

# On Simulation of Edge Stretchability of an 800MPa Advanced High Strength Steel

Nikky Pathak, Cliff Butcher, Michael Worswick  
University of Waterloo  
n3pathak@uwaterloo.ca

**Abstract.** In the present work, the edge stretchability of advanced high strength steel (AHSS) was investigated experimentally and numerically using both a hole expansion test and a tensile specimen with a central hole. The experimental fracture strains obtained using the hole expansion and hole tension test in both reamed and sheared edge conditions were in very good agreement, suggesting the tests are equivalent for fracture characterization. Isotropic finite-element simulations of both tests were performed to compare the stress-state near the hole edge.

## 1. Introduction

The hole expansion test can effectively capture the influence of different edge conditions, such as sheared, drilled or reamed, but is sensitive to the punch geometry and burr-orientation [1]. However it is unable to resolve variation in the fracture strain with material direction since the edge crack always develops in the direction with the lowest ductility. For numerical characterization, the hole expansion test is challenging since there is tool contact, a strong tendency to incite hourglass modes and initially strong through-thickness stress and strain gradients. In a study unrelated to sheared edge cracking, Dunand and Mohr [2] used a tensile specimen with a central hole (hole tensile test) for both numerical and experimental characterization of fracture in uniaxial tension. Hole tensile tests are well suited for numerical characterization to simulate edge fracture since there is no friction, tooling contact or shear burr orientation effects. Additionally, anisotropy of the fracture strains can be investigated. The objective of the present work is to directly compare the hole expansion and hole tensile tests as characterization tests to investigate edge cracking of a typical dual phase steel, DP780. Isotropic finite element models of the hole tension test and hole expansion test with a reamed edge are used to demonstrate the effectiveness of the proposed experimental methodology that does not require inverse finite-element modeling to obtain accurate engineering estimates for edge formability. This investigation will assist in the development of an alternative to the hole expansion test that is better suited for experimental and numerical characterization of edge fracture.

## 2. Experimental Procedure

### 2.1. Hole Expansion Test

The hole expansion test consists of expanding a hole in a blank with a conical punch until the onset of edge cracking. The formability metric in a hole expansion test is typically the hole expansion ratio (HER), defined as the ratio of the initial and final inner diameters of the hole as

$$HER (\%) = 100 \cdot (d_f / d_o - 1) \quad (1)$$

Hole expansion testing was conducted for both sheared and reamed (ideal) edge conditions using the ISO-16630 standard hole size of 10 mm. The procedure for the hole expansion test is outlined in [1]. The strains at the hole edge during the hole expansion test cannot be readily tracked using digital image correlation (DIC) techniques since the sheet thickness is not seen by the camera system until the hole has been expanded a sufficient amount and the hole edge rotates out-of-plane and into view of the cameras. Additionally, DIC techniques do not resolve edges so the strain measurement near the edge is very challenging. An analytical method developed by Butcher et al. [3] to determine the equivalent failure strain in a hole expansion test has been shown to be a very good estimation of the local strain in an isotropic axisymmetric simulation of a hole expansion test of DP600. The equivalent fracture strain



can be estimated by measuring the inner and outer hole diameters at fracture as well as the thickness around the circumference as:

$$\varepsilon_{eq}^{macroscopic} = \frac{2}{3}(\varepsilon_c - \varepsilon_t), \quad \varepsilon_c = \ln\left(\frac{d_{outer} + d_{inner}}{2d_o}\right), \quad \varepsilon_t = \ln\left(\frac{t_{edge}}{t_o}\right) \quad (2-4)$$

This method is used in present study to estimate the fracture strains in a hole expansion test without using DIC techniques.

## 2.2. Hole Tension Test Procedure

A tensile specimen of gauge length 35 mm and width 22.5 mm was fabricated with a hole of diameter 10 mm at the center. The specimen was subjected to tension until a visible crack appeared at the edge. The majority of samples failed along the rolling direction during the hole expansion test. The transverse loading direction was therefore selected to replicate failure conditions during the hole expansion test. A 3-D DIC system by Correlated solutions Inc. was used to record the full-field strain during the test experiment using a frame rate of 4 per seconds and image size in 2448 x 2048 pixels. A vertical virtual extensometer of length 21 mm was used to measure displacement to failure. The fracture strain at the crack location was measured from the DIC analysis using a circle of size 0.25 mm.

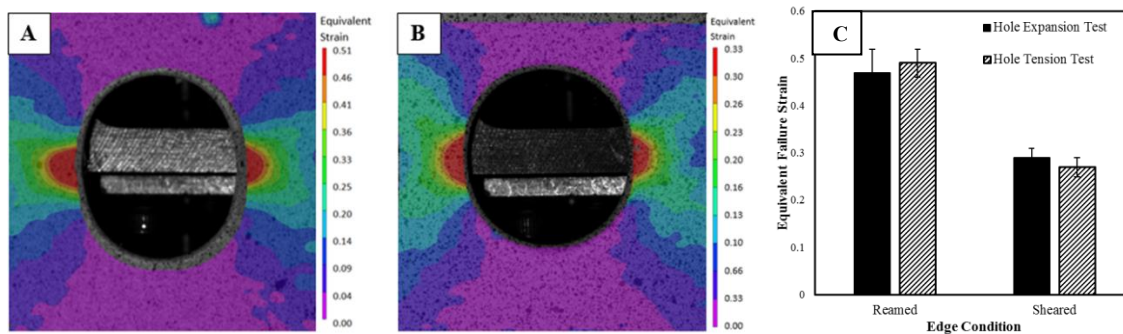
## 3. Edge Stretchability

### 3.1. Hole Expansion Test Results

The HER for the sheared hole in the burr-up orientation was 22% and lower than the burr-down orientation, with its HER of 30%. The HER reported for the reamed edge is 51% which is significantly higher than the sheared edge because almost no damage exists at the reamed edge, corresponding to the condition of the base microstructure. The shearing process, on the other hand, introduces work-hardening and pre-nucleated voids behind the sheared edge. This pre-existing damage leads to the initiation of cracks at lower strains and consequently reduces edge stretchability. The influence of the shear burr-orientation is observed on the HER as a result of through-thickness stress and strain gradients.

### 3.2. Hole Tension Test

The edge stretching limit in a hole tension test is quantified by an equivalent strain obtained from DIC analysis. It is important to state that due to the inherent limitations of DIC in resolving edges, the failure strains are not true edge strains but were calculated at a distance approximately 0.1-0.3 mm away from the edge. The contour plots of equivalent strain for reamed and sheared edges just before failure are shown in Figure 1a and 1b respectively. The strain localizes near the edge during the hole tension test and therefore the edge sensitivity can be captured effectively. Figure 1c shows the plot of equivalent failure strain for the reamed and sheared holes determined from the hole tension test and hole expansion test. The equivalent strains obtained in the burr-up and burr-down positions during the hole expansion test are combined to represent an “average value” for a sheared edge condition. The equivalent strain just before fracture at the reamed edge is 0.49 and at the sheared edge is 0.27. Similar to the hole expansion test, the difference in the stretching-limit for the reamed and sheared edges during the hole tension test is evident from the values of failure strain. The displacement to failure measured by a virtual extensometer is 1.64 (±0.08) mm for the reamed edge and 0.82 mm (±0.05) for the sheared edge. The confidence intervals of failure strain for the reamed edge obtained from the two tests overlap and suggest there is no significant difference between the limit-strains of edge determined from the two tests. The average failure strains of the sheared edge determined from the hole expansion and hole tension tests matches exactly.



**Figure 1: Contour plots of equivalent strain for (a) reamed and (b) sheared edge conditions during the hole tension test. (c) Equivalent failure strain obtained during the hole expansion and hole tension tests for the reamed and sheared edges**

#### 4. Numerical Modeling

A finite element model of the hole tension and hole expansion tests have been developed to validate the proposed methods for estimating the fracture strain. A one-eighth finite element model of the hole tension geometry and a quarter model of hole expansion geometry with a reamed edge condition were created using the commercial finite-element code, LS-DYNA. Only the reamed edge condition is considered since additional experiments are required to estimate the residual strain field in the sheared edge. The geometries were meshed using constant stress solid elements with an average equivalent length of 0.1 mm in the region near the hole edge with 8 elements through the half-thickness. A displacement boundary condition was enforced at the free-end of the hole tension specimen and an implicit solution was obtained under quasi-static loading. The displacement-to-failure was measured using the nodes that correspond to the half-length of the extensometer gauge length of 21 mm. The simulation is terminated when the experimental displacement to failure is reached. For the simulation of hole expansion test, the steel punch, binder and draw ring are modeled as rigid surfaces with a coefficient of friction of 0.10 with the blank. The simulation is terminated when the hole expansion ratio determined experimentally is achieved. The material is assumed to obey the von Mises yield criterion with the flow stress curve from [4] used to represent the material behavior in the transverse direction. No failure treatment is included within the model at present since the objective is to use the model to evaluate the transferability of the experimental hole expansion and hole tensile strains to the local strains within the material. The deformed mesh plots of hole tension and hole expansion tests are shown in Figure 2 a and b respectively.

Figure 3a shows the plot of equivalent strain versus displacement obtained by the numerical simulation of the hole tension test for a reamed edge. The equivalent strain taken at the element located at the minimum section of hole tension specimen on the hole edge. The strain accumulation with respect to displacement of the center element and the element at the hole edge is almost similar throughout the test and suggests relatively uniform deformation in a through-thickness direction. The measured strain history at the point of failure, experimentally derived from the DIC analysis, is also plotted. The failure strain derived numerically at the displacement to failure (1.64 mm) is 0.52 and lies close to the failure strain derived experimentally and hence validates the numerical model. The fracture strain of 0.51 ( $\pm 0.05$ ) from the hole expansion test would also give very good predictions for the displacement to failure.

The stress-triaxiality at the hole edges during the hole tension and hole expansion tests are shown in Figure 3b. The center element and element at the edge of expanding hole during the hole tension test are under constant uniaxial tension state throughout deformation with a constant stress-triaxiality of 1/3. This stress-state is similar to the upper element of the expanding hole during the hole expansion test. The lower edge of hole expansion test however is in compression state due to the punch contact. This mechanism generates a through-thickness stress-gradient which converges to uniaxial tension as deformation continues. Since, the DP780 reamed edge experiences fracture after the convergence of

stress-gradient, the assumption of hole tension test replicating hole expansion test is appropriate. This demonstrates that the hole tension test is an efficient experiment to capture edge stretchability.

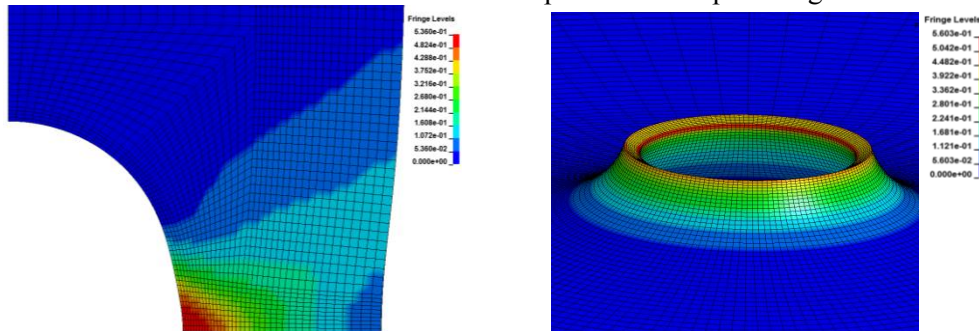


Figure 2: Deformed mesh plots of (a) hole tension test and (b) hole expansion test

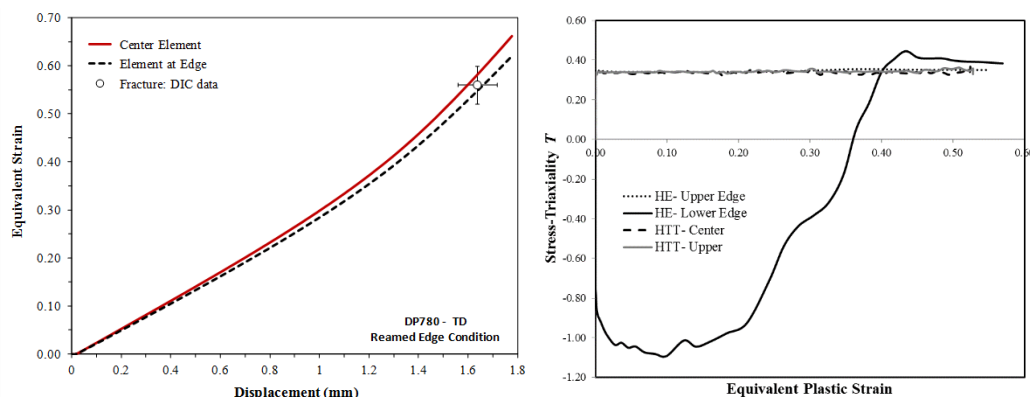


Figure 3: (a) The plot of equivalent strain versus displacement for the reamed hole tension test (b) The stress triaxiality at the edge during hole tension test

## 5. Conclusions

The following conclusion can be drawn from the present investigations:

1. A significant reduction in HER for the sheared edge was observed compared to the reamed edge due to the presence of pre-nucleated voids and residual strain from the shearing process.
2. Similar to the hole expansion test, the edge condition has a significant influence on the failure strain of the hole tension test.
3. An experimental method to estimate the failure strains in the hole expansion test for the reamed and sheared edge conditions is in very good agreement with the hole tensile failure strains obtained using DIC analysis.
4. Isotropic finite-element simulation shows that a nearly constant uniaxial stress state is achieved at the edge during the hole tension test, at least for the current material and ductility. A stress-gradient exists at the hole edge during the initial deformation of hole expansion test, which later converges to a uniaxial state.

## References

- [1] N. Pathak, C. Butcher, M. Worswick, Assessment of critical parameters influencing the edge stretchability of AHSS sheet, submitted to Journal of Materials Engineering and Performance, 2016.
- [2] D. Matthieu, and D. Mohr. 'Hybrid Experimental-Numerical Analysis Of Basic Ductile Fracture Experiments For Sheet Metals'. International Journal of Solids and Structures 47.9 (2010): 1130-1143.
- [3] C. Butcher, L. ten Kortenaar, M. Worswick, Experimental characterization of the sheared edge formability of boron steel, IDDRG conference 2014, Paris, France.
- [4] A. Abedini, C. Butcher, D. Anderson, M. Worswick, and T. Skrzek, (2013). Fracture Characterization of Automotive Alloys in Shear Loading. SAE , 2015-01-0528.