Three-dimensional digital image correlation to quantify deformation and crack-opening displacement in ductile aluminum under mixed-mode I/III loading

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Abstract. Fractures in ductile thin-sheet structures, such as a fuselage or automobile panels, often occur under complex loading conditions. In particular, under remote mixed-mode I/III loading conditions, a cracked structure is subjected to a combination of in-plane tension and large out-of-plane tearing deformation, which may lead to crack growth consisting of all three fracture modes (modes I, II, and III). Understanding such fracture events in ductile materials is an important component of the structural integrity analysis of load-bearing structures containing ductile, thin sheets. Due to the complex nature of mixed-mode I/III fracture in ductile thin-sheet materials, reports of experimental investigations are very limited in the literature. We configure three-dimensional digital image correlation (3D-DIC) systems to acquire full-field deformations during the loading and stable tearing processes. The full-field deformation measurements are used to characterize the stable crack extension behavior of an aluminum alloy undergoing quasistatic and dynamic mixed-mode I/III loading. Results confirm that 3D-DIC is an excellent methodology for measuring 3-D deformations in the presence of large out-of-plane warping and motion, both dynamically and statically. Data obtained during the fracture process indicate that the introduction of a mode III component into the loading process alters the crack tip displacement and strain fields relative to those measured in the nominally mode I loading. Furthermore, the measured crack-opening displacement (COD) values during quasistatic and impact mixed-mode I/III fracture show that (1) COD is nearly constant for crack extension beyond 2 mm and (2) COD under combined-mode I/III loading is four times larger than observed during mixed-mode I/II or mode I fracture of the same material, indicating that the magnitude of the critical COD is a function of loading mode in highly ductile, thin-sheet materials. © 2007 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2741279]

Subject terms: stereovision; three-dimensional surface deformation measurements; crack tip fields; mixed-mode I/III loading; crack-opening displacement; aluminum alloy; impact loading.

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1 Introduction

Ductile thin-sheet components in an actual structure are often subjected to complex loading conditions, involving a varying combination of in-plane tension (mode I), in-plane shear (mode II), and out-of-plane shear (mode III) (Refs. 1–5). Thus, a crack in such components is likely to be subjected to mixed-mode loading, with stable crack growth (SCG) in the ductile material observed before instability occurs. Understanding such fracture events in ductile materials is an important component of structural integrity analysis for ductile thin-sheet structures. Though there has been an increasing awareness of the importance of mixed-mode fracture in practical applications of tough ductile materials and mixed-mode I/III fracture has been the focus of several recent investigations,1–19 much of the work focused on fracture toughness measurement and evaluation in both brittle and ductile materials,7–14 and not on stable tearing. The experimental results for fracture toughness show no single trend with regard to the effect of superimposed mode III loading. The imposition of mode III loading results in a drastic reduction in the fracture toughness in some materials, whereas it has little effect or results in an increase in the fracture toughness in other materials.8,10,11

Due to the cumbersome and sophisticated nature of experimental methods employed in mixed-mode I/III fracture studies, experimental investigation on the crack tip field characterizations are very limited in the literature.15–18,20 To experimentally characterize the near crack tip fields in structural components undergoing large 3-D deformations, a method for measuring full-field 3-D displacements in the presence of large out-of-plane warping is required. Optical
whole-field techniques that give displacement or strain fields are of great interest for mixed-mode I/III fracture study.

Three-dimensional digital image correlation (3D-DIC) is a computer-vision-based, noncontacting, full-field optical method that utilizes modern digital image-processing concepts to measure both shape and deformation for planar or nonplanar objects. The modern DIC technique overcomes many of the limitations and disadvantages of previous optical techniques (such as photoelasticity, moiré, and interferometry), providing quantitative measurement of the full, 3-D displacement field in the presence of large 3-D motions by correlating a pair of digital images (before and after a deformation increment is applied). Once the displacement field for each deformed image is known, the in-plane surface strain is determined by estimating the gradients of the surface displacements. This technique has been successfully used for the measurement of the 3-D shape and deformation of wide, thin, center-notched, 2024-T3 aluminum panels undergoing a far-field tensile load. Results clearly demonstrate that the combination of stereovision and DIC is capable of accurately measuring true 3-D structural deformations in regions undergoing both large out-of-plane displacements and large displacement gradients.

Sutton et al. experimentally investigated crack growth in thin-sheet 2024-T3 aluminum under tension-torsion loading using 3D-DIC. The complicated nature of mixed-mode I/III fracture was observed in their study, including a combination of slant crack growth and interior tunneling that occurred simultaneously, with the amount of tunneling decreasing significantly with an increasing torsion/tension ratio. In their studies, when torsion is nonzero, the fracture surfaces always slanted in such a way as to interfere during the crack growth process. The surface strain fields just after crack growth in a tension-torsion specimen at a moderately high tension/torsion ratio were obtained by using 3D-DIC. The measured strain fields indicated that there was coupling of in-plane deformations with the out-of-plane displacement field. The study also demonstrated that the surface strains (, , and ) are less than 0.06 just after the crack growth in tension-torsion specimen. However, the authors did not determine how the crack tip strain fields vary with increasing load in a stationary crack or during crack extension in a growing crack, leaving this as an unresolved issue in mixed-mode I/III ductile fracture of thin sheet material. Recently, the authors further studied the crack tip field characteristics of stationary cracks under quasistatic mixed-mode I/III loading in thin-sheet ductile aluminum alloy and steel using 3D-DIC. However, characterization of crack tip fields for a growing crack in ductile thin-sheet materials under quasistatic and impact mixed-mode I/III loading is required so that an improved understanding of the fracture behavior of ductile thin-sheet materials under mixed-mode I/III loading conditions can be developed.

For thin-sheet materials, mixed-mode I/III ductile fracture is complicated by the presence of large-scale yielding, significant warping of the specimen (hence, coupling between the in-plane strains and out-of-plane deformations) and the 3-D character of the stress and strain fields near the crack tip. Large-scale yielding that develops in ductile materials under mixed-mode loading has led investigators to evaluate a range of fracture criteria, including a generalized form of COD (crack-tip-opening displacement) that might explain and predict both the instant and direction of crack growth when a ductile material is subjected to nomi-
nally mixed-mode I/III conditions.

Specifically, a critical value for a general mixed-mode COD was shown to be a viable crack growth criterion for 2024-T3 aluminum alloy under monotonically increasing far-field tension-torsion loading. As noted in Ref. 15, the measured critical COD for tension-torsion loading (1) is \( \approx 18\% \) larger than observed for in-plane tension-shear and (2) is approximately constant for crack extension, \( \Delta a > 3t \), where \( t \) is the specimen thickness. Since limited data exists regarding the evolution of COD under nominally mixed-mode I/III loading, additional experimental evidence is required to determine whether the critical COD is a function of loading mode in highly ductile, thin-sheet materials and whether modest changes in loading rate affect the critical COD values in ductile thin-sheet materials under mixed-mode I/III loading.

To gain further understanding of mixed-mode I/III stable tearing of thin ductile materials, the authors performed a series of quasistatic and dynamic mixed-mode I/III fracture experiments on thin aluminum alloy specimens. A 3-D-DIC system was used to measure the displacement field on one surface of the specimens during the loading and stable tearing processes. Critical generalized COD, a parameter that is being used to predict fracture in a wide range of ductile materials, was also assessed under quasistatic and dynamic mixed-mode I/III loading with severe out-of-plane deformation. Key results from these experiments are presented, including (1) 3-D full-field surface displacement and strain fields, (2) crack path data referenced to the undeformed specimen configuration, and (3) critical generalized COD measurements as a function of crack extension. These results are used to understand the nature of the stable crack extension during nominally mixed-mode I/III loading, as well as to provide quantitative surface data for finite element modeling.

2 Principle of 3-D Computer Vision (3D-DIC)

From the early work of Ranson and Peters for 2-D digital image correlation through the work of Sutton et al., Peters et al., Anderson et al., and Chu et al., focused on adapting the method for application in a wide range of applications, the field has recently expanded to include stereovision methodologies and associated applications.

2.1 Pinhole Model

As shown in Fig. 1, a stereo-vision system consists of at least two imaging systems viewing an object from two different locations. In this study, each image system is modeled as a pinhole camera. Intrinsic parameters for each camera include (1) the focal length \( f \); (2) the image plane center \( (C_x, C_y) \); (3) radial lens distortion coefficient \( k \); and (4) scale factors \( \lambda_x \) and \( \lambda_y \), relating metric distance on the object to pixel position in the image plane. Extrinsic parameters for each camera include (1) three independent components of the rotation matrix \( \mathbf{R} \) and (2) three components of the translation vector to orient the world coordinate system (WCS) with axes \( (X_W, Y_W, Z_W) \), relative to the camera coordinate system at the pinhole \( H \).

In practice, the WCS axes \( (X_W, Y_W, Z_W) \) often are defined to be at a specific object position during the calibration process. For example, if a 2-D planar grid is used for calibration, then (1) the plane of the grid lines in the initial set of calibration images can be assumed to be the plane \( (X_W, Y_W, 0) \), (2) the grid intersection at the lower left corner can be defined to be the origin \((0,0,0)\), and (3) the \( Z_W \) axis is perpendicular to the planar grid.

In a similar manner, each camera coordinate system (CCS) is generally located at the pinhole \( H \) of each camera. In many cases, the \( Z_C \) axis is aligned with the optical axis through points \( H \) and \( C \), while \( X_C \) and \( Y_C \) are oriented to align with the camera sensor axes.

The final coordinate system defines the sensor coordinate system (SCS) with \( (X_S, Y_S) \) aligned with the row and column directions of the sensor plane, and \( Z_S \) perpendicular to the sensor plane. Located in the retinal or image plane of the pinhole camera, the SCS has units of pixels for \((X_S, Y_S)\) to define sensor locations.

Assuming the rows and columns in the sensor plane are orthogonal, transformations between the WCS, CCS, and SCS are performed to develop the relationship between sensor plane coordinates \((X_S, Y_S)\) and the 3-D position of a point \((X_W, Y_W, Z_W)\). The resulting scalar form can be written as

\[
\begin{align*}
X_S &= C_x + f \sum R_{11} X_w + R_{12} Y_w + R_{13} Z_w + t_x, \\
Y_S &= C_y + f \sum R_{31} X_w + R_{32} Y_w + R_{33} Z_w + t_y.
\end{align*}
\]

In Eq. (1), \((t_x, t_y, t_z)\) is the translation vector, and the rotation matrix \( \mathbf{R} \) can be written in terms of a modified form of Euler angles. Here, three successive rotations about specific axes are used to describe the orientation of an object. Assuming the first rotation \( \theta_1 \) is about \( X_W \), the second rotation angle \( \theta_2 \) is about the rotated \( Y_W \) axis, and the last rotation angle \( \theta_3 \) is about the twice-rotated \( Z_W \) axis:

\[
R_{11} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_1 & \sin \theta_1 \\ 0 & -\sin \theta_1 & \cos \theta_1 \end{bmatrix},
R_{21} = \begin{bmatrix} 0 & \cos \theta_2 & \sin \theta_2 \\ 0 & \sin \theta_2 & \cos \theta_2 \\ -\sin \theta_2 & \cos \theta_2 & 0 \end{bmatrix},
R_{31} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}.
\]

2.2 Lens Distortion

Several lens distortion models have been proposed in the literature and the following third-order radial lens distortion model has been widely used in the digital image correlation. Radial lens distortion at any point in the sensor plane can be defined as the difference between undistorted sensor plane position \((X_S, Y_S)\) and distorted sensor plane position \((X_S', Y_S')\) in the form

\[
d = kr^3 e_r = k\left((X_S'(g) - C_x)^2 + (Y_S'(g) - C_y)^2\right)^{3/2},
\]

where \( k \) is the radial distortion coefficient; \( r \) is the radial distance from the center of the sensor \((C_x, C_y)\) to \( g \), a point in the sensor plane; and \( e_r \) is the radial unit vector defined relative to the lens center location. Using Eq. (3), the
distortion-corrected position is determined by the equation

\[
(X_s, Y_s) = (X^i_s, Y^i_s) + (d_x, d_y).
\]  

(4) Since the digitized intensity pattern is known at integer pixel locations, the distortion-corrected positions typically form a nonuniform grid at noninteger positions.

### 2.3 Camera Calibration

As shown in Eqs. (1) to (3), there are eleven independent parameters for each camera in the stereovision system: six extrinsic parameters \((t_x, t_y, t_z, \theta_x, \theta_y, \theta_z)\) and five intrinsic parameters \((C_x, C_y, f, \alpha_x, \alpha_y, k)\). A typical camera calibration process uses a calibration target with known grid spacing, such as shown in Fig. 2. During the calibration process, the target is translated and/or rotated in three dimensions, with images acquired by both cameras at each position during the motion sequence. As discussed in Sec. 2.1, in this paper the initial image pair for the calibration grid is used to define the WCS.

To obtain initial estimates for the position and orientation of the calibration grid in each image, the current positions of intersection points generally are determined by locating and identifying specific features on the grid standard. By locating several (a minimum of three is required) noncollinear points in each deformed image, the extrinsic parameters for each view (orientation and translation) are estimated and used to give initial locations for corresponding grid points throughout the view.

Defining an image-based objective function in the form

\[
E = \sum_{i=1}^{M} \sum_{j=1}^{N} \left( \left( X_s^{ij} \text{ measured} - X_s^{ij} \text{ model} \right)^2 \right) + \left( Y_s^{ij} \text{ measured} - Y_s^{ij} \text{ model} \right)^2,
\]  

(5) where \(X_s^{ij} \text{ model} \) and \(Y_s^{ij} \text{ model} \) are given by Eqs. (1) to (4) and the measured locations of features in the calibration standard \((X_s^{ij}, Y_s^{ij})\) are extracted from \(j=1,2,...,N\) pixel locations by analyzing all \(i=1,2,...,M\) images of the calibration grid standard. The model values \((X_s^{ij} \text{ model}, Y_s^{ij} \text{ model})\) for the \(N\) pixel locations for all grid intersection points are obtained by minimizing the functional in Eq. (5).

Though several approaches have been used to perform the nonlinear optimization of Eq. (5) for camera calibration, a common method requires a linearization of the functional in terms of the required parameters. Once the linearization has been completed, the optimization process results in a linear set of equations that are solved for the remaining unknowns. The solution to the linear equations is then used to obtain initial estimates for the parameters. The initial estimates are used to perform nonlinear optimization on Eq. (5) and complete the calibration process. The nonlinear optimization is performed using approaches such as steepest descent, Newton-Rhapson, or a combined method such as Levenberg-Marquardt.

### 2.4 Three-Dimensional Measurements

If one considers a specific point \(G\) with position \((X_W, Y_W, Z_W)\), then Eq. (1) relates this position to the corresponding image location \((X_s, Y_s)\) in the sensor plane for each camera. When Eq. (1) is applied to both calibrated cameras, there are four equations with three unknowns, specifically the 3-D position of point \(G\). An optimal solution can be obtained through a least square process to locate the best estimate for the position \((X_W, Y_W, Z_W)\). By repeating this process for each position of interest, a full field of 3-D points can be determined.

### 2.5 Image-Based Correlation for Subset Matching

To determine the corresponding image location \((X_s, Y_s)\) in the sensor plane of each camera with utmost accuracy, we used images of the object obtained either before or after deformation (see Fig. 3). The procedure used in this study is to perform optimal matching of image plane subsets. The image plane subsets may be (1) from the first camera viewing the object in the undeformed state or a specific deformed state or (2) from the second camera viewing the object in the undeformed state or the same deformed state.
Importance of intensity interpolation in accurate matching was the subject of a recent publication. In this paper, bicubic spline interpolation is used to perform interpolation of the intensity pattern in the deformed or cross-camera images.

To account for the change in position and shape, the local displacement vector field for a general point \( Q \) in a reference subset can be written \( \{ u(Q), v(Q) \} \). In terms of \( \Psi_S \) and \( \Lambda_S \), the deformed sensor position of \( Q \) can be written:

\[
X_S^d = \Psi_S^Q + X_S^p + u(\Psi_S^Q, \Lambda_S^Q),
\]

\[
y_S^d = \Lambda_S^Q + Y_S^p + v(\Psi_S^Q, \Lambda_S^Q). \tag{7}
\]

The choice of displacement function for optimal matching was the subject of a recent publication. If a linear variation in displacement is assumed within the subset, then the subset displacement functions can be written as:

\[
u = A + B\Psi_S + CA_S,
\]

\[
v = D + E\Psi_S + FA_S, \tag{8}
\]

where \( \{ \Psi_S^Q, \Lambda_S^Q \}=(0,0) \). Thus, \( \{ u(P), v(P) \}=(A,D) \) is the image plane displacement of the subset center \( P \). The six coefficients in Eq. (8) are determined by optimally matching the intensity values at each point in the undeformed subset to corresponding values of intensity in the corresponding second image. Though a variety of matching metrics can be used, in this paper, the normalized cross-correlation metric is employed. The epipolar constraint shown in Fig. 1 is used to minimize the search space during cross-camera image matching:

\[
C(A,B,C,D,E,F) = 1 - \sum_{j=1}^{N} \sum_{i=1}^{N} \left[ I'(\Psi_{Si}, \Lambda_{Sj}) \times I'(\Psi_{Si} + u(A,B,C,D,E,F), \Lambda_{Sj} + v(A,B,C,D,E,F)) \right]^2. \tag{9}
\]

The coefficient values that minimize Eq. (9) represent the best estimates of each subset’s local displacement components.

Since a nonlinear search process is required to obtain the local coefficients in Eq. (9), most applications use an initial estimate for the parameters to initiate the search process. Typically, initial estimates for the rotation and translation of a subset are determined visually by locating the pixel positions for at least matching points and using these approximate matches to initiate the search process. As with the camera calibration problem, a wide range of optimization methods has been used successfully. In this paper, a form of the Levenberg-Marquardt approach is used to optimize Eq. (9).

Finally, in this paper, image correlation is performed using uncorrected coordinates in each image. After correlation has been completed and the optimal matching location in the deformed image determined, the displacement field is corrected using Eq. (4).

2.6 Overall Procedure for 3-D Vision-Based Measurements

The following outline is typical for most practical situations that employ a stereo-vision system to acquire full-field deformations.

1. Identify the object region of interest for measurements.
Fig. 4 Schematic of procedure to measure the shape of an object both before and after deformation. Image correlation is used to perform cross-camera matching and identify matching subsets for shape measurement.

2. Select the camera and lens to maintain the visual field of view for the region of interest. For a stereo-vision system, the cameras and lenses typically are matched to simplify the setup and calibration procedures.

3. Lens selection and camera positioning processes must include consideration of the potential for defocusing during experiment. In practical applications, initial studies may be required to ensure that the expected out-of-plane motions of the specimen are within the depth of field for the experimental arrangement. These initial experiments may include actual loading and deformation of a specimen (within the range of conditions of interest) to ensure that the images do not experience defocus.

4. Arrange the cameras to be consistent with physical constraints for application. In many cases, the position of the cameras is dictated by the layout (e.g., laboratory configuration).

5. Calibrate the camera system using calibration target. During this process, it is recommended that image acquisition be synchronized among all cameras.

6. Install specimen in the test system and perform experiment. During the experiment, the image acquisition process is synchronized so that both cameras acquire images simultaneously during the experiment.

7. Postprocess images to determine shape and deformations. After acquiring $N$ pairs of images during the loading process, the analysis process requires that an image from one camera be designated as the “reference” image (e.g., camera 1).

8. To determine the initial shape (see Fig. 4), subsets are selected in camera 1 and image correlation is performed to locate the matching position in the initial image for camera 2. Using the dense set of centerpoint locations obtained by the correlation process, the procedure described in Sec. 2.4 is used to obtain a dense set of 3-D points in both the initial and deformed configurations. These are used to define the 3-D displacement vector for each point after undergoing deformation.

\[
[U(G), V(G), W(G)] = [X_W(G)]_\text{deformed} - [X_W(G)]_\text{un-deformed},
\]

\[
[Y_W(G)]_\text{deformed} - [Y_W(G)]_\text{un-deformed},
\]

\[
[Z_W(G)]_\text{deformed} - [Z_W(G)]_\text{un-deformed}.
\]

Note that the correlation process can also be carried out with the initial image from camera 2 used as the “undeformed” image. In this case, two dense sets of data can be acquired (e.g., for initial shape and/or for any deformed shape) over the same object domain.

3 Applications in Ductile Fracture

The method of 3D-DIC is especially well suited for quantitative, 3-D shape and deformation measurements under conditions of large strain and substantial out-of-plane motion. Since the method measures all displacement components simultaneously, there is no loss in accuracy under these conditions, providing a robust measurement process under such conditions.

In the following sections, 3D-DIC is employed to make unique and difficult deformation measurements during mixed-mode I/III loading and stable tearing of thin-sheet Al6061-T6 specimens undergoing both impact and quasi-static loading.

3.1 Loading Fixture for Mixed-Mode I/III Experiments

Figure 6 shows a picture of the loading fixture and specimen system, where the mode I ($\Phi=0$ deg) and mode III ($\Phi=90$ deg) loading holes are as indicated; the remaining pairs of loading holes are for mixed-mode I/III (30 and 60 deg) loading. The loading fixture is fabricated using 4140 steel. After heat treatment (quenching and tempering), the yield stress is $>1000$ MPa. The fixture was used for
fatigue precracking, quasistatic fracture experimentation, and dynamic fracture experimentation under impact loads without introducing excessive plastic deformation in the fixture.

Thin-sheet, single-edge cracked specimens employed in the mixed-mode I/III experiments are fabricated from 2-mm-thick ductile aluminum alloy AL6061-T6, with a yield stress and ultimate stress of 332 and 350 MPa, respectively. The specimens are laser cut with a notch length of 28.6 mm. The in-plane dimensions of the 2-mm-thick fracture specimens are shown in Fig. 7. All specimens are oriented in the LT direction (i.e., crack is perpendicular to the sheet’s rolling direction). All specimens are fatigue precracked under nominally mode I conditions to produce a sharp crack tip for subsequent mixed-mode I/III fracture experiments. The total fatigue precrack length is controlled so that the initial crack length is 33±1 mm for all specimens.

Prior to performing each mixed-mode I/III experiments, all specimens are lightly painted to obtain a random black-and-white speckle pattern having a spatial variation in intensity that is appropriate for displacement measurement. The speckle size was between 0.03 and 0.1 mm for COD measurements at high magnification, and between 0.05 and 0.4 mm for shape measurements at low magnification. To improve the bonding between the coating and the specimen, specialty high heat white enamel spray paint and Stops Rust Flat Black enamel spray paint manufactured by Rust-Oleum® were adopted for the speckle pattern on all specimens.

4 Experimental Measurements Considerations
4.1 QuasiStatic Mixed Mode I/III Loading
The typical setup of the loading and imaging system for quasistatic mixed-mode I/III experiments is illustrated in Fig. 8. All experiments are performed on an MTS® 810 hydraulic test machine under displacement-controlled conditions using different loading angles $\Phi$. The loading rate for a typical specimen is 0.04 mm/s. During the experiments, rotation of the lower (moving) grip around the loading axis was fully constrained using a specially designed constraint mechanism (see Fig. 8).

The 3D-DIC system used in this study is composed of two Q-Imaging® QICAM digital cameras with a CCD resolution of 1392×1040 pixels, a sensor pixel size of 4.65×4.65 μm, and 12 bits for intensity resolution. Nikon AF Nikkor® 28- and 200-mm F/2.8 D lenses were used in the experiments. The distance between the camera and the specimen was 350 mm for the experiments. Two sets of experiments were performed to obtain global and local crack tip measurements. Typical magnification factors are 21 pixels/mm for the low-magnification experiments (to measure overall deformations and shape of the specimen by using 28-mm Nikon lenses) and 80 pixels/mm for the high-magnification experiments (to improve the accuracy of crack tip COD measurements by using 200-mm Nikon lenses).
Images of the specimen’s front surface were taken by the synchronized cameras in a time-controlled mode during loading (typically every 2 s for one image) as the load and far-field grip displacements were also recorded and synchronized with the image acquisition process. In this paper, results are reported for loading angle $\Phi=0$, $30$, and $60$ deg in the AL6061-T6 mixed-mode I/III experiments. Since the columns of the load frame are used to support the stereovision system, both cameras were mounted to a rigid cross-member to minimize relative motion between the two cameras during the experiment. The cross-member is mounted to a three-axis translation stage so that the camera system could be moved to retain focus during the experiments.

4.2 Mixed-Mode I/III Impact Loading

Figure 9 shows the experimental arrangement for the impact experiments. All experiments were performed in the Dynatup\textsuperscript{®} drop weight facility shown in Fig. 9(a) using the loading frame shown in Fig. 9(b). Load transfer from the drop weight to the specimen is through vertical impact rods to the transverse bar shown in Fig. 9(b) that is pin-connected to the lower specimen fixture. In this paper, a weight of 2669 N struck the lower load transfer bar with an impact speed of 1 m/s. The selection of this relatively low impact speed is necessary for the cameras to capture a sufficient number of images of the deformed specimen (before complete fracture) so that COD values can be measured throughout the stable tearing process. Specifically, previous studies have shown that restricting crack extension between two consecutive images to values $<1$ mm will significantly simplify the extraction of COD values (COD is measured $\approx1$ mm behind the crack tip in this paper).

Based on the quality of results obtained by one of the authors in a recent study,\textsuperscript{52} two Vision Research Phantom\textsuperscript{®} high-speed cameras were selected for development of the stereovision system used to capture the impact images.\textsuperscript{5} Due to safety concerns, the vision system must be located outside of the steel protection barrier surrounding the specimen. To meet these space limitations, the high-speed stereo vision system was placed in the nonstandard configuration shown in Fig. 9(c). To enable the cameras to be placed outside of the protection barrier, two Nikon AF Nikkor 200-mm F1:4 lenses were used for the imaging process. To minimize the relative motion between the two cameras during the experiments, the two cameras were mounted to a rigid cross-member via a pair of translation stages that enabled minor adjustments without disassembly of the components. A typical magnification factor is 15 pixels/mm for the low-magnification experiments on specimen shape measurements ($\Phi=0$, $30$, and $60$ deg) and 70 pixels/mm for high-magnification experiments to measure the COD values ($\Phi=30$ deg). For the increased magnification configuration system, a $2\times$ magnifier and two extender tubes were used for each lens.

For the high-speed camera arrangement, the depth of field was approximately 25 to 30 mm. Since the measured out-of-plane displacements were less than 15 mm for all images, a sufficient number of images of the deformed specimen (before complete fracture) so that COD values can be measured throughout the stable tearing process. Specifically, previous studies have shown that restricting crack extension between two consecutive images to values $<1$ mm will significantly simplify the extraction of COD values (COD is measured $\approx1$ mm behind the crack tip in this paper).

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loading cases, there was no observable blurring in the images, and hence the 3-D deformation measurement process was not influenced by defocusing.

The cameras are triggered using the output signal of an accelerometer mounted to the lower load transfer bar. All images were acquired at $800 \times 600$-pixel resolution at a frame rate of 4800 fps (frames per second). The shutter speed of the Phantom high-speed camera is 1 $\mu$s. The two cameras are synchronized to within $\pm 1 \mu$s to record crack propagation on the patterned specimen surface.

With regard to the effect of the small synchronization time difference between cameras for the impact experiments, two points are noted. First, an upper bound on the sensor-plane positional error in either camera can be obtained using the known impact speed of 1 m/s. In this case, the maximum difference in in-plane position is 1 m/s, as all of the intrinsic parameters for both cameras, including all lens distortion factors and magnification factors.\(^3\)

\(^{3}\)Note that the calibration process includes a lens distortion correction function to correct for imperfections in the imaging process. For a cubic radial distortion model, calibration for the stereo-vision system using Q-Imaging cameras resulted in corrections near the outer edge of the sensor plane $=0.70$ mm for both cameras in the stereo pair.

For a typical quasistatic mixed-mode I/III experiment setup with the image scale factor being about 21 pixels/mm, the calibration results show that the standard deviation of residuals for all calibration images is less than 0.03 pixels and the pan angle $\beta$ between the optical axes of the two cameras is $\approx 14.2$ deg. Based on the preceding information, the accuracy of the in-plane and out-of-plane displacement measurements can be estimated according to the pinhole model in Fig. 1. By projecting a random 0.03-pixel error in each sensor plane of the two cameras to the optimal 3-D position using the inverse of Eq. (1) for each camera and optimal estimation of the closest point for the two rays, the estimated accuracy is 0.0012 mm for the in-plane displacement measurement and 0.0097 mm for the out-of-plane displacement measurement.\(^5\) To improve the accuracy of the correlation, cubic or other appropriate higher order intensity interpolation schemes are used.\(^{50,53}\) For an image scale factor of $\approx 13$ pixels/mm, the calibration results for the Phantom camera arrangement indicate that the standard deviation of residuals for all images is $\approx 0.06$ pixels, which is somewhat larger than for static experiments.

### 5 Crack Growth and Surface Deformation Measurements

Prior to loading, undeformed images of the specimen were acquired by both cameras and used to determine the initial shape of the specimen, while also serving as references for the deformation process (see Fig. 7). Since all displacements and strains are based on the undeformed image configuration (the initial configuration), the specimen based world coordinate system, $(X, Y, W)$, shown in Fig. 7 (origin at the precrack tip, $X$ axis along the precrack direction, $Y$ axis perpendicular to the crack direction and directed toward the stationary grip, $Z$ axis perpendicular to the specimen surface) was used for all analyses.

Here, $(U, V, W)$ denote surface displacement compo-

\[^5\]The commercial software VIC-3D developed by Correlated Solutions Inc.\(^6\) was used to perform both the calibration process and the image acquisition and subsequent displacement measurements for the deformed object.

\[^6\]The accuracy estimate assumes only errors in the subset matching process of $\approx 0.02$ pixels and nominal parameter values for all calibration parameters.
ponents in the \((X,Y,Z)\) directions and correspond to the in-plane shearing, crack opening, and out-of-plane displacements, respectively (local slanting is not considered for this definition).

### 5.1 Crack Paths

Figure 11 presents the material points in the original undeformed specimen configuration \((X-Y)\) plane that correspond to points along the measured crack paths for 2-mm-thick AL6061-T6 pre-cracked specimens loaded at \(\Phi=0, 30,\) and \(60\) deg\(^1\) in the stable tearing mixed-mode I/III experiments. As can be seen in Fig. 11(a), the crack paths under quasi-static loading in AL6061-T6 specimens at loading angles \(\Phi=0\) and \(30\) deg initially grow slightly toward the upper (fixed-fixture) portion of the specimen before straightening, with a deviation of \(\approx 1\) mm from the centerline of the specimen. The crack path for the \(\Phi=60\) deg AL6061-T6 specimen has a greater tendency to propagate toward the upper (fixed-fixture) portion of the specimen with a maximum deviation of \(\approx 4.5\) mm.

As shown in Fig. 11(b), under impact loading the crack paths for \(\Phi=0, 30,\) and \(60\) deg are slightly curved downward (moving fixture) and straight, respectively, with the most significant difference between static and dynamic being for \(60\) deg.

### 5.2 Deformed Shape Measurements

To obtain 3-D surface data, images were obtained with the stereovision systems as shown in Figs. 8 and 9(c), respectively, using commercial software VIC-3D (developed by Correlated Solutions Inc. as noted earlier in the paper) to perform the image correlation for both cameras and also to convert the matching sensor coordinates into 3-D surface displacements. As noted previously, the analysis is performed using (1) normalized cross-correlation [Eq. (9)] to perform the image correlation process, (2) cubic-order or other higher order subpixel interpolation schemes\(^2\) to improve accuracy, (3) radial lens distortion correction estimation [Eq. (3)], and (4) linear shape functions for subset deformations [Eq. (8)].

**The step size controls the spacing of the points that are analyzed during correlation. A step size of 2 pixels means that image correlation will be carried out using subsets shifted by 2 pixels in either the horizontal or vertical directions. A spacing smaller than the subset size is used to obtain additional data for strain computations.

**The strain window size is the number of local neighborhood points (not pixels) where the derivatives of the displacement field are calculated. The window size and subset spacing controls the amount of smoothing applied to the data. Larger values correspond to a higher degree of smoothing.

To obtain comparable results on shape and displacement measurements for quasistatic (dynamic) loading, a \(21 \times 21\) \((15 \times 15)\) pixel subset size, corresponding to about a \(1 \times 1\) mm\(^2\) region in the specimen, was used to estimate the displacement field near the crack tip for the low-magnification images obtained from quasistatic (dynamic) loading experiments. Since subset size dictates the spatial resolution for the displacement measurements, the size of the subsets used to estimate COD was minimized to get as close to the crack line as possible, while still maintaining a sufficiently distinctive pattern contained in the area used for correlation. To ensure that the spatial resolution for the measured displacement and strain fields is controlled by the subset size, a 2-pixel step size\(^*\) and a \(5 \times 5\) strain window size\(^\dagger\) from the measured data are used for local strain estimation when using the low-magnification images to quantify the displacement gradients at the center of each subset.

Figure 12 presents the measured 3-D deformed specimen configuration for quasi-static [Fig. 12(a)] and low-speed impact (at rate of \(1\) m/s) loading [Fig. 12(b)] for all three mixed-mode I/III loading angles and crack extension from 9 to 14 mm. As shown in Fig. 12, even for the nominal tension (mode I) loading, the deformed specimen shapes under static and dynamic loading are complex, fully 3-D in shape with nonnegligible out-of-plane displacement due to a combination of local necking and crack slanting.\(^1\)

For \(\Phi>0\) deg, increased out-of-plane warping and specimen curvature are clearly visible as the applied torque increases. Note that the deformed shape is similar for both quasi-static and low-speed impact loading, implying that there is minimal strain-rate effect.

### 5.3 Three-Dimensional Surface Displacement Measurements

Figure 13 presents the measured components of the surface displacement fields \((U, V, W)\) during stable tearing under...

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\(^1\)Mapping from the highly deformed crack positions during stable tearing to the original material points was performed using sequential image analysis, with an estimated accuracy of \(\pm 1\) pixel.

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**Fig. 11** Crack path in the undeformed configuration for an Al6061T6 specimen loaded at mode mixity angles of \(\Phi=0, 30,\) and \(60\) deg under (a) quasistatic and (b) impact loading.
quasistatic loading conditions for all three loading angles. As shown in Fig. 13, all three displacement components are nonzero for each loading angle. Similar results are obtained during low-speed impact for all loading angles and hence these results are not shown.

For $\Phi=0$ deg (nominally mode I loading), the $V$ component is the largest and $W$ is the smallest, with negative values for $W$ around the crack tip, indicating necking exists ahead of the crack, even though the necking amplitude is small (less than 0.11 mm).

For $\Phi=30$ deg, Fig. 13(b) indicates that the measured displacement fields are entirely different than those measured for $\Phi=0$ deg. Here, $W$ is the largest displacement and $U$ is the smallest. Results also show that the subregion being imaged undergoes appreciable 3-D rotation during loading, due to both large structural deformations and limited in-plane grip rotations.

For $\Phi=60$ deg, the $U$ and $W$ displacement fields are similar to those measured when $\Phi=30$ deg. However, the $V$ field is somewhat different, implying that the differences in measured crack paths for these two cases are related to this change in local response.

To validate the measurements and better understand mixed-mode I/III fracture of thin-sheet ductile materials, a 3-D subregion model was developed to simulate mixed-mode I/III fracture behavior. Results show that there is good agreement between the experimental displacement measurements and the simulation data.
5.4 Surface Strain Fields

Each dense set of 3-D surface displacements \((U, V, W)\) is converted to the surface strain field \((\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{xy})\) in the area of interest using the Lagrangian large strain formulation in terms of the displacement gradients:

\[
\begin{align*}
\varepsilon_{xx} &= \partial U/\partial X + 1/2[(\partial U/\partial X)^2 + (\partial V/\partial X)^2 + (\partial W/\partial X)^2], \\
\varepsilon_{yy} &= \partial V/\partial Y + 1/2[(\partial U/\partial Y)^2 + (\partial V/\partial Y)^2 + (\partial W/\partial Y)^2], \\
\varepsilon_{xy} &= 1/2[(\partial U/\partial Y + \partial V/\partial X)(\partial U/\partial X) + (\partial V/\partial Y)(\partial U/\partial Y) + (\partial W/\partial X)(\partial W/\partial Y)].
\end{align*}
\]

The partial derivatives of the displacement field were computed from the quadratic function approximation of the displacement field in a local neighborhood containing 25 \((5 \times 5)\) displacement measurements (total size of region is \(10 \times 10\) pixels when using 2-pixel spacing).

Figure 14 shows typical surface strain fields for growing cracks under quasistatic mixed-mode I/III loading at \(\Phi=0\), 30, and 60 deg. Similar results are obtained during low-speed impact for all loading angles, and hence, these results are not shown.

For \(\Phi=0\) deg (nominally mode I loading), Fig. 14(a) shows that the tensile strain \(\varepsilon_{yy}\) is the dominant strain component, with the peak value for \(\varepsilon_{yy}\) nearly an order of magnitude larger than either \(\varepsilon_{xx}\) or \(\varepsilon_{xy}\). The presence of high plastic strain around the lower (moving) fracture corresponds with the orientation of the observed slanted crack surfaces; the thinner specimen region after crack slanting corresponds to the region with larger residual plastic strain.

The results for both \(\Phi=30\) deg and \(\Phi=60\) deg are similar, with \(\varepsilon_{yy}\) the dominant strain component. However, mixed-mode I/III loading does increase both \(\varepsilon_{xx}\) and \(\varepsilon_{xy}\) by \(3\times\) and \(5\times\), respectively, relative to the measured values for \(\Phi=0\) deg.

Finally, direct comparison of the measured data in Figs. 14(a)–14(c) shows that the strain distributions under mixed-mode loading are appreciably different. For example, mixed-mode I/III loading introduces a large shear strain component \(\varepsilon_{xy}\), visibly increasing asymmetry in the surface deformation fields during tension-torsion loading.

6 COD Measurements

Figures 15 and 16 provide the basic information necessary to quantitatively determine COD. As shown in Fig. 15, subsets located near the crack tip in the previous image will be \(1 \text{ mm}\) behind the crack tip in the current image. Since the finite size of the subset will introduce an offset in the \(\pm Y\) direction, values for each displacement component are determined along a \(Y\) line with \(X \approx 1\) mm behind the crack tip.
in the current crack tip, and then linearly extrapolated to the crack surface ($Y=0$).‡‡ This process is shown in Fig. 16, with values in the upper (lower) half of the specimen denoted by 1 (2). Letting $(U_1, V_1, W_1)$ and $(U_2, V_2, W_2)$ be the extrapolated values of the displacement components in the upper and lower halves of the specimen, then the COD components and total COD values at $=1$ mm behind the current crack tip could be calculated based on the crack tip local coordinate system in the preceding deformed configuration:

\[
\begin{align*}
\text{COD}_I &= V_1 - V_2, \\
\text{COD}_{II} &= U_1 - U_2, \\
\text{COD}_{III} &= W_1 - W_2, \\
\text{COD} &= (\text{COD}_I^2 + \text{COD}_{II}^2 + \text{COD}_{III}^2)^{1/2}.
\end{align*}
\]

‡‡The X-Y-Z directions change with the deformation and crack growth process. The X direction at each step is defined to be along the current crack growth direction; it is the unit vector from the previous crack tip to the current crack tip. The Y direction is defined to be perpendicular to X and in the best fit tangent plane to a small region surrounding the previous crack tip. The Z direction is obtained using the cross-product.

To improve the accuracy of the COD measurements, a series of additional experiments were planned with a magnification of $\approx 80$ pixels/mm. With an increase in magnification, major modifications to the camera system and lighting were necessary to maintain focus on the required field of view throughout the loading process.

For quasistatic loading, it was possible to reconfigure the stereo-vision system so that high-magnification measurements could be made for $\Phi=0$, 30, and 60 deg and all COD

![Fig. 14 Contours of surface strains for a growing crack with crack extension $\Delta a$ in 2-mm-thick AL6061-T6 specimens under quasistatic loading at $\Phi=0$, 30, and 60 deg during mixed-mode I/III experiments.](image)

![Fig. 15 Definition of local coordinate system (on the preceding image) for COD analysis: $P$ is the preceding crack tip and $C$ is the previous position (on the preceding image) of current crack tip for current image and the distance $PC$ represents about 1 mm of crack growth.](image)
measurements for quasistatic loading were at high magnification. For impact loading, a 3-D high-speed stereo-vision system with a magnification of ≈70 pixels/mm was configured successfully to measure COD values during crack growth for Φ=0 and 30 deg. However, due to both the presence of large out-of-plane motion and requirements to maintain a large offset from the specimen for safety reasons, it was not possible to arrange the system properly for Φ=60 deg. Thus, images with a magnification of ≈15 pixels/mm were used to analyze the COD variation with crack extension for Φ=60 deg. §§

Figure 17 shows typical variations of COD components and total COD under low-speed impact with Φ=60 deg, along with a compilation for the average and standard deviation in COD and its components. Similar trends are observed in impact loading at Φ=30 deg and quasistatic loading at Φ=30 and 60 deg. For all mixed-mode cases, when Δa ≳ t, where t is the specimen thickness, it was observed that

1. CODIII is the dominant component.
2. CODI ≈ 0.5 CODIII.
3. CODII ≈ 0.2 CODIII.

A compilation of all measured COD versus Δa results is shown in Fig. 18. There are two general trends shown in Figs. 17 and 18 that require discussion. First, there is a well-defined transition in the early stage of crack growth (Δa ≲ t), with COD decreasing rapidly. Second, for all crack growth so that Δa > t, the values for the COD components and total COD are nearly constant. These trends were seen in a variety of fracture experiments. For highly ductile materials, it was shown that the initially high values are directly correlated with the crack tip plastic strains accumulated during the fracture process.

The average stable COD values for the quasistatic and dynamic experiments with Φ=30 and 60 deg are, respectively, 0.395, 0.393, 0.402, and 0.397 mm at 1 mm behind the current crack tip, indicating that (1) low-speed impact does not introduce measurable rate effects in the COD measurements and (2) modest increases in torsional loading do not have a significant effect on the critical COD values.

Also shown in Fig. 18 are (1) the stable critical COD values for mode I loading and (2) the average COD values obtained from a series of mode I/III experiments on the same material, which were a part of the baseline study by the investigators. The setup for mixed-mode I/III experiments and the procedure to measure corresponding COD can be found in Ref. 55. These indicate that the critical COD ≈ 0.100 mm, a value that is 4× smaller than measured in the same material under combined tension and torsional loading. These results indicate that the magnitude of the critical COD is a function of loading mode in highly ductile, thin-sheet materials. Though the precise reason for the large increase in COD is not fully understood, it is believed that the large structural, out-of-plane bending introduced by the mode III component in combined tension-torsion loading are relevant to the measured values of COD in these materials.

7 Concluding Remarks

Recent advances in both digital camera technology and software for data acquisition and image analysis have made it possible for state-of-the-art noncontacting measurement technology to be applied in industrial, academic, and re-

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For high magnification, all subsets were 21×21 pixels (0.25 × 0.25 mm). For the low-magnification studies, the subset size was reduced to a minimum in an effort to improve the accuracy of the extrapolated values; the COD displacement measurements were made at low magnification with an 11×11-pixel subset (0.55×0.55 mm) whenever possible.
search laboratory settings. In this paper, stereo-vision systems were constructed and used to make 3-D (1) dynamic and (2) quasistatic deformation measurements. In this paper, 3D-DIC was used to characterize the stable crack extension behavior of a ductile automotive aluminum alloy undergoing quasistatic and dynamic mixed-mode I/III loading. The method was shown to be an ideal methodology for 3-D full-field surface displacement and strain fields, (3) crack path during stable tearing, and (4) unique measurements determining the critical generalized crack opening displacement as a function of crack extension under combined I/III loading.

For both quasistatic and low-speed impact conditions, results showed that the measured displacement and strain fields are (1) similar for both mixed-mode loading angles $\Phi=30$ deg and $\Phi=60$ deg and (2) distinctly different from the fields measured for mode I loading angle $\Phi=0$ deg, with no rate effects discernible during the low-velocity impact process. Specifically, for $\Phi=0$ deg the in-plane opening displacement $V$ and opening strain $e_{yy}$ are the dominant components in the displacement and strain fields, respectively, during crack growth. For $\Phi=30$ deg and $\Phi=60$ deg, the out-of-plane displacement $W$ is dominant with $e_{yy}$ being the largest strain. The presence of substantial shear strains $e_{xy}$ clearly indicates asymmetry present in the surface deformation fields during mixed-mode I/III loading.

Furthermore, recent computational simulations of mixed-mode I/III fracture in thin-sheet aluminum alloys, where the experimental data obtained by 3-D computer vision was used to define far-field boundary conditions, show that there is excellent agreement between the experimental displacement measurements and the simulation data throughout the region inside the prescribed boundary.

Measured critical COD values during quasistatic and impact mixed-mode I/III loading show that, after an initial transition process, the value is nearly constant throughout the crack growth process. The value measured is 4 times larger than has been measured previously during mode I/II

loading, confirming that the magnitude of critical COD may be a function of loading mode in highly ductile, thin-sheet materials.

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