On the Design of Novel Multi-failure Specimens for Ductile Failure Testing

Bruce W. Williams$^1$ and C. Hari M. Simha*$^2$

$^1$CanmetMATERIALS, Natural Resources Canada, 183 Longwood Road South, Hamilton, ON L8P 0A5, Canada
$^2$College of Engineering and Physical Sciences, University of Guelph, 50 Stone Road East, Guelph, ON N1G 2W1, Canada

*csimha@uoguelph.ca

Abstract. To quantify uncertainty in the failure response of metallic alloys, conventional experiments may not be suitable owing to the lack of significant scatter in stress states that lead to ductile tearing. In contrast, our testing experience indicates with structures containing strategically located cutouts lead to multiple failure paths and display sufficient scatter in the failure response. Accordingly, we describe the design of dog-bone shaped structures with an ensemble of cutouts, so that at least three different failure paths are observed. In conjunction with Digital Image correlation for full-field displacement measurement and numerical computations, we show how multiple failure paths are obtained when these samples are used. Tests on 2-mm thick 6061-T61 aluminum sheets were conducted using a novel guillotine-style fixture that allows the use of high-speed press. The latter allows testing at strain rates as high as 1 1/s. The primary purpose of this article is to make the case for the use of these samples that not only minimize number of tests required to garner data to calibrate stress-based damage models that capture the entire failure envelope of the material, but also display sufficient scatter that allows quantification of uncertainty in the failure response.

1. Introduction
The typical fracture envelope of a metallic alloy subject to ductile failure is depicted in Figure 1. In this description, the effective strain to failure is dependent upon stress triaxiality (mean stress divided by effective stress). As detailed by Xue [1], the failure response is bounded and for a given stress triaxiality the range can be described by the Lode angle (the third invariant of the stress deviator). Several damage models have been developed to describe failure of metal undergoing fracture over this wide range of loading conditions, which includes the Fracture Forming Limit Diagram (FFLD). These models include the shear modified Gurson [2], the modified Mohr-Coulomb (MMC) [2], and Xue-Wierzbicki (XW) [3] fracture models. The MMC and XW models are damage-mechanics based models that use a scalar damage parameter to degrade strength upon damage initiation.
In each of these models, the failure strain constitutes a three-dimensional surface whose independent variables are triaxiality and Lode angle. A number of mechanical tests are required to characterize this surface by varying the triaxialities and Lode angles. For instance, the stress triaxiality, $\eta$, for uniaxial tension is equal to 1/3 with a Lode angle, $\theta_L = -30^\circ$. For pure shear, $\eta = 0$ and $\theta_L = 0^\circ$ and for sharp notches higher positive triaxialities can be achieved and the Lode angle can be computed using stress analysis. Dunand and Mohr [2] describe a dual actuator system, sometimes referred to as the ‘butterfly’ rig, which uses vertical and horizontal actuators to generate various loading paths. Beese et al. [4] detail five fracture tests to generate failure data under uniaxial tension, plain strain, notched tension, equi-biaxial stretching, and ‘butterfly’ specimens as detailed in [2]. Paredes et al. [5],[6] detailed a number of mechanical test specimens to generate fracture data under a wide range of stress triaxialities and Lode angles for X65 pipeline and TC128 steel. All of these test methods are intended to generate a single failure point under one loading condition. With the use of full-field displacement measurement using Digital Image Correlation (DIC) multiple paths can be measured in a single specimen.

Driemeier et al. [7] developed a bi-failure specimen that underwent notched tension and shear with the strain measured using DIC techniques. Tests were performed on an AA2024-T351 alloy with 9.72 mm thickness and it was concluded that the specimen is useful for the evaluation of failure criteria. The current work builds upon the geometry of Driemeier et al. [7] to include an additional failure path. It is not the intent of the present article to calibrate/validate damage models, but rather focus on the development of a specimen geometry that undergoes multiple failures under loading conditions relevant for the study of damage models.

To calibrate coefficients for damage models, a combination of the mechanical test data and numerical simulations is required. Finite element simulations are required to accurately calculate the stress triaxiality and Lode angle at the location of failure in the various fracture geometries. As detailed by Paredes et al. [6], an optimization method is used to determine the damage model coefficients through error minimization of experimental and numerical data. The calibration of damage models using such an optimization procedure is not addressed in this paper.
2. Experimental Method
Details of the multi-failure specimen test fixture were initially given in [8]. For brevity, only brief details are given in the current paper. The fixture shown in Figure 2 was designed to subject the sample to tensile loading but in a compression press. Gripping was achieved by matching the curved segments of the sample with the corresponding curvature on the fixture. The middle of the multi-failure sample was visible to the DIC system, which was setup in a 2D configuration, as seen in Figure 2. The top and bottom base-plates of the fixture were attached to the T-slots on the press. The top frame was bolted to the top plate and applied pressure on the bottom of the sample. The top frame strut prevented the top frame from spreading during the test. The bottom frame supported the loading pins which press on the top of the sample. The middle of the bottom frame was cut-away to give a line of sight for the DIC system. Two alignment blocks kept the front and back plates of the bottom frame parallel to each other. The bottom frame was not fixed to the base plate so that the assembly was not over-constrained. For thin sheet metal specimens, sample braces were bolted to the grip sections of the sample to prevent out-of-plane buckling during the test.

![Figure 2. Fixture for pulling tension samples in compression press](image)

The multi-failure specimen geometry is detailed in Figure 3. Two geometries are shown each with two uniaxial, two notched tension, and shear ligaments, for a total of five failure ligaments. For Geometry #1, the two uniaxial tensile ligaments (Ligaments 1 and 2) and the shear ligament (Ligament 3) were 2 x 2 x 4 mm. For the two notches (Ligament 4 and 5), the radius was 4 mm, a value that could be reduced to produce higher triaxiality for a specimen with greater thickness. For Geometry #2, round cut-outs with a diameter of 10 mm and a centre-to-centre spacing of 12 mm were used. All cut-outs were machined.
3. Experiment Results

The current work only presents results for AA6061-T6 sheet with 2-mm thickness. Tests were performed at punch displacement rates of 0.016 mm/s. This corresponded approximately to strain-rates in the uniaxial tensile ligaments of 0.003 s\(^{-1}\) (quasi-static). The force versus (punch) displacement results for Geometry #1 and #2 are compared in Figure 4. For Geometry #1, it was found that there was some compliance in the load frame. This was addressed for the Geometry #2 by increasing the stiffness of the system. Consequently, there was a small difference in initial loading slope between Geometry #1 and #2. For Geometry #2, the figure indicates that the load response is repeatable. The progression of failure for Geometry #1 was reported in [8] at a higher strain-rate than in the current work. The failure progression reported in [8] for a higher rate tests is shown in Figure 5, and the sequence of failure was very similar for
the slower Geometry #1 case. The DIC frame rate was set at 500 frames per second and failure is seen from 4 images over 23 stages (0.002 seconds/stage). The progression of the failure for Geometry #2 is shown in Figure 6, in which the major strain is overlain with the (speckled) specimen image from DIC. The frame rate was set at one frame per second and failure is seen from 6 images over 111 stages. Figure 4 shows the inherent test-to-test variation in the global load-displacement response observed in Geometry #2.

![Images of measured contours of major strain with DIC overlay image of Geometry #1 at stage a) 402 b) 405 c) 409 and d) 424; maximum major strain of 0.45 given by the red zones.](image)

Figure 5. Measured contours of major strain with DIC overlay image of Geometry #1 at stage a) 402 b) 405 c) 409 and d) 424; maximum major strain of 0.45 given by the red zones [8]
Figure 6. Measured contours of major strain with DIC over-lay image of Geometry #2 at stage a) 170 b) 204 c) 205 d) 261 e) 354 and f) 381; image rate of 1 frame/second with maximum major strain of 0.60 given by the red zones

One main difference between Geometry #1 and #2 is that the transition of failure from the uniaxial ligaments to the notched tensions ligaments is clearly distinguished for Geometry #2 by a sudden drop in load at about 2.5 mm of displacement. For Geometry #1, this transition from uniaxial to notched tension failure was essentially instantaneous as it was not seen the load response curve. A load drop to distinguish failure would be ideal to simplify damage model coefficient calibration, but not necessary.

For both Geometry #1 and #2, there was a major drop in load after failure of the notched tension ligaments upon transitioning to the shear ligament. Figure 6e and Figure 6f indicate that failure did not initiate in the middle of shear ligament, but rather at the corners where there are stress concentrations (with high triaxiality). This is a typical issue with shear specimens and it is suggested that the shear ligament design in future multi-failure test geometries be improved to delay the onset of failure at stress concentrations.

The strain versus time response in the uniaxial and shear ligaments for Geometry #2 is compared in Figure 7. The uniaxial tensile strain was based on the true strain in the ligament measured from DIC, where as the shear strain was calculated based on the shear angle from DIC. The figure indicates that reasonably high strains could be measured in the multi-failure test, as would be required for damage model calibration.
4. Numerical Simulation

Numerical simulations of the multi-failure specimen were performed to determine the stress triaxiality and Lode angle for the failure ligaments in the specimen. The simulation was performed with von Mises yielding and the hardening law for AA6061-T6 detailed by Beese et al. [4] which is given by,

$$\bar{\sigma} = 438.0 \left( 0.00434 + \bar{\varepsilon}^p \right)^{0.07}$$  \hspace{1cm} (1)

where $\bar{\sigma}$ is the effective stress (from the rolling direction of the material) and $\bar{\varepsilon}^p$ is the effective plastic strain. To simulate failure in the FEA models, the XW damage model was used for crack initiation and propagation. The XW damage model was utilized with the parameters for AA2024-T351 detailed by Xue and Wierzbicki [3] to describe the relation ship between initiation strain and damage evolution with stress triaxity and Lode angle. By using the damage parameters for AA2024-T351, accurate failure predictions of AA6061-T6 would not be expected from the simulation. However, the stress triaxialities and Lode angle would be precise in determination of the loading path which was the objective of the simulation effort. There were 88,000 solid elements with 9 elements through the thickness in the model. The XW damage model detailed by Simha et al. [5] was implemented in the explicit solvers of DYNA3D and used in this study.

The effective strain versus stress triaxiality or Lode angle for Ligaments 1, 3, and 5 (the results are equivalent for Ligaments 1 and 2; also for Ligaments 4 and 5) predicted for the Geometry #1 simulation are shown in Figure 8. Both the uniaxial and notched tensile ligaments initially have $\eta \sim 1/3$, but then as the damage progresses the stress triaxiality changes going down to about $\eta \sim 0.2$ just before failure of the tensile ligament and increasing to about $\eta \sim 0.74$ at the notch. For the shear ligament, $\eta \sim 0$ with $\theta_L \sim 0^\circ$. As per the definition of Lode angle in [1], both uniaxial and notch tensile ligaments have $\theta_L \sim -30^\circ$ increasing slightly near failure. Though not achieved in the current loading configuration, an additional Lode angle of interest would be at $60^\circ$ which could be achieved through equi-biaxial loading conditions.
Figure 8. Predicted effective strain versus stress triaxiality and Lode angle for Geometry #1 [8].

Contour plots of the predicted mean stress, Lode angle (with units of radians), effective plastic strain, and damage for the Geometry #2 simulation is shown in Figure 9 at a step just beyond failure of the uniaxial tension ligaments. The figure indicates achievement of good variability of mean stress and Lode angle in the multi-failure specimens. The mean stress contour plots indicates the highest mean stress at the notched tensile ligaments. As can also be seen, stress concentrations at the corners of the shear ligament are already noticeable even before full loading on this ligament. The effective stress and mean stress yield a triaxiality of 0.017 and the Lode angle is approximately zero. Corresponding failure strain is greater than 30\%, which is more than that observed with Geometry #1. The maximum value on the contour plot of damage is 0.25 (an element is deleted at a damage level on one) and shows that damage is starting to accumulate at the tensile notches.

5. Conclusions

The present report is a preliminary outline of the design of a specimen wherein multiple failure paths can be obtained. While the proposed specimen geometry reduces the testing the number of tests required for damage-model calibration, the observed uncertainty in the response can be used for uncertainty quantification in the damage model. Additionally, by using a ductile liner, the proposed specimens can be subjected to bi-axial loading. In future designs, consideration will be given to the modifications of the shear ligament geometry to reduce stress concentrations at this location.

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Figure 9. Contour plots of mean stress, Lode angle, effective plastic strain, and damage for Geometry #2.