FORMABILITY AND FRACTURE CHARACTERIZATION OF DP980 AND 3RD GEN STEELS

A collaborative project between Honda Research Americas, SMDI, Bowman, and the University of Waterloo

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PROJECT TEAM

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PROJECT GOALS

1. Characterize properties of 3rd GEN 980 and 1180 MPa steels provided by the Steel Marketing Development Institute (Blind Study)

2. Apply optimized fracture testing methodology established for Advanced High Strength Steels (GDIS 2017 and GDIS 2018) to 3rd GEN Steels

3. Focus upon formability and fracture characterization of 3rd GEN Steels to integrate into CAE toolkit from forming-to-crash (GDIS 2019)

4. Design forming process of full-size B-pillar for mid-size SUV using CAE toolkit with Bowman Precision Tooling and Honda R&D (GDIS 2020)

5. Perform dynamic B-pillar impact tests to evaluate CAE toolkit and methodology to design 3rd Gen. steel components from concept to crash the formed B-Pillar (GDIS 2020)
MATERIAL PERFORMANCE

- Superior tensile performance of 3rd GEN Steels compared to “optimized” DP980
- 980 3rd GEN. has comparable v-bend performance with 2x the uniform elongation as DP980 optimized for local formability
CONSTITUTIVE CHARACTERIZATION: ANISOTROPY

Rather mild anisotropy in both 3rd GEN steels $\rightarrow$ Calibrated Yld2000 model

<table>
<thead>
<tr>
<th>$\sigma_0/\sigma_0$</th>
<th>$\sigma_{22.5}/\sigma_0$</th>
<th>$\sigma_{45}/\sigma_0$</th>
<th>$\sigma_{67.5}/\sigma_0$</th>
<th>$\sigma_{90}/\sigma_0$</th>
<th>$\tau_{12}/\sigma_0$</th>
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<tbody>
<tr>
<td>980-3rd Gen Lot 112</td>
<td></td>
<td></td>
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<tr>
<td>$R_0$</td>
<td>0.92</td>
<td>1.00</td>
<td>0.98</td>
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<tr>
<td>$R_{22.5}$</td>
<td>0.95</td>
<td>0.98</td>
<td>0.97</td>
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<tr>
<td>$R_{45}$</td>
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<td>0.97</td>
<td>0.98</td>
<td>1.00</td>
<td>0.586</td>
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<tr>
<td>$R_{67.5}$</td>
<td>0.98</td>
<td>1.00</td>
<td>1.00</td>
<td>0.98</td>
<td>0.605</td>
</tr>
</tbody>
</table>

| 1180 3rd Gen Lot 111 |
|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $R_0$            | 0.86            | 1.00            | 1.00            | 0.98            | 1.00            |
| $R_{22.5}$       | 0.92            | 1.05            | 1.04            | 0.99            | 0.92            |
| $R_{45}$         | 1.05            | 1.01            | 1.01            | 0.99            | 0.586           |
| $R_{67.5}$       | 0.98            | 1.02            | 1.02            | 0.99            | 0.605           |
| $R_{90}$         | 1.00            | 1.00            | 1.00            | 0.98            | 1.00            |

![Graphs showing anisotropy results](image-url)
CONSTITUTIVE CHARACTERIZATION: ISOTROPIC HARDENING

- Isotropic hardening response obtained using tensile & shear tests
- Methodology in Rahmaan et al. (2017) and refined in Noder & Butcher (2019)
- Kinematic hardening characterization in-progress for springback simulations


CONSTITUTIVE CHARACTERIZATION: TENSILE & SHEAR TESTS

Step 1: Convert tensile and shear tests to Stress vs. Plastic work and obtain shear-to-tensile ratio

Step 2: Convert shear stress post tensile UTS, deconstruct work to equivalent plastic strain & fit model


CONSTITUTIVE CHARACTERIZATION: TENSILE & SHEAR TESTS

Hardening response obtained until large strains without inverse FEA
Method assumes anisotropy does not evolve past the tensile UTS

Relatively simple to select and calibrate a hardening model, uncertainty with extrapolation is reduced
CONSTITUTIVE CHARACTERIZATION: ELEVATED STRAIN RATES

Hardening response of 980 & 1180 evaluated at 0.001/s, 1/s and 100/s

Positive rate-sensitivity: Appreciable non-linear hardening with strain rate in 980 3rd GEN
CONSTITUTIVE CHARACTERIZATION: ELEVATED STRAIN RATES

Strain rate effects are appreciable at strain-rates for forming operations: Improves Formability

980 3rd GEN has 5% higher flow stress at 1/s and is 10% higher at 100/s
FORMABILITY CHARACTERIZATION

- B-Pillar design is influenced by material limitations
  - Accurate formability characterization is required

- Bowman Precision Tooling in charge of B-Pillar design, machining of the die set, and forming trials
  - AutoForm software was used to identify critical sections in the B-Pillar
  - Material cards and FLCs created by UWaterloo to finalize the design
FORMABILITY CHARACTERIZATION

Nakazima dome tests: *Out-of-Plane Stretching*

→ Higher limiting strains and non-linear strain path

Marciniak tests: *In-plane deformation*

→ Approximately linear strain path & consistent with theoretical models for FLC
FORMABILITY COMPARISON

- Same conclusions for Nakazima & Marciniak FLCs:
  - Superior formability of 980 3rd GEN. vs. DP980
  - Similar FLC for DP980 and 1180 3rd GEN.
FORMABILITY: NAKAZIMA VS. MARCINIAK FLC

Which Forming Limit Curve to use?

Nakazima FLC has “process effects” of bending, non-linear strain paths and tool contact that alter the limit strains

Nakazima tests are generally preferred for simplicity of testing

Inconsistent to use Nakazima FLC data without compensating for process effects

Adopted methodology of Min et al. (2016) to correct the FLC data of DP980 and 3rd GEN. steels

FLC PROCESS CORRECTIONS

- Details of correction methodology provided in Min et al. (2016, IJMS)
- Applied for DP980 and 3rd GEN.

Apply Non-linear Strain Path (NLSP) Corrections for DP980 (1.2 mm)

Significant correction for NSLP in Nakazima tests

Minor NSLP effects in Marciniak. Largest in Biaxial Stretching

FLC PROCESS CORRECTIONS: TOOL CONTACT

- Stress-based mapping strategy for 3D and Plane Stress forming limits used to remove influence of contact stress

FLC & ANALYTICAL PREDICTION: DP980

Corrected Nakazima FLC in good agreement with Marciniak

Analytical prediction of FLC using Modified Maximum Force Criterion of Hora et al. (2013) in very good agreement: *Only requires yield surface & hardening model*

FLC & ANALYTICAL PREDICTION: 3\textsuperscript{RD} GEN. STEEL

Corrected Nakazima FLCs for 3\textsuperscript{rd} GEN. also in good agreement with Marciniak

Simple MMFC model with isotropic assumption can predict the FLCs with only hardening data. No calibration parameters
INDUSTRIAL STRATEGY FOR PLANE STRESS FRACTURE CHARACTERIZATION

1. Perform 4 Plane Stress Characterization Tests
   - Shear
   - Conical Hole Expansion
   - V-Bend (VDA238-100)
   - Biaxial Dome (R = 5 mm)

2. Experimental Fracture Locus
   - Assume failure locus form & calibrate with 4 points
   \[ \varepsilon_f^{\text{exp}} = \varepsilon^{\text{UW}}(T, a_{i-4}) \]
   Physically meaningful fracture locus: *Not an FE construct*

3. Plane Stress Models with Various Mesh Sizes

4. Regularize Exp. Fracture Locus for CAE
   - Assume damage model & scale locus with mesh size, R:
   \[ D = \frac{d\varepsilon^p}{\varepsilon_f(T)} \]
   \[ \varepsilon_f^{\text{CAE}}(R, \varepsilon_f^{\text{exp}}) = R \cdot \varepsilon_f^{\text{exp}}(T, a_i) \]

Fracture characterization and CAE application to rail sections detailed in GDIS 2017 & 2018
Smaller punch radii suppress necking and thus give higher failure strains.
Marciniak is best for formability, not for fracture.
FRACTURE COUPON SELECTION: PLANE STRAIN

- Marciniak, Nakazima or notch tests could be used for plane strain but have strain localization: *Not plane stress until fracture and NLSP*.
- DIC often underestimates fracture strain for coupons with localization.
- VDA bend test with DIC avoids necking and provides linear path.
POST-MORTEM CORRECTIONS 980 3RD GEN.

Non-linear strain path and underestimation of failure strains with DIC for necking-based fracture
POST-MORTEM CORRECTIONS 1180 3\textsuperscript{RD} GEN

Reduced necking of 1180-3\textsuperscript{rd} GEN from plane strain to biaxial stretching
FRACTURE CHARACTERIZATION

- DP980 and 1180 3rd Gen. have similar FLCs (global formability) but very different local formability
  
  ➔ Trade-offs between formability (need high FLC) and crash performance (want high fracture strain)
FRACTURE IN FORMABILITY TESTS: 980 3rd GEN.

Ductile-type fracture with necking in formability tests of 980 3rd GEN.

Nakazima tests:
- Necking
  - Uniaxial Tension
  - Plane Strain Tension
  - Equi-biaxial Stretching

Marciniak tests:
- Necking
  - Uniaxial Tension
  - Plane Strain Tension
  - Equi-biaxial Stretching

No Necking
FRACTURE IN FORMABILITY TESTS: 1180 3\textsuperscript{RD} GEN.

1180 3\textsuperscript{rd} GEN is showing marginal necking and through-thickness shear fracture.

Nakazima tests:
- Uniaxial Tension: Minor Necking
- Plane Strain Tension: No Necking
- Equi-biaxial Stretching: No Necking

Marciniak tests:
- Uniaxial Tension: Minor Necking
- Plane Strain Tension: No Necking
- Equi-biaxial Stretching: No Necking
ISO-method and time-dependent (LBF) limit strains are not realistic for stretch side

*Through-thickness shear fracture without necking from plane strain to biaxial stretching*

Stretch-side of 1180 3rd GEN. FLC is conservative: Fracture limits are effective limit strain

**Marciniak tests**

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**Diagram:**

- 1180-GEN3 Lot 111 (Marciniak)
- Major strain vs. Minor strain
- Data points and curves for different strain states
OUTLOOK & FUTURE WORK

High-rate constitutive model to large strains and fracture locus for two 3rd GEN steels have been developed

Next steps:
• Transfer from coupon level testing to a structural component (B-Pillar)
• Experimental characterization for kinematic hardening to study springback
• B-pillar impact tests and CAE simulations from forming-to-crash
FOR MORE INFORMATION

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Presentations will be available for download on SMDI’s website on Wednesday, May 22