GREAT DESIGNS IN STEEL

THE DIC REVOLUTION IN METAL PROPERTY CHARACTERIZATION

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GM Global R&D Center, GM Tech Fellow
MOTIVATION

1) Why is a revolution in material testing needed?

2) What is revolutionary about Digital Image Correlation?

3) What is the potential of a SINGLE Uniaxial Tension Test?

➢ Example of DP 980
HISTORY OF CONSTITUTIVE MODELS

1) Von Mises Yield Model (1913)  
Requires only a single hardening law

2) Hill 1948 Fully Anisotropy Model  
... also requires $R_0$, $R_{45}$, $R_{90}$

3) Barlat 2000-2d Model  
... also requires $Y_{S_0}$, $Y_{S_{45}}$, $Y_{S_{90}}$ and $Y_{S_{EB}}$, and $R_{EB}$

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Experimental Data
von Mises
Hill 1948
Barlat 2000-2d
Calibration Data
TRADITIONAL UNIAXIAL TENSION TEST

Standard Results
1) 0.2% Offset Yield Stress
2) Ultimate Tensile Strength
3) Uniform Elongation
4) Total Elongation
5) Hardening Behavior
6) Elastic Modulus
7) Proportional Limit

Add a Width Strain Gauge
8) R Value
9) Poisson Ratio

Additional Needs
10) m Value (jump tests)
11) YM degradation (load/unload)
12) Property variation (repeats)

Additional Tension Tests
What if we could get a handle on this from a SINGLE Uniaxial Tension Test?

What if we could experimentally define the hardening behavior beyond ‘UE’?
What if we could detect onset of localized necking and determine the necking limit?
What if we could measure the fracture strain?
HOW TO BEST USE DIC

**Standard Results**

1) Young’s Modulus
2) Ultimate Tensile Strength
3) Uniform Elongation
4) Hardening Behavior
5) Total Elongation

Includes Width Strain Gauge

6) R Value
7) Poisson Ratio

Implicitly Includes Multiple Loading Conditions

8) m Value (jump tests)
9) YM degradation (load/unload)
10) Property variation (repeats)

Multiple Points

201 Points
X, Y, Z
Exx, Eyy, Exy
VSG = 0.5 mm

50 mm
y = 0.0

y = 50.0

201 Points

X, Y, Z

Exx, Eyy, Exy

VSG = 0.5 mm

50 mm

y = 0.0

y = 50.0

camera coordinate system
2) Change in slope is attributed to
   - Change in R Value (crystal texture).
   - Rise of Non-uniaxial tension conditions.
   - Both

3) No noise in 201 Strain Paths → Insignificant error using the 0.5 mm VSG

4) R Value at 201 points provides material variation information

Benefits of DIC

1) R Value can be defined properly, in terms of ratios of plastic strain rates

\[
\text{slope} = -\frac{1 + r}{r}
\]

2) Change in slope is attributed to
   - Change in R Value (crystal texture).
   - Rise of Non-uniaxial tension conditions.
   - Both

\[
\text{slope} = -\frac{1 + r + \alpha r}{r + \alpha(1 + r)}
\]
2) Change in slope is attributed to:
- Change in R Value (crystal texture).
- Rise of Non-uniaxial tension conditions, or
- Both

3) No noise in 201 Strain Paths → Insignificant error using the 0.5 mm VSG

**R VALUE MEASUREMENT**

1) Benefits of DIC:
- R Value can be defined properly, in terms of ratios of plastic strain rates

$$\text{slope} = \frac{-1}{r} + \alpha$$

201 Strain Paths

3 Tests with 603 R Values

1 Test with 201 R Values

Save $
HOW TO BEST USE DIC

**Standard Results**

1) Young’s Modulus
2) Ultimate Tensile Strength
3) Uniform Elongation
4) **Hardening Behavior**
5) Total Elongation

Includes Width Strain Gauge

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Implicitly Includes Multiple Loading Conditions

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End Points

201 Points

X, Y, Z

$\text{VSG} = 0.5 \text{ mm}$

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Multiple Points
USEFUL INFORMATION BEYOND “UE”

**Benefits**

1. All 201 Points trace the ‘same’ hardening curve
2. Extends experimental curve from 8.2% engineering strain to ~61% true strain
3. Quantifies the degradation of the Elastic Modulus
4. Enables measurement of the m Value for strain rate sensitivity modeling
5. ‘Same’ hardening curve shows variation on hardening law parameters

**DP 980**

- Common constitutive behavior
- Elastic unloading after 8% to ~28% plastic strain
- Loading under 10x range of strain rates
- All from a SINGLE Uniaxial Tension Test SPECIMEN

7.7 times increase in experimental definition
DETECTION OF ONSET OF LOCALIZED NECKING

Evidence of necking from a convolution of Diffuse Neck (width ~ 12 mm) with a Local Neck (width ~ 2*sheet thickness).

2 camera coordinate system

y

y=0.0

y=50.0

X, Y, Z
Exx, Eyy, Exy
VSG=0.5 mm

100x Magnified

50 mm

201 Points
DETECTION OF ONSET OF LOCALIZED NECKING

Signature of Localized Neck

1) One very high positive curvature at the valley of the candidate groove in the last DIC frame.

2) Two high NEGATIVE peak curvatures at a location within 2*sheet thickness of the location of the positive peak, corresponding to the two shoulders on the drop into the neck groove.

3) Rapid drop in the peak curvatures from frame to earlier frame to levels of curvature consistent with calculated curvatures at points outside the candidate groove (noise level).
CURRENT APPLICATIONS OF DIC TESTING

DIC technology has been aggressively and successfully applied to

- **Uniaxial Tension Tests**
  - Measure R Value to High Strain
    - Average
    - Std Deviation
    - Evolution
  - Measure Hardening Law to High Strain
    - Average
    - Std Deviation
    - Strain-Rate Sensitivity
    - Young’s Modulus Degradation
  - Detect Onset of Localized颈ing
    - Enables accounting of Nonlinear Strain Path Effect

- **Bulge Tests**
- **Nakajima Tests**
- **Marciniak Tests**
- Applying to other tests...
FUTURE

1) Proposal to adopt industry standard for 2 Camera DIC Data Acquisition for all ASP and Supplier/OEM material testing

➢ Propose application to all ‘standard’ tests
➢ Propose ‘adaption’ to all non-standard tests

2) Methods undergoing testing/evaluation at CAL/NIST

3) Propose support of a National Database based on DIC Data
The objective of simulation is to ELIMINATE physical testing...

Can we achieve this if we compromise on the definition and calibration of our Material Models?

Can we achieve this if we compromise on Material Testing?
ACKNOWLEDGEMENTS

JUNYING MIN, FORMERLY GM R&D, TONGJI UNIVERSITY
JOHN CARSLEY, FORMERLY GM R&D, NOVELIS
JEONG-WHAN YOON, KAIST & DEAKIN UNIVERSITY
MARK IADICOLA, CAL/NIST
SANTE DICECCO, UNIVERSITY OF WATERLOO
FOR MORE INFORMATION

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GREAT DESIGNS IN STEEL

THANK YOU
## UNIAXIAL TENSION DATA FOR SIMULATION

1) **Young’s Modulus & Poisson Ratio**
   - **Anisotropy of Elasticity**
     - Typical 10-20% variation affects spring-back proportionally
   - **Degradation of YM with strain**
     - Requires load/unload/reload test

2) **Proportional Limit (Elastic-to-Plastic Transition)**
   - 0.2% Offset Yield Stress

3) **Hardening Law (True Stress vs Plastic Strain)**
   - **Extension beyond max load**
     - Needed if expecting to predict conditions up to fracture
   - **Kinematic Hardening**
   - **Anisotropic Hardening**
   - **Strain rate effects**
     - Requires tension-compression test
     - Requires tests in at least 3 loading orientations
     - Requires jump test or multiple tests

4) **R Value (Ratio of Plastic Strain Rates)**
   - Based on Total NET Strain

5) **Onset of Localized Necking**
   - Not detectable

6) **Local Fracture Strain**
   - Not measured
HISTORY OF CONSTITUTIVE MODELS

The ultimate objective of simulation is to ELIMINATE physical testing...

Can we achieve this if we compromise on the definition and calibration of our Material Models?

- Von Mises Yield Model (1913)
- Hill 1948 Fully Anisotropic Model
- Barlat 2000-2d Model

- Requires only a single hardening law
- Also requires $Y_{S0}$, $Y_{S45}$, $Y_{S90}$, and $Y_{S_{EB}}$, and $R_{EB}$

Experimental Data
von Mises
Hill 1948
Barlat 2000-2d
Calibration Data

Stress Ratio ($Y_{S_x}/Y_{S0}$)
TRADITIONAL UNIAXIAL TENSION TEST

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Additional Tension Tests

What if we could get a handle on this from a SINGLE Uniaxial Tension Test?
What if we could experimentally define the hardening behavior beyond ‘UE’?
What if we could detect onset of localized necking and determine the necking limit?
What if we could tightly measure lower/upper bounds of fracture strain?
DIC Analysis Clearly Shows the Answer is NO

Strain field is NOT uniform during UE

% Stretch of end points of a 50 mm Gauge

DIC measured strains at 201 points along the 50 mm

DP 980

‘UE’
### Example of CSV File Content

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**1st of 201 Points...**

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PROPOSED DIC FILE NAMING CONVENTION

U45Fe_DP1180___RnnnTt.tttWww.ww-L.csv

5 Character Prefix Code

1st Character: BUMNVCS Code: Bulge, Uniaxial, Marciniak, Nakajima, V-Bend, Cruciform, Shear

Character 2&3: Two-digit angle of Major Loading Axis to the RD of the sheet

Character 4&5: Chemical code of Primary Element (Fe, AL, or Mg)

(used to initialize elastic properties to improve automation of the elastic fitting)

4 Part Multi-Character Suffix Code

‘-L’: File defines a section running down the longitudinal axis of the specimen; other recognized codes are ‘-S’, ‘-R’, ‘-T’, and ‘-W’

Required www.ww defines the gauge width of the uniaxial specimen

Required t.ttt defines the thickness of specimen to appropriate # of digits

nnn digits define the repeat test number ID (required when t.ttt is the same for 2 tests)

User defined material name (may include other details of the test in a complex DOE)