A Design of Experiments Approach for Determining Sensitivities of Forming Limit Analyses to Experimental Parameters

Mark A. Iadicola and Dilip K. Banerjee
100 Bureau Drive, STOP 8553
National Institute of Standards and Technology
Gaithersburg, MD 20899

ABSTRACT

Forming limit testing is widely used to characterize materials for use in forming operations. Subset-based Digital Image Correlation (DIC) has become a common method used in research laboratories to measure the forming limit strain fields, but no consistent method exists for forming limit determination from these data. In this work, we apply a design of experiments approach along with Finite Element Analyses to exercise potential experimental measurement requirements numerically (especially varying expected image resolutions and frame rates) to quantifying the sensitivities of various proposed forming limit analysis methods to changes in experimental setup and DIC processing parameters. The main goal is to determine the appropriate hardware to produce benchmark experimental data, and possibly highlight which forming limit analysis methods may be either overly sensitive, or preferably insensitive, to subjective processing decisions.

Keywords: Forming Limit, Sheet Metal, DIC, Design of Experiments, FEA

Backgound

Forming limit testing is widely used to characterize materials for use in forming operations. The result of the test is a material's forming limit curve (FLC) that is drawn in strain space. The FLC denotes the boundary between a safe and unsafe level of plastic strain achieved through nominally linear strain-ratio paths. During the test, a sheet is locked in an axi-symmetric binder and deformed until necking or failure [1,5,6] using either a hemispherical dome (i.e. Nakajima type) or cylindrical punch with a radius edge (i.e. Marciniak type).

Motivation

There has been a concerted effort to improve the repeatability and reliability of the forming limit test results through clearly defined procedures in conjunction with the use of digital image correlation (DIC) or similar strain field measurements [6]. Obviously, a clearly defined FLC analysis method for the measured strain field information from each test is required. Although there is a defined analysis method described in ISO 12400-2 [6], it is not widely accepted. This results in a standard test procedure that is followed, but often with a non-standard FLC analysis method. Many FLC analysis methods have been proposed and demonstrated on specific material classes using specific DIC hardware, but sometimes these procedures cannot be used on other material classes or using other common hardware. Generally, the analysis methods fall into two main categories; those focused on spatial analysis of the strain field at a specific time in the strain history (e.g. [6,8]), or those focused on a temporal analysis of the strain at one or two specific locations on the sample (e.g. [9]).

Not surprisingly, each FLC analysis method has advantages and disadvantages, but they also each have unintended assumptions and requirements regarding the DIC strain measurements to be analyzed. DIC can create a data set that could be used for either a spatial or temporal analysis, but the effect of DIC system hardware and processing parameters are often ignored, even though they can have substantive effects on the DIC strain fields. The choice of the appropriate FLC analysis method for a material, or intended use, is not obvious. One possible path forward is to develop a benchmark set of forming limit tests with DIC image acquisition and associated calibrations that researchers could analyze with their preferred DIC software, various DIC processing parameters, and proposed FLC analysis method. This is somewhat similar to the DIC Challenge [7] concept, but more focused on a test method and its interpretation, and less on the DIC measurements themselves. Setting up an experiment to create such a benchmark set is not trivial. Many methods seemingly require either very fine spatial resolution in their images or very fine temporal sampling. The initial range of DIC setup properties being considered includes: camera resolution, lenses, lighting, stereo angle, DIC pattern, exposure time, imaging rate, frame timing uncertainty, DIC system calibration, and air currents.

In addition to the DIC hardware (and setup), the DIC processing parameters can have a large influence on the position and strain measurements. Various artifacts resulting from processing parameters exist. For example, [3,4] demonstrated that the displacement errors vary with subset size and pattern quality, and [3] also showed that the subset size can spatially smooth the measured 3D shape of a test piece. It is not clear how individual aspects of hardware and processing will affect the FLC determination. The initial DIC processing parameters to be considered include: subset size, subset overlap (step size), subset shape function, interpolant, strain calculation method, strain filtering. Some are clearly selectable (e.g. subset size), but some artifacts that need to be considered are the result of a combination of the DIC hardware and processing (e.g. measurement in-plane uncertainty). There are both obvious and subtle interactions between many of these variables, and although some of these interactions are deterministic others can be stochastic.

Proposed Solution

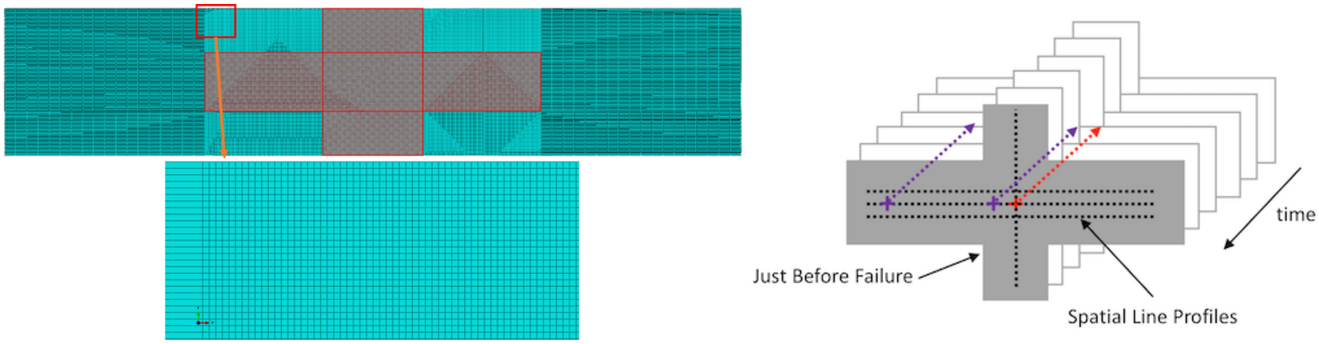
Here we propose a numerical approach using the Design of Experiments (DOE) technique to determine the sensitivity of the FLC result using a combination of FEA, DIC setup and processing parameters, and various FLC analysis methods. The DOE approach should allow the study of the influence of input parameters on the resulting FLC, identification of possible input parameter interactions, efficient evaluation of a multi-parameter design space and estimate of an optimum design point, and develop an approximate model of the sensitivities within the design space. The DOE results can be viewed through main effects plots, interaction effects plots, correlation graphs, and optimum design point determinations. These results will be used to select the hardware for the benchmark testing, and should illuminate the strengths and weaknesses of the various FLC analysis methods.

Since each analysis method is known to result in a different FLC, they cannot be checked against a known reference result. However, they can be checked for their individual sensitivity to various parameters, and they can be checked against FLC determined based on an ideal set of strain data with no artifacts of DIC hardware or processing parameters. To that end, we assume that a Finite Element Analysis (FEA) (e.g. Fig. 1a shows a mesh for a uniaxial test piece) can produce a set of data at a refinement beyond any desired measurement precision (e.g. camera resolution and/or frame rate) and without error (e.g. noise free) to be analyzed for FLC to serve as the reference value that should be predicted after the measurement artifacts have been added. These artifacts will be abstracted to be easily implemented through processing of the FEA data. For example, the subset size will be used to average the position data over a patch similar to the subset size, and noise will be added based on experience for that subset size in conjunction with a typical DIC pattern (see [3,4]). More advanced methods could be applied similar to [2], but the added complication would add substantial computation time for what might be minimal additional understanding. This is left to a possible future extension of the work. In addition to computational time, there are also storage issues (write out and read in) that affect the overall computational time. Although the candidate FLC methods require a wide range of data from the test, there is substantial overlap regarding the data needed. Additionally, the data from an actual test using DIC would only be surface displacement information. These two factors allow the determination of FLC from a much smaller data set than the entire FEA model. Figure 1a shows this surface area set in grey on the initial mesh that is centered on the area that begins to neck in the model. The DOE will operate on the results calculated at the nodes within this surface set of data. Figure 1b is a schematic of the data used in the FLC determination. Generally, the spatial methods use profile samples of the DIC data (black dashed lines in Fig. 1b) on a specific image (typically one or two before failure), whereas the temporal methods will track some behavior at a specific point through the time of the test (color dashed lines with arrows in Fig. 1b). The grey area shown in Fig. 1 is required to extend beyond the dashed lines, due to the size of the DIC subset that may be used to measure the displacements and calculate strains.

The numerical process is shown in Fig. 2 as a flowchart. In order to determine a FLC reference value and permit a consistent basis for comparison of FLC results, the FEA is only run one time for a given strain ratio (e.g. uniaxial in Fig. 1a) at a very refined spatial and temporal resolution with the results written to disk only for the critical portion of the test piece (grey area in Fig. 1a). Even when writing only the limited data set (grey area in Fig. 1a over time), initial work demonstrated that the required data precision and refinement of the FEA model requires that the data be written in binary format for reasonable scalability of the problem. Before the DOE process cycle begins, a DOE parameter set matrix (lower left in Fig. 2) is developed to efficiently sample the multi-parameter design space. The number of combinations of input factors is user selectable, but must be greater than the number of parameters to be varied. For each run, the DOE process cycle takes one of these DOE parameter sets from the matrix and uses it to select the data to be processed from the FEA output. These data are then processed through Matlab[1] scripts of the abstractions for the DIC hardware and processing parameters (e.g. camera resolution and subset size averaging) based on the selected DOE parameter set. After the DIC processing step, the data are passed to the routines for all the FLC analysis methods under consideration resulting in a single FLC value for each. Then the next DOE matrix parameter set is selected and the process is repeated. In addition to the FLC values determined for each DOE matrix set, the resulting sensitivities and parameter interactions can be assessed (right hand side of Fig. 2) after completing the entire DOE matrix. Those results should determine the appropriate hardware to produce benchmark experimental data, and possibly highlight which FLC analysis methods may be either overly sensitive, or preferably insensitive, to subjective processing decisions.

---

[1] Certain commercial software is identified to describe a procedure or concept adequately. Such identification is not intended to imply recommendation, endorsement, or implication by NIST that the software or materials are necessarily the best available for the purpose.



(a) (b)

Figure 1. (a) FEA mesh of a uniaxial specimen with sampling on the surface (grey cross) to be used in DOE. (b) Schematic of data used in DOE for the various FLC determinations: spatial (black dashed lines) and temporal (color dashed lines).

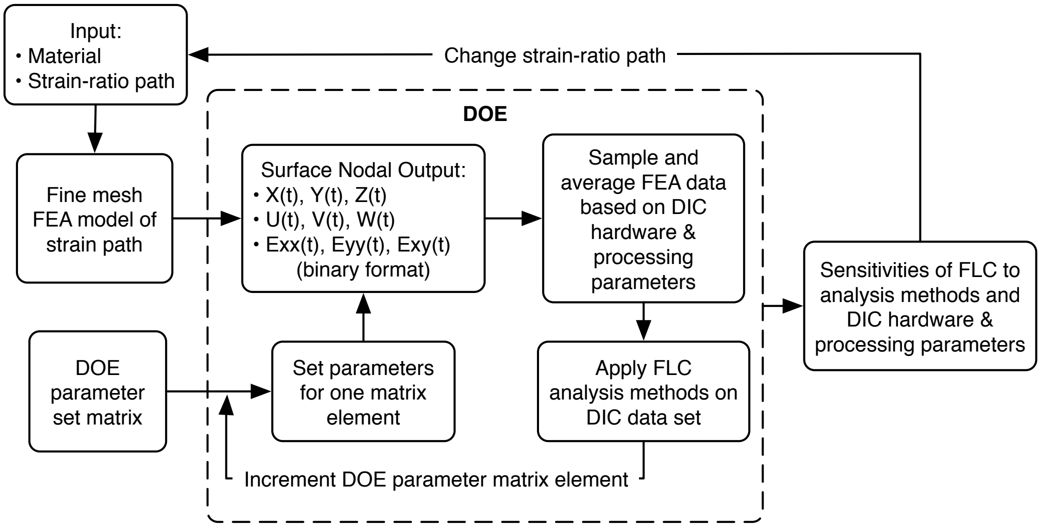


Figure 2. Flow chart of the Design of Experiments (DOE, dashed rectangle) including the Finite Element Analysis (FEA), Forming Limit Curve (FLC) determination method, and the Digital Image Correlation (DIC) parameters.

References

[1] ASTM, "Standard Test Method for Determining Forming Limit Curves", E2218-16, ASTM International, 2016.

[2] Balcaen R, *et al*, “Stereo-DIC Calibration and Speckle Image Generator Based on FE Formulations.” Experimental Mechanics 57 (5):703-718. doi:10.1007/s11340-017-0259-1. 2017

[3] Iadicola, M.A., “Augmented Use of Standard Mechanical Testing Measurements for Sheet Metal Forming: Digital Image Correlation for Localized Necking” in NUMISHEET 2014 Part B General Papers, edited by Yoon J.W., et al., AIP Proceedings 1567, American Institute of Physics, Melville, NY, pp. 614 - 619, 2014

[4] Iadicola, M.A. and Creuziger, A.A. “Uncertainties of Digital Image Correlation Near Strain Localizations” Proceedings of the SEM annual Meeting 2014, 2014.

[5] ISO, "Metallic materials-Sheet and strip-Determination of forming-limit curves-Part 1: Measurement and application of forming- limit diagrams in the press shop", ISO12004-1:2008, 2008.

[6] ISO, "Metallic materials-Sheet and strip-Determination of forming-limit curves-Part 2: Determination of forming-limit curves in the laboratory", ISO12004-2:2008(E), 2008.

[7] Reu, P.L. *et al*, “DIC Challenge: Developing Images and Guidelines for Evaluating Accuracy and Resolution of 2D Analyses” Experimental Mechanics. https://doi.org/10.1007/s11340-017-0349-0. 2017

[8] Situ Q., *et al*. “A suitable criterion for precise determination of incipient necking in sheet materials.” 10th International Conference on Aluminium Alloys (ICAA- 10), Vancouver, CANADA, JUL 09-13, 2006. Materials Science Forum, Vol. 519-521, pages 111– 116, 2006.

[9] Sriram S., *et al*. “Comparison of forming limit curves for advanced high strength steels using different techniques.” SAE International Journal of Materials and Manufacturing, 2(2009-01-1173):472–481, 2009.