

Extending Tensile Curves beyond Uniform Elongation Using Digital Image Correlation: Capability Analysis

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ABSTRACT

A uniaxial stress-strain curve obtained from a conventional tensile test is only valid up to the point of uniform elongation, beyond which a diffuse neck begins to develop, followed by localized necking and eventual fracture. However Finite Element Analysis for sheet metal forming requires an effective stress-strain curve that extends well beyond the diffuse necking point. Such an extension is usually accomplished by analytical curve fitting and extrapolation. Recent advancement in Digital Image Correlation (DIC) techniques allows direct measurement of full-range stress-strain curves by continuously analyzing the deformation within the diffuse neck zone until the material ruptures. However the stress-strain curve obtained this way is still approximate in nature. Its accuracy depends on the specimen size, the gage size for analysis, and the material response itself. An extensive numerical study is presented in this paper to evaluate the capability of extending tensile curves based on DIC measurement data. A numerical model for uniaxial tensile test is established and used to simulate the experimental tests. The results are used as the input for DIC analysis. A wide range of conditions are considered, and the “full-range stress-strain curve” obtained from the DIC analysis is compared with the actual curve in the numerical model to assess the measurement error. It is found that, within 5% error range, DIC analysis can provide sufficient stress-strain curve extension for FEA analysis. The study also concludes that narrower test specimens give longer-range extensions of the tensile curve and closer to the actual material response.

INTRODUCTION

Material stress-strain curves used in FEA simulations are usually obtained from a standard tensile test. In the test,

engineering strains are measured from an extensometer at a fixed initial gage length. Since the tensile strains are no longer uniform after the onset of necking, the obtained stress-strain curves are valid only up to point of the maximum uniform elongation. Beyond that point a diffuse neck begins to develop, followed by localized necking and eventual fracture (As illustrated in [Figure 1](#)). However Finite Element Analysis for sheet metal forming requires an effective stress-strain curve that extends well beyond the diffuse necking point. Such an extension is usually accomplished by curve fitting and extrapolation using either power law for steels or Voce's law for aluminum alloys (As shown in [Figure 2](#)). Equi-biaxial tests such as bulge test are sometimes conducted to calibrate such extensions. In addition to the complexity of test setup, a specific yield surface criterion has to be assumed in order to transform the obtained equi-biaxial bulge test data to the effective stress-strain curve.

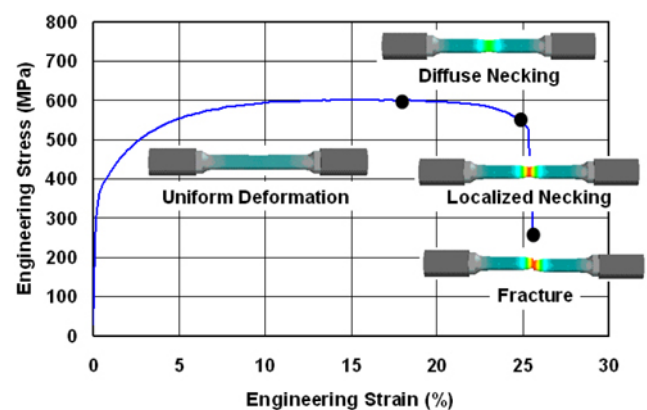
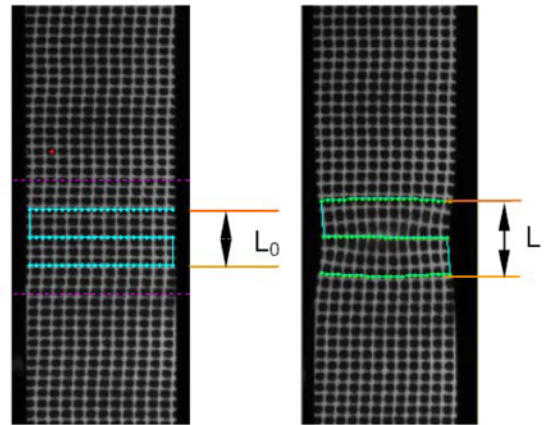


Figure 1. Engineering Stress-Strain Curve Obtained from Unit-axial Tensile Test



(a) ARAMIS DIC Measurement System



(b) Original Grids

(c) Deformed Grids

Figure 3. DIC System to Obtain Stress-Strain Curves at Gage Length L

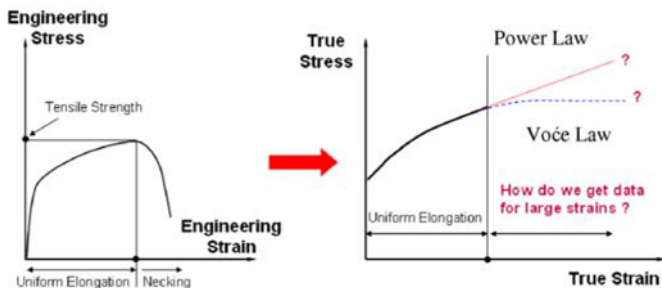


Figure 2. Extension of True Stress-Strain Curve for Finite Element Analysis

Recent advancement in Digital Image Correlation (DIC) techniques allows direct measurement of full-range stress-strain curves by continuously analyzing the deformation within the diffuse neck until material rupture. Digital Image Correlation (DIC) was first developed at the University of South Carolina [1][2][3] in the early 1980s and has been since improved [4] considerably. Such systems also became commercially available in recent years. It is a computer-based image analysis technique that enables the non-contact measurement of strains on material surfaces with application in many areas. DIC has proven to be very effective at mapping deformation in macroscopic mechanical testing. In recent year, the technology is applied to the measuring of fracture strains, determining forming limit curves and obtaining material stress-strain curves beyond the uniform elongation [5][6][7]. Figure 3 shows the measurement of stress-strain curve using an ARAMIS DIC system. The pattern on the specimen surface can be regular square grids or random speckles.

However, the extended stress-strain curves obtained in DIC analysis are still approximate in nature. Although the DIC

instrument has sufficient accuracy in displacement measurement, there still exists systematic error from data processing in obtaining the stress and strain values after necking starts. The uniaxial stress-strain curve is defined as the effective stress-strain curve in a tensile test. This is certainly true when the specimen is uniformly deformed and the material is subject to stresses in only one direction. After necking is initiated, 3D stress and strain states appear within the localized area and the deformation is no longer uniform. The effective stress-strain curve will not coincide with the axial stress-strain curve after uniform elongation. Due to this non-uniform deformation, the true area used to calculate the true stress is also approximate in nature. Bridgman [8] proposed a correction factor to compensate the non-uniform stress distribution after necking. However no systematical investigations are available to understand the likely errors one would get from DIC analysis. In this paper, focus is on the capability evaluation of extending stress-strain curves obtained from DIC analysis. An extensive numerical study is presented to determine the valid range of the stress-strain curve extension; the best specimen dimensions which are likely to give more reliable and longer range extensions of the stress-strain curves; and the sensitivity of the curve extensions to the chosen gage size used in the analysis.

<figure 3 here>

TECHNICAL APPROACH

In DIC analysis, stress-strain curves are calculated from measured displacements from tensile test. In this study, a numerical model in ABAQUS is established and used to simulate the standard tensile tests. To accurately capture the failure mode, a full 3D analysis with very fine solid elements is modeled. As illustrated in Figure 4 (a), a 6mm wide ASTM standard sub-size specimen is used. Due to the symmetric

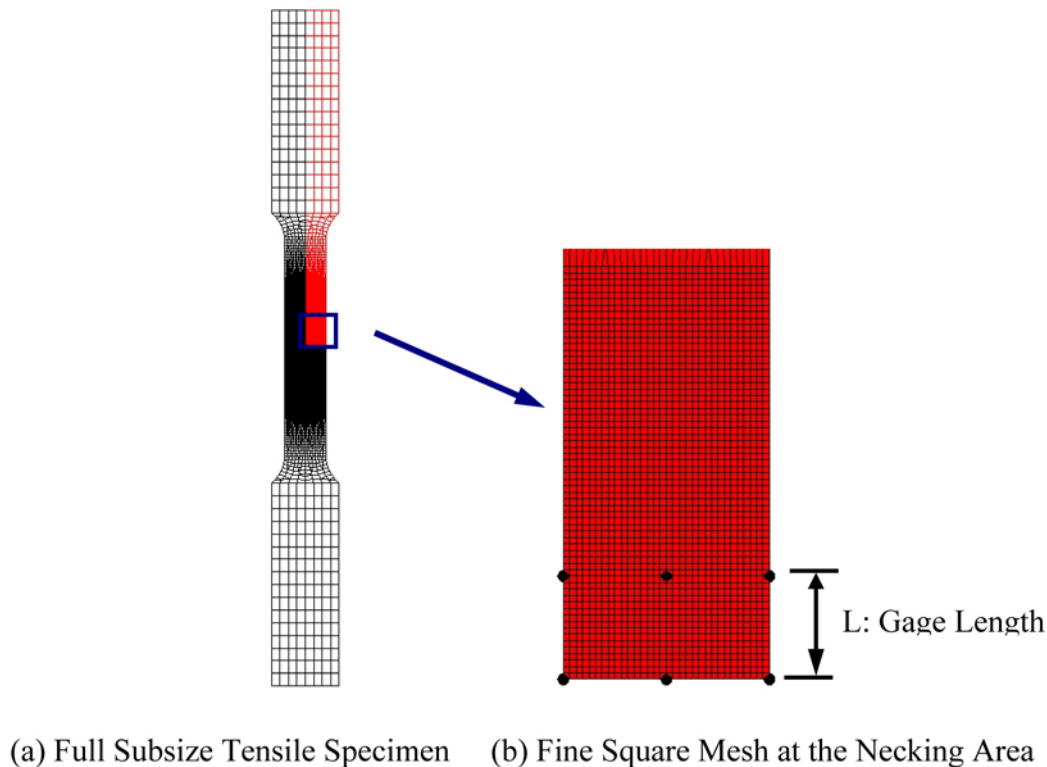


Figure 4. Finite Element Mesh on Tensile Test Specimen

condition, only one eighth of the specimen is modeled. A quasi-static analysis is conducted in this study, so strain rate effect is not considered.

The same procedure as in DIC analysis is followed to process the displacement data and calculate stress and strain values. The only difference is the use of displacement fields calculated from FEA replacing the measured displacement in DIC analysis. An effective stress-strain curve is given in the actual FEA simulation. This mimics the real material behavior in the test. The stress-strain curve calculated from simulated displacement is considered as the DIC analysis results. It is then compared against the given effective stress-strain curve to evaluate data processing capabilities in DIC analysis.

The analyzed stress-strain curves are based on grid deformation within the necking area. The FEA mesh size around interested area is around 0.1mm for both in-plane and thickness directions with regular brick mesh. Thus various gage length can be chosen for analysis (As illustrated in [Figure 4\(b\)](#)). The effective stress is calculated from dividing total pulling force by the true area of the cross section. The effective strain is calculated using the conventional finite element method. No corrections to the stresses and strains are applied in this study, so the error should be interpreted as the upper bound.

<figure 4 here>

RESULTS AND DISCUSSIONS

GAGE SIZE EFFECT

In the traditional tensile test, an extensometer such as 2" long is used to measure the specimen deformation. Thus the strain value obtained from the traditional test is actually the averaged over the 2" span. At uniform deformation stage, the strain is uniform along the full 2" length. After necking initiates, deformation will become localized at a very small region, thus the strain values will depend on the length of the extensometer.

The advantage of DIC analysis is that the displacements of millions of speckles are recorded on the specimen surface. So the gage length used to calculate the strain can be very small. In this section, gage length of 0.75mm, 1.5mm and 3.0mm are chosen to analyze the gage sensitivity. Mild Steel with isotropic material property is used in this simulation. The width-to-thickness (w/t) ratio of the specimen in this case is 12.

[Figure 5](#) shows the stress-strain curves obtained from numerical simulation on various gage length as compared with the input stress-strain curve. To better interpret the obtained results, the stress is normalized by the corresponding input flow stress and the strain by the n-value of the power law, and the normalized results are plotted in [Figure 5\(b\)](#). The same normalization scheme will be applied