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 ?)
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

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Steel Plates, Carriage, and Indenters

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Apparatus & Test Specimen Particulars

**MLA Force Capacities**
- Vertical Force: 500 kN
- Horizontal Force: 250 kN

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

**Material Properties**
- Structural Steel Grade 50W
  - Cold-rolled
  - $\sigma_y = 344 \text{ MPa}$

Sequential or simultaneous vertical and horizontal motions
- Sequential for these experiments
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: 0.06557
  - Y: 5.449e+04

**Single Frame**

Resultant Force vs. Horizontal Displacement

- X: -547.8
  - Y: 9.778e+04

- X: 550
  - Y: 6.397e+04

**Vertical Displacement vs. Time**

- X: 12.5
  - Y: 24.61

- X: 25
  - Y: 20.16

- X: 66.09
  - Y: 39.45

- X: 103
  - Y: 30.49

**Force vs. Time**

- **125kN Moving Load on 6.35 mm Plate**
- **250kN Moving Load on 12.7 mm Plate**

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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, $\eta$

$$\eta = \frac{p}{\sigma_{\text{vm}}} = \frac{1}{3} l_1$$

$p = \frac{1}{3} l_1$ is hydrostatic stress

$\sigma_{\text{vm}} = \sqrt{3} J_2$ is von Mises equivalent stress

$\eta = +ve$ represents a tensile hydrostatic stress

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

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, $\theta_l$

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

- Or Lode parameter, $\xi$

$$\xi = \frac{3\sqrt{3}}{2} \left( \frac{J_3}{J_2^{3/2}} \right)$$
where $-1 \leq \xi \leq 1$

Fig. 15. A newly postulated 3D asymmetric fracture locus.
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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

Quarter Inch Sample
Time = 2.025
Contours of Triaxiality Factor (p/ρm)
reference shell surface
min=0, at elem# 12256
max=0.666433, at elem# 6107

Triaxiality: 2/3

Stationary Load – Lode Parameter

Quarter Inch Sample
Time = 2.025
Contours of Lode Parameter (-2(σ2+σ1+σ3)(σ2+σ1-σ3))
reference shell surface
min=-0.939813, at elem# 6107
max=0.997204, at elem# 418

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
Sliding Load:
Plastic Plane Strain Tension

Moving Load:
Leading Edge Triaxiality

Quarter Inch Sample
Time = 2.3
Contours of Triaxiality Factor (p/vm)
reference shell surface
min=-0.0140962, 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*sig2-sig1-sig3)/(sig1-sig3)
reference shell surface
min=-0.996064, at elem# 6129
max=0.996576, at elem# 1057

Triaxiality: $\frac{\sqrt{3}}{3}$
Lode Parameter: 0

Plastic Plane Stain Tension
Comparison with Solid Elements

**Quarter Inch Sample**

Time = 2.25

Contours of Lode Parameter: \(-2*(\sigma_2-\sigma_1-\sigma_3)/(\sigma_1-\sigma_3)\)

min = 0.997676, at elem = 3482979
max = 0.999851, at elem = 2299881

- 1,858,396 Ideally Shaped Solid Elements
- 67,071 Non-ideally Shaped Solid Elements
- 12,255 1:1:1 Shell Elements
Validatin: 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]

0 1 2 3 4 5

0 0.05 0.1 0.15 0.2 0.25
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, 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.
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Thank you

Questions?