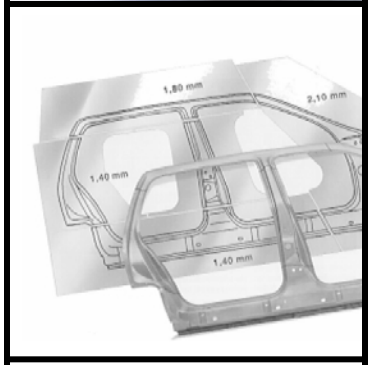
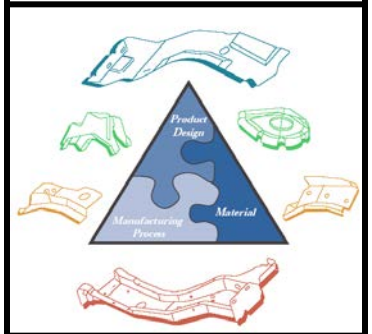
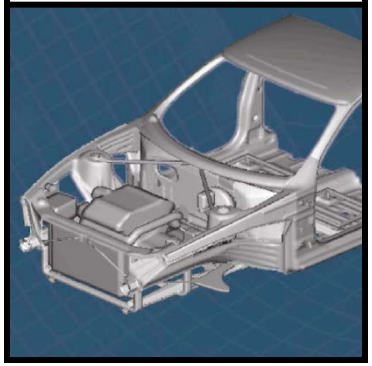






AK Steel
ArcelorMittal
ArcelorMittal DOFASCO | HAMILTON
CHRYSLER
Ford
NUCOR
ThyssenKrupp
U. S. Steel
GM
Severstal
U.S. DEPARTMENT OF ENERGY
USAMP

Non Linear Strain Paths
A-SP 061

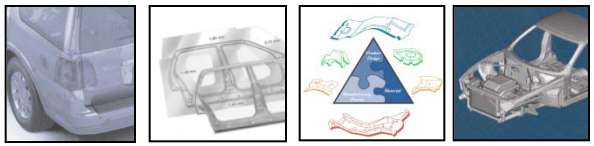
Thomas B. Stoughton
General Motors Company

May 18, 2012

Project ID LM064

A/SP Auto/Steel Partnership

www.a-sp.org



OVERVIEW

Timeline

- Start – Oct. 1, 2009
- Finish - Sept. 30, 2011
- 100% Complete

Barriers

- Predictive modeling tools
- Tooling and prototyping
- Performance

Budget

Total project funding

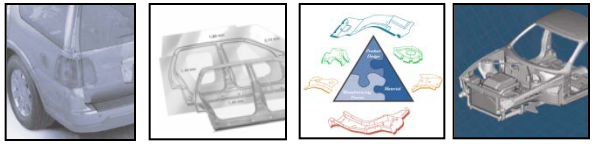
- DOE: $712K
- Cost Share: $712K

- Funding received in FY11:
  - DOE: $512K

- Funding for FY12:
  - DOE: $ 13K

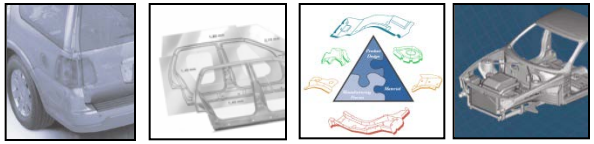
Partners

- Project Leads:
  - Chrysler Group LLC
  - Ford Motor Company
  - General Motors Company
- Interactions/ collaborations:
  - ArcelorMittal / US Steel
  - Livermore Software Technology Co.
  - SuperiorCam
  - NIST
  - Oakland Univ. / Wayne State Univ. / MIT / Tokyo Univ. of A&T



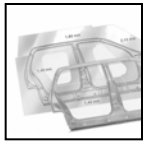
OBJECTIVES

- Deliver a comprehensive set of experimental data and associated predictive models for the deformation of Advanced High-Strength Steels (AHSS) under nonlinear strain paths.
- The models include constitutive behavior, necking limit and fracture criteria for simulations of stamping, hydroforming, and vehicle crashworthiness.
- The project will
  - Enable efficient vehicle design to take advantage of the rapid hardening behavior of AHSS for more weight reduction opportunities
  - Enable the acceleration of AHSS usage by reducing the cost and time for reliable validation of AHSS manufacturing processes and vehicle performance



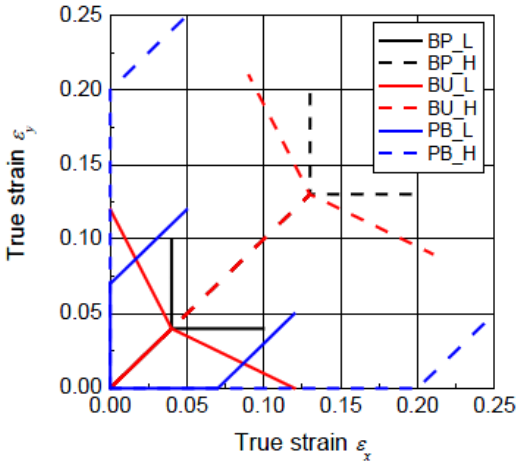
MILESTONES

Month/Year	Milestone or Go/No-Go Decision
June-2011	Milestone #1: A database of biaxial transient hardening and forming limit behavior under continuous strain path change conditions using steel tube hydroforming technology and verification of constitutive models.
July-2011	Milestone #2: A comprehensive database of biaxial transient hardening and forming limit behavior under uniaxial tension after prestrain in uniaxial and equal-biaxial tension, sufficient to develop and validate advanced models.
July-2011	Milestone #3: Validation of forming limit behavior under continuous strain path change conditions in a manufacturing environment.
Sept-2011	Milestone #4: Fracture model for trim edge condition; experiments for different trim conditions, model development and validation.
Sept-2011	Go/No Go Decision: Based on state of the science in modeling metal deformation under nonlinear strain paths, should industry continue to collaborate research in this area using alternate funding sources?

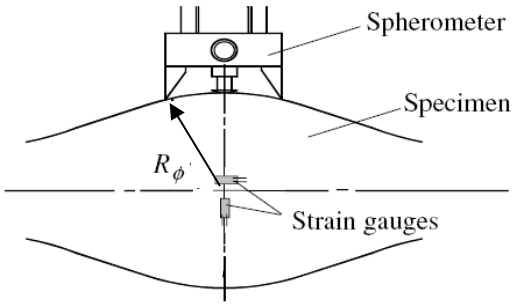
APPROACH/STRATEGY FOR TASK 1

Transient hardening and forming limits under general biaxial strain path changes for deep draw quality (DDQ) steel.



- Adaptive control of axial loading vs. pressure to achieve desired linear and bilinear strain paths involving combinations of Uniaxial (U), Plane-Strain (P), and Equal-Biaxial (B) Tensions

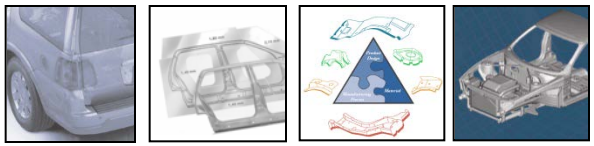
- Apply bilinear paths with and without unloading between stages (prior works suggest this is a factor)



- Calculate stresses from mechanical relations of applied loads and geometry to describe the shape of yield surface and evaluate normality rule

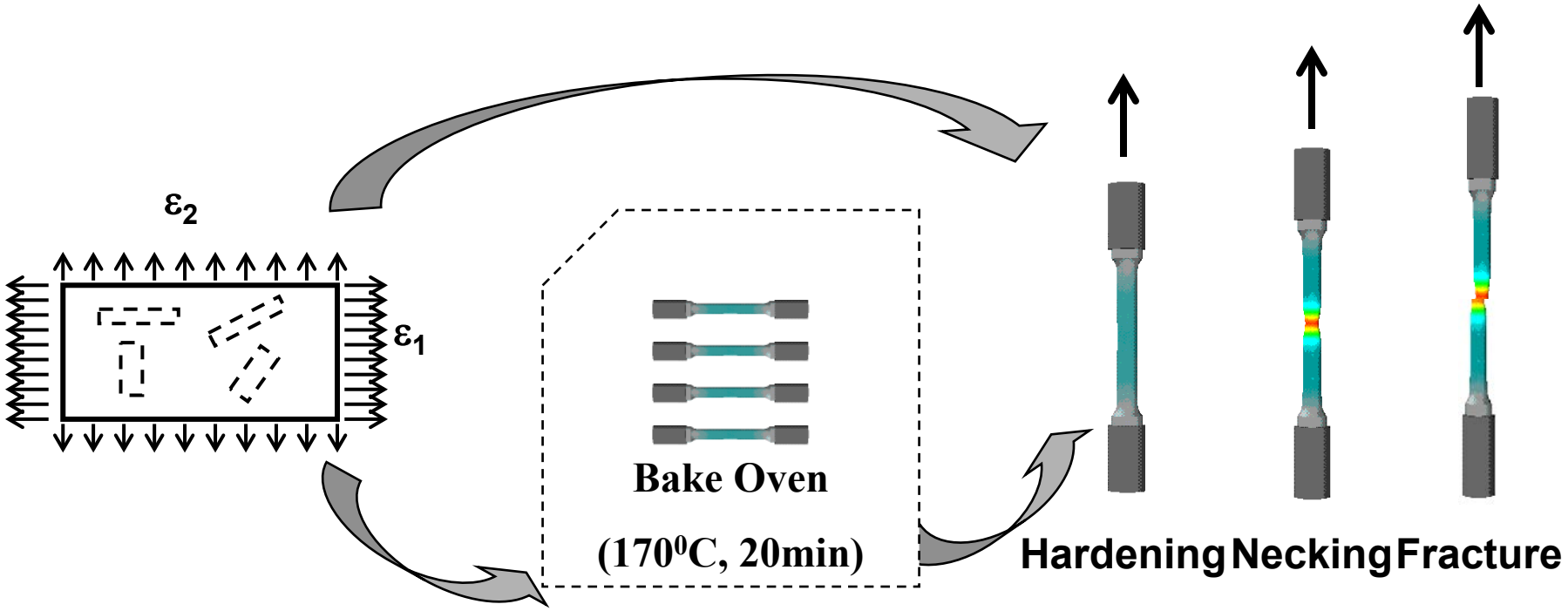
- Document the effect of strain path change on the forming limits and constitutive model

Courtesy of
Yoshida & Kuwabara
Tokyo University of Agriculture and Technology



APPROACH/STRATEGY FOR TASK 2

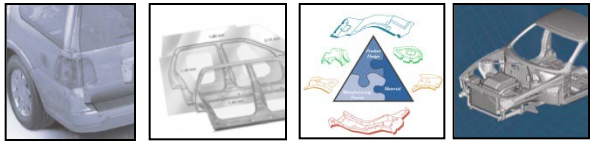
- Transient hardening and bake-hardening effects under uniaxial tension after prestrain in uniaxial or equi-biaxial tension.
- Use DIC to extract strain data beyond uniform elongation
- *Challenge: extraction of useful stress data beyond uniform elongation*



Uniaxial (R/T/D) and Biaxial Pre-strain

Bake-Hardening *(for BH & DP Steels)*

Uniaxial Tensile to Fracture

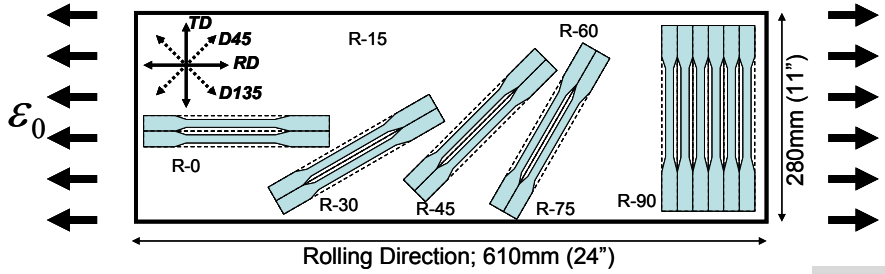


APPROACH/STRATEGY FOR TASK 2

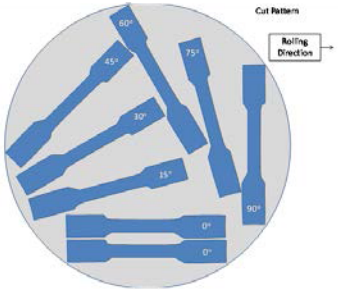
Transient Hardening & Bake-Hardening (A total of 882 tests):

- 6 Steel Grades: DDQ, BH210, DP600, DP780, TRIP780, DP980
- 3 Pre-strain Orientations: Rolling, Transverse, Diagonal directions
- 7 Pre-strain Levels: Uniaxial 0%, 5%, 10%, 15%, 20%;
  Equibiaxial: 5%, 10%
- 7 Subsequent Tensile Orientation (relative to pre-straining orientation):
  0^0, 15^0, 30^0, 45^0, 60^0, 75^0, 90^0.
- Digital Image Correlation for strain measurement inside the Diffuse Neck

Uniaxial

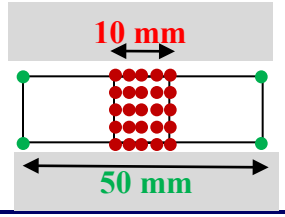


Equi-biaxial

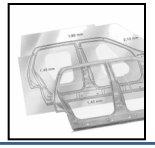


DIC Point Locations →

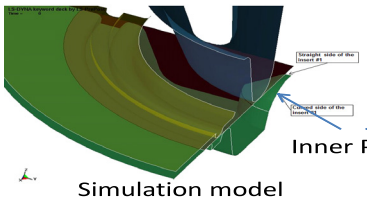
4 Point Virtual Extensometer

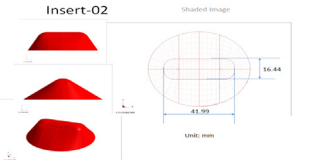


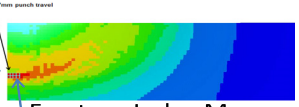
99 Point Grid in Diffuse Neck

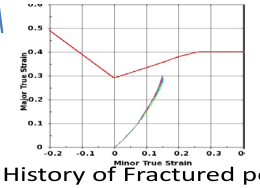



APPROACH/STRATEGY FOR TASK 3

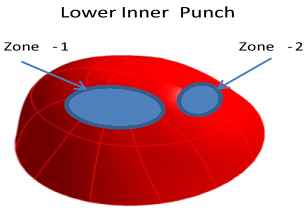

Simulation model




Fracture Index Map



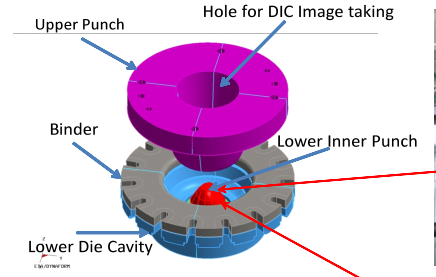
Strain History of Fractured point

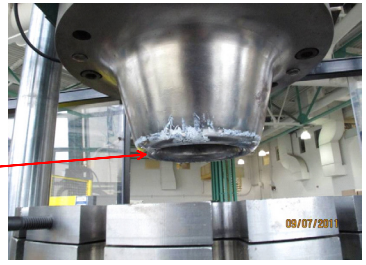


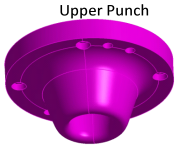
Non-Axisymmetric

Inner Punch Surface for Release

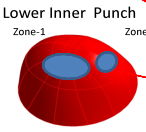
Forming System



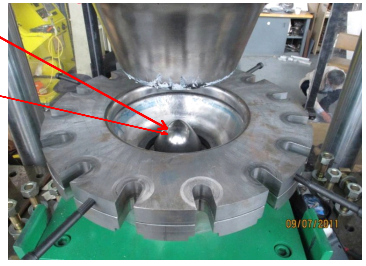




Axisymmetric
To provide biaxial tension condition



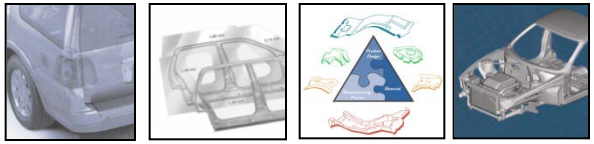
Non-Axisymmetric



Prediction of Necking Under Nonlinear Strain Path

A nonlinear strain path is created by late contact between the biaxially stretching sheet and a non-axisymmetric inner punch

Tests on deep draw quality (DDQ) and TRIP 780 steels

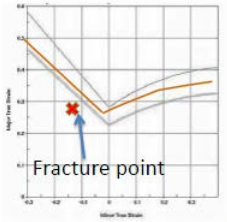


APPROACH/STRATEGY FOR TASK 4: FRACTURE MODELING

Using shear fracture butterfly tests and reverse engineering methods to describe fracture conditions over a range of tests that have been used to develop advanced fracture models at MIT, conduct tests of edge fracture in hole expansion and, evaluate, make improvements, and validate the MIT model for edge fracture.

Challenge →

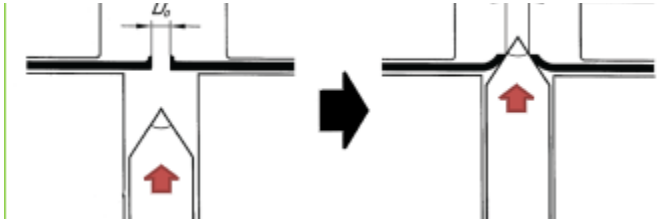
Fracture at edge during stamping, by M.F. Shi

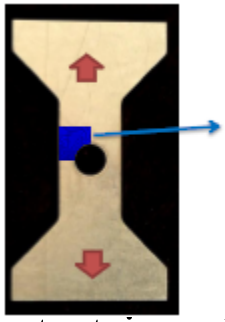


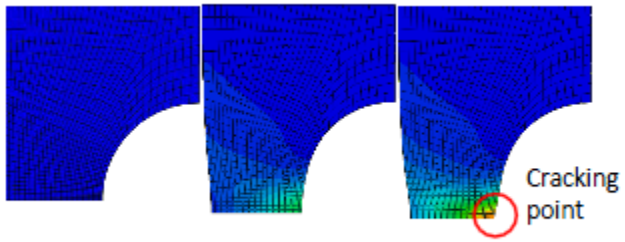
Hole expansion simulation and its strain path on FLD for DP780, by C Chiriac, et, al

❑ Experimental study on DP780 for 3 different trim edge conditions (punched (3 clearances), milled, water jet cut) and two types of test.

Hole Expansion Test

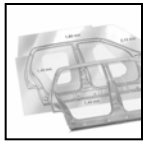






Central Hole Specimen Tension Test

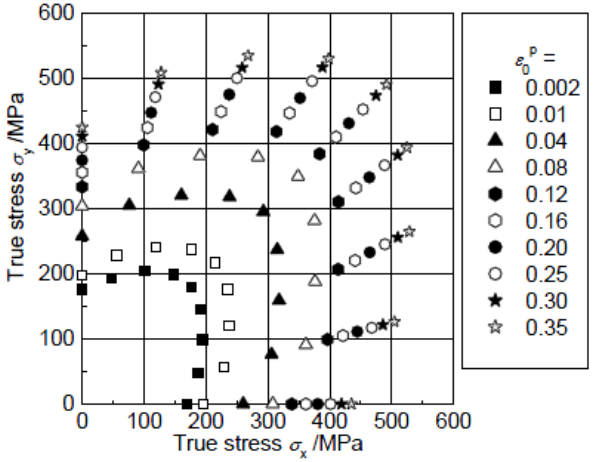
❑ Develop models to predict damage due to trimming based on simulation using solid element analysis and subsequent formability of trimmed edges based on simulation using shell elements.

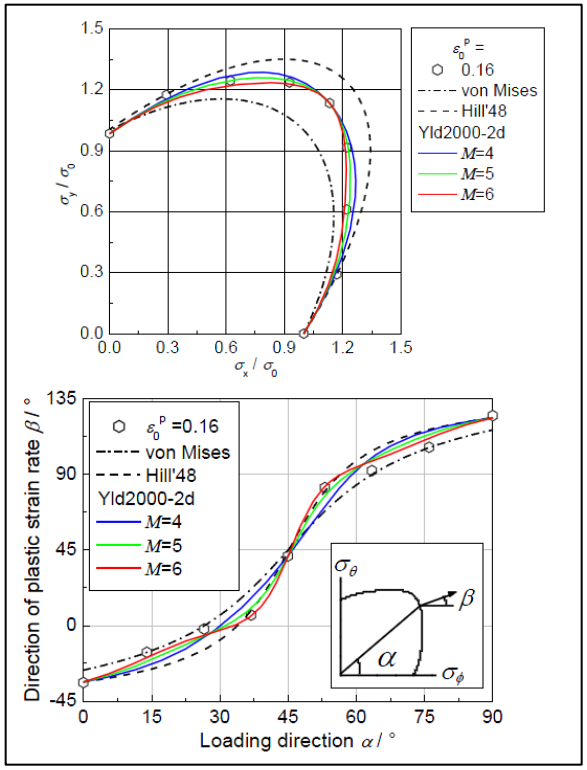
TECHNICAL ACCOMPLISHMENTS FOR TASK 1

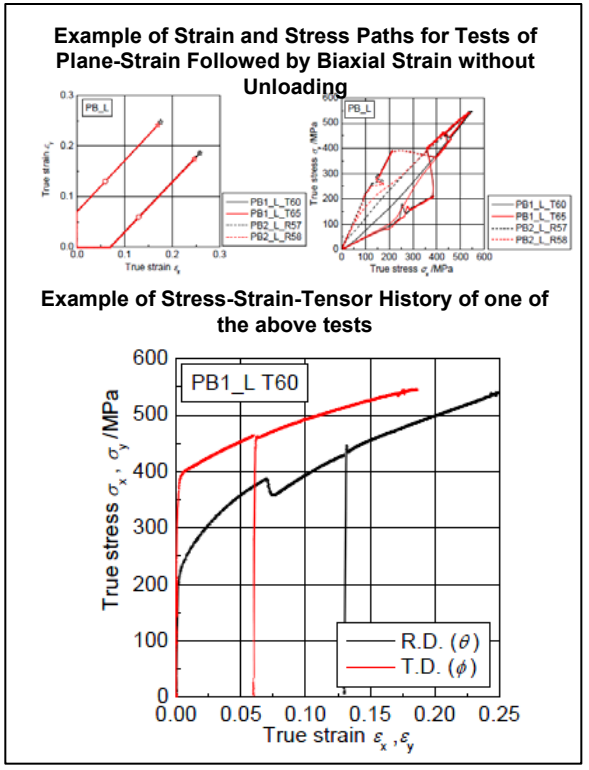
FY11 Accomplishments:

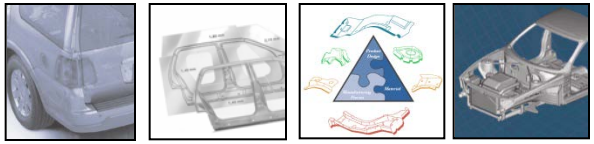
- Measured Yield Surface Shape (Plastic Work Contours) and Plastic Strain Directions for Deep Draw Quality steel tubes;
- Verified Yld-2000-2d Model with M=6 for linear strain path
- Obtained continuous stress-strain data for biaxial stress histories up to necking for nonlinear model development and validation



Results for 16% strain shown here







TECHNICAL ACCOMPLISHMENTS FOR TASK 2

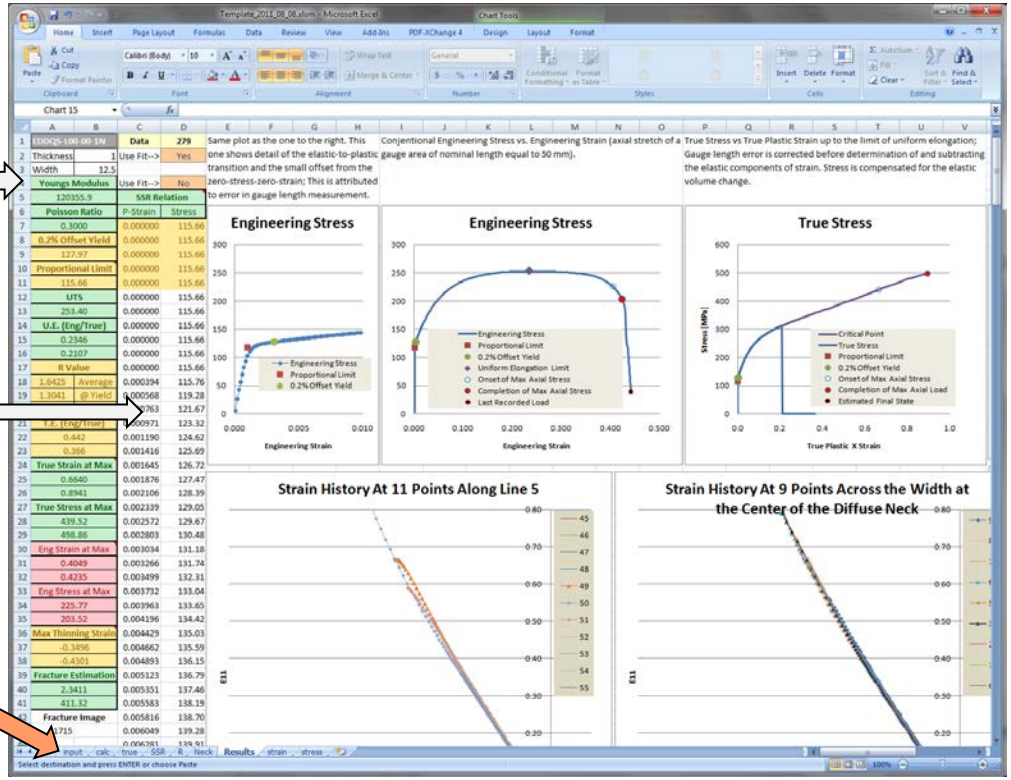
FY11 Accomplishments:

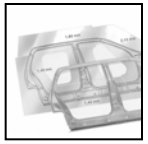
- Developed and Verified Analytical Tool for Automated Data Processing of up to 300 time recordings of strain and position of 103 DIC point data
- Applied to 882 Tensile Test Conditions
- Initiated Compilation of Effects of Strain Path Change on Material Properties

Standard Elastic and Plastic Properties

True Stress vs. True Plastic Strain Relation

Input Raw Data Sheet (Copy & Paste) causes automatic update of calculations and figures

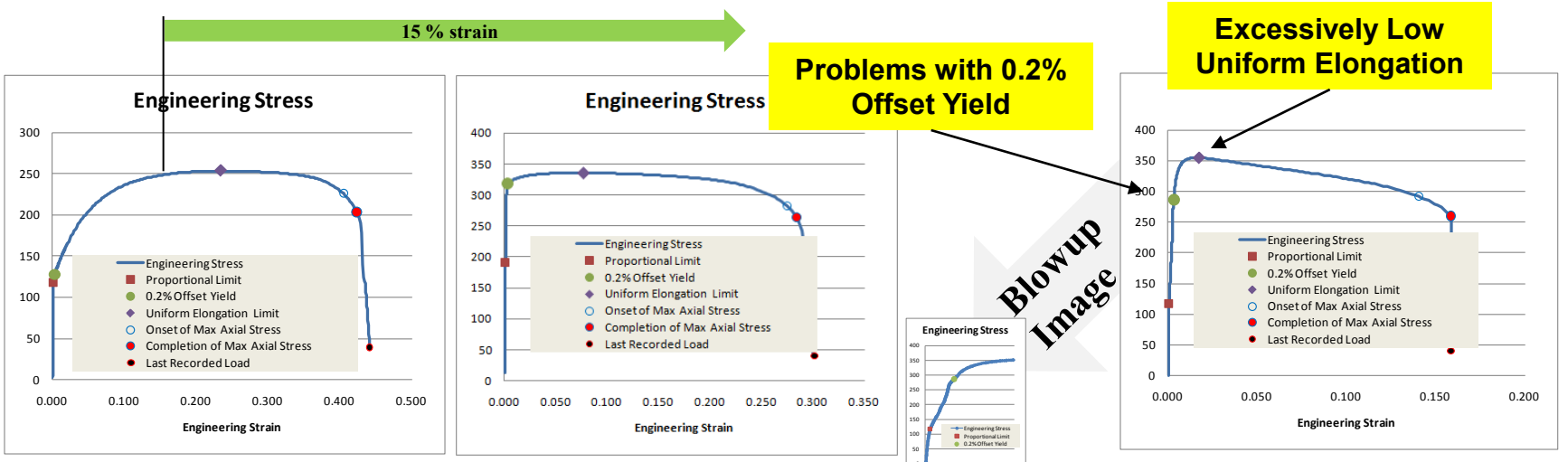


TECHNICAL ACCOMPLISHMENTS FOR TASK 2

FY11 Accomplishments:

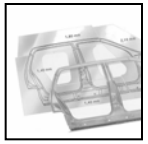
- Documented unusual behaviors that arise in nonlinear strain paths



DDQ along Rolling (R) Direction

Along Rolling after 15% strain along Rolling Direction

Along Transverse after 15% strain along Rolling Direction

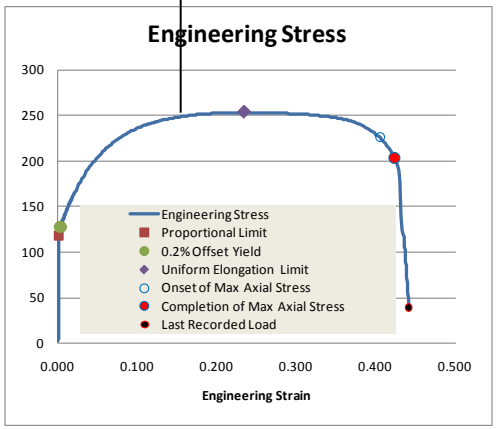



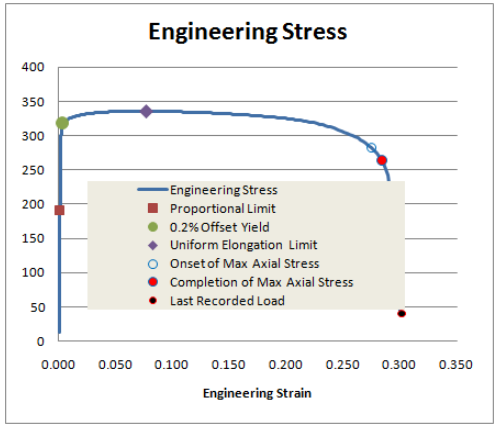
TECHNICAL ACCOMPLISHMENTS FOR TASK 2

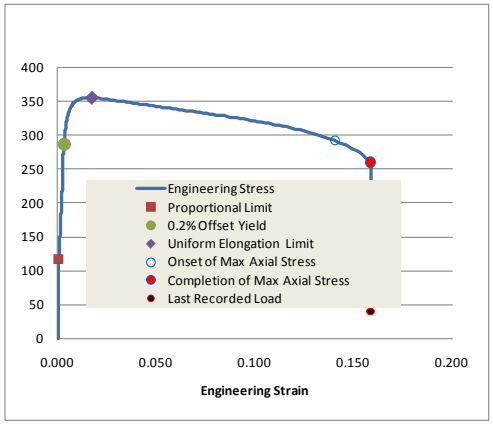
FY11 Accomplishments:

- Documented unusual behaviors that arise in nonlinear strain paths
- Developed algorithm to extend stress-strain relation to high strain

15 % strain



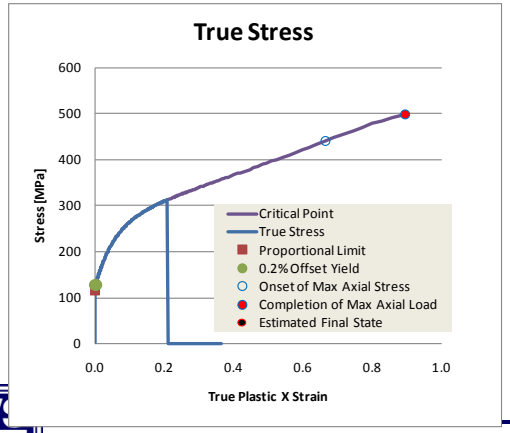


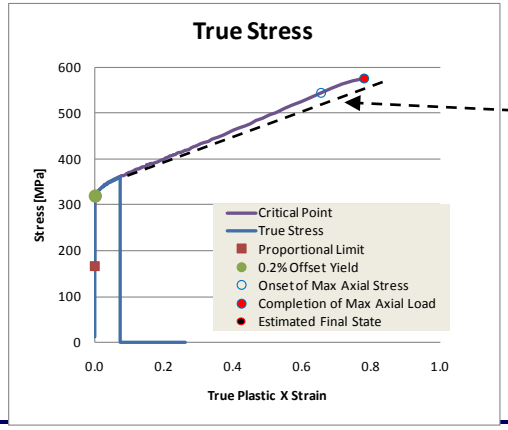


DDQ along Rolling (R) Direction

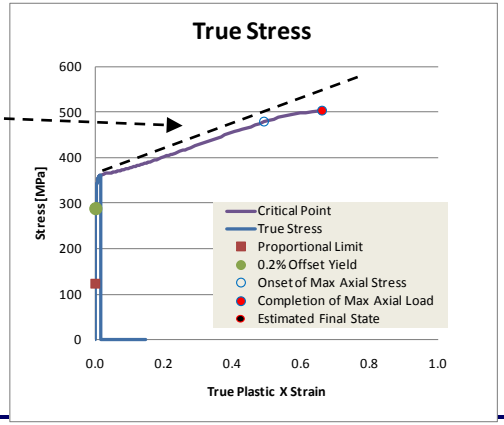
Along R after 15% strain along Rolling Direction

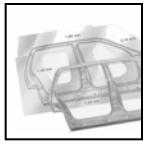
Along T after 15% strain along Rolling Direction





Monotonic Uniaxial Tension

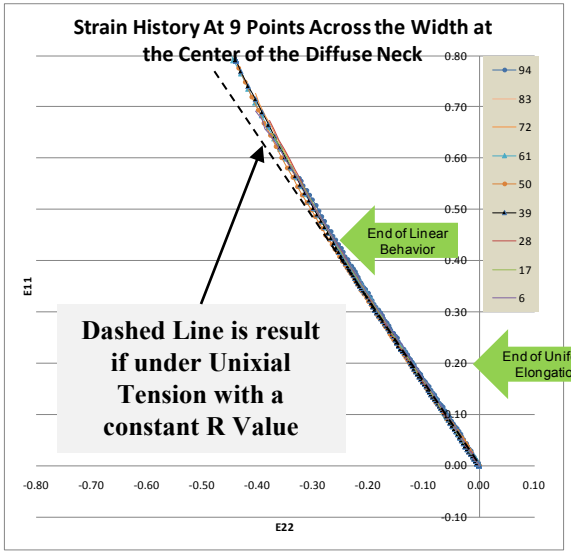


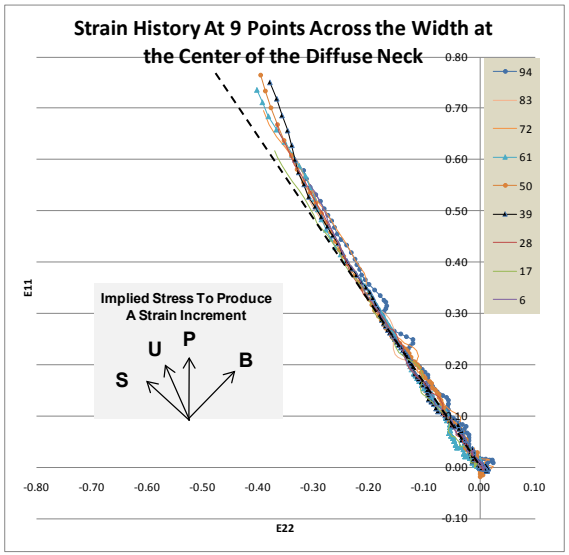
TECHNICAL ACCOMPLISHMENTS FOR TASK 2

FY11 Accomplishments:

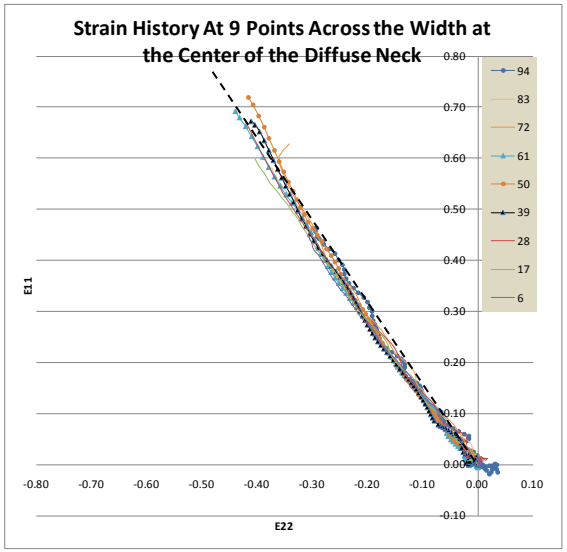
- Discovered Uniaxial Tension Extends Beyond the End of Uniform Elongation for Linear Loading (to at least twice as high)
- Discovered evidence of microscale (0.5 mm X 0.5 mm gauge area) oscillations in local strain field for nonlinear loading… averaging uniaxial but imply jumping stress states between shear→equal-biaxial



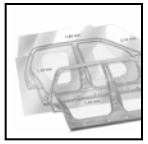
DDQ along Rolling (R) Direction



Along R after 15% strain along Rolling Direction



Along T after 15% strain along Rolling Direction

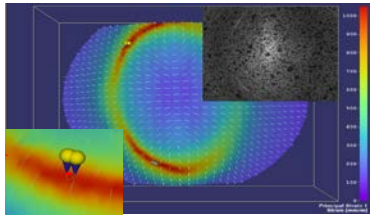



TECHNICAL ACCOMPLISHMENTS FOR TASK 3

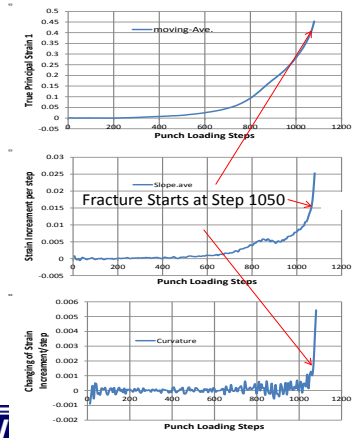
FY11 Accomplishments:

- Developed and Verified Analytical DIC Method to Identify Onset of Necking
- Verified Dynamic Effect of Nonlinear Strain Path on Necking
- Dynamic Formability Index Allows Prediction of Necking in Nonlinear Paths

Method to Extract Necking/Fracture Data



Algorithm to Define Necking Condition

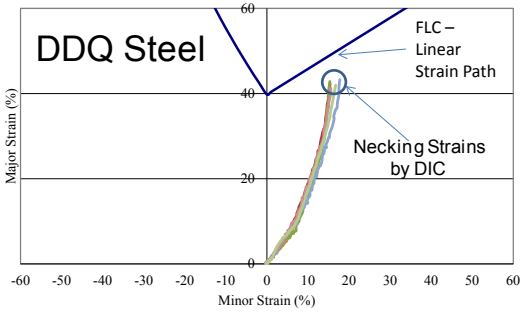


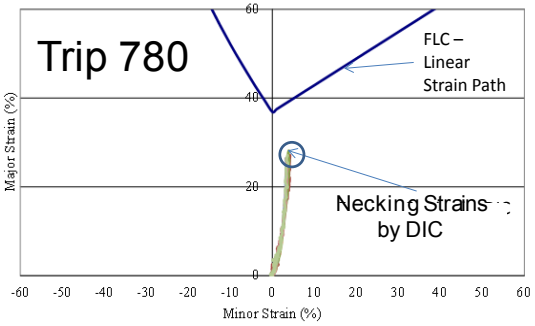
← 5 point rolling average of strain to smooth data

← 1st Derivative (strain rate)

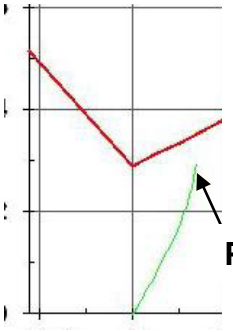
← 2nd Derivative:
A neck is defined to occur when value permanently exceeds noise.

Dynamic FLC Effect



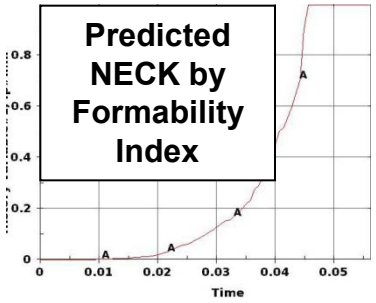


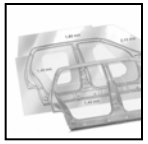
Appears SAFE by Strain FLC



Prediction

Predicted NECK by Formability Index



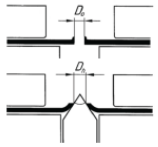



TECHNICAL ACCOMPLISHMENTS FOR TASK 4

FY11 Accomplishments:

- Completed series of edge fracture experiments for DP 780
- Applied DIC method to minimize variation of fracture measurements
- Abacus implementations of fracture model for solid and shell elements
- Description of experiments and calibration method for fracture model

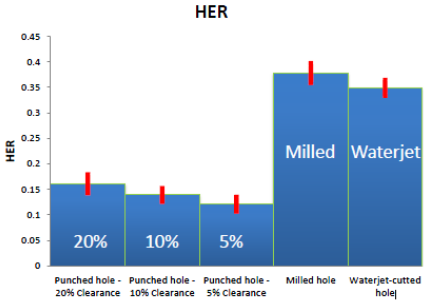
HER Test

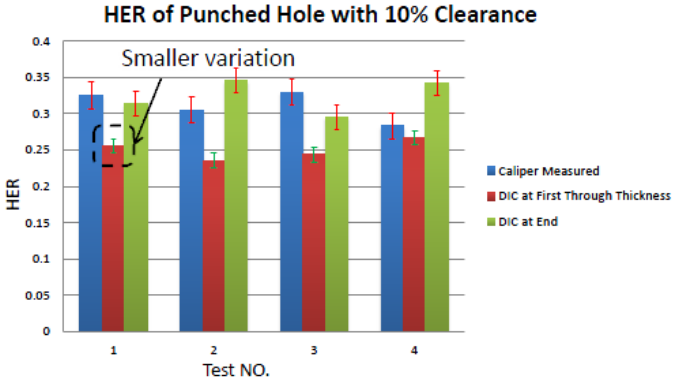


Hole Expansion Ratio:

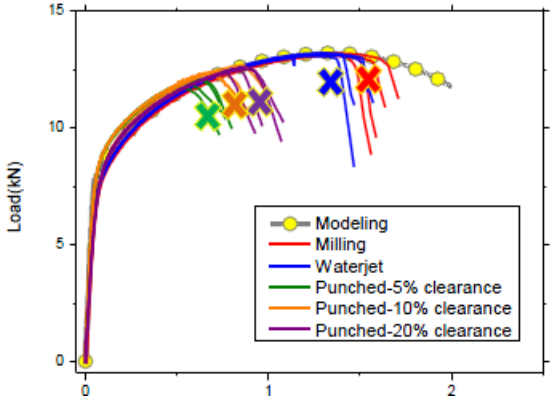
$$HER = \frac{D_h - D_0}{D_0} \times 100\%$$

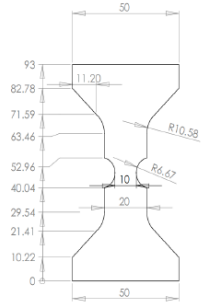
D_h: diameter at cracking
D_0: initial diameter



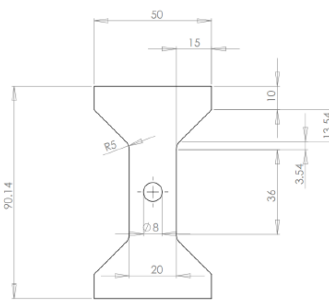


CHST Test

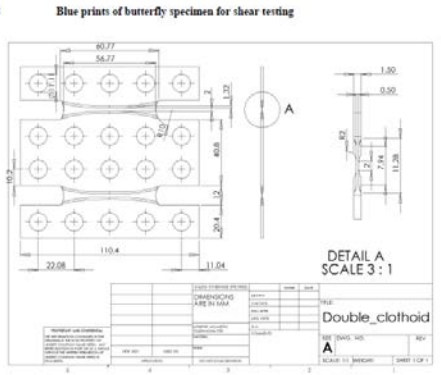


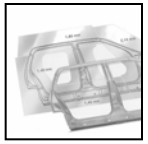


(c) Tensile Specimen with 6.67mm cutouts



(d) Tensile specimen with a central hole

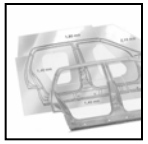


TECHNICAL ACCOMPLISHMENTS / PROGRESS

FY11 Progress against Milestones:

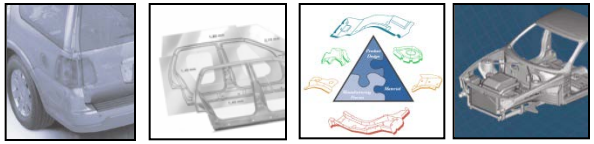
Target Date for Completion	FY11 Milestone	Status
June-2011	Milestone #1: A database of biaxial transient hardening and forming limit behavior under continuous strain path change conditions using steel tube hydroforming technology and verification of constitutive models.	Completed
July-2011	Milestone #2: A comprehensive database of biaxial transient hardening and forming limit behavior under uniaxial tension after prestrain in uniaxial and equal-biaxial tension, sufficient to develop and validate advanced models.	Completed
July-2011	Milestone #3: Validation of forming limit behavior under continuous strain path change conditions in a manufacturing environment.	Completed
Sept-2011	Milestone #4: Fracture model for trim edge condition; experiments for different trim conditions, model development and validation	Completed
Sept-2011	Go/No Go Decision: Based on state of the science in modeling metal deformation under nonlinear strain paths, should industry continue to collaborate research in this area using alternate funding sources?	Decision to continue funding through the Auto-Steel Partnership

COLLABORATIONS

Partners:

- ArcelorMittal (Industry – Prime; within VT): provide sheet steels for testing; uni-axial pre-straining; expertise on metallurgy and behavior.
- US Steel (Industry – Prime; within VT): provide sheet steels for testing; bake-hardening; expertise on metallurgy and behavior.
- Livermore Software Technology Co (Industry – Prime; outside VT): develop and implement simulation models in the commercial software LS-DYNA; conduct simulations for tooling design.
- SuperiorCam (Industry – Sub; outside VT): tooling design and fabrication.
- Oakland University (Academic – Sub ; outside VT): DIC tests and analysis.
- Wayne State University (Academic – Sub ; outside VT): temperature-dependent tests and analysis; perform tests using SuperiorCam tools.
- MIT (Academic – Sub; outside VT): fracture modeling
- Tokyo University of A & T (Academic – Sub ; outside VT): transient hardening tests under biaxial continuous strain changes.
- NIST Center for Metal Forming (Federal laboratory – Sub ; outside VT): expertise and guidance on materials and test standards.



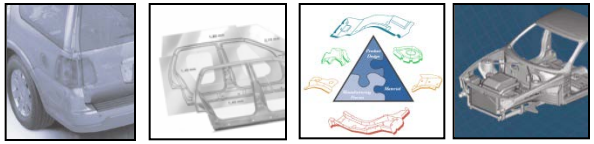
FUTURE WORK

FY12:

- Project was completed on Sept 30, 2011; Final Report on Dec 18, 2011
- Technology is undergoing evaluation and implementation at the automotive OEMs (Chrysler, Ford and GM) and at the AISI companies (ArcelorMittal, US Steel, etc.)
- ASP-061 activities in 2012 are limited to residual reporting obligations

Beyond FY12:

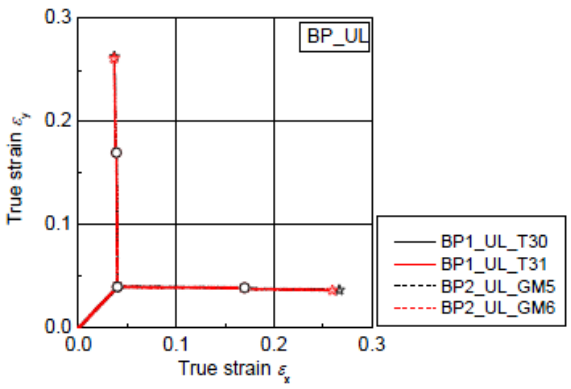
- Auto-Steel Partnership is continuing work in this area using non-government funding in 2012 and beyond
- Work includes additional biaxial testing to better understand local vs. macro scale effects on modeling
- Development of improved constitutive models for combining nonlinear forming with and without heat treatment effects

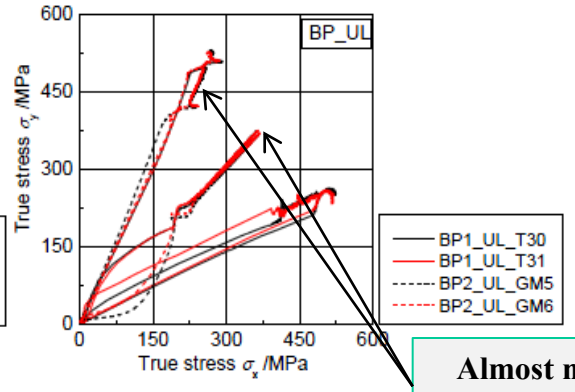


Technical-Backup Slides

FY11 Accomplishments: Example of Results with and without unloading

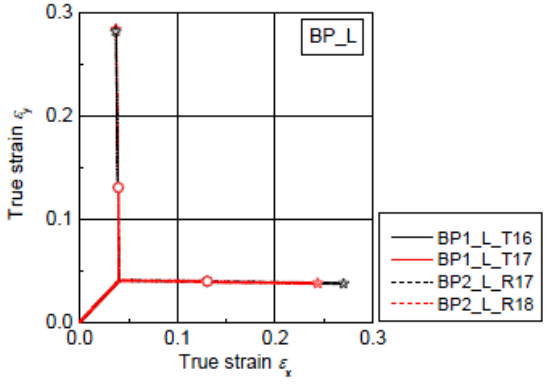
- Equal Biaxial to 4% strain, followed by Unloading, then Plane Strain to fracture

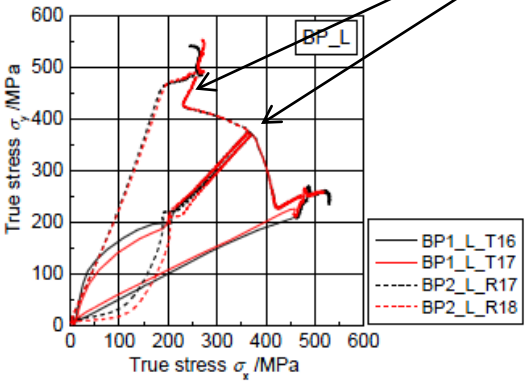


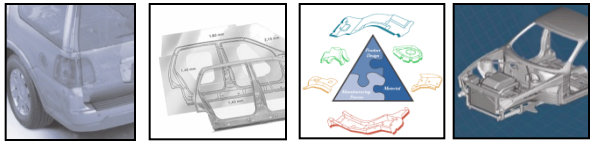


Almost no difference with and without unloading

- Equal Biaxial to 4% strain, then Plane Strain to fracture without unloading







APPROACH/STRATEGY FOR TASKS 2 & 3

Digital Image Correlation (DIC) and Tracking System:

- Enables the real-time measurement of 3D non-uniform full-field deformation such as displacements and strains from digital images.
- Offers a sufficient spatial resolution to measure deformations locally at the region of interest, including beyond uniform elongation and hopefully including post localized necking and fracture;
- Allows real-time measurement and characterization of transient behavior of material responses without resorting to a numerical or analytical model.