EVALUATION OF DAMAGE ACCUMULATION FRACTURE MODELS IN NON-LINEAR STRAIN PATHS

Prof. Cliff Butcher
University of Waterloo
PROJECT TEAM

University of Waterloo
Armin Abedini, PhD, Project manager
Farinaz Khameneh, PhD Candidate
Jacqueline Noder, PhD
Cole Fast-Irvine, MASc
Kenneth Cheong, PhD Student
Cliff Butcher, Associate Professor

Auto-Steel Partnership: Constitutive & Fracture Modelling Team
Eric McCarty, A/SP Project Manager

Technical Leads for DP1180 Project
Dr. Thomas Stoughton, General Motors
Dr. Andrey Ilinich, Ford Motor Company
OVERVIEW OF FRACTURE MODELLING FOR CRASH

1. Construct Proportional Fracture Loci from Coupon Tests: *Experimental or Inverse FE Approaches Used*

Step 2. Assume Damage Model for Non-Linear Loading, Pair with Fracture Locus

\[
\Delta D^{GISSMO} = \left[ \frac{n}{\varepsilon_f(T)} D^{\left( \frac{1}{n} \right)} \right] \Delta \varepsilon^p
\]

Step 3. Regularize for element size & apply to structural CAE models

Need Objective Evaluation of Phenomenological Fracture Models

3-Point Bend of Rail Section

Axial Crush of Front End Crush Structure

Axial Crush of Hot Stamped Rail
BRIEF REVIEW OF PROPORTIONAL FRACTURE

Example: Consider isotropically hardening material. Yield surface expands

Fracture: Define failure surface: Tresca is simplest with straight line for fracture

Intersection of yield and fracture surface creates the fracture locus (2D) or surface (3D)

\[ (\sigma_1)^f = \text{constant (plane stress, tensile quadrant)} \]
BRIEF REVIEW OF PROPORTIONAL FRACTURE

Change Tresca to Mohr-Coloumb for Difference in Tension and Compression (still linear fracture model)

Mohr-Coulomb Criterion: \[ \sigma_1 - \sigma_3 + c(\sigma_1 + \sigma_3) = b \]

- \( b \) = related to shear stress;
- \( c \) = cohesion (controls compressive response);
- \( c = 0 \) (Tresca – Max shear stress criterion)

C parameter acts as hinge at uniaxial tension. Cusp in plane stress fracture locus created by corner

Problem Statement: Identify the Fracture Potential Function in Stress Space. Natural extension to anisotropy, complex loading

![Graph showing fracture potential function in stress space with increasing c showing sharp cusp from discontinuity in fracture potential.]
BRIEF REVIEW OF PROPORTIONAL FRACTURE

Inversion of fracture surface with yield and hardening models used to create equivalent strain representation with triaxiality and Lode parameter. Ex: MMC-5 parameter model

\[ \epsilon_f^{MMC5} = \left[ c_2 \left[ c_\theta + \frac{\sqrt{3}}{2 - \sqrt{3}} (c_\theta^{ax} - c_\theta) \left( \sec \left( \frac{\pi \tilde{\theta}}{6} \right) - 1 \right) \right] \right]^{-1} \left( \frac{\sqrt{3}}{3} \cos \left( \frac{\pi \tilde{\theta}}{6} \right) + c_1 \left[ T + \frac{1}{3} \sin \left( \frac{\pi \tilde{\theta}}{6} \right) \right] \right) \]

Convenient but breaks explicit link between plasticity and fracture surface. Now many versions in the literature

Procedure for Experimental Fracture Characterization
1. Characterize plasticity and hardening behavior
2. Characterize fracture strains in proportional loading → what tests to use?
3. Select & calibrate fracture function → Shape can vary between calibration points...
4. How to generalize to non-proportional model → need damage model if using eq. strain (ex: GISSMO)
ANISOTROPIC PLASTICITY

Detailed experimental characterization of anisotropy:
- Uniaxial tension (7 directions)
- Simple shear (3 directions)
- Plane Strain tension (3 directions)
- Disc compression test for biaxial R-value

Non-associated Yld2018 (Drucker-type) yield & plastic potential

\[ \sigma_{eq} = \frac{1}{3} \sum_{i=1}^{6} (J_i^{(eq)})^2 - c(J_3^{(eq)})^{2/6} \]

\[ c = 1.226 \text{ BCC} \]
CONSTITUTIVE CHARACTERIZATION

Shear hardening behavior nearly identical in RD-TD and TD-RD shear loading (orthotropic yield surface)

→ Reverse shear test did not show complex hardening response. Reversion to monotonic shear response

→ Characterization of hardening in complex strain path changes outside of scope → future work

Assumption of orthotropic response is typical in popular yield criteria like Yld2000, Yld2004, Yoshida, etc.
ISOTROPIC HARDENING BEHAVIOR

Hardening to large strains obtained using UW’s shear conversion methodology in RD & TD

- Uniform elongation is ~5% but shear conversion provides data to 60% plastic strain
- Isotropic hardening reasonable assumption for DP1180

\[
\left( \frac{\tau}{\sigma_{RD}} \right)^{exp} = 0.603
\]

Normalized shear stress ratio

\[
\sigma^{RD} (\text{MPa}) = \frac{\sigma^{TD}}{1.025}
\]

Isotropic hardening reasonable assumption

EVALUATIONS OF PLASTICITY MODEL

- JIS Tensile (shear band)
- Mini Tensile (triaxial neck)
- Plane Strain Notch Tension
  - FE Model (Mid-plane Element): Mesh Size = 0.1 mm
  - FE Model (Surface Element)
  - Experiment (DIC Point): VSG Size = 0.625 mm
- DP1180 – 1.0 mm thickness
- Simulations of shear tests with shell elements Type 16
  - Element size: 0.1 mm
- Nakazima Dome Test
  - FE (Shells)
  - Element size: 0.6 mm
- Combined Tension & Shear
  - FE – Anisotropic
  - Experiment
- Simple Shear
  - Simulations of shear tests with shell elements Type 16
  - Element size: 0.1 mm
FORMABILITY IN TRANSVERSE DIRECTION

Forming limit curve (FLC) required to identify pre-straining limits for fracture tests

Marciniak and Nakazima tests performed in Transverse direction (limiting direction)

→ Process corrections for Nakazima converged to Marciniak limit strains

→ Modified Maximum Force Criterion (MMFC) predicted the FLC. No calibration parameters!

PROPORTIONAL FRACTURE: SIMPLE SHEAR

Shear fracture strains extremely sensitive to DIC settings and gage length
Detailed study in Khameneh et al. (2022)

→ Used DIC gage length of 0.50 mm throughout the study
→ Fracture appeared to occur in center of gauge region based on void damage

Shear strain can be measured from DIC & line rotation

Shear fracture strains extremely sensitive to DIC settings and gage length

Strong sensitivity to gage length

Influence of gage length on fracture locus

Influence of gage length on fracture locus
PROPORTIONAL FRACTURE: PLANE STRAIN

V-bend test (VDA238-100) most reliable for plane strain fracture characterization

→ V-bend provides proportional plane strain tension without necking
→ DIC is inaccurate for Plane strain tests with necking. Stress state is triaxial...
→ Necking-based tests can be improved with thickness strain correction

Fracture Strain at VDA load threshold
Convergence in fracture strain

Punch radius: 0.2, 0.4, 1.0 mm
Bend severity: 5, 2.5, 1 mm

VDA load drop
V-bend Crack Initiation
PROPORTIONAL FRACTURE: BIAXIAL STRETCHING

Biaxial fracture strains are significantly affected by necking

→ Smaller punch radii suppress necking and create linear strain path to much higher strains

→ Apparent linearity can be misleading. Incremental analysis shows localization

→ Nakazima (R = 50 mm), Marciniak and Bulge tests tend to be lower bounds for biaxial strains in AHSS

Increase bend severity

<table>
<thead>
<tr>
<th>Punch radius</th>
<th>Eq. Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mm</td>
<td>0.60 ± 0.02</td>
</tr>
<tr>
<td>25 mm</td>
<td>0.77 ± 0.05</td>
</tr>
<tr>
<td>10 mm</td>
<td>0.78 ± 0.05</td>
</tr>
<tr>
<td>5 mm</td>
<td>0.86 ± 0.03</td>
</tr>
</tbody>
</table>
Uniaxial tension might be most challenging test due to necking instability and its type of localization. Tensile geometry affects localization mode... the hole tension failed behind edge for DP1180. *DIC fracture strains in necking-based samples require thickness correction or are too conservative.*

Conical hole expansion (R = 5 mm) with machined hole gave best estimate for DP1180. No necking. Hole expansion methodology and FE verification in Narayanan et al. (2022).

Specimen geometries of (a) JIS No.5, (b) miniature tensile, (c) tapered sub-sized ASTM-E8 tensile, (d) central hole tension, and (e) schematic of hole expansion test with machined hole.

CONICAL HOLE EXPANSION FOR UNIAXIAL FRACTURE

Conical hole expansion induces through-thickness strain gradient to suppress necking.

Fracture initiates at outer edge that is in uniaxial tension for entire test.

Use outer radius to fracture location with image processing. Easy!
Proportional fracture model calibrated using tests without necking: Approx. constant triaxiality in plane stress

All tests analyzed with a consistent virtual strain gauge length (VSGL) of 0.5 mm.

UW Generalized Drucker Prager (GDP) Model:

\[
\sigma_i^f (m,b,c,d) = \frac{m \Phi_{\text{eq}} (\tilde{T}, m = 2)}{\Phi_{\text{eq}} (\tilde{T}, m = 2)} + c\left(2T + f_i(\tilde{T}) + f_j(\tilde{T})\right)
\]

\[
T = \frac{\sigma_{\text{eq}}}{\sigma_{\text{eq}}} ; \quad \tilde{T} = 1 - \frac{2}{\pi} \cos^{-1} \left(\frac{27}{2} \frac{J_i}{\sigma_{\text{eq}}^2}\right)
\]

\[
\Phi_{\text{eq}} (\tilde{T}, m) = \frac{\sigma_{\text{eq}}}{\sigma_i} \left(\frac{1}{2} (f_i - f_j)^m + \frac{1}{2} (f_i - f_j)^m + \frac{1}{2} (f_i - f_j)^m\right)
\]
FRACTURE IN BI-LINEAR STRAIN PATHS

How do the fracture strains vary in non-proportional loading?

In-Plane Pre-straining in uniaxial, plane strain and biaxial conditions

Select secondary fracture tests without necking and approx. linear strain paths

Major experimental effort: > 250 tests performed. Subset of data provided for NUMISHEET 2022 Benchmark
FIRST STAGE: IN-PLANE PRE-STRAINING

**Uniaxial Pre-Straining:** Oversized rectangular samples (strain variation < 1%)

**Plane Strain & Biaxial Pre-Straining:** Marciniak tests (strain variation of 2% or less)

Local DIC strain history tracked for mapping to secondary fracture tests

**FIRST STAGE: IN-PLANE PRE-STRAINING**

**Uniaxial Pre-Straining:** Oversized rectangular samples (strain variation < 1%)

**Plane Strain & Biaxial Pre-Straining:** Marciniak tests (strain variation of 2% or less)

Local DIC strain history tracked for mapping to secondary fracture tests
Fracture strains constant for plane strain stretch + plane strain bend

Convergence – highlights plane strain fracture was accurately characterized

Not a significant change in fracture strains
SELECT NLSP DATA: V-BEND AFTER BIAXIAL STRETCH

Repeatable strain paths and fracture strains

Comparable major principal strain at fracture in different strain paths

Cumulative equivalent fracture strain increases with biaxial pre-straining
SELECT NLSP DATA: SHEAR AFTER BIAXIAL STRETCH

*Repeatable strain paths and fracture strains*

*Cumulative equivalent fracture strains in shear increase with biaxial stretch*
DAMAGE ACCUMULATION AND FRACTURE MODELS:
APPLYING PROPORTIONAL FRACTURE DATA TO NON-LINEAR STRAIN PATHS

All models are equally valid in proportional loading... but what happens in non-proportional loading?

Stress-based representations do not require a damage counter: \( \sigma_i > \sigma^f_i (T, L) \)

Equivalent strain representations employ phenomenological damage models (no physical foundation)

Linear damage (Johnson & Cook, 1983) commonly used

\[
D = \int \frac{d\varepsilon_{eq}}{\varepsilon_f (T, L)} \quad \text{Fracture: } D = 1
\]

Power Law Damage (Xue, 2007)

\[
\frac{\Delta D}{\Delta \varepsilon^p_{eq}} = \frac{n_D}{\varepsilon_f (T, L)} \left( \frac{\varepsilon^p_{eq}}{\varepsilon_f (T, L)} \right)^{n_D(1-1/n_D)}
\]

GISSMO: Based on Power Law but implemented differently

\[
\frac{\Delta D^{\text{GISSMO}}}{\Delta \varepsilon^p_{eq}} = \frac{n_D}{\varepsilon_f (T, L)} \left[ D \right]^{1-1/n_D}
\]

Neukamm, F., Feucht, M., Häufe, A. Consistent damage modelling in the process chain of forming to crashworthiness simulations. LS-DYNA Anwenderforum, Bamberg 2008
In-Plane Biaxial Pre-strain to Plane Strain Bending (change from highest to lowest fracture strains)

GISSMO overestimated fracture. Linear slightly better than non-linear with recommended $n = 2$

Power Law damage was conservative. Influence of exponent can be different than GISSMO
**DAMAGE ACCUMULATION EXAMPLE 2: DP1180**

*Plane Strain Pre-Strain followed by Biaxial punch (path change from lowest to highest fracture strains)*

GISSMO underestimated fracture. Non-linear did better by reducing influence of first path in plane strain

*Power Law Damage similar to GISSMO when going from severe-to-mild stress state*

---

**Graph 1:**
- Fracture: General Drucker-Prager Model
- Calibration Points: Experiment
- Non-Linear Strain Path: Experiment
- Fracture in NLSP

**Graph 2:**
- Fracture in NLSP: Biaxial Pre-Strain to Plane Tension
- GISSMO: Damage Exponent = 1
- GISSMO: Damage Exponent = 2
- Xue Power Law Damage: Damage Exponent = 2

---

**Legend:**
- Fracture Locus: Gen. Drucker-Prager Model
- Calibration Points: Experiment
- Non-Linear Strain Path: Experiment
- Fracture in NLSP

---

**Key Points:**
- Pre-Strain to 15% of Plane Strain Fracture Strain
- Equivalent Plastic Strain
- Triaxiality

---

**Experiment:**
- D = 1
EVALUATION OF FRACTURE LOCUS: GISSMO

Evaluate all non-linear strain path tests: 3 Fracture Loci with 4 parameters calibrated from 4 data points

Paired with GISSMO damage model using n = 2

Define correlation metric to evaluate model predictions

\[ D = \frac{\varepsilon_{eq}^{f\text{Predicted}}}{\varepsilon_{eq}^{f\text{Test}}} \]

\[ D = 1 \quad \text{Perfect correlation} \]
Select Generalized Drucker-Prager model (marginally better)

MMC model rather conservative for second stage biaxial loading

Drucker-Yoon model overestimated fracture in second stage shear

\[ D = \frac{\varepsilon_{eq}^f - \text{Predicted}}{\varepsilon_{eq}^f - \text{Test}} \]

\( D = 1 \)  Perfect correlation

Asymptotic behavior in biaxial tension

→ Triaxiality has poor resolution

→ Consider additional biaxial tests and use NLSP due to necking as evaluation

*Results also depend upon choice of damage model and calibration of loci
FRACTURE REPRESENTATIONS: DP1180

→ All NLSP fracture data showed with terminal values
→ Principal Stress representation has apparent convergence
→ Eq. strain representation shows sensitivity to hardening model
→ Proportional fracture locus of DP1180 appears conservative in NLSP.
→ Need to evaluate damage models
GISSMO DAMAGE MODEL EVALUATION

GISSMO Damage Accumulation:

\[ D = \int \frac{n_D}{\varepsilon_f(T)} D^{(1-1/n_D)} d\varepsilon_{eq} \]

Assume Damage exponent: \( n_D = 1, 2 \)

**Advantages:** Widely used and available in LS-DYNA, Linear form = Johnson-Cook model

Eq. Strain based (relatively convenient)

**Disadvantages:** No physical foundation – user assumes damage exponent;

Damage accumulation unrelated to hardening ability

<table>
<thead>
<tr>
<th>Damage Model</th>
<th>Eq. Strain Damage Exponent = 1</th>
<th>Eq. Strain Damage Exponent = 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage Metric &amp; Parameters</td>
<td>( \varepsilon_f^{\text{model}} / \varepsilon_f^{\text{exp}} )</td>
<td>Average</td>
</tr>
<tr>
<td>Fracture Metric:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary Path</td>
<td>Plane Strain Tension (12 Paths)</td>
<td>1.05 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>Biaxial Stretching (9 Paths)</td>
<td>0.91 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>Shear (12 Paths)</td>
<td>0.94 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>Uniaxial Tension (12 Paths)</td>
<td>0.90 ± 0.06</td>
</tr>
</tbody>
</table>

**Observations:** Recommended non-linear damage \( (n = 2) \) performed better than linear damage (Johnson-Cook)

\( \rightarrow \) Linear damage more conservative and will predict more fracture in FEA

\( \rightarrow \) Non-linear GISSMO over-predicted when switching to path with lower fracture strain (localization...)

- Secondary Path
- Fracture Metric:
- Damage Metric & Parameters
- Damage Model
- GISSMO
**Power Law Damage Accumulation:**

\[ D = \int \frac{n_D}{\varepsilon_f(T)} \left( \frac{\varepsilon_p}{\varepsilon_f(T)} \right)^{n_D-1} d\varepsilon_p \]

Assume Damage exponent: \( n_d = 1, 1.5, 2 \)

**Advantages:** Appears to be consistent version of damage model GISSMO was based upon

Equivalent to GISSMO and Johnson-Cook for Linear Damage

**Disadvantages:** Same as GISSMO - No physical foundation – user assumes damage exponent

Damage accumulation unrelated to hardening ability

<table>
<thead>
<tr>
<th>Damage Model</th>
<th>GISSMO</th>
<th>Power Law Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Damage Metric &amp; Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eq. Strain</td>
<td>Eq. Strain</td>
<td>Eq. Strain</td>
</tr>
<tr>
<td>Damage Exponent = 1</td>
<td>Damage Exponent = 2</td>
<td>Damage Exponent = 1.5</td>
</tr>
<tr>
<td><strong>Fracture Metric:</strong> ( \frac{\varepsilon_f^\text{model}}{\varepsilon_f^\text{exp}} )</td>
<td>Average</td>
<td>Std. Dev</td>
</tr>
<tr>
<td>Secondary Path</td>
<td>Plane Strain Tension (12 Paths)</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>Biaxial Stretching (9 Paths)</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>Shear (12 Paths)</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>Uniaxial Tension (12 Paths)</td>
<td>0.90</td>
</tr>
</tbody>
</table>

**Observations:** Performed superior to GISSMO with \( n = 1.5 – 2.0 \) recommended for DP1180

⇒ Significant improvement in predicting failure when second path is more severe as in localization

⇒ Overall, slightly conservative across all NLSP while GISSMO was not
CONCLUSIONS AND FUTURE WORK

Fracture Characterization

→ Accurate plasticity model is required to differentiate stress states
→ Select proportional characterization tests without necking for fracture calibration
→ Choice of fracture loci and calibration is important: **Biaxial region is critical.**

![Fracture Characterization Tests](image)

**Fracture Models:** (Targeted for GDIS2024)

→ Linear damage relatively conservative for fracture of DP1180
→ Power law damage model superior to GISSMO for non-linear damage
→ Investigate anisotropic fracture and application to higher ductility steel
→ Consider physically-based alternate models: Stress and/or plastic work based
ADDITIONAL INFORMATION: PUBLICATIONS FOR DP1180


FOR MORE INFORMATION

Name: Cliff Butcher
Company: University of Waterloo
Email: cbutcher@uwaterloo.ca

Name: Thomas Stoughton
Company: General Motors
Email: thomas.b.stoughton@gm.com

Name: Eric McCarty
Company: Auto-Steel Partnership
Email: emccarty@a-sp.org

More Questions? Meet the speaker(s) at the Auto/Steel Partnership booth.