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Effect of Subset Parameters Selection on the Estimation of Mode-I Stress Intensity Factor in a Cracked PMMA Specimen using Digital Image Correlation

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Abstract: Polymethyl methacrylate (PMMA) tension specimens with double edge cracks are considered in this study. Surface displacements of the samples are obtained using digital image correlation technique using different values of subset size and subset distance. Results of displacement components from various regions in front of the crack are utilized in a least squares fitting procedure to obtain the first stress intensity factor. This is accomplished using series representation of displacement components of a cracked structure in plane loading conditions. Effects of two adjustable parameters of digital image correlation analysis, including subset size and subset spacing, on the obtained values of stress intensity factor are investigated, while the number of terms truncated from the series representation and the radius of data extraction zone are varied. Results indicate that small subsets may not properly converge to accurate results, irrespective of the value of subset spacing. Moderate subset sizes will usually yield acceptable results while large subset sizes and subset spacing may not include sufficient data to reproduce the desirable value of stress intensity factor. It is also shown that at least three or more terms in conjunction with a sufficiently large radius of data extraction region should be considered in least squares fitting to acquire a reasonable estimate of stress intensity factor in cracked specimens.

Key words: Digital Image Correlation; Stress Intensity Factor; Crack; Polymer

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1. Introduction

Transparent methacrylate polymers have extensive use in various engineering applications due to their good stability and durability. From pressure hulls of submersibles to their extensive use in medical and dental applications, PMMAs can be found in modern structures. However, applied loads and/or thermal gradients may trigger initiation of micro-cracks at notch tips, and after sustained loading the cracks may grow, leading to lack of structural integrity or undesirable performance. Thus, it is important to analyze fracture parameters when a crack or a sharp notch is present in the material. PMMAs show brittle fracture at room temperature, and thus analysis based on linear elastic fracture mechanics (LEFM) principles using stress intensity factor (SIF) as the characterizing parameter of stress field head of the crack is justified in the analysis of cracked PMMA specimens [1]. In calculation of stress intensity factor for various loading conditions and geometrical configurations, analytical or numerical approaches may be adopted. However, analytical solutions are limited to special and simple cases, and numerical simulations are time consuming and sensitive to the quality of simulation, and they should be verified by appropriate experimental methods. In this regard, non-contact and full-field optical measurement methods such as moiré interferometry [2], holographic interferometry [3], and photoelasticity [4] have gained considerable attention for fracture parameter characterization of various materials. Among these methods, digital image correlation (DIC) has recently been widely used as a versatile method for various engineering applications including fracture mechanics analysis [5–8]. The implementation of this method in an in-house code is relatively easy since it is essentially based on the comparison of digital images captured before and after deformation to calculate the deformation map of the surface of the sample. Considering experimental test setup and experimental procedure, the method is relatively simple and needs little effort for calibration and data acquisition. These advantages have made DIC the preferred optical non-contact method in material characterization [9,10], micro and nano deformation measurements [11], and quasi-static and dynamic fracture [12,13].

One approach to using DIC in determination of fracture mechanics parameters using LEFM relations, is to fit experimentally obtained surface displacement components of the cracked structure ahead of the crack tip into appropriate asymptotic expression of the fields in the crack front vicinity and then utilize any suitable scheme to derive unknown parameters (e.g. rigid body rotation, stress intensity factors and T-stress) [14–16]. This raises some questions on the validity of the obtained results. First, the radius of the data extraction zone is a matter of concern that should be taken into consideration when using an asymptotic series solution to determine unknown parameters. More terms of the series should be considered for larger data extraction zones, while smaller zones may not contain sufficient accurate data due to intense field gradients at the crack tip or inherent errors of the algorithm and/or experiment conditions. Another issue is pertained to the formation of a small plastic zone, even for relatively small applied loads, in which the LEFM relations are no longer valid. Thus, consideration of any small zone that contains this plastic deformation area may lead to inaccurate results. These issues have been addressed in a previous article by the authors where the effect of radius of data extraction zone in combination with minimum number of Williams series expansion terms that should be considered to achieve convergence are discussed for edge-notched PMMA samples under tensile loading [17].

In performing DIC post-processing analysis, there are two important parameters that affect the accuracy and resolution of the obtained displacement fields. These are namely “subset size” and “subset spacing” which denote the size of the cells for which correlation is performed between the two images, and the distance between two subsequent subsets, respectively. The effect of subset size on the accuracy of the DIC algorithm has been investigated both theoretically and experimentally for homogeneous deformation fields [18,19]. The aim of this paper is to investigate the effect of these parameters on the accuracy and convergence of stress intensity factor obtained by a least-squares fit of the experimental displacement field from DIC analysis, and asymptotic series expansion of the displacement field in front of the crack. Intensive convergence studies have
been conducted to show the effect of subset size and subset spacing and also the radius of data extraction zone and the number of truncated series expansion terms on the values of first intensity factor.

2. SIF estimation by DIC analysis

2.1. DIC principles and features

Comparison of digital images taken before and after loading using a mounted camera is the basic of the two-dimensional DIC method. However, for the images to be comparable digitally there should be sufficient contrast variation available on the surface of the specimen. This is usually accomplished by applying a black and white speckle pattern on the surface of the sample. It is assumed that this pattern reflects the actual deformation of the specimen surface, thus two images are captured before and after deformation. Using a suitable post-processing technique and by defining appropriate criterion to define the degree of similarity between two images, images are compared digitally where the grey level value of each pixel in the images are used for mathematical computations. The usual and traditional approach in comparison of the images is to define an area of interest (AOI) and divide this area into many small squares of several pixels in size that are called subsets. The number of pixels located in a particular subset defines its size, e.g. a M×M subset contains M pixels in each direction (horizontal and vertical). The distance between two consecutive subsets is called subset spacing, which determines the resolution of the acquired displacement field (Fig. 1). If subset spacing is lower than subset size, then the two subsets overlap and the resolution increases.

The position of subset in the reference image (image captured before deformation) is located in the deformed image (image captured after deformation takes place) using a correlation coefficient where the change in shape of the subset may be taken into account using a linear or quadratic shape functions. Various correlation coefficients may be defined to achieve sub-pixel accuracy in determination of displacement components of the center point of the subset. For example, the normalized correlation coefficient defined by Eq. (1) may be used [20]:

\[
C(x, y, u, v, \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial v}{\partial x}, \frac{\partial v}{\partial y}) = \frac{\sum \sum (G_r(x, y) - G_d(x', y'))}{\sum \sum (G_r(x, y))^2}
\]

where \(u\) and \(v\) are the displacement components at the center of the subset, \(G_r\) and \(G_d\) are the grey levels of the reference and deformed images, respectively, \((x, y)\) and \((x', y')\) are the coordinates of a point in the subset before and after deformation. The sum is calculated over all the pixels located in the current subset. Considering linear shape functions, \((x', y')\) is related to \((x, y)\) as follows:

\[
x' = x + u + \frac{\partial u}{\partial x} \Delta x + \frac{\partial u}{\partial y} \Delta y ; \quad y' = y + v + \frac{\partial v}{\partial x} \Delta x + \frac{\partial v}{\partial y} \Delta y,
\]

in which \(\Delta x\) and \(\Delta y\) are distances from the subset center to the point \((x, y)\) in the \(x\) and \(y\) directions respectively. Considering Eqs. (1) and (2), six unknowns (including displacements and displacement gradients) are to be determined by minimizing the coefficient \(C\).

2.2. Least squares fitting for SIF estimation

For a specimen with a crack under mixed mode loading conditions, the deformation field components in \(x\) and \(y\) directions can be written as [6]:
where \( r \) and \( \theta \) are polar coordinates of any point in front of the crack and are measured relative to a local coordinate system located at the crack tip as Fig. 2 shows. \( \kappa \) is a parameter that depends on the state of stress in crack front region and is given by \((3-\nu)/(1+\nu)\) for plane stress and \(3-4\nu\) for plane strain conditions, where \( \nu \) is Poisson’s ratio. Since DIC data are extracted from the surface of the specimen, the value of \( \kappa \) for plane stress state is considered in this study. Also, \( \mu \) is the shear modulus of material. It should be noted that, in the close vicinity of the crack, the first terms of the series in Eq. (3) are dominant, and in regions far from crack tip higher order terms must be taken into account to accurately determine the crack tip deformation field.

Considering Eq. (3), in a two-dimensional digital image correlation experiment, additional terms should be considered for the expressions of displacement components to compensate for rigid body translation and in-plane rotation of the specimen. Thus, for any data point extracted from a DIC experiment, the corresponding displacement terms could be re-written as:

\[
\begin{align*}
    u_j &= \frac{1}{2\mu} \sum_{n=1}^\infty a_n r_j^{n/2} \left[ \left( \kappa + \frac{n}{2} + (-1)^n \right) \cos \frac{n}{2} \theta_j - \frac{n}{2} \cos \left( \frac{n}{2} \right) \right] + \\
    v_j &= \frac{1}{2\mu} \sum_{n=1}^\infty b_n r_j^{n/2} \left[ \left( \kappa - \frac{n}{2} - (-1)^n \right) \cos \frac{n}{2} \theta_j + \frac{n}{2} \cos \left( \frac{n}{2} \right) \right]
\end{align*}
\]

where \( r_j \) denotes the \( j^{th} \) data point with the coordinate \((x_j, y_j)\) of \( M \) total data points. \( u_j \) and \( v_j \) are the displacement components in the local \( x \) and \( y \) directions respectively. \( \alpha \) is the rigid body rotation angle in radians. Polar coordinates of a point, \((r_j, \theta_j)\), relative to the crack tip location are related to Cartesian coordinates, \((x_j, y_j)\), as shown in Fig. 2:

\[
r_j = \sqrt{(x_j - x_0)^2 + (y_j - y_0)^2} \quad ; \quad \theta_j = \tan^{-1} \left( \frac{y_j - y_0}{x_j - x_0} \right). \]

where \((x_0, y_0)\) is the coordinates of crack tip location. It should be noted that the following relations exist between the leading coefficients of displacement components series and the stress intensity factors:

\[
    K_I = \sqrt{\pi a_i} \quad ; \quad K_{II} = \sqrt{\pi b_i}
\]

Here, a tensile PMMA specimen (mode I loading) with two symmetric edge cracks is considered and linear least squares fitting will be used to determine unknown terms in Eq. (4). This is
accomplished by establishing an over-determined system of linear equations in unknown parameters (coefficients of series and rigid body movements), and then minimizing the sum of the squares of the error between experimental and theoretical displacements at \( m \) selected points in front of the crack. The resulting expression can be written as [21]:

\[
R_{(2N+3) \times (2N+3)} \{x\}_{(2N+3) \times 1} = \{\Lambda\}_{(2N+3) \times 1}
\]

\( N \) is the number of terms by which the series in Eq. (4) is truncated. There would be \( 2N \) unknowns pertaining to the coefficients \( a_n \) and \( b_n \). The three additional unknown terms are the horizontal and vertical rigid body displacements and the in-plane rotation term. Unknown vector \( \{x\} \), matrix of coefficients \( [R] \), and the vector \( \{\Lambda\} \) are given by:

\[
\{x\} = [a_1 \cdots a_N \ b_1 \cdots b_N \ u^* \ v^* \ \alpha^\top]
\]

\[
[R] = [A^\top \ A] + [B^\top \ B]
\]

\[
{\Lambda} = [A^\top \ \{u\}] + [B^\top \ \{v\}]
\]

where \([A]\) and \([B]\) are \( m \times (2N+3) \) matrices constructed by inserting the coefficients of unknowns \( a_n \) and \( b_n \) from the expressions for \( u \) and \( v \) in Eq. (4) in a column order fashion for \( m \) selected points, respectively. \( \{u\} \) and \( \{v\} \) are \( m \times 1 \) column vectors containing DIC extracted displacement data in \( x \) and \( y \) directions, respectively.

The following expression of first stress intensity factor for this type of geometry and loading condition (Fig. 3) is proposed in [22]:

\[
K_I = \sigma \sqrt{\pi a} \left[ 1.12 - 0.20 \left( \frac{a}{W} \right) - 1.20 \left( \frac{a}{W} \right)^2 + 1.93 \left( \frac{a}{W} \right)^3 \right]
\]

where \( \sigma \) is the remote tensile stress, \( a \) is the crack length and \( W \) is the half-width of the specimen. The above relation holds for \( 0 < \frac{a}{W} < 0.7 \).

3. Specifications of specimen and test setup

As previously mentioned, a polymethyl methacrylate (PMMA) specimen with two edge cracks was used as the test sample. A uniaxial tension test has been performed on a standard PMMA specimen (ISO 527), using a servo control system universal testing machine (AI-7000-M GOTECH testing Machines Inc.) with 20 kN capacity, to evaluate its elastic mechanical properties. Elasticity modulus was determined to be \( E = 3.33 \) GPa. Considering the curve shown in Fig. 4, the Poisson’s ratio of the material was measured to be \( \nu = 0.33 \).

The specimen for DIC experiment was prepared by first applying a white layer of paint on its surface and then spraying black dots to create a suitable pattern. Specimen and test setup are shown in Fig. 5. Tensile loads of 45 kgf and 80 kgf were applied to 50.0 mm wide specimens with 4.2 mm thickness where the length of each edge crack was 10 mm. The experiment was conducted under the conditions of constant loading rate of 0.1 mm/min. Random patterns on the specimen surface were recorded by a charged-coupled device (CCD) camera (Art-Cam 320p equipped with a Fujian 55 mm lens), as shown in Fig. 5. The images were captured with a spatial resolution of 2288 \( \times \) 1700 pixels, while the setup was settled on a vibration isolated table in order to eliminate noise. Each 1 mm of real distance corresponds to 20.41 pixels in each direction in the scaled images used for analysis. Images were post processed with a trial version of the commercial software VIC-2D, from Correlated Solutions Inc., exclusively used for performing investigations made in the current study.

To investigate the effect of subset size and subset spacing, DIC post processing were conducted using subset sizes ranging from \( 21 \times 21 \) to \( 101 \times 101 \) pixels in a 20 pixels increment in subset size.
For each subset size, subset spacing values were chosen such that the ratio of subset spacing to subset size varies from 0.05 to 0.5 in 0.05 steps.

4. Results and discussion

Figure 6 shows the displacement field obtained from DIC analysis for a specimen under 45 kgf load. By defining a circular region in front of the crack, results of displacement components in this area are used in Eq. (8) for the evaluation of stress intensity factor utilizing a linear least square scheme.

To investigate the effect of subset size and subset spacing, results of derived stress intensity factor for an applied load of 45 kgf are shown in Fig. 7 (a)-(i). Three subset sizes corresponding to small (21×21 pixels), medium (61×61 pixels) and large (101×101 pixels) are considered while, for each subset size, three subset spacing values are investigated and corresponding graphs are shown. It is clear that, for a sufficient number of terms and relatively larger radius of data region, more accurate results are obtained. This is mainly due to the intense gradients of displacement components in the near crack tip region, which gradually diminish at higher distances. However, at regions far from the crack tip, higher order terms of the series should be considered for accurate determination of displacement components. This explains why the stress intensity values obtained by considering only the first term do not converge to the analytical solution; displacements near the crack tip are noisy, and at long distance from the crack tip single term solution does not prevail. It is clear that by increasing the number of series terms, more accurate results are obtained. However, there is no significant improvement in the results when more than 4 terms are considered. The same trend is also shown for the value of data extraction region radius. These two trends were also proven to exist for specimens with sharp edge notches [17]. For small subset size, a steady value of error will exist regardless of the values of d, r, and N. When a subset size of 61×61 pixels is used for DIC post-processing, it is observed that the results converge to the value obtained from Eq. (9) when \( N \geq 4 \). The value of subset spacing has negligible effect on this behavior. Large subset size and subset spacing may not converge to the proper value of SIF when small data extraction zones are considered (Figs. 7 (h) and 7 (i)), even when a sufficient number of series terms are considered (\( N \geq 4 \)). This is to be expected since the number of data points that reflect the state of stress ahead of cracks may decrease considerably, yielding inaccurate parameter estimation from the least squares fit. However, large subset size and small subset spacing may still converge to desirable values (Fig. 7 (g)).

To further investigate the effect of choosing subset size and subset spacing, results of stress intensity value for an applied load of 80 kgf when 5 terms of the series solution are considered, are shown in Fig. 8 (a)-(c). Fig. 8 (a) presents the results when the subset spacing is about 0.1 of the subset size (small \( d \)). It is clear that, at small values of \( r \), results obtained considering large subset sizes are far from those predicted by Eq. (9). However, as the radius of data extraction zone enlarges sufficiently, results for all values of \( M \) converge to the same value. Increasing the value of \( d \) has little effect for small subsets, i.e. 21×21 and 41×41 pixels, while making the results of larger subsets oscillatory at small radius. Further increase in \( d \) to the value of half of the subset size, may lead to delay in convergence of the results obtained from considering large subset sizes (Fig. 8 (c)). It is to be noted that results of small subset sizes, i.e. 21×21 pixels, are essentially uninfluenced by the magnitude of subset spacing. This is mainly because small subsets inherently provide enough data for least squares fitting. However, small subset sizes contain noisy data which may lead to inaccurate estimation of stress intensity factor.

To investigate the effect of number of terms for higher loading levels, results of stress intensity factor for an applied load of 80 kgf are given in Table 1. Numerical results reproduced in this table are derived considering the highest value of data extraction zone radius, and are given for \( N = 2 \) and \( N = 5 \). Similar to the results of Fig. 7, small subsets yield different values compared to those obtained by considering moderate and large subsets. It is interesting to note that, when \( N = 2 \), the
results are over-estimated, while $N=5$ results in under-estimated stress intensity factor. However, results of $N=5$ may contain errors not related to the procedure adopted here but to the persistent errors of the experiment. Sources of error may include uncertainty in reading load values, systematic and inherent errors of DIC analysis and errors pertaining to the geometric features of specimen (crack length and finite crack tip radius). Finally, the same analysis in a non-dimensional basis is performed for the applied load of 45 kgf and shown in Fig. 9, where the magnitude of stress intensity factor error obtained for $N=5$ is illustrated versus non-dimensional $d/M$ (subset spacing to subset size) ratio. The error is defined as:

$$ Error \% = \left| \frac{K_{I,\text{DIC}} - K_{I,\text{Eq.}(9)}}{K_{I,\text{Eq.}(9)}} \right| $$

(10)

It is obvious that the highest error is related to the smallest subset size, i.e. $M=21$ pixels. The level of error in estimating SIF decreases as larger subset sizes are considered for DIC post processing. As mentioned before for moderate subset sizes, subset spacing has little effect on the derived value for first stress intensity factor. However, for $M=81$ pixels and $M=101$ pixels, high subset spacing values increase the error. This is mainly due to the fact that larger subset sizes with high values of subset spacing result in fewer data points available from the region of interest in front of the crack. Thus, it is to be expected that the available data extracted with these configuration of subset size and subset spacing (i.e. high values of $M$ and large values of $d/M$), may not properly reflect the deformation map in front of the crack, and the stress intensity factor obtained by DIC post-processing is not accurate enough.

5. Conclusions

An experimental study was performed on PMMA specimens with double edge cracks under mode-I tension loading. Surface displacements of the sample were registered using digital image correlation analysis. Results of DIC post-processing for the displacement field in a specified region in front of crack tip were used in a linear least squares data fitting process to determine unknown parameters, including first stress intensity factor and rigid body movements. Two key parameters in accuracy and resolution of DIC post-processing analysis, subset size and subset spacing, were investigated and the effects of variation of these two parameters on the results of stress intensity factor were studied. Small, moderate and large subset sizes were chosen and for each subset size the value of subset spacing was changed to extract intensive (corresponding to small subset spacing) to sparse (corresponding to large subset spacing) data points. It was shown that too small subsets may not produce accurate results, regardless of the value of subset spacing. However, moderate subsets result in converged and appropriate SIF values. The effect of loading value was also considered and it was shown that the same trend prevails in the present case. It was also demonstrated that small data extraction regions are not sufficient for derivation of accurate SIFs, even when enough number of series representation are selected and small subsets are chosen for DIC processing.
References


Figure Captions:

Fig. 1. Subsets in reference image (left), and the deformation of a subset in the image captured after loading (right)

Fig. 2. Cartesian and polar coordinates at the crack tip of a planar specimen

Fig. 3. Schematic of a sample with two edge cracks under uniform tension

Fig. 4. In-plane transverse strain vs. longitudinal strain in the sample

Fig. 5. Experimental test setup

Fig. 6. Contours of displacement field in the vicinity of cracks in (a) horizontal and (b) vertical directions (tension load is applied in vertical direction)

Fig. 7. Stress intensity factor under applied load of 45 kgf for different subset size and subset spacing values: (a) M = 21, d = 2, (b) M = 21, d = 5, (c) M = 21, d = 10, (d) M = 61, d = 6, (e) M = 61, d = 15, (f) M = 61, d = 31, (g) M = 101, d = 10, (h) M = 101, d = 30, and (i) M = 101, d = 50 (all in pixels)

Fig. 8. Effect of subset size and subset spacing on the obtained stress intensity factor under applied load of 80 kgf with \( N = 5 \) for (a) small, (b) moderate, and (c) large values of \( d/M \)

Fig. 9. Error in stress intensity factor estimation for applied load of 45 kgf with different subset sizes \( (N = 5) \)
Table 1. Comparison of obtained SIFs for an applied load of 80 kgf for different subset size and subset spacing values. (Eq. (9) gives the value of 0.6436 MPa.$\sqrt{m}$)

<table>
<thead>
<tr>
<th>Subset size (pixels)</th>
<th>Subset spacing (pixels)</th>
<th>$K_I$ for $N = 2$ (MPa.$\sqrt{m}$)</th>
<th>$K_I$ for $N = 5$ (MPa.$\sqrt{m}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21×21</td>
<td>2</td>
<td>0.6922</td>
<td>0.6331</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.6940</td>
<td>0.6336</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.6958</td>
<td>0.6353</td>
</tr>
<tr>
<td>41×41</td>
<td>2</td>
<td>0.6841</td>
<td>0.6255</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.6873</td>
<td>0.6258</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>0.6833</td>
<td>0.6232</td>
</tr>
<tr>
<td>61×61</td>
<td>3</td>
<td>0.6834</td>
<td>0.6248</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.6866</td>
<td>0.6258</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>0.6871</td>
<td>0.6226</td>
</tr>
<tr>
<td>81×81</td>
<td>4</td>
<td>0.6852</td>
<td>0.6259</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.6823</td>
<td>0.6236</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>0.6874</td>
<td>0.6287</td>
</tr>
<tr>
<td>101×101</td>
<td>5</td>
<td>0.6857</td>
<td>0.6263</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0.6865</td>
<td>0.6243</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.6974</td>
<td>0.6490</td>
</tr>
</tbody>
</table>
A subset size (MxM pixels) and subset spacing (d pixels) are defined. The region of interest in the reference image is compared to the search area in the deformed image. The displacement vector (u, v) indicates the transformation between the two images.
crack