Sliding Loads and their Effect on the Stress Triaxiality and Lode Parameter Responses of Plates

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Motivation
- Effect of Sliding Ice Loads on Hull Response

Recent Developments
- Sliding Load Hull Response
- Ductile Fracture of Metals

Current FE Fracture Practice
- Lode and Triaxiality of Plates and Frames subject to Sliding Loads
- Summary
Motivation: Sliding Loads and the Development of Initial Hull Fracture

Collision & grounding (C&G) scenarios:
- Much work over last 30 years
- Various-scale experiments:
  - Plates, grillages, ships, ...
  - Steady-state plate cutting
  - Sliding motion:
    - Quinton (2015): Controlled laboratory biaxial indentation of plates and frames.
    - No fracture

Nonlinear numerical simulations:
- Plasticity, fracture, and sometimes complex fluid structure interaction (FSI)
- Validation:
  - Range: tensile tests to field or laboratory experiments.

C&G scenarios often consider hull response to steady-state hull fracture.
- Where development of initial fracture plays a negligible role in the system energy.

Some scenarios may not attain steady-state hull fracture:
- Ice-strengthened ships/offshore structures
- Open-water (non-ice class) ships for accidental impact with:
  - Ice, or other soft/blunt objects
  - Grounding on a soft bottom

The “impact-to-fracture” phase (i.e. development of hull fracture) generally dominates these scenarios.
- Does sliding motion affect the initiation of hull fracture?
Relevant Recent Developments

- Path dependent hull response
    - Experimental confirmation (Quinton 2015)
- Ductile fracture theory for metals
  - Ductile fracture for many metals is a function of triaxiality (Bao & Wierzbicki, 2004)
    - Ductile fracture for some metals is a function of Lode parameter & triaxiality (Bia & Wierzbicki, 2008)
- Finite element codes adopt Lode & triaxiality based fracture models (~2010 ?)

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Path Dependent Hull Response: Effect of Sliding Loads?

- Ship and offshore structure design ice loads are invariably stationary loads.
  - Most often statically applied, stationary loads.
  - Real ice loads often slide along the hull.

- In 2008, Quinton and separately Alsos, numerically predicted a “reduced hull structural capacity” for sliding loads causing plastic damage.
  - I.e. *path-dependent* hull response.

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- MLA:
  - Steel plates or single frames subject to biaxial indentation.
    - Simultaneous or sequential “normal direction” indentation and “lateral direction” sliding.
  - It allowed variations in:
    - Indenter type
    - Ambient temperature
    - Loading rate (in both directions).
Moving Load Apparatus
Steel Plates, Carriage, and Indenters

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Apparatus & Test Specimen Particulars

**MLA Force Capacities**
- Vertical Force: 500 kN
- Vertical Stroke: 15 cm
- Maximum Speed: 100 mm/s
- Horizontal Force: 250 kN
- Horizontal Stroke: 1.22 m
- Maximum Speed: 185 mm/s

- Sequential or simultaneous vertical and horizontal motions
  - Sequential for these experiments

**Steel Plate Specimens**
- Length: 1.65 m
  - 1.5 m usable
- Width: 0.55 m
  - 0.4 usable
- Thicknesses tested:
  - 6.35 mm
  - 12.7 mm

**Material Properties**
- Structural Steel Grade 50W
  - Cold-rolled
  - \( \sigma_y = 344 \text{ MPa} \)
Load Details

- **Rigid Wheel Load Path - “In-Along-Out”**
  - Simplest load path so that normal and lateral indentations were decoupled.
  - No friction
    - Except rolling friction between the steel wheel indenter and the plate.
- **Displacement control or force control.**

- Lateral travel length was from the start position to beyond the +550 mm position (longitudinal direction).
Experiments: Plate & Frame Response to Sliding Loads

**Plates**

Resultant Force vs. Horizontal Displacement

- **2cm "Centre" Indentation: Resultant Force**
  - X: -0.005472
  - Y: 8.769e+04

- **2cm "End" Indentation: Resultant Force**
  - X: 550
  - Y: 6.397e+04

**Single Frame**

Force vs. Time

- **MovingLoad21 - Resultant Force**
- **MovingLoad21 - Vertical Force**
- **MovingLoad21 - Total Horizontal Force**

Vertical Displacement vs. Time

- 125kN Moving Load on 6.35 mm Plate
  - X: 12.5
  - Y: 24.61

- 250kN Moving Load on 12.7 mm Plate
  - X: 25
  - Y: 20.16
Layout

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  ▪ Effect of Sliding Ice Loads on Hull Response
• Recent Developments
  ▪ Sliding Load Hull Response
  ▪ Ductile Fracture of Metals
• Current FE Fracture Practice
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Recent Developments: Ductile Fracture of Metals

- 2004 – Bao & Wierzbicki (and others) show that the ductile fracture of many metals depends on triaxiality.

- Triaxiality, $\eta$

\[ \eta = \frac{p}{\sigma_{vm}} = \frac{1}{3} \frac{l_1}{\sqrt{3} j_2} \]

- $p = \frac{1}{3} l_1$ is hydrostatic stress
- $\sigma_{vm} = \sqrt{3} j_2$ is von Mises equivalent stress
- $\eta = +ve$ represents a tensile hydrostatic stress

- Range of triaxiality:
  - Plane stress:
    - Shell and some thick-shell elements:
      \[ -\frac{1}{3} \leq \eta_{shell} \leq \frac{1}{3} \]
  - 3D stress
    - Solid and some thick shell elements:
      \[ -\infty \leq \eta_{solid} \leq \infty \]
      - but practically:
        \[ -1 \leq \eta_{solid} \leq 1 \]

Fig. 20. Dependence of the equivalent strain to fracture on the stress triaxiality.

Figure reproduced from:
Recent Developments:
Ductile Fracture of Metals

- 2008 – Bai & Wierzbicki showed that the ductile fracture of some metals depends on triaxiality and Lode parameter.

- Lode angle, $\theta_l$
  \[ \theta_l = \frac{1}{3} \cos^{-1} \left[ \frac{3\sqrt{3}}{2} \left( \frac{J_3}{J_2^{\frac{3}{2}}} \right) \right] \]
  for $0 \leq \theta_l \leq \frac{\pi}{3}$

- Or Lode parameter, $\xi$
  \[ \xi = \frac{3\sqrt{3}}{2} \left( \frac{J_3}{J_2^{\frac{3}{2}}} \right) \]
  where $-1 \leq \xi \leq 1$

Figure reproduced from:
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Current FE Fracture Modeling Practice

- Fracture by material model
  - Failure strain (effective plastic strain)
    ▪ Simple input: fracture strain
  - Failure strain vs. triaxiality
    ▪ Curve of failure strain vs. triaxiality
  - Failure strain vs. triaxiality vs. Lode parameter
    ▪ Table of curves of failure strain vs. triaxiality for various Lode parameters
  - Other failure criteria …
    ▪ Variations on these for strain-rate and temperature
    ▪ …

- Types beyond the scope of this presentation:
  - Cohesive elements
    ▪ Usually zero-volume elements
    ▪ Connects adjacent “normal” elements
    ▪ Disappear when failure criterion/criteria met
  - Other non-traditional FE types:
    ▪ SPH – Smoothed Particle Hydrodynamics
    ▪ DEM – Discrete Element Method
    ▪ EFG – Element Free Galerkin Method
    ▪ XFEM – Extended FE Method
Simulation Results:

Lode and Triaxiality of Plates subject to Sliding Loads
Significant States of Stress

- **Stationary Load Results**
  - No compression zones (i.e. –ve triaxiality).
  - No uniaxial tension or pure shear in way of the indenter.
  - No plastic plane strain tension.
  - Identified zones of:
    - Equi-biaxial Plane Stress Tension

- **Sliding Load Results (frictionless)**
  - There are compressive zones.
  - No uniaxial tension or pure shear in way of the indenter.
  - Identified zones of:
    - Equi-biaxial Plane Stress Tension
    - Plastic Plane Strain Tension

Figure reproduced from:
Stationary Load: Equi-biaxial Plane Stress Tension

Stationary Load - Triaxiality

Stationary Load – Lode Parameter

Triaxiality: 2/3
Lode Parameter: -1
Sliding Load: Equi-biaxial Plane Stress Tension

Moving Load: Leading Edge Triaxiality

Triaxiality: 2/3

Equibiaxial Plane Stress Tension

Moving Load: Leading Edge Lode Parameter

Lode Parameter: -1
Moving Load:
Leading Edge Triaxiality

Quarter Inch Sample
Time = 2.3
Contours of Triaxiality Factor (p/vm)
reference shell surface
min=0.0140492, at elem# 6122
max=0.666554, at elem# 6157

Moving Load:
Leading Edge Lode Parameter

Quarter Inch Sample
Time = 2.3
Contours of Lode Parameter - (2*\(\sigma_{2}\)-\(\sigma_{1}\)-\(\sigma_{3}\))/(\(\sigma_{1}\)-\(\sigma_{3}\))
reference shell surface
min=-0.99606, at elem# 6129
max=0.99576, at elem# 1057
Comparison with Solid Elements

Quarter Inch Sample
Time =  2.25
Contours of Lode Parameter -(-2*sig2-sig1-sig3)/(sig1-sig3)
min=-0.997676, at elem# 3482979
max=0.999851, at elem# 2299881

1,858,396 Ideally Shaped Solid Elements

12,255 1:1:1 Shell Elements

67,071 Non-ideally Shaped Solid Elements

1,858,396 Ideally Shaped Solid Elements
Validating: Comparison with Experiment

6.35 mm Plate - Stationary then Sliding Load

Legend
- A Experiment
- B 1:1:1 Shells
- C Non-ideal Solids
- D Ideal Solids

Normal Force [N] (E+6)

Time [s]
Summary

• It is clear that there is a change in the state of stress due to indenter motion.

• For sliding loads, fracture will occur on the leading side of the indenter.
  ▪ Whereas for stationary loads, it fracture location is often less certain.

• For a material that is not sensitive to Lode parameter, onset of fracture may be predicted correctly for either stationary or moving loads.

• For a material that is sensitive to Lode parameter, onset of fracture may not be predicted correctly by triaxiality alone, for moving loads.
Acknowledgments

• Much of this work was funded by the STePS\textsuperscript{2} project at Memorial University of Newfoundland.
  ▪ Its government and industry partners:
    ◦ Atlantic Canada Opportunities Agency (ACOA) through its Atlantic Innovation Fund (AIF)
    ◦ Research & Development Corporation (RDC) through its Collaborative R&D program
    ◦ American Bureau of Shipping
    ◦ BMT Fleet Technology Ltd.
    ◦ Husky Energy
    ◦ Rolls-Royce
    ◦ Samsung Heavy Industries
    ◦ National Research Council of Canada - Ocean, Coastal, River Engineering (formerly the Institute for Ocean Technology)
    ◦ MITACS through their Accelerate program
    ◦ Memorial University of Newfoundland’s Offshore Technology Research – an NSERC CREATE program.
Thank you

Questions?