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

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Layout

- 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:
        - Rodd (1996): Sled mounted 1/5th scale hull grillage impacting steel cone.
          - Fracture
        - 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
  - Numerical Prediction: sliding motion affects plastic hull response (Quinton 2008 and Alsos 2008)
    - 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?

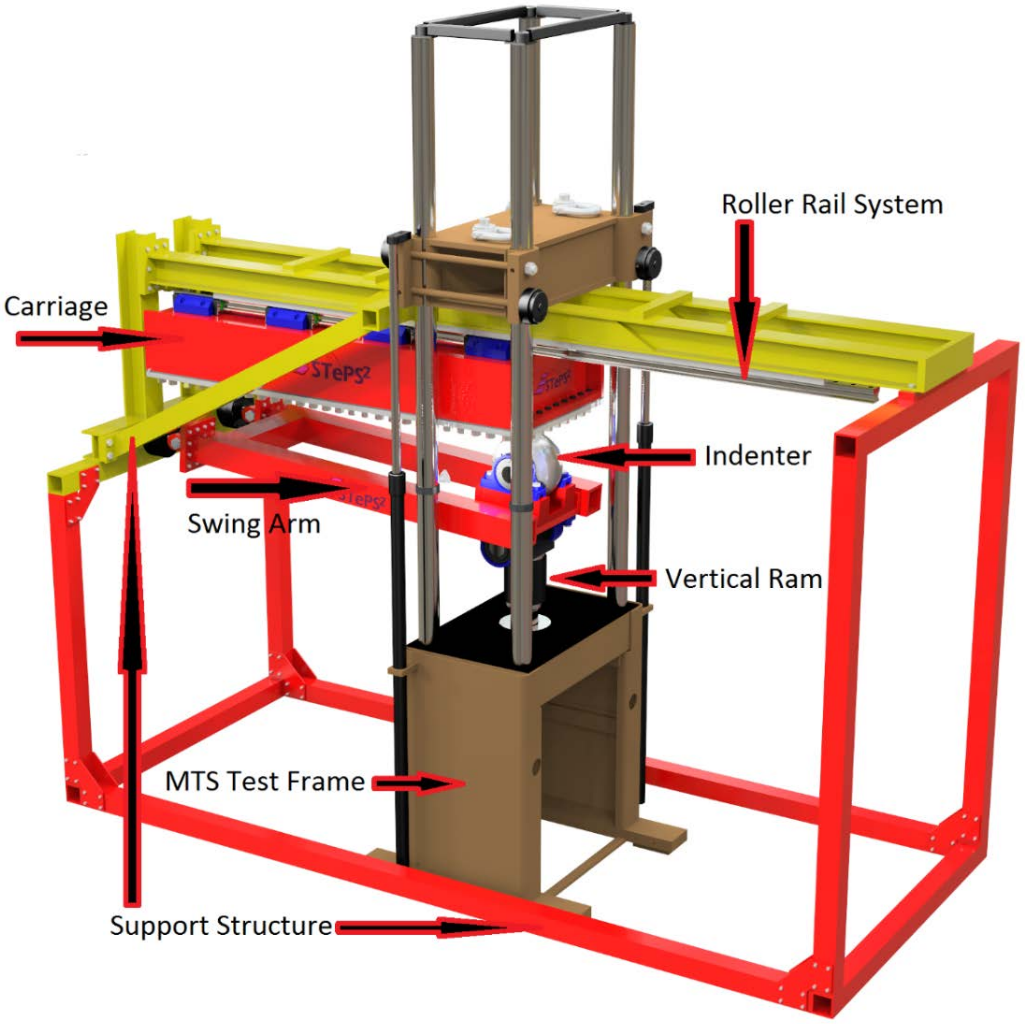
- Ship and offshore structure *design* ice loads are invariably stationary loads.
  - Most often *statically* applied, stationary loads.
  - *Real* ice loads often slide along the hull.

- 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.

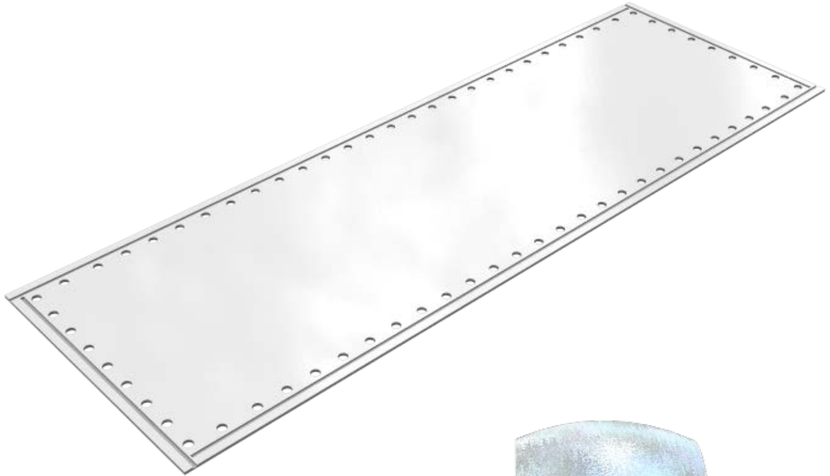
Quinton (2015) Experimental Confirmation: Effect of Sliding Loads on Hull Response

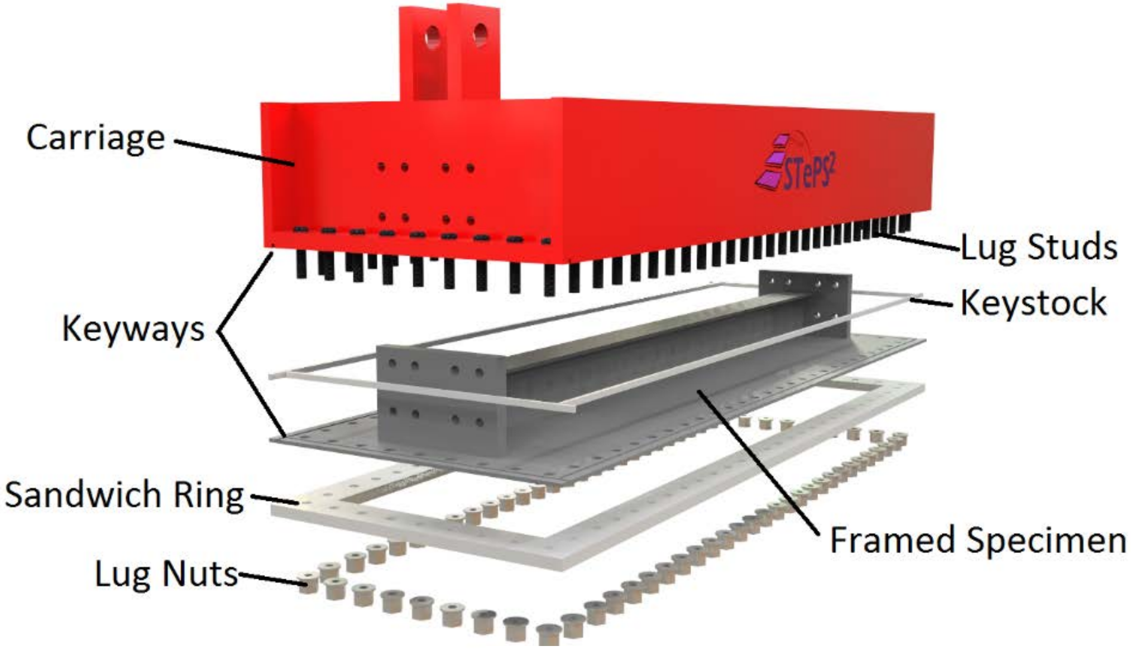
- MLA:
  - Steel plates or single frames subject to biaxial indentation.
    - Simultaneous or sequential "normal direction" indentation and "lateral direction" sliding.
  - It allowed variations in:
    - Indenter type
    - Ambient temperature
    - Loading rate (in both directions).

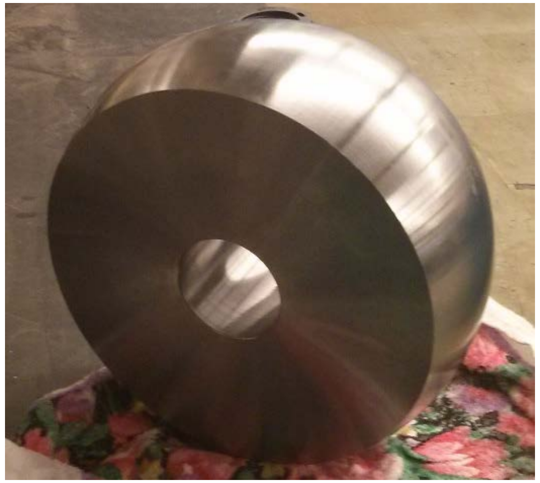
Moving Load Apparatus

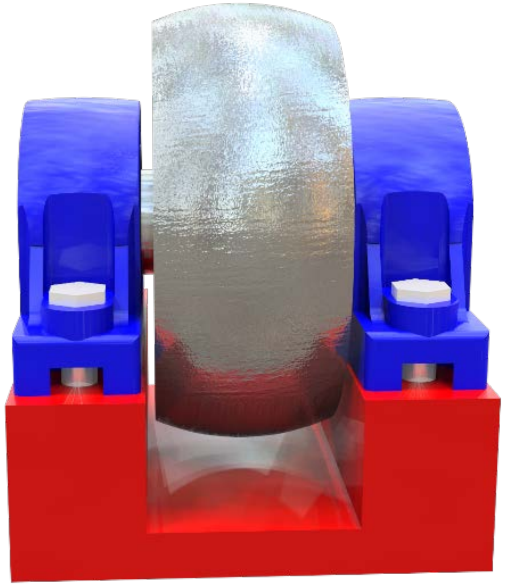


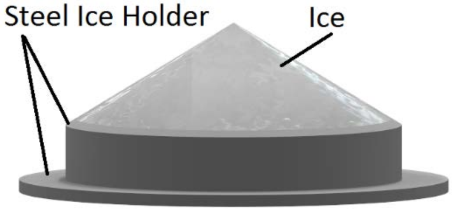
Steel Plates, Carriage, and Indenters

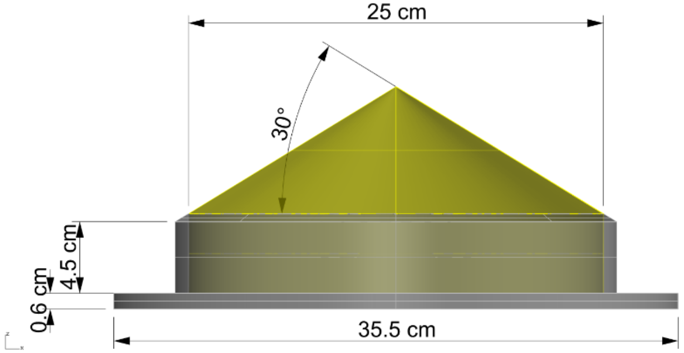












Apparatus & Test Specimen Particulars

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 useable
- Width: 0.55 m
  - 0.4 useable
- Thicknesses tested:
  - 6.35 mm
  - 12.7 mm

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

Load Details

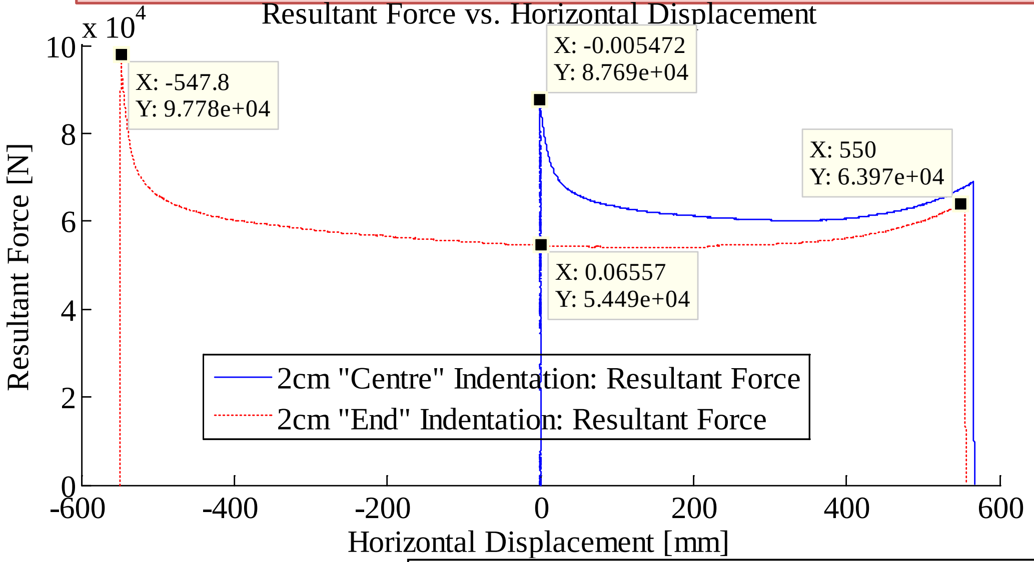
- Rigid Wheel Load Path - "In-Along-Out"
  - Simplest load path so that normal and lateral indentations were decoupled.
  - No friction
    - Except rolling friction between the steel wheel indenter and the plate.

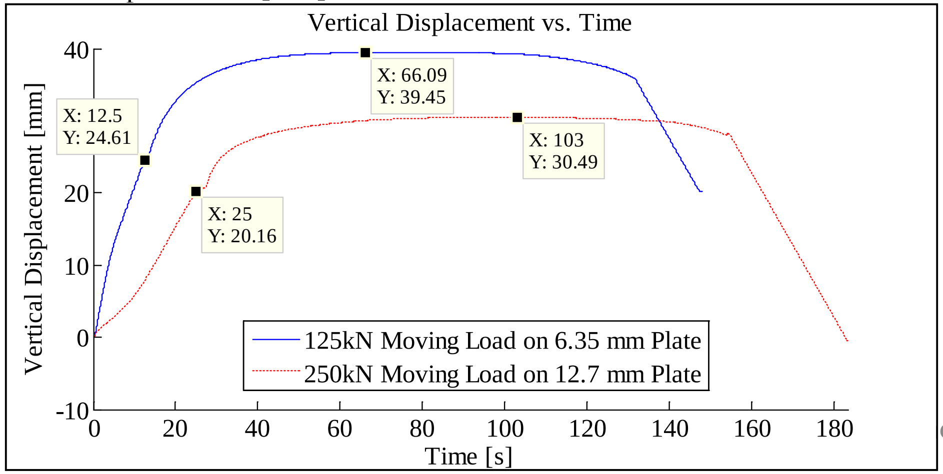
- Displacement control or force control.

- Lateral travel length was from the start position to beyond the +550 mm position (longitudinal direction).

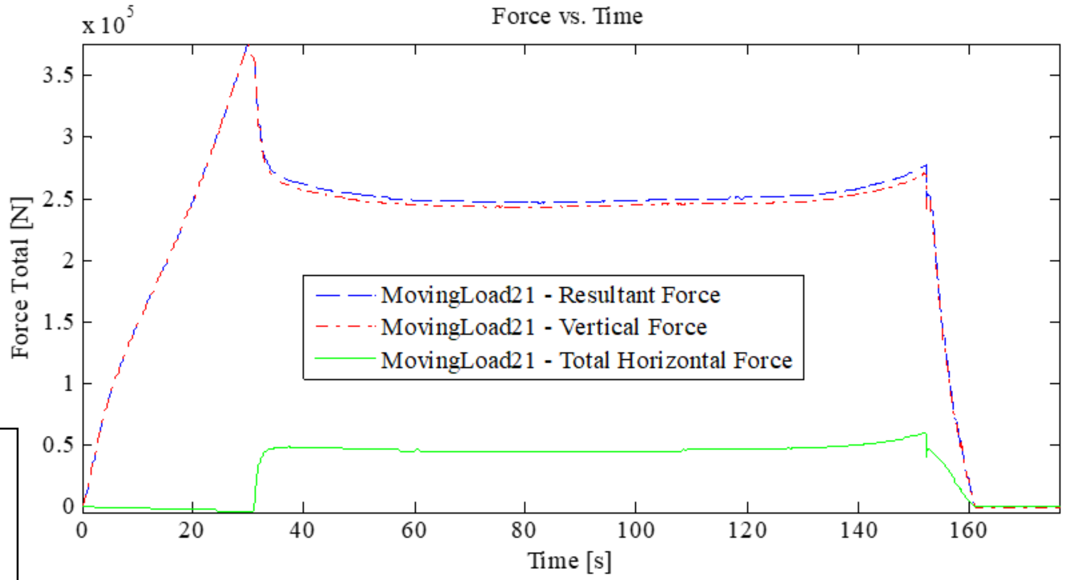
Experiments: Plate & Frame Response to Sliding Loads

Plates





Single Frame



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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, η

$$\eta = \frac{p}{\sigma_{vm}} = \frac{\frac{1}{3}I_1}{\sqrt{3J_2}}$$

$p = \frac{1}{3}I_1$ is hydrostatic stress

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

η = +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:

$$-1 \leq \eta_{solid} \leq 1$$

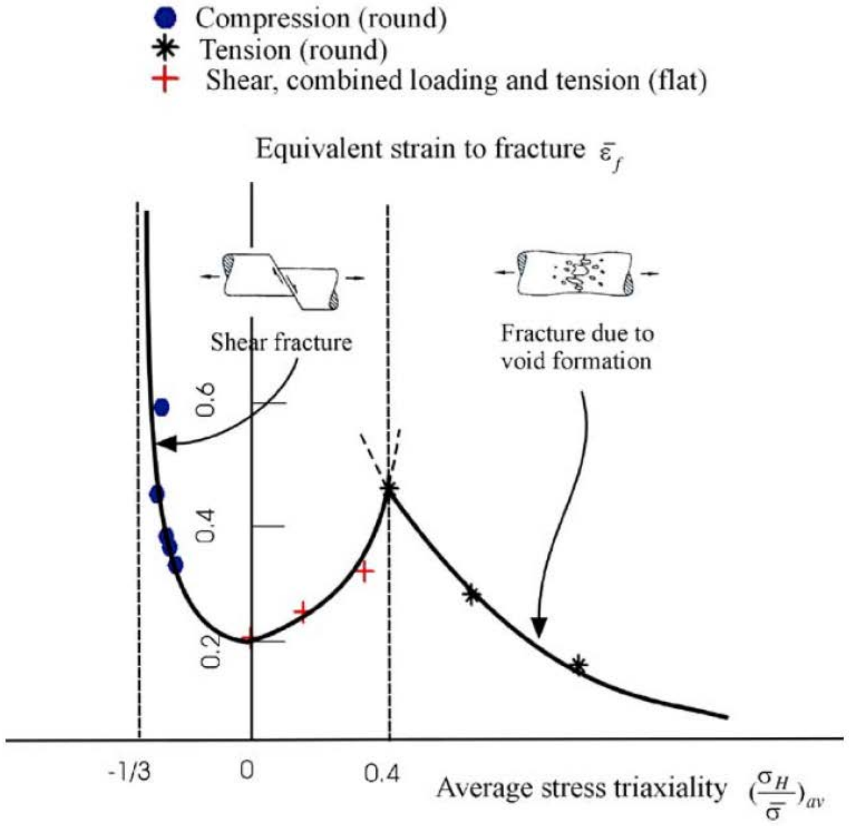

Fig. 20. Dependence of the equivalent strain to fracture on the stress triaxiality.

Figure reproduced from:
Bao & Wierzbicki, 2004. On fracture locus in the equivalent strain and stress triaxiality space. Int. Journal of Mech. Sci., vol. 46, pp. 81-98.

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, θ_l

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

for $0 \leq \theta_l \leq \frac{\pi}{3}$

- Or Lode parameter, ξ

$$\xi = \frac{3\sqrt{3}}{2}\left(\frac{J_3}{J_2^{\left(\frac{3}{2}\right)}}\right)$$

where $-1 \leq \xi \leq 1$

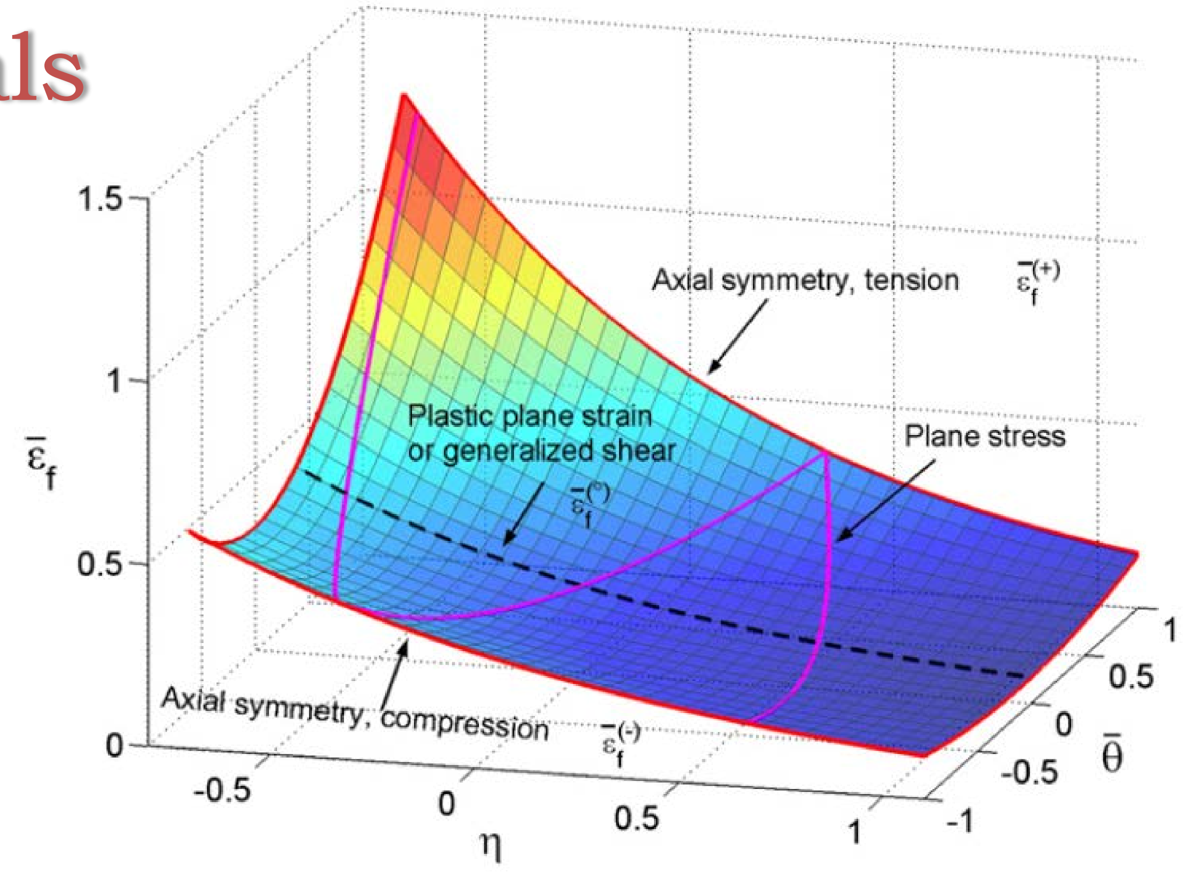

Fig. 15. A newly postulated 3D asymmetric fracture locus.

Figure reproduced from:
Bai & Wierzbicki, 2008. A new model of metal plasticity and fracture with pressure and Lode dependence. Int. Journal of Plasticity, vol. 24, pp 1071-1096.

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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

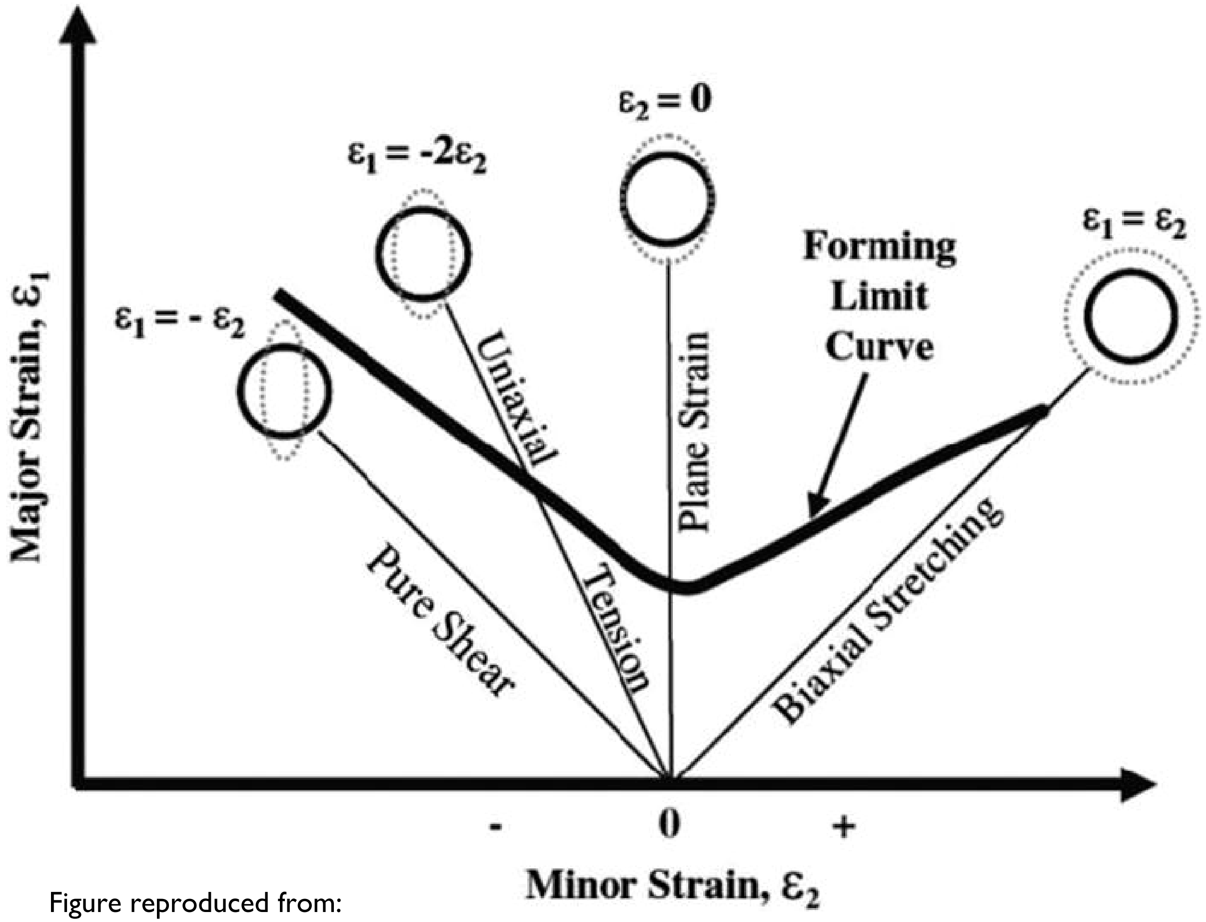
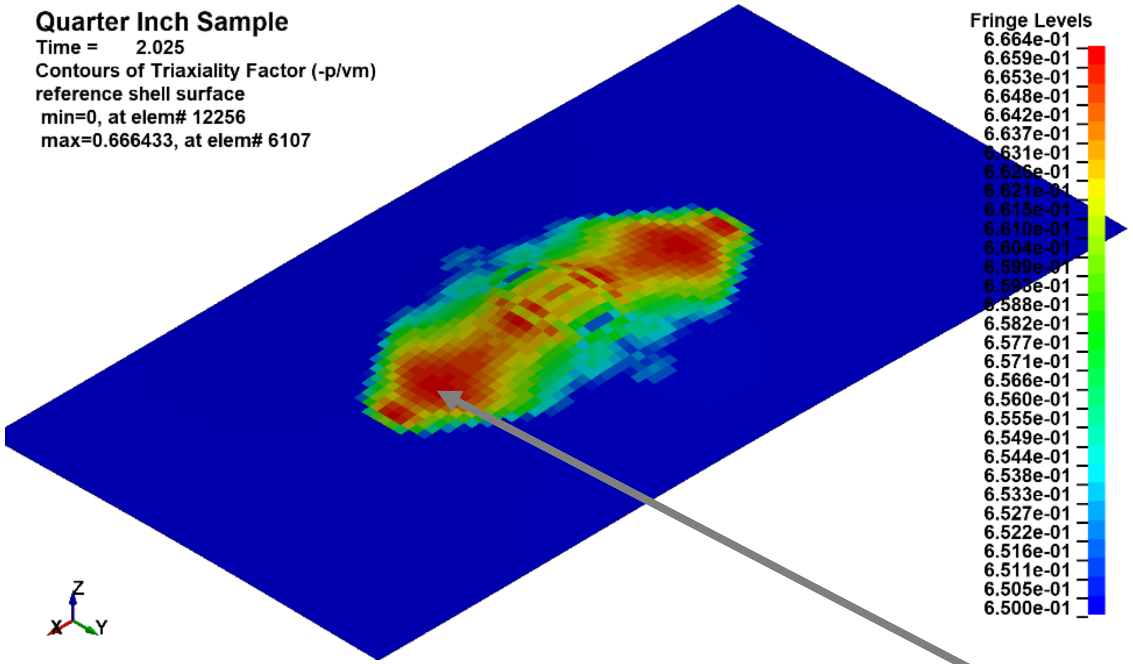


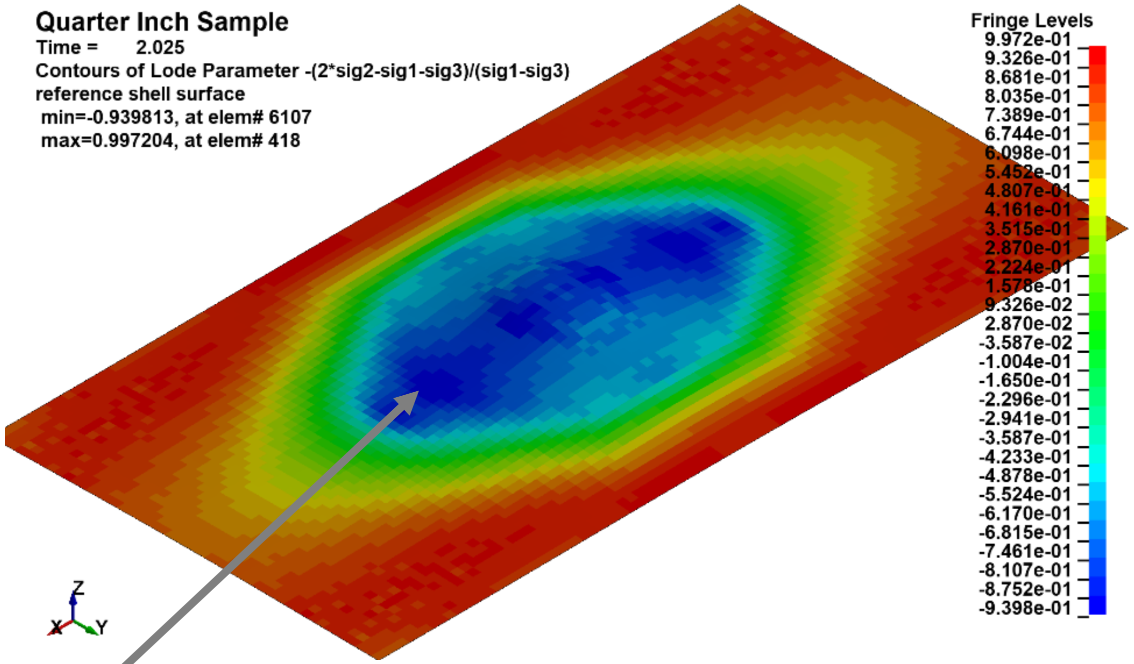
Figure reproduced from:
Hasan, RZ., Kinsey, BL., and Tsukrov, I., 2011. Effect of Element Types on Failure Prediction Using a Stress-Based Forming Limit Curve. J. Manuf. Sci. Eng 133(6).

Stationary Load: Equi-biaxial Plane Stress Tension

Stationary Load - Triaxiality



Stationary Load – Lode Parameter



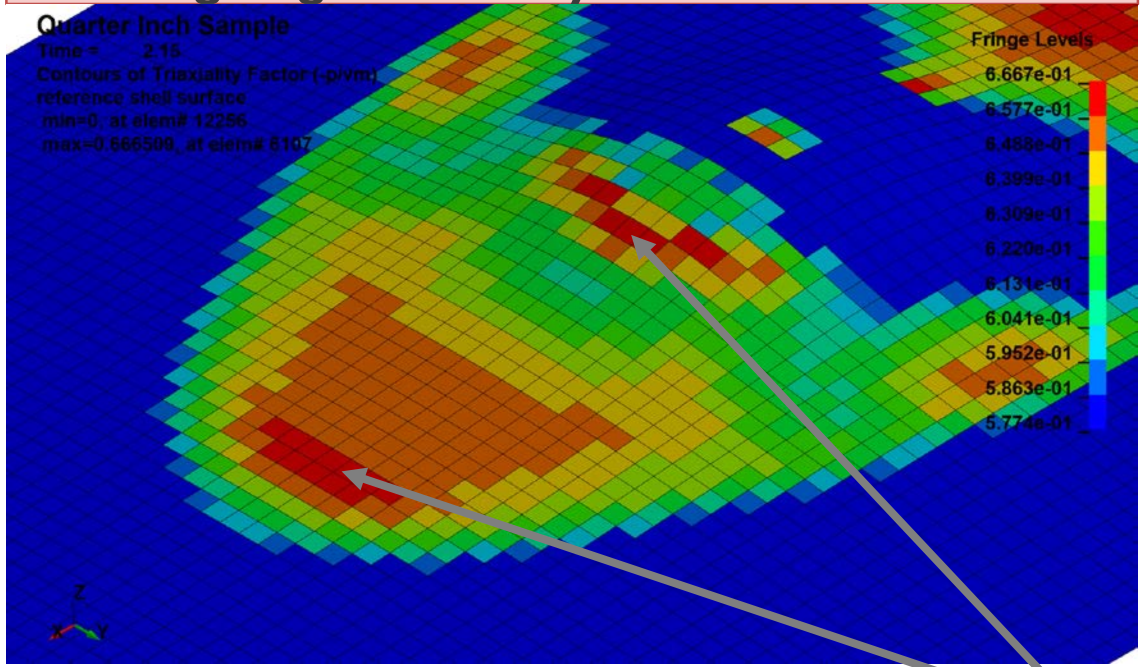
Triaxiality: 2/3

Equi-biaxial Plane Stress Tension

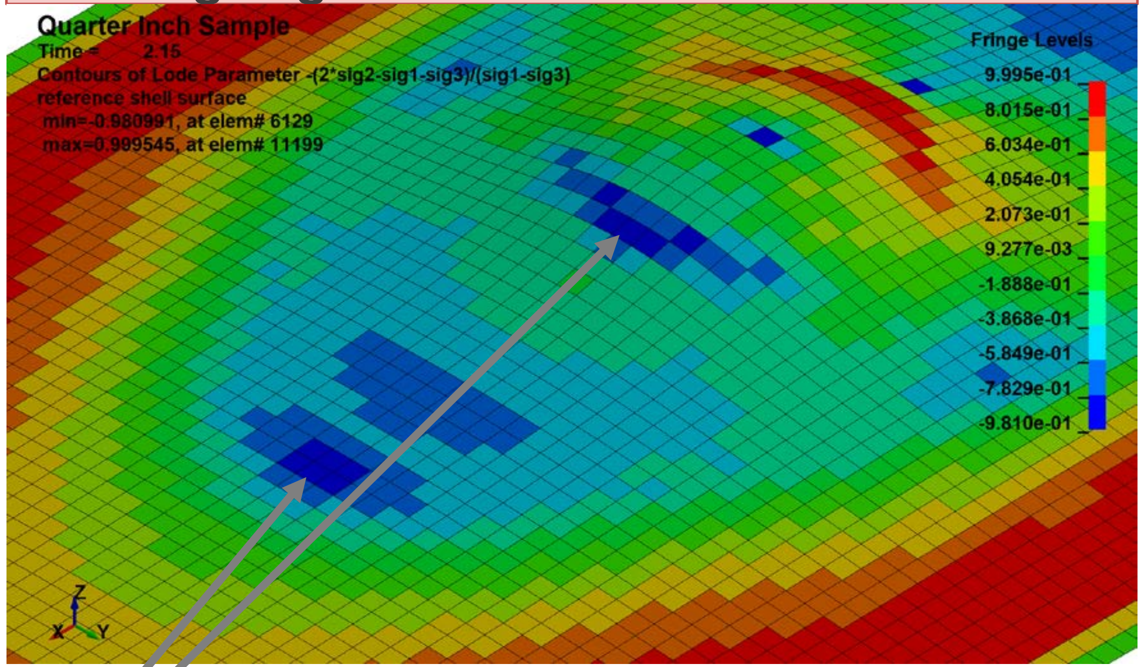
Lode Parameter: -1

Sliding Load:
Equi-biaxial Plane Stress Tension

Moving Load:
Leading Edge Triaxiality



Moving Load:
Leading Edge Lode Parameter

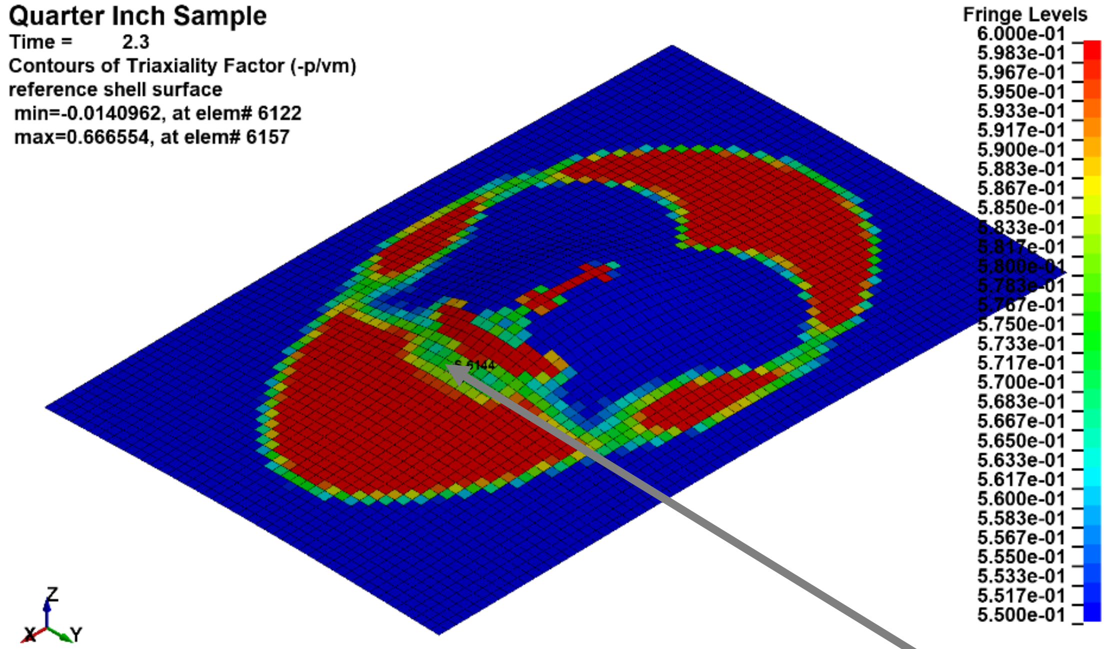


Triaxiality: 2/3
Lode Parameter: -1

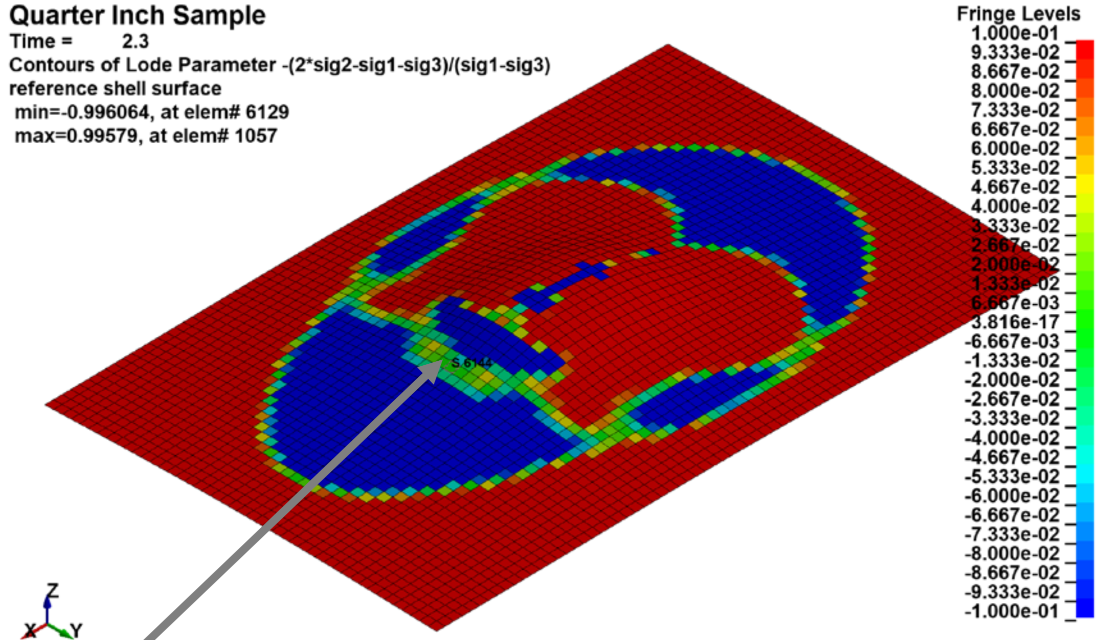
} Equibiaxial Plane Stress Tension

Sliding Load:
Plastic Plane Strain Tension

Moving Load:
Leading Edge Triaxiality



Moving Load:
Leading Edge Lode Parameter

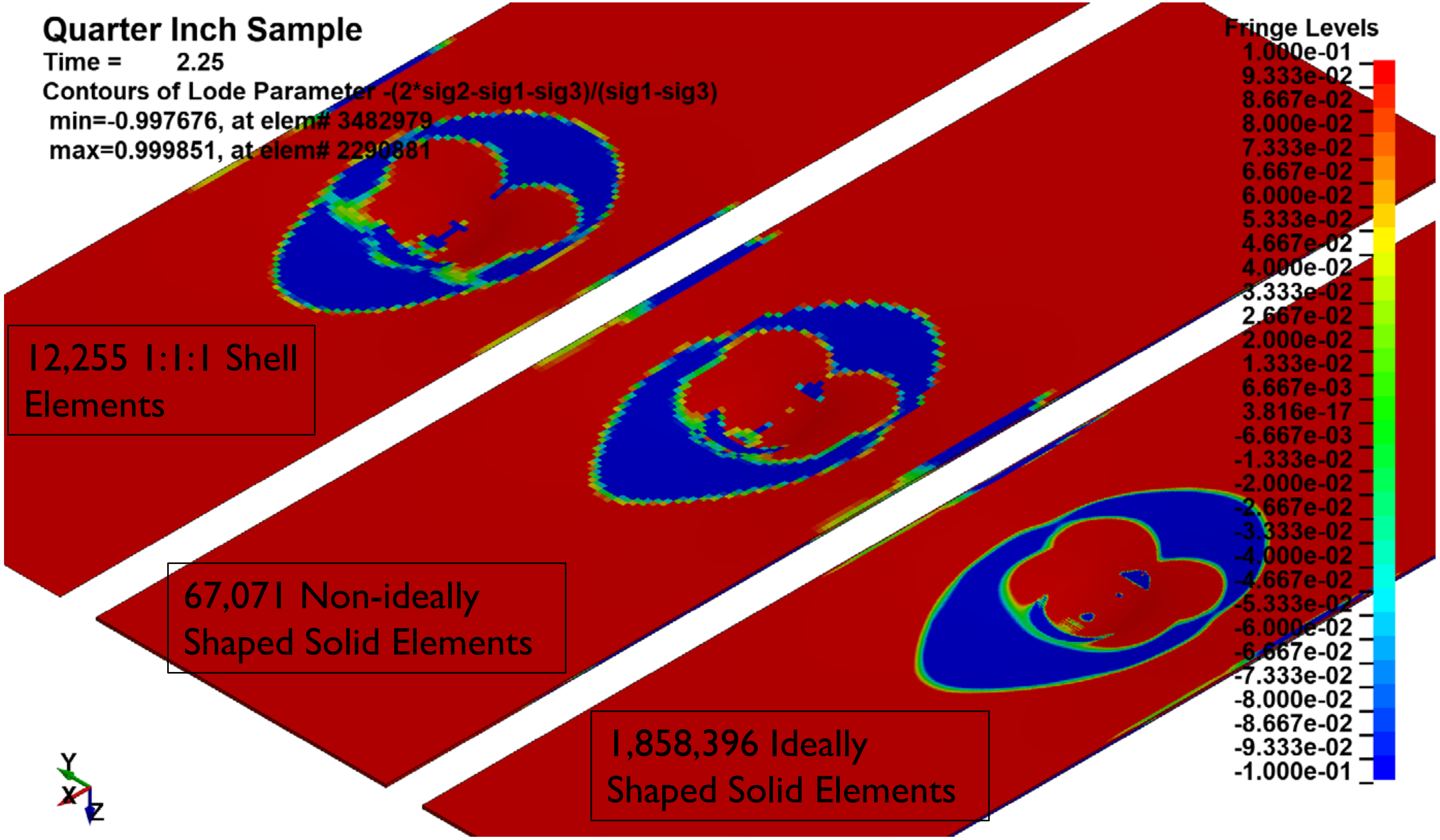


Triaxiality: $\frac{\sqrt{3}}{3}$

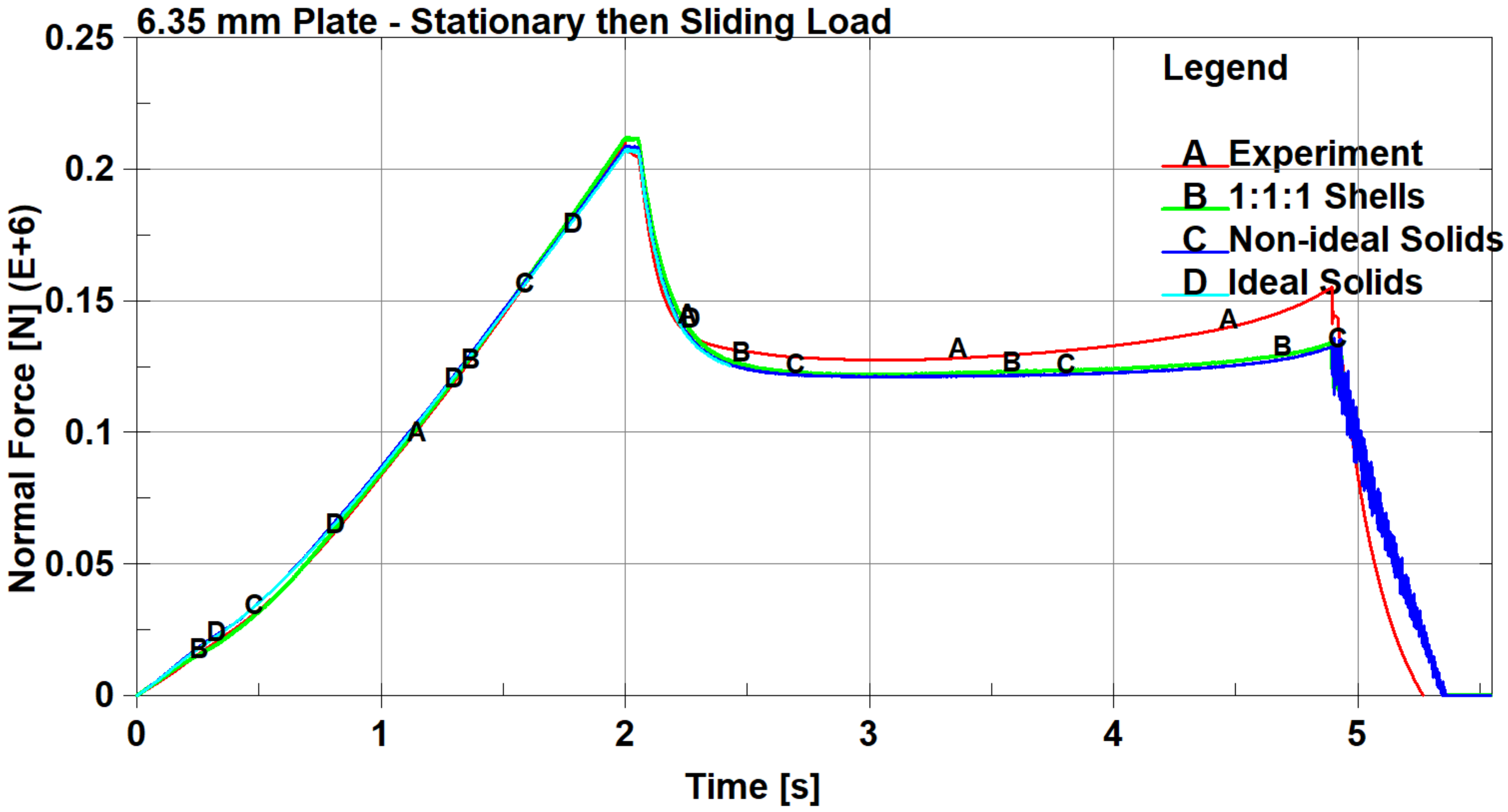
Lode Parameter: 0

} Plastic Plane Stain Tension

Comparison with Solid Elements



Validatin:
Comparison with Experiment



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

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    - BMT Fleet Technology Ltd.
    - Husky Energy
    - Rolls-Royce
    - Samsung Heavy Industries
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    - MITACS through their Accelerate program
    - Memorial University of Newfoundland's Offshore Technology Research – an NSERC CREATE program.

Thank you

Questions?