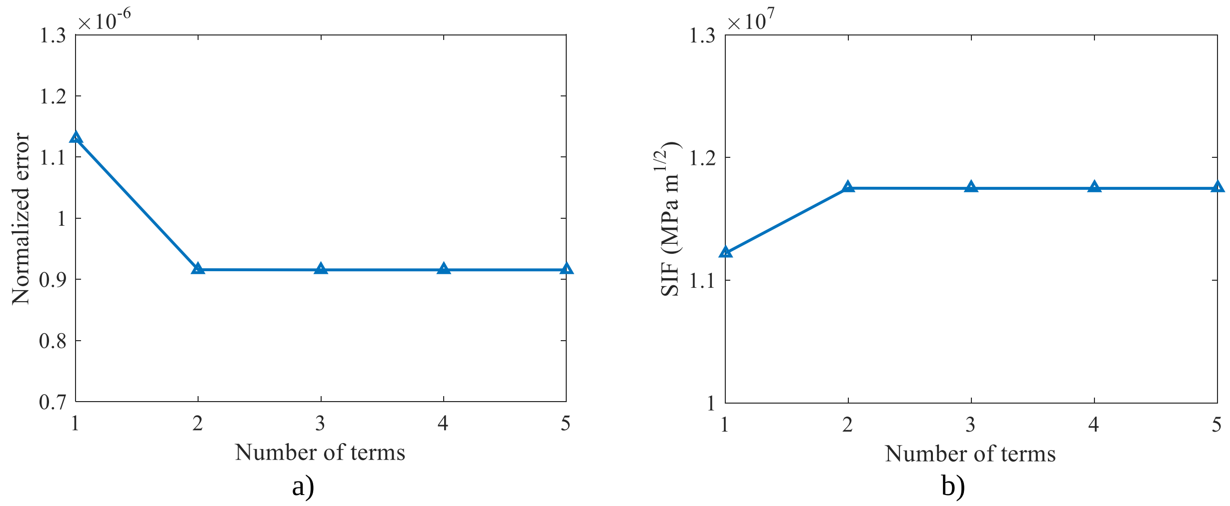
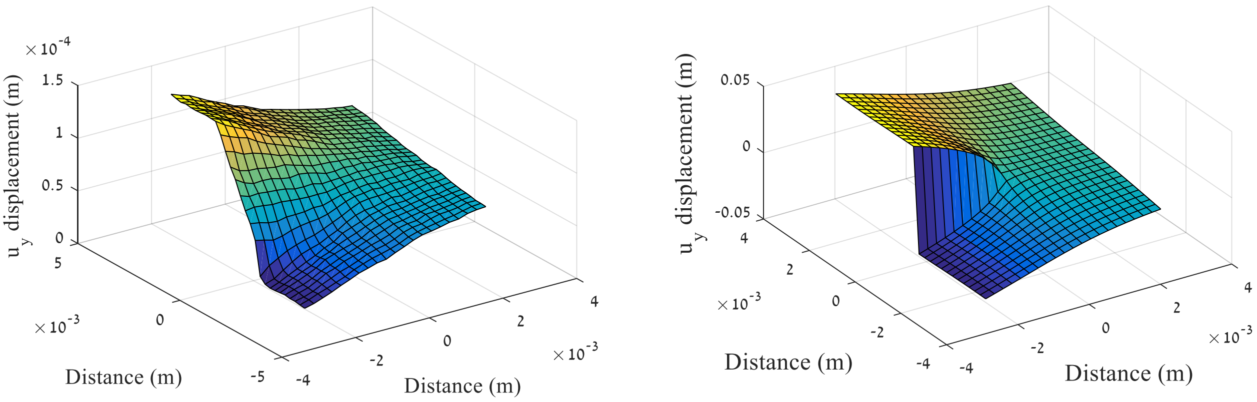


Figure 2. Effect of the number of terms in the displacement expression. a) SIF variation with the number of terms. b) Normalized error distribution with the number of terms.

The experimental and analytical displacement fields for the comparison are shown in Figure 3. The displacement in the cartesian coordinate system is converted into the Fourier space during the analysis for better noise removal and accuracy. Instead of comparing individual data points which contain the information about one location, the characteristic frequencies which captures a trend in the domain are examined. Each point in the Fourier space contains a frequency and an amplitude that contributes a trend to the displacement field. The main advantage of implementing the analysis in the Fourier space is the efficient noise removal. This is attained by looking at the analytical displacement field and considering only the relevant frequencies for the comparison. So, the process implicitly removes the random noise which is dominant in the DIC data.

A set of points along the crack path (Figure 5b) is considered with the corresponding analytical displacement field and they are overlapped with the experimental displacement field. The precision of the overlap is quantified with the error in the mapping and it is assessed (Eq. 2) using the least square method. The error is normalized by the number of data points in the displacement field. The variation of overlapping error is examined along the crack path to obtain the least error which corresponds to the best overlap (Figure 6a).

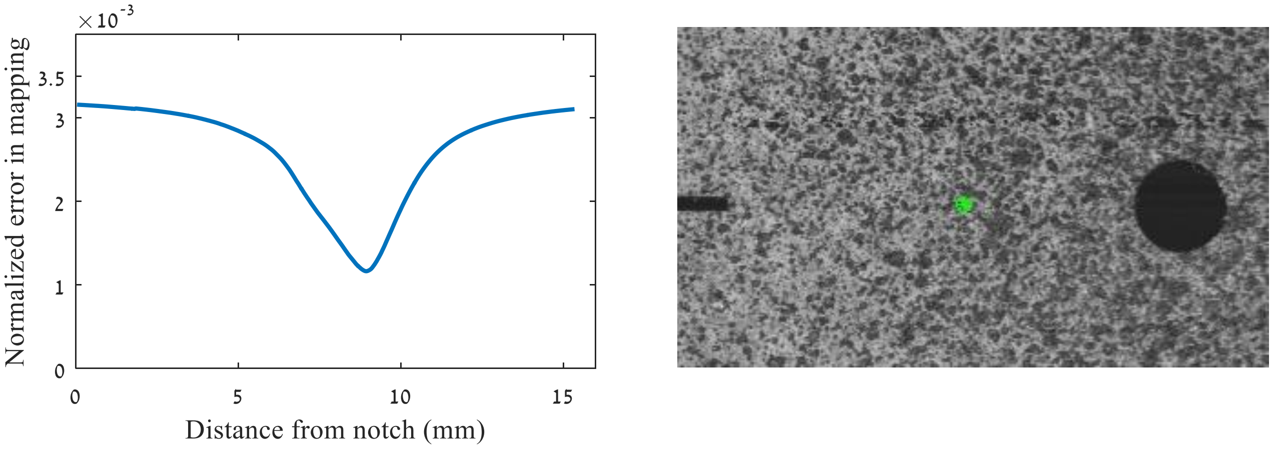


a) b)

Figure 3. U_y displacement field near the crack tip. a) Experimental data from DIC, b) Formulated displacement field.

$$e = \left| u_y{}^e - u_y \right| = \left| u_y{}^e - \left[u_{y0} + \sum_{i=1}^{n} \frac{K_i f}{2G} \left(-\alpha_1 r_1^{i/2} \sin\left(\frac{i\theta_1}{2}\right) + h_i r_2^{i/2} \sin\left(\frac{i\theta_2}{2}\right) \right) \right] \right| \tag{2}$$

The location corresponds to the least error is represented the crack tip of that instance (Figure 8b) and the coefficients K_i, in the mapping provides the SIF.



a) b)

Figure 4. Crack tip evaluation. a) Error distribution along the crack path in displacement field mapping. b) Crack tip according to the minimum error.

This process of identifying the crack tip from the overlap of displacement fields is carried out for all of the instances during the fracture and the corresponding SIFs are evaluated. Once the crack tips are evaluated, the crack propagation velocity is found using the crack tip locations and time interval between the frames.

Although this method is efficient and accurate, crack tip detection is challenging if the displacement field is not fully developed or the domain if interest has some irregularities such as voids or bad speckles. In those cases, the analysis is corrected and carried out by comparing the crack path manually with the experiment data. Due to the finite resolution of the image, there is an uncertainty associated with the crack tip which leads to a minor vagueness of the SIF. Error of the SIF is estimated from the length represented by the single pixel of the image.