Characterizing Crack Growth in Thin Aluminum Panels Under Tension-Torsion Loading Using Three-Dimensional Digital Image Correlation


Abstract: The enclosed work was performed to determine whether a critical crack opening displacement (COD) criterion can be used to predict the stable crack growth behavior of thin, 2024-T3 aluminum fracture specimens experiencing tension and torsion loading. Due to the complexity of the large deformations that occur near the crack tip in a single edge-cracked specimen under torsion loading, a state of the art three-dimensional computer vision system was developed and employed to make the three-dimensional vector displacement measurements required to determine COD. Results from the experimental program indicate that the three-dimensional surface profile and deformation measurement system was fully capable of making the required measurements, even in the presence of large, out-of-plane displacements and surface strains that occurred during the tension-torsion loading process. Specifically, the measurements show that (a) critical COD for tension-torsion loading is constant during crack growth, (b) COD is approximately 8% larger than observed for in-plane tension-shear and (c) the surface strain fields during crack growth are quite complex due to the coupling of out-of-plane displacements and in-plane surface strains.

Keywords: mixed mode fracture experiments; tension-torsion loading; three-dimensional digital image correlation; non-contacting measurements; crack opening displacement

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INTRODUCTION

Recent mixed-mode I/II fracture experiments [1-4] and theoretical developments [5,6] indicate that two-dimensional COD is a robust fracture parameter that can be used to accurately predict the onset and direction of stable crack growth. Here, two-dimensional COD is defined as

\[ \text{COD}_{2D} = \sqrt{[\text{\Delta u}^2 + \text{\Delta v}^2]} \]  

(1)

where the relative displacement components, \( \Delta u \) and \( \Delta v \), in the x-direction (along original crack direction) and y-direction (perpendicular to crack), respectively, are computed at a specific distance behind the current crack tip by the equations:

\[
\begin{align*}
\Delta u &= u^{\text{above}} - u^{\text{below}} \\
\Delta v &= v^{\text{above}} - v^{\text{below}}
\end{align*}
\]  

(2)

where \( u^{\text{above}} \) (\( v^{\text{above}} \)) and \( u^{\text{below}} \) (\( v^{\text{below}} \)) are the displacements in the x-direction (y-direction) for points located above and below the existing crack line, respectively, at a fixed distance behind the current crack tip. In this work, and in previous work, the authors selected the distance behind the crack tip to be 1mm.

It is well known that flaws growing in aerospace structures oftentimes are subjected to a combination of mixed mode I/II/III conditions. In thin fuselage material, these complex crack tip conditions are due to local, out-of-plane motion [7] of the unconstrained cracked surfaces. The out-of-plane deformation will occur under either internal pressure or tensile loading [8].

To develop a better, physical understanding of the crack growth processes that occur under mixed mode loading, as well as provide a quantitative set of measurements for use in model verification, a series of tension-torsion [9,10] laboratory-scale experiments using thin sheet, 2024-T3 aluminum specimens have been performed. During these experiments, the crack tip opening displacement data was acquired using a state-of-the-art, three-dimensional computer vision system. In the following sections, the test specimen is presented along with the experimental procedures used to perform the experiments. Next, a brief summary of the three-dimensional computer vision method is given. Then, results from a series of tension-torsion experiments are presented, including (a) the first known three-dimensional COD data and (b) typical strain fields acquired just prior to stable crack growth. Finally, a short discussion of the results is presented.

TENSION-TORSION SPECIMEN AND TEST CONFIGURATION

Figure 1 presents a schematic of typical tension-torsion specimen geometry. The 2.3 mm thick specimens were machined from unclad 2024-T3 aluminum and fatigue pre-cracked under tensile loading in the L-T orientation so that the initial crack length to width ratio is \( a/w = 0.0833 \). All tests were performed on a 50K MTS test frame using an MTS Testar system with PID controller and user-
generated control programs. To perform each experiment, the following control system process was employed. Axial displacement was used to control load application to the specimen. During the loading process, axial load cell output was input to the torsion actuator to generate a proportional, applied torque. Finally, the torsion rotation was increased until the required torque was attained. Since three channels of input are used to control the test process, it is necessary to set appropriate tuning factors for all three channels of input to ensure stability of the system for the type of specimen being tested. It is noted that the control process described above was slightly unstable at low levels of applied loading; for loads greater than 400 N, the system was unconditionally stable.

Defining stress components on a rectangular cross-section by $S_T = 3T(t^2 w)^{-1}$ and $S_P = P(t w)^{-1}$, where $t$ is the specimen thickness and $w$ is the specimen width, experiments were performed at five levels of $S_T/S_P$ in the range $0.0 \leq S_T/S_P \leq 6.64$. In this work, COD results are reported for $S_T/S_P = 0, 1.66, 3.32, 4.98$ and 6.64. Additional results, such as crack surface profiles and strain fields, are reported for $S_T/S_P = 0.00, 3.32$. 

Figure 1: Tension-torsion specimen (units in mm)

Figure 2: Large deformations during loading of tension torsion specimen
OVERVIEW OF THREE-DIMENSIONAL DEFORMATION MEASUREMENT PROCESS

Figure 2 graphically illustrates the large deformations that occur prior to and during stable crack extension as the rectangular specimen is quasi-statically loaded in tension and torsion; fatigue pre-cracking did not result in large specimen deformations. To measure the three-dimensional vector displacements for points on the specimen surface in Fig. 2, a unique digital image correlation system (DIC-3D) was developed specifically for this experiment. The DIC-3D system is capable of measuring the full, three-dimensional surface displacement field for a structure deforming in three-dimensions [8,9], including the presence of large in-plane and out-of-plane rotations, large displacements and large strains.

To make accurate displacement and shape measurements with a 3-D vision system, both (a) high quality calibration of the system and (b) a matching process that accounts for both lens and perspective effects when determining the optimal deformation parameters are required. Figure 3 shows a typical 3-D vision system.

In our work, the camera and lens systems are modeled as a pinhole device with a correction to account for Seidel lens distortion [9-11].

The pinhole camera projection equations that govern the use of these cameras typically require that the imaging characteristics of a camera are modeled by five parameters. In this work, the parameters are (1) pinhole distance (phd), (2,3) location of the center of the image (C_x, C_y), (4) lens distortion parameter, κ, for Seidel correction and (5) the aspect ratio, λ, of the sensors. In addition to these parameters, six parameters (X_0, Y_0, Z_0, and α, β, γ) are required to describe the relationship between a camera and the coordinate system of the calibration grid. Here, (X_0,Y_0,Z_0) describe the position in space of the grid relative to the camera and (α,β,γ) describe the angular orientation of the grid relative to the camera.

Calibration of the two-camera computer vision systems determines the relative position and orientation of the camera relative to the grid, as well as the operating characteristics of both cameras. The calibration system is based on a series of images of a grid with known line spacing [10, 11]. Each camera is
calibrated to the grid individually. Since the positions of both cameras are known relative to the same grid, their relative orientation and position are also known. To calibrate each camera in the stereo-vision system, an image of the grid is taken. The camera is then moved perpendicular to its sensor plane and a second image is taken. Non-linear optimization is used to obtain the parameters that best describe the position and operating characteristics of the camera. The process is then repeated, without moving the grid, for the second camera. Verification tests are discussed in detail in Reference [11].

Once calibration is completed, the stereo vision system can be used to measure both the shape of the object surface (profiling) and also the full field, three-dimensional displacement measurements. Similar to two-dimensional image correlation, the three-dimensional measurement system uses a random pattern bonded to the surface to provide a unique set of features to map image locations from one camera to the other. Software, designated DIC-3D, has been written to perform the process of optimal matching of subsets in both cameras to locate the position and orientation of this region on the object. The analysis uses two pairs of images taken of the surface of the object by camera one and camera two, with each pair of images acquired at the same time. The two pairs of images are used to obtain the three-dimensional surface displacement field by employing a small square section of the image taken by camera one before deformation as the "reference" image. Using a "projection with back-projection" process developed by the authors, both the initial position of the subset on the object (e.g., the surface profile) and the three-dimensional surface displacement of the same subset due to deformation can be measured.

Cross-correlation is used to establish an error measure and obtain the best match of the reference gray level pattern to corresponding patterns in each of the images. The error function is optimized to determine the initial position and displacement of a specific subset on the surface of the object. By continuing the analysis on other portions of the image in camera one, both the full-field profile and the full-field, three-dimensional displacements of the surface of the object for the entire field of view shared by both cameras are measured. A complete explanation of the 3D image analysis process is given in [11].

THREE-DIMENSIONAL COMPUTER VISION SYSTEM FOR COD AND SURFACE STRAIN MEASUREMENTS FOR TENSION-TORSION SPECIMEN

Conceptually, COD should be measured sufficiently close to the crack tip to reflect the crack tip deformations that result in crack tip damage and crack extension. Since the specimen surfaces are expected to undergo three-dimensional displacements, a generalized definition for three-dimensional crack opening displacement (COD) is given in the following equation

$$\text{COD} = \left[ (\Delta u)^2 + (\Delta v)^2 + (\Delta w)^2 \right]^{\frac{1}{2}}$$  \hspace{1cm} (3)
where the additional relative displacement component, $\Delta w$, is perpendicular to the original specimen surface and is measured at the same distance behind the current crack tip as are $\Delta u$ and $\Delta v$ in (2) and is given by the equation;

$$\Delta w = W^{\text{above}} - W^{\text{below}}$$  \hspace{1cm} (4)

Following procedures outlined previously [1-6], COD was measured at 1 mm behind the current crack tip in this work. To quantify COD accurately in this region behind the current crack tip, the DIC-3D system was used to image a region approximately 4 mm by 4 mm in size. Due to both the high magnification required and the need to follow the moving crack tip, special considerations were used when setting up the two-camera system. These considerations included (a) camera mounting, (b) system stability and (c) crack-tip tracking.

The camera mounts used for these tests were specially designed to reduce any motion of the camera and lenses by incorporating the mount into the C-mount to Canon lens adapter, while providing full support for the lens system. Special care was used to align the camera mounts with the translation stages. To obtain camera translation that was perpendicular to the sensor plane, both camera mounts were adjusted (using thin shims) until the translation of the camera produced a displacement field indicating a nearly pure radial dilation of the image.

To achieve overall stability in the vision system, the cameras were attached to an extruded aluminum cross bar. The honeycomb construction of the cross bar created a lightweight, yet rigid, support member for the camera system. In addition to the rigid cross bar, the connecting mount securing the cross bar to the calibration fixture and to the translation stage was re-designed to minimize any bending forces produced when clamping the system to the holding fixtures.

To track the crack tip region during stable crack extension, the vision system was mounted on a four-axis translation/rotation system. The system was capable of translating in all three directions, as well as rotating about a vertical axis to adjust for torsion/twisting of the specimen. Moving and rotating the entire system maintained a focused view of the crack tip area throughout the crack extension process.

Finally, translation tests were performed to assess the accuracy of the system. For our tension-torsion experimental setup, calibration and translation tests indicate that the standard deviation error in each displacement component was +/- 1 $\mu$m. This error estimate was obtained by fitting a least square constant vector displacement to the measured data for each translation test. It is worth noting that conversion of displacement errors to strain error estimates is difficult due to the dependence of strain errors on (a) the form of the functional fit to the measured displacement data and (b) the gage length used to estimate strain, this is part of an on-going research effort to quantify potential errors in the 3D measurement methodology.

After completing the alignment and calibration processes, image data was acquired as follows. First, prior to loading the specimen, a series of overlapping images of 4 mm by 4 mm areas located approximately 38 mm ahead of the initial
crack position were acquired as reference images for later strain measurements. The camera system was then translated to observe the initial crack tip region. During loading, images were acquired of the crack tip region. The system was translated and rotated during the experiment so that the crack tip area could continue to be imaged as the crack grew.

The three-dimensional surface displacement fields were converted to in-plane strain fields in the vicinity of the initial crack tip region using the Lagrangian strain formulation in terms of the displacement gradients

\[
\varepsilon_{xx} = \frac{1}{2} \left\{ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial u}{\partial x} \right) \left( \frac{\partial v}{\partial x} \right) + \left( \frac{\partial w}{\partial x} \right)^2 \right\}
\]

\[
\varepsilon_{yy} = \frac{1}{2} \left\{ \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial v}{\partial y} \right) \left( \frac{\partial w}{\partial y} \right) + \left( \frac{\partial w}{\partial y} \right)^2 \right\}
\]

\[
\varepsilon_{xy} = \frac{1}{2} \left\{ \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) + \left( \frac{\partial w}{\partial y} \right) \left( \frac{\partial w}{\partial x} \right) \right\}
\]

(5)

Here, \((u,v,w)\) are displacements relative to an \((x,y,z)\) coordinate system located at the initial crack tip position. Since unknown rigid body deformations were introduced during the experiment by moving the optical setup, it is important to note that the strain tensor components defined by Eq. (5) are invariant with respect to arbitrary rigid body motion.

To obtain the displacement gradient field, a local surface fit was obtained for each of the \(u(x_i,y_i,z_i)\), \(v(x_i,y_i,z_i)\) and \(w(x_i,y_i,z_i)\) data sets and the partial derivatives of the resulting best-fit displacement surfaces were used in Equation (5) to determine the surface strains. To ensure optimal accuracy of the displacement gradients, two approaches were taken in the data analysis. First, a strip of data was removed from the region along the crack line and the data was processed as three separate regions to eliminate errors in the measurements that could be introduced if the subsets crossed the crack line. Second, data along the edges of each of the three separate regions were discarded to eliminate errors in the gradient data introduced by edge effects.

**EXPERIMENTAL RESULTS**

Using the procedures described in the previous sections, COD was measured throughout the crack extension process for all \(S_T/S_P\) values using Equations (2,3,4). Figure 4 presents the first known three-dimensional COD-\(\Delta a\) measurements from the tension-torsion tests, as well as a horizontal line representing the mean value for the COD data for \(\Delta a > 10\) mm. In this work, all crack extension measurements are derived from the camera images using established procedures for identifying the growing crack tip location in each image [1-3].

In addition to COD, the surface displacement fields were also measured during the loading process. For \(S_T/S_P = 3.32\), typical results for the out of plane displacement field, \((w(x,y))\), just after initiation of crack extension are shown in Figure 5. Here, positive values for \(w(x,y)\) correspond to motion towards the camera.
For $S_T/S_p = 3.32$, typical results for the in-plane surface strain fields ($\varepsilon_{yy}$, $\varepsilon_{xx}$, $\varepsilon_{xy}$) just after initiation of crack growth are shown in Figure 6. For $S_T/S_p = 0.00$ and $3.32$, Figure 7 shows the fracture surfaces after complete separation has occurred.

![Figure 4: COD versus crack extension for combinations of tension and torsion](image)

![Figure 5: Out-of-plane displacement fields in crack tip region just after surface crack growth, $S_T/S_p = 3.32$](image)
Crack line (a) $\varepsilon_{yy}$

Crack line (b) $\varepsilon_{xx}$

Crack line (c) $\varepsilon_{xy}$

Figure 6: Crack tip strain fields just after crack growth, $S_7/S_p = 3.32$
Figure 7: Profiles of fracture surfaces for 2024-T3 aluminum specimen and two combinations of tension and torsional loading

\[ S_T/S_P = 0.00 \]

\[ S_T/S_P = 3.32 \]
Discussion of Experimental Results

Figure 4 clearly shows that for all \( S_I/S_P \), the average COD \( \equiv 0.118 \) mm for \( \Delta a \geq 10 \) mm. This value is somewhat larger than measured for L-T specimens under mixed mode I/II loading [1-4]. The initial transient in COD values has been observed by many investigators [1-4], and is widely known to be related to three-dimensional crack tip conditions that stabilize after crack growth of approximately 1-2 specimen thickness. As was observed in previous Mode I/II tests, the initial transient in COD was a clearly defined rapid increase to a maximum value, followed by a decrease to an average value.

As shown in Figure 7, the specimen experienced large shape changes during loading. Figure 6 shows that the surface strain fields are qualitatively similar to those expected for planar, through-thickness flaws growing in the presence of large plasticity. Specifically, the opening strain field is large just ahead of the crack tip, \( \varepsilon_{xx} \) has the opposite sign consistent with the requirement for incompressibility and \( \varepsilon_{xy} \) is concentrated along bands on either side of the surface crack direction. However, as shown in Figure 7, the fracture surface is not planar. The crack plane transitions to a slant as the initial crack extension processes are occurring. In this context, interpreting the measured surface strain fields becomes more difficult. Given the complexity of the processes occurring during crack extension in the tension-torsion specimen, it seems clear that a good use of the measured fields would be for validation of FEA model predictions. Once validated, the models can be used to obtain three-dimensional field data to better understand how the fracture process is proceeding.

Finally, it is noted that for \( S_I/S_P > 0 \), slant fracture such as is shown in Figure 7 always occurred in a manner that tended to cause overlapping and interference of the opposing crack surfaces. Though several reasons may be conjectured for this observation, detailed three-dimensional crack growth simulations using the measured crack paths are now underway to provide quantitative stress fields and strain fields in the crack tip region for determining the conditions required for crack advance.

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