5. Plasticity and Fracture Prediction Under Nonlinear Loading

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Executive Summary:

- **Objective/Industrial Need**: The capability of quickly predicting macroscale properties based on microstructure evolution.
- **Approach**: Data-driven multiscale modeling using reduced order Self-consistent Clustering Analysis (SCA) [1000x faster in 3D sim.]
- **Deliverable**: Experimentally-validated simulation tools.
- **Budget and Timeline**: $500K for 3 years; supports 3 RAs (micro/meso-scale modeling, meso/macro-scale modeling, experimental characterization).
Industrial Needs and Relevance:

- Plasticity and fracture lead to failure of metallic material during processing and service
- High-fidelity simulation tools can:
  - Predict part’s behavior under nonlinear loading
  - Improve understanding of material’s properties
  - Reduce number of experiments and cost

Plasticity and Fracture Prediction Under Nonlinear Deformation Paths

Industrial Needs and Relevance:

Save development time and less iteration in product and process design

(a) Strain reversal in a punching process
(b) Edge crack of Advanced High-Strength Steel sheets
(c) Forming to crash simulation in car bodies
Project Objectives:

• Develop data compression and data analysis methods to accelerate computations
• Combine data processing techniques and multiscale simulation methods to establish a data-driven multiscale simulation framework
• Use such framework to reduce computational cost while keeping accuracy in modeling
• Extend this framework to plasticity and fracture prediction
• Under this common goal, the project objectives include, but are not limited to:
  1. Simulate different metal forming processes
  2. Predict macroscale properties based on microstructure evolution
  3. Increase computational efficiency by data-driven multiscale modeling
Approach/Methodologies:

The group has many technologies ready to use or in development stage. Selected technologies are listed below:

a) Multiresolution Continuum Theory (MCT)
b) Self-consistent Clustering Analysis (SCA)
c) Experiments for fracture calibration
Multi-resolution Continuum Theory

- Too expensive to model microstructure explicitly
- Captures size effects
- Mesh independent

- Low computational cost
- Captures only one scale
- Cannot capture size effects
- Mesh dependent

- Low computational cost
- Captures multiple scales of localization
- Captures size effects
- Mesh independent
Reduce Order Modeling by SCA

Offline or training stage (SCA)

1) Domain decomposition (k-means clustering): find material clusters.

- Strain concentration tensor is used for characterizing the responses:
  \( \varepsilon^{\text{micro}}(x) = A(x) : \varepsilon^{\text{macro}} \)

2) Compute the interaction tensors based on Green’s function

Online or predictive stage (SCA)

Self-consistent clustering analysis based on Lippman-Schwinger equation.

Computational time drastically reduced


Numerical modeling of ductile fracture mechanisms

• Remeshing algorithm
• Large plastic strain
• Ductile matrix

Void growth & coalescence

• Composite with brittle particles
• Cracks modeled with Level-Sets & remeshing
• Plastic localization and void coalescence

Particle debonding & fragmentation

Concurrent Simulation Based On SCA

- Same microscale SCA database is used for materials with hard and soft inclusions
- The SCA reduced order module is implemented as a VUMAT in ABAQUS under 2D plane strain condition.
Evolution of The Macroscale Effective Plastic Strain Field

Hard inclusions

Soft inclusions

Displacement $\Delta$ (mm)
Damage Parameter Comparison: 1-step vs. 3-step homogenization

One-step homogenization

Three-step homogenization

elastoplastic material without damage

Reference material without damage
- 1-step homogenization
- 3-step homogenization
SCA Concurrent simulation: Damage evolutions (Hard Inclusions)

- Hard inclusions help to carry the load and increase the overall stiffness. The damage initiation is sensitive to the shear loading.
Relation to A/SP Projects

- Numerical models developed here can be used as numerical experiments to simulate loading paths that are impossible or hard to obtain in physical tests
- Provide more realistic deformation mechanisms at the microstructure level
- Use microstructure and fracture data already generated from A/SP projects as a starting point to build up and validate the multi-scale model
Experimental Characterization

– Microstructure characterization
– Tests for determining fracture models
– In-situ damage evolution using ANL facilities

Proposed testing efforts under monotonic and multiaxial loadings

Most tests can be done in one universal testing machine.
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Deliverables:

• An experimentally-verified computational platform for evaluating fracture and material damage of advanced materials while incorporating micromechanical effects with macrostructural models.

• A multiscale software interface and integration tool for fracture prediction in existing commercial CAE tools (e.g., ABAQUS, LS-DYNA), with documentation

• Training and consulting services for new software interface.
5. Plasticity and Fracture Prediction Under Nonlinear Deformation Paths

Budget and Timeline:

Estimated cost of the project is $500K for three years, including 3RAs and experimentation cost.

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<th>Task / Milestone</th>
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Discussions:

– Are the industrial need and relevance accurately captured?
– Are the objectives realistic and complete?
– Are the approaches technically sound and appropriate?
– Are there alternative implementation paths or better approaches?
– Are the deliverables impactful to industrial partners?
– Are the budget and timeline reasonable?
– Are there conflicts with intellectual property or trade secrets?
– List additional project specific questions are appropriate.