

Estimating the Strain-Based FLC of a Tube from Straight Tube Hydroforming Experiments and Numerical Models

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ABSTRACT

The Extended Stress-Based Forming Limit Curve (XSFLC) failure criterion has been shown to provide good qualitative and quantitative predictions of failure (necking) in straight tube hydroforming when the Keeler-Brazier (K-B) approximation is used to define the XSFLC failure curve. Depending on the level of end-feed (EF) used during hydroforming, the failure criterion has a tendency to over predict failure pressure at low EF and under predict failure pressure for high EF. The over/under predictions suggest that the strain-space ϵ FLC, which the XSFLC is based on, has too high of a plane-strain intercept (FLC_0), when it is obtained using the K-B approximation (developed for sheet metal).

Using the results of DP600 straight tube hydroforming experiments with EF, the hydroforming process was modeled using the finite element code LS-DYNA and a numerical parametric study was conducted to show that the FLC_0 , which most accurately predicted failure, was lower than the FLC_0 predicted by the K-B approximation for the zero and 67kN EF cases. For the 133kN EF case, the FLC_0 determined by the K-B approximation under predicted the measured burst pressures. This inconsistency suggests that the shape and FLC_0 of a tube's strain-based forming limit curve (ϵ FLC) is different than that of sheet metal as shown by Keeler and Brazier. The coefficient of friction (COF) was also varied in the models to show the effect it has on failure prediction using the XSFLC. The COF parametric study showed that the XSFLC method is very sensitive to the COF used in the numerical models. This is most evident at high EF, when a small change in COF resulted in a large change in the predicted failure pressure.

INTRODUCTION

The use of advanced high-strength steel (AHSS) in hydroformed automobile structural components is of great interest to the automotive industry because of the potential to reduce vehicle weight. Reduced vehicle weight improves fuel efficiency, which in turn reduces greenhouse gas emissions. In addition to weight reduction, hydroforming possesses the following advantages over traditionally manufactured structural

parts which typically include stamping and welding; improved strength and stiffness due to work hardening, part consolidation/reduced scrap and improved dimensional accuracy [1-3].

In high pressure hydroforming within a die, friction plays a large role in burst (fracture) failure because it retards material flow and causes high tensile stresses in the hoop direction of the tube. Straight and pre-bent tube (steel and aluminum) hydroforming experiments conducted at the University of Waterloo have consistently shown that failure occurs at the transition zone between tube/die contact and the free expansion region [4-7] (Fig. 1). Within the transition zone, a three-dimensional state of stress exists due to the through thickness stress component. It has also been shown that the addition of end-feed (EF) during straight tube hydroforming increases the formability of a tube by delaying the onset of fracture which results in greater corner-fill expansion (CFE) [5, 6].

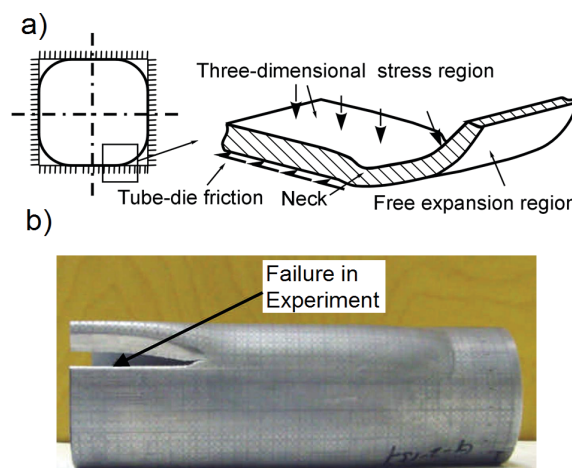


Figure 1: a) Transition zone where 3D stress state exists
b) Observed typical burst failure at transition zone [5].

The experimental and numerical (finite element) work of Bardelcik and Worswick [5] (denoted as article 1 hereafter) showed that finite element models using a constitutive model and a coefficient of friction (COF), as measured by the uniaxial tension and wrist compression test (respectively), resulted in good prediction of end-

feed displacement (EFD) and corner-fill expansion (CFE) when compared at the same exp./predicted pressure.

The extended stress-based forming limit curve (XSFLC) failure criterion [4, 7] was also used to predict failure (necking) of the article 1 straight tube hydroforming experiments. The XSFLC is a full three-dimensional stress state failure criterion. The XSFLC curve was created by first transforming the strain-based forming limit curve (ϵ FLC) [8] into two-dimensional principal stress space (σ FLC) [9] which was followed by a second conversion into extended stress space which is defined by the mean stress and effective stress axis. Since no ϵ FLC data was available for the DP600 tubular material, the Keeler-Brazier (K-B) approximation [10], which was developed for sheet metal, was used to define the ϵ FLC. The results of article 1 showed that for the zero and 67kN end-feed (EF) cases, the XSFLC over predicted the failure pressure. For the 133kN EF case, the XSFLC under predicted the measured burst pressure (this is a correction from article 1). For all EF levels, the failure location at the transition region (Fig. 1) was predicted accurately. The results of article 1 suggest that the K-B approximation may not be applicable to tubes, as it over/under predicted the failure pressure for different EF cases. The findings imply that the FLC_o and shape of the ϵ FLC is most likely different than the predicted ϵ FLC using the K-B approximation. Recently, Sorine *et al.* [6] used free-expansion burst test (plane strain deformation) data to calibrate the XSFLC, which was then back calculated to show that the ϵ FLC had a considerably lower plane strain intercept (FLC_o) than the ϵ FLC predicted using the K-B approximation.

To address the viability of using the Keeler-Brazier approximation as a method of defining the ϵ FLC for tubes, a numerical parametric study was conducted for this work. Multiple ϵ FLC's (with different FLC_o's) were used to define XSFLC curves that were used to predict failure in the straight tube hydroforming models. In addition to varying the ϵ FLC, the coefficient of friction (COF) was also varied in an effort to observe the sensitivity of failure prediction with respect to COF.

EXPERIMENTS AND MODELS

A description of the experiments used to measure the constitutive model and coefficient of friction (inputs for the numerical models) are briefly presented. Also, the straight tube hydroforming experiments with various levels of end-feed (EF) and the finite element models are described as well. For a more detailed description of all experiments and numerical models, refer to article 1.

MATERIAL AND FRICTION CHARACTERIZATION - Measurement of the DP600 tube material and friction characteristics were conducted using the uniaxial tension and twist compression test (TCT) respectively. The uniaxial tension test provided the constitutive model and the TCT provided the coefficient of friction (COF) for the numerical model (Fig. 2a).

For the tension tests, multiple tensile specimens were tested from the 3, 6 and 9 o'clock orientations of the tube as shown in Fig. 2a. A single flow stress relationship (true stress vs. plastic strain) was curve-fit from the set of tests and is shown as the curve with open circles. Note that the flow stress curve was extrapolated from a strain of ~0.15, which is the strain at which the ultimate tensile strength of the material is reached.

D.A. Stuart Hydrodraw 625 solid-film lubricant was used for the hydroforming experiments. The average dynamic COF of the lubricant, as measured by the TCT was 0.035 as shown in Fig. 2a.

HYDROFORMING EXPERIMENTS - Hydroforming experiments were conducted using the die shown in Fig. 2b. End-Feed (EF) rams with an internal polymeric sealing system were used to apply three levels (zero, 67kN and 133kN) of load control end-feed during hydroforming. For the zero EF case, the EF rams remained stationary during pressurization. For the 67kN and 133kN EF cases, the tube was "pre-pressurized" without EF up to 35MPa. From 35MPa to 38MPa the full EF load was applied and then the pressure was increased linearly until burst occurs (refer to article 1 for EF load vs. internal pressure schedule). An interrupted test up to 90% of the average burst pressure was also conducted to measure corner-fill expansion using the LVDT probes that are embedded within the hydroforming die.

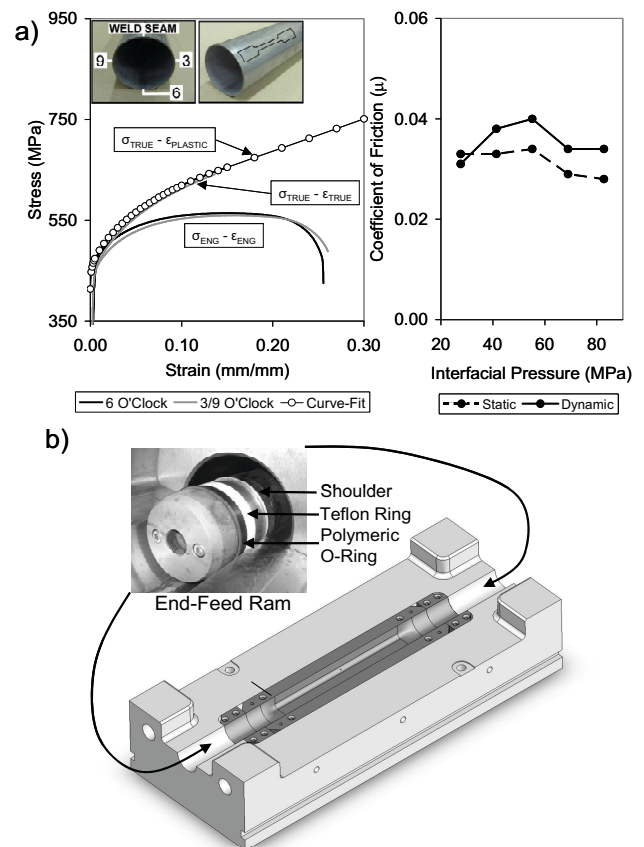


Figure 2: a) Uniaxial tension and twist compression test results b) Solid model of hydroforming die with EF [5]