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X-Prize:
A Double Blind Benchmark Assessment of Failure Modeling Methodologies

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

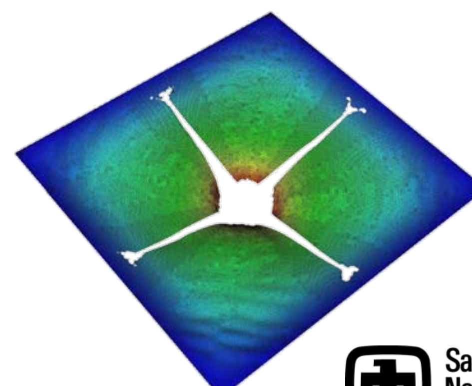
The X-Prize Concept and Goal

- Get the competitive and corporative juices flowing
  - It is a ***co-opetition***, according to Brad Boyce.

- Benchmark Sandia's current capability to model ***ductile failure*** including constitutive models, computational methods, and mesh convergence.

- Several X-Prize competitions have occurred
  - ***Revolution through Competition***
  - Dating back to 1919 for navigation
  - The current "hot" one is the Google Lunar X-Prize
    - » $30M prize; 29 teams; robot to moon

- Ductile Fracture X-Prize
  - ***Revelation through Co-opetition***
  - Stepping through a progressive series of increasingly complex prediction challenges



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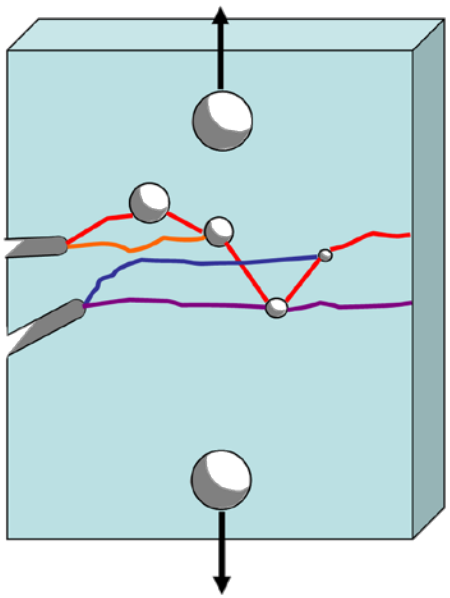
Four Teams to Represent the Breadth of Sandia's Failure Modeling Approaches

Paradigm	Key Modeling Attributes
FEM with Tearing Parameter	• An equivalent plastic strain evolution integral incorporating effects of stress triaxiality • Critical crack opening strength
Localization Elements	• Finite element surfaces governed by traction-separation law to permit 'debonding' of element interfaces • BCJ damage model with Cocks-Ashby void growth
Peridynamics	• Bond-node based meshless method, particularly suitable for discontinuous displacement fields • Critical stretch
Extended Finite Element (XFEM)	• Crack-like asymptotic displacement fields and discontinuities embedded in the finite element approximation. • No explicit meshing of crack surfaces is needed. • Maximum principal stress; equivalent plastic strain; …

Specimen Design Principles

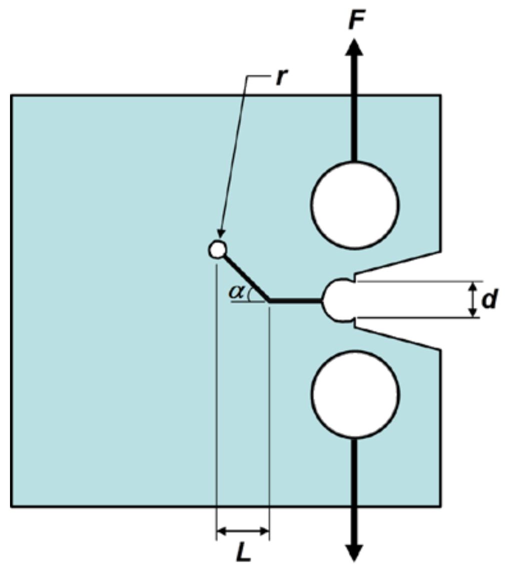
- No intuitively obvious or closed-form solution
- Single, unambiguous, repeatable solution
- No stress-gradients or unusual surface conditions
- Quick, cheap and easy to manufacture in a wide range of materials with reasonable manufacturing tolerances
- No buckling or other unwanted deformation modes



"Crack-in-a-maze" Concept

Three challenge puzzles were designed and used.

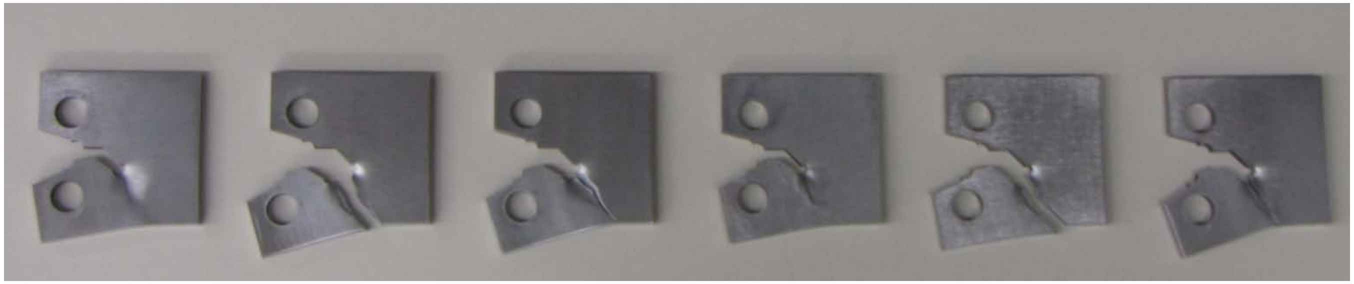
The 1st Challenge is about Predicting Conditions of Crack Initiation



Specimen Thickness 0.125”

For a specimen as shown on the left, made from alloy PH13-8 H950 (precipitation hardened stainless steel):

- What is the ***load-line displacement Δd***, needed to induce crack initiation?
- What is the ***peak force F*** applied to the sample prior to crack initiation?



Two test labs & several repeats builds confidence in experimental results

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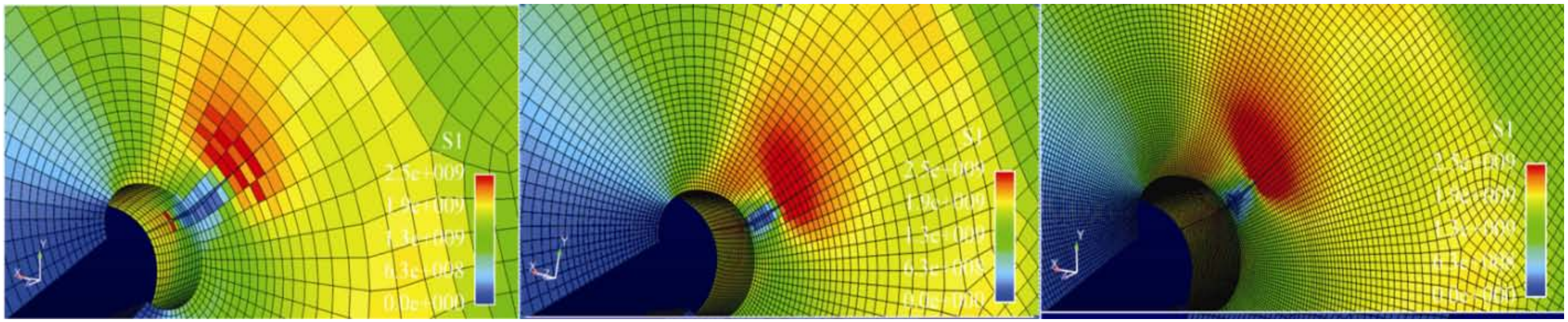
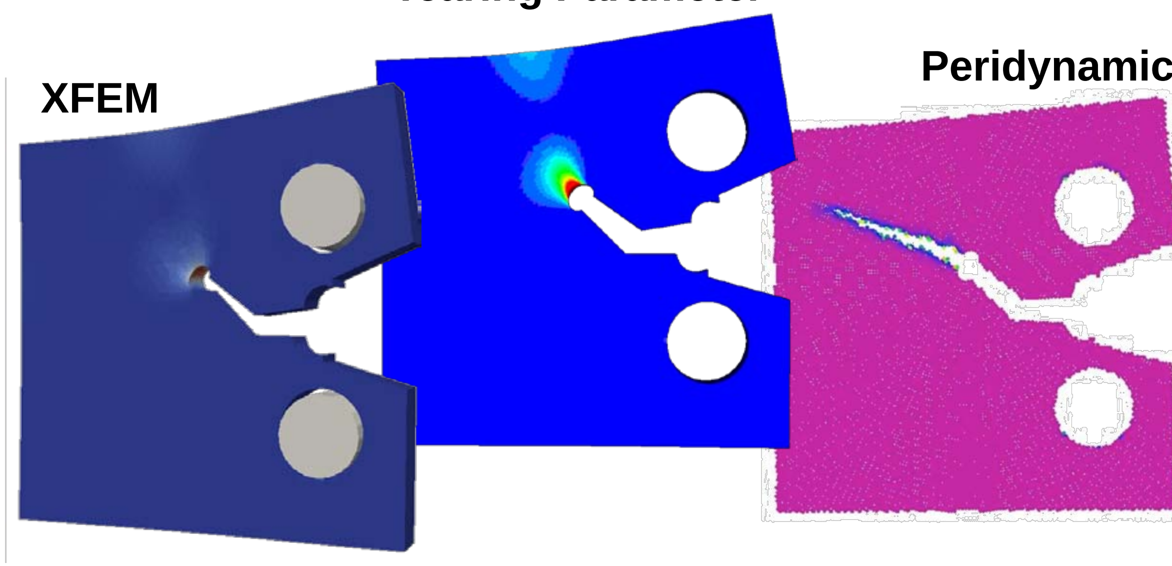
All Four Team Provided Predictions to the 1st Challenge



Localization Element, showing convergence



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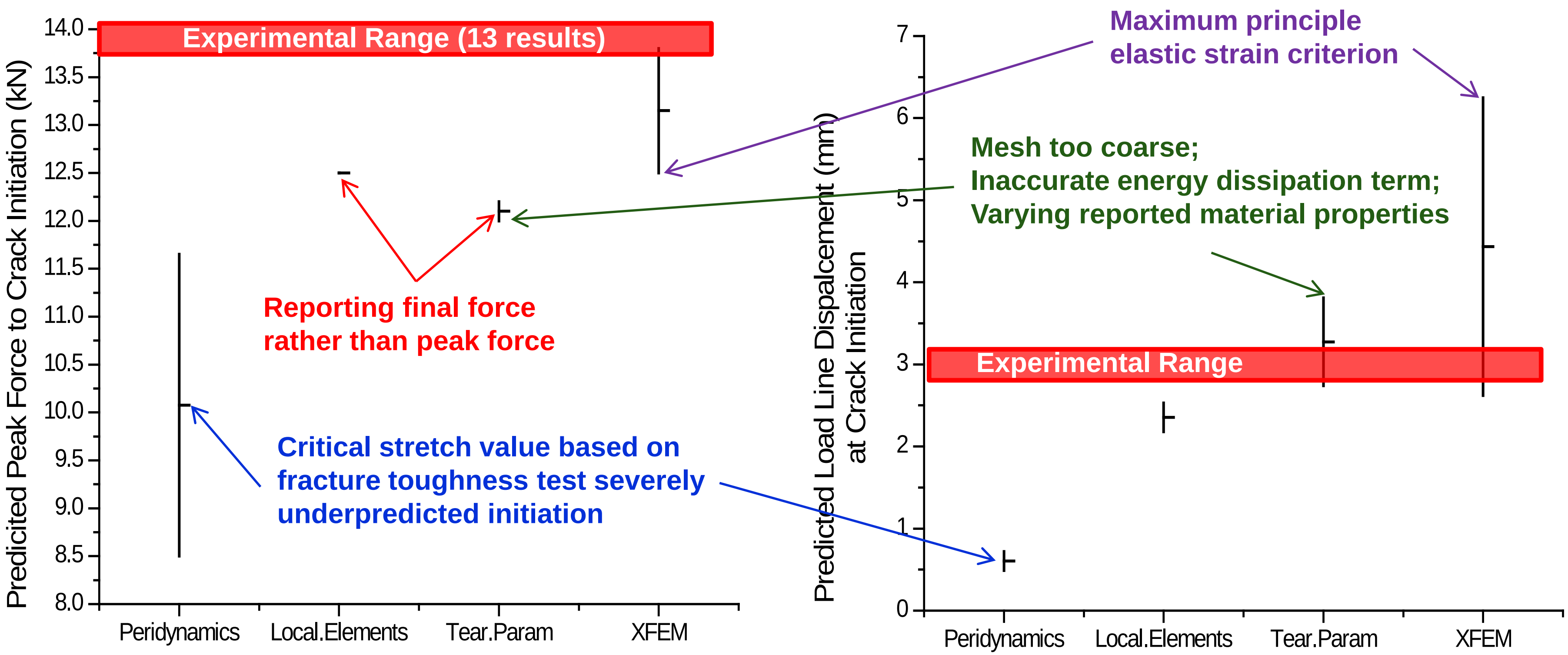
All 4 Teams Underpredicted the Force of Crack Initiation but Some Nailed Displacement



Diagnosis of sources of error revealed many pitfalls

- Physics (e.g. constitutive model; failure criteria)
- Numerics (e.g. physics implementation; mesh resolution)
- Boundary conditions
- Human errors (e.g. misinterpretation of question or results)

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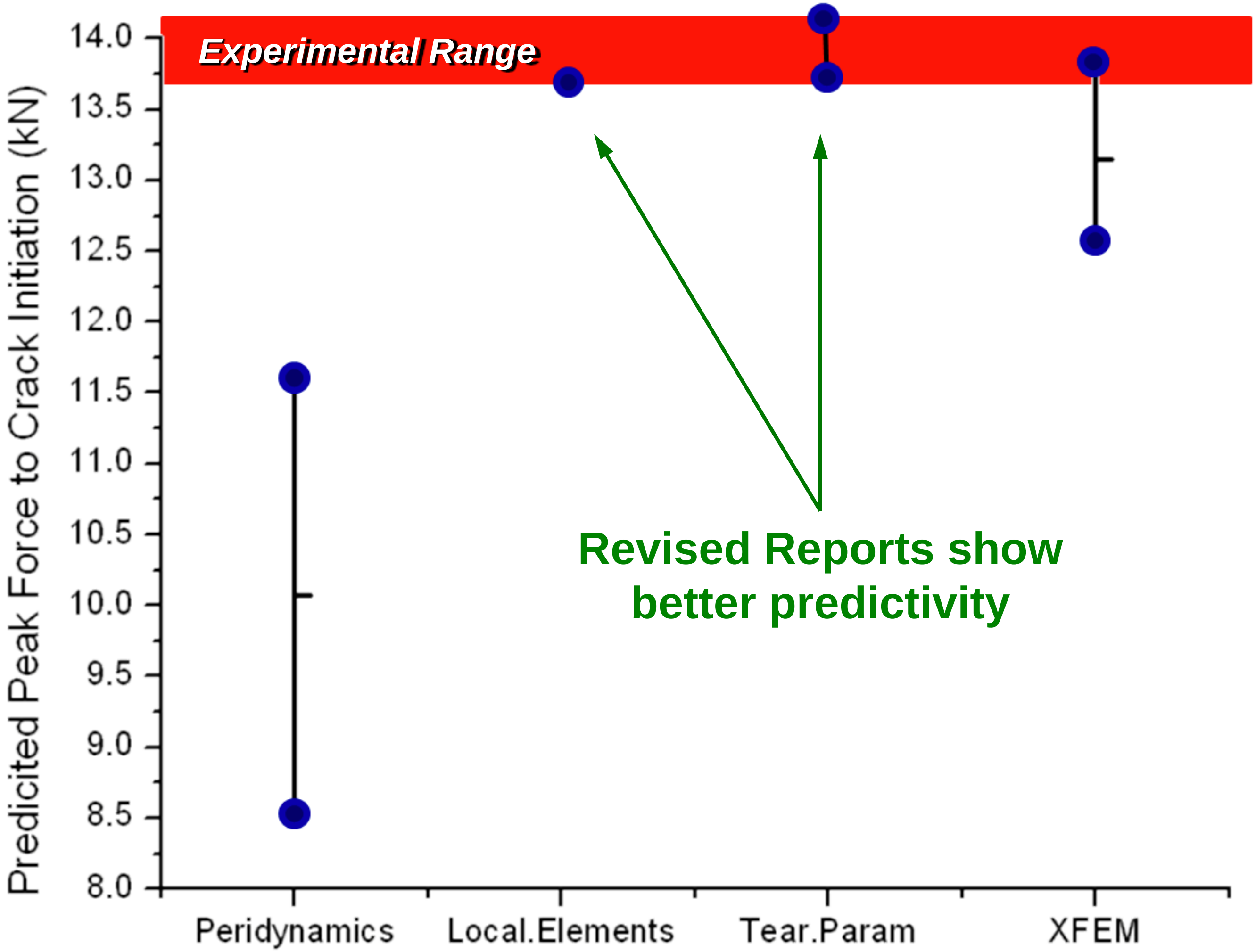
Revised Prediction of the 1st Challenge after 2 Teams Remedied Their Reporting Errors



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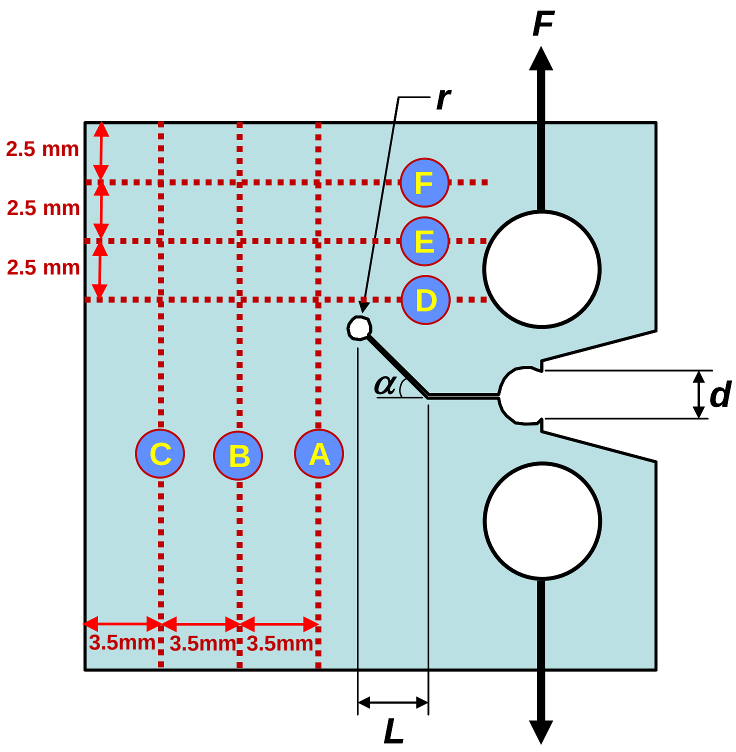
The 2nd Challenge is to Benchmark Crack Propagation Prediction

For a specimen as shown on the right, made from aluminum alloy 2024-T3

- **What is the *load-line displacement* Δd and the *peak force* prior to crack initiation?**
- **What is the *order of crack propagation* (e.g. A-B-D-C, etc.)?**
- **What is the *force* and *displacement* at which the crack reaches the 1st line?**
- **What is the *force* (kN) and load-line *displacement* (mm) at which the crack reaches line E?**



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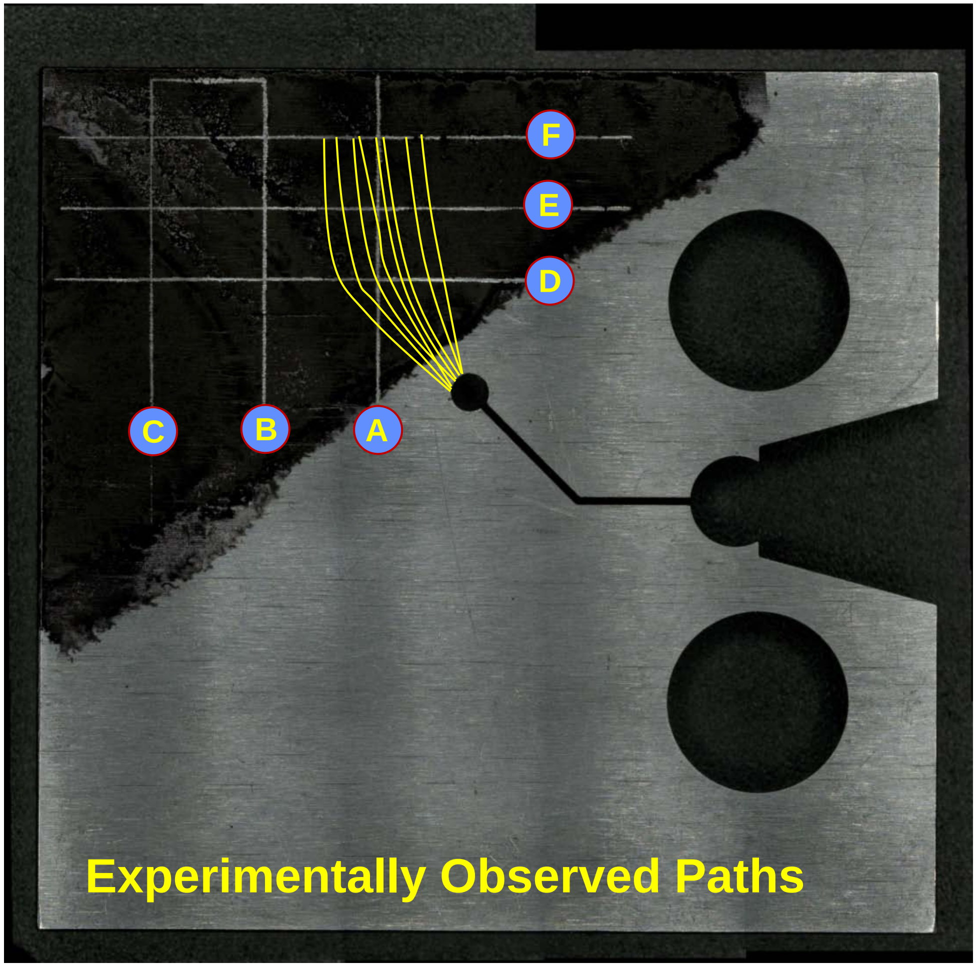
2nd Challenge Results



Predicted Path:

Localization Elements	D-A-E-F-B
Peridynamics	D-E-A-F or D-E-F-A
Tearing Parameter	D-E-F-(A?)
X-FEM Abaqus	D-E-A-F or D-E-F-A
X-FEM Sierra	A-B-C

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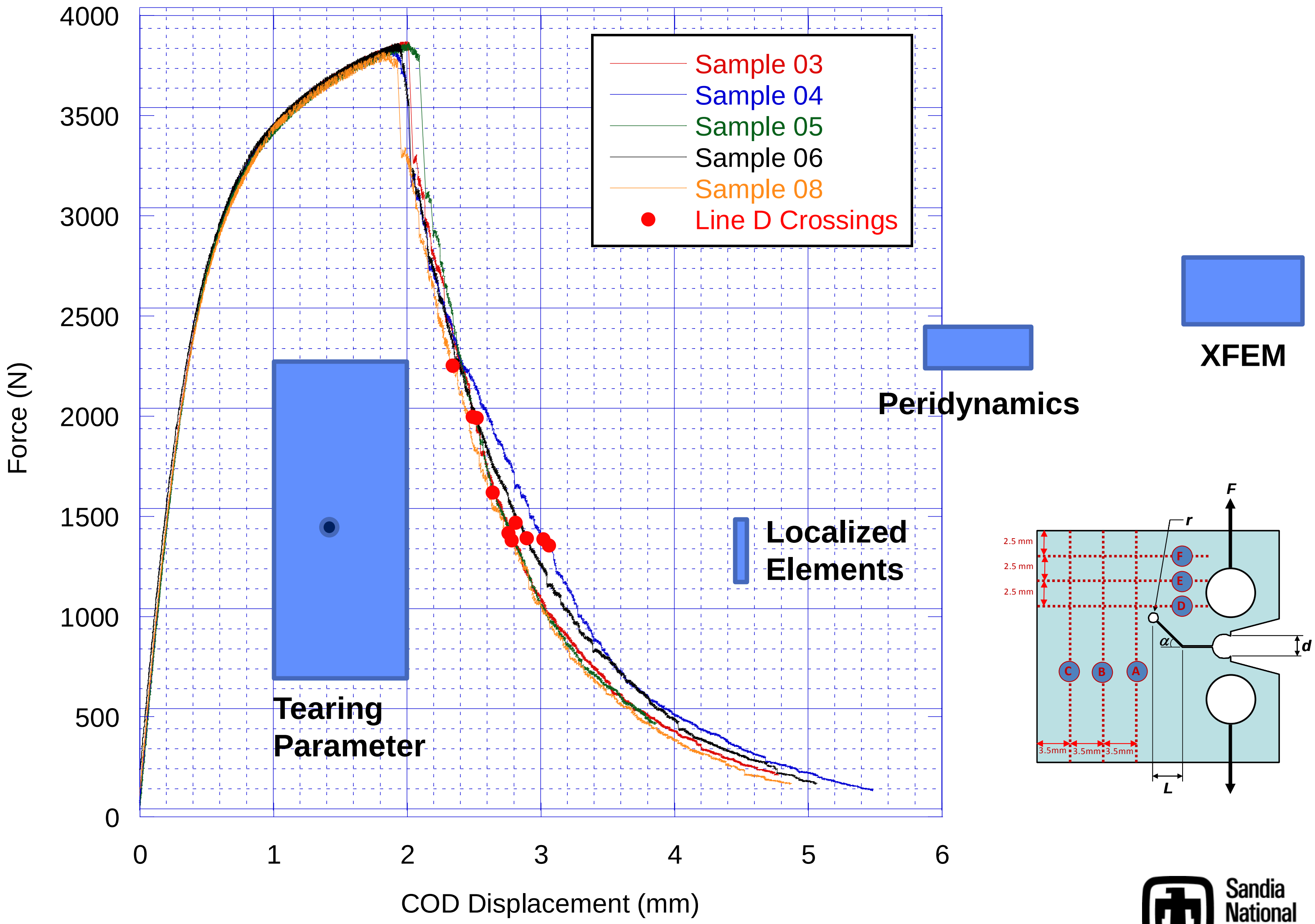
2nd Challenge Results: Prediction of Force-COD as the Crack Cross Line D



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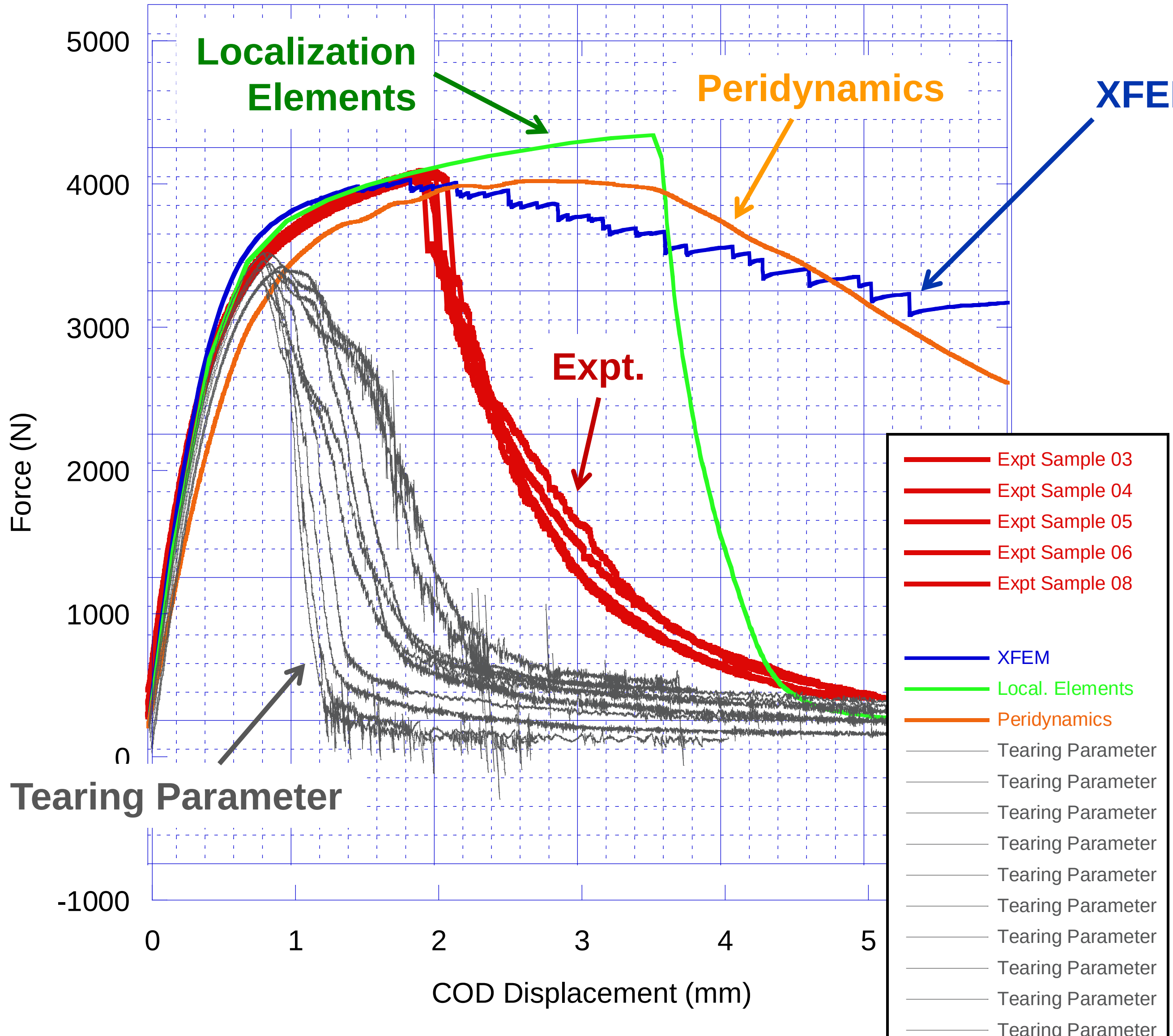
2nd Challenge Results: Force-Deflection Curves



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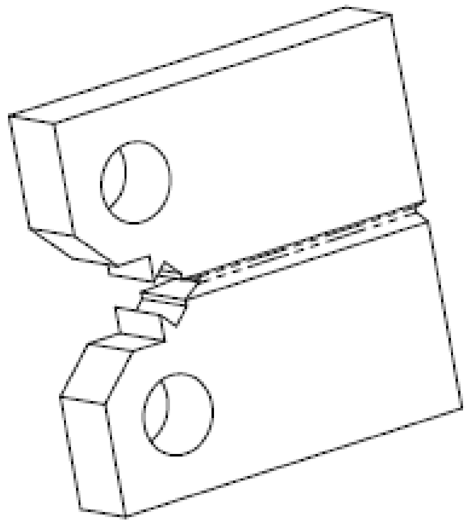
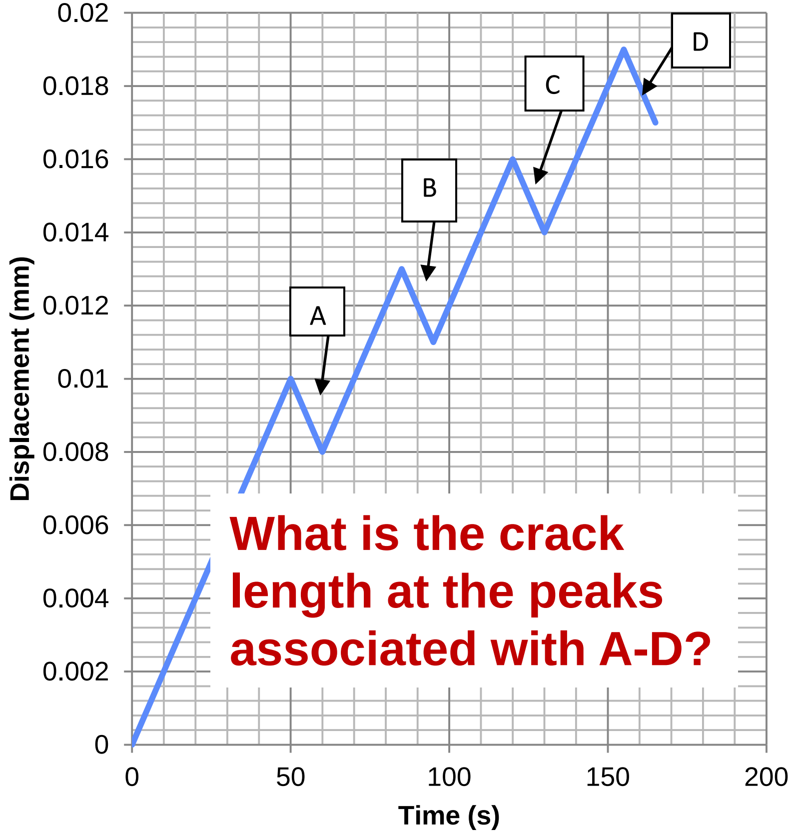
The 3rd Challenge is to Evaluate Capability of Predicting Fatigue Cracking

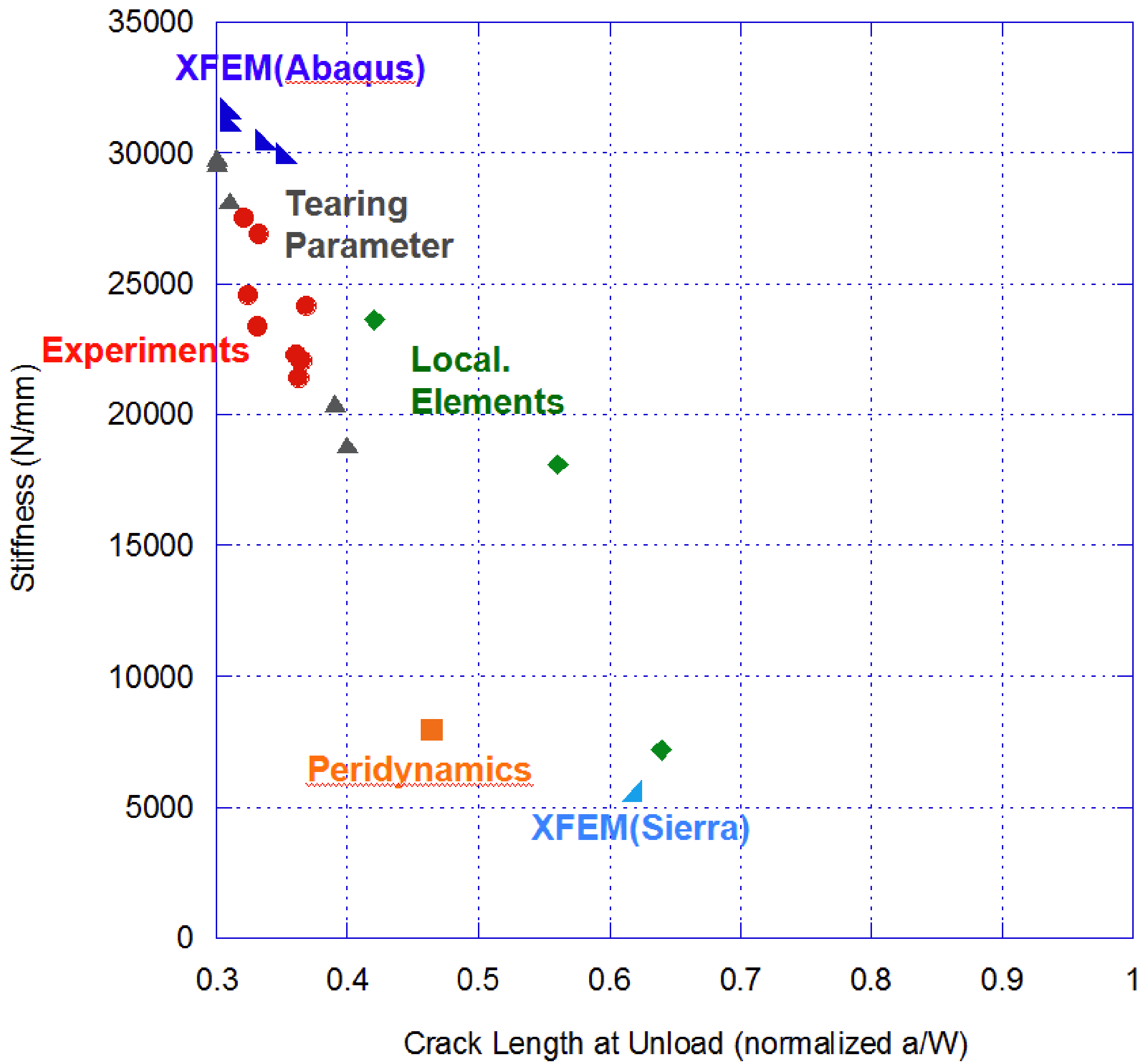




3rd Challenge Specimen

- **2024-T3** aluminum alloy
- Thickness 0.25" (double from previous)
- Straight pure Mode I notch
- Mode I fatigue pre-crack, per ASTM E399
- Deep V-groove on both sides to ensure Mode I crack path

3^{rd} Challenge Result: Stiffness and Crack Length at Unload "A"



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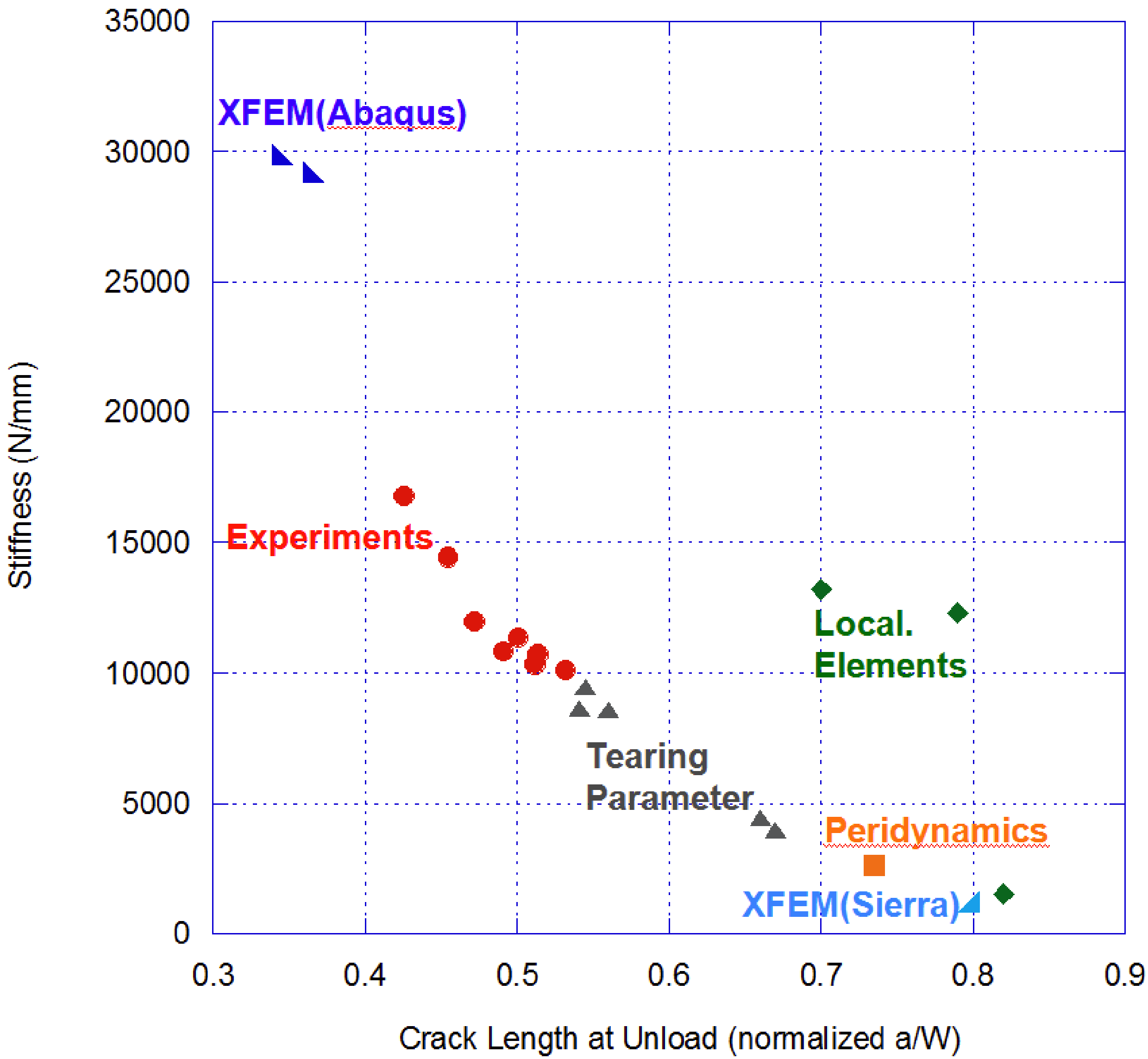
3rd Challenge Result: Stiffness and Crack Length at Unload "C"



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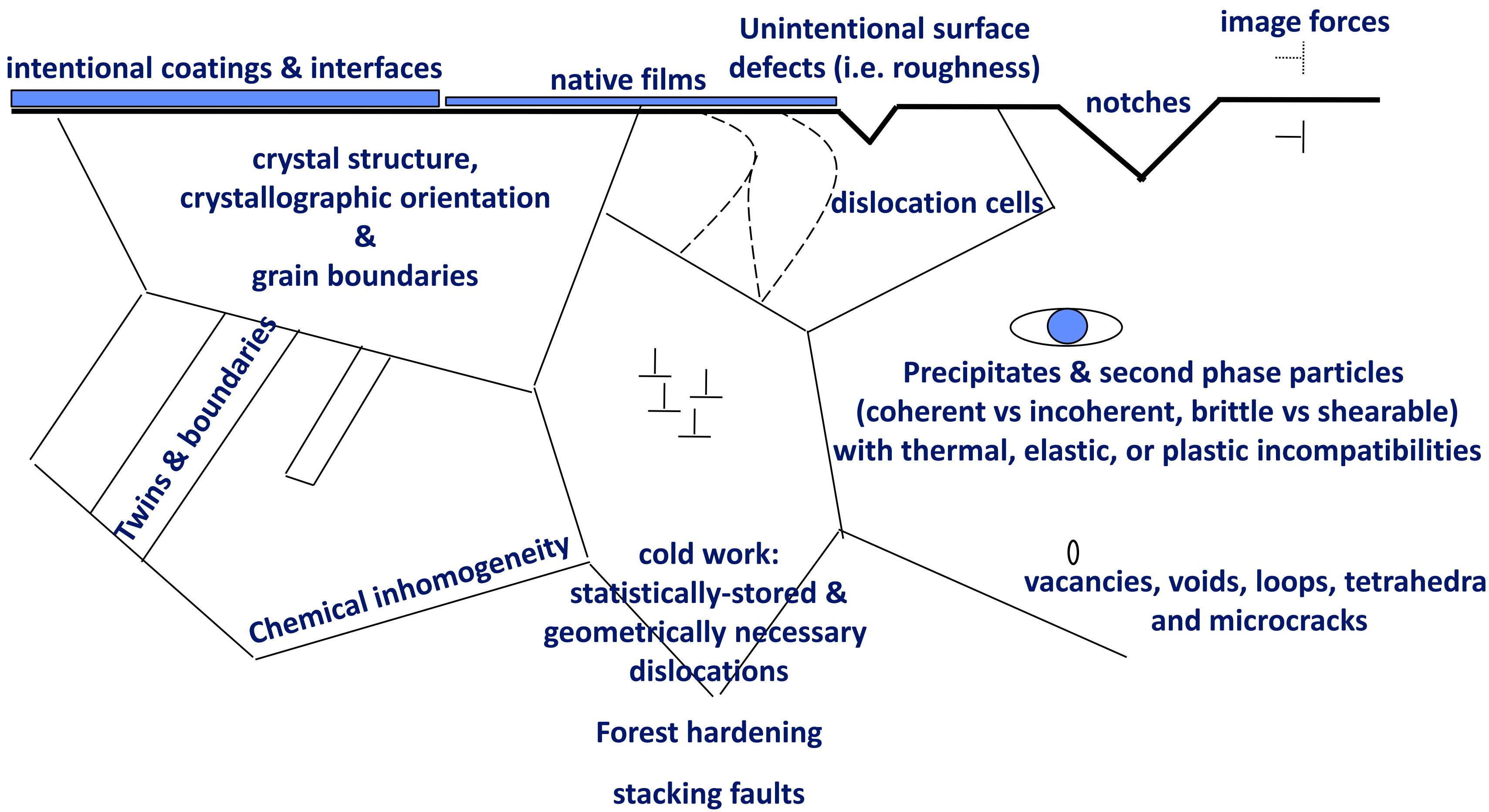
Summary

- Predicting ductile failure initiation and crack propagation remains an extremely difficult problem.
- Wide variation in simulation results suggest our methods are not yet predictive.
- The 4 modeling approaches have different levels of maturity.
  - The X-Prize effort quantifies the current state-of-performance, not the potential for future improvement.
- Although engineering drawings were provided, none of the teams used machining tolerance to bound their prediction uncertainties.
  - No guidance on UQ was given.
  - Everybody has different ideas / approaches to do UQ.
- 6061-T6 is a preferred X-Prize material, but it gives inconsistent test results.
  - Predicting crack propagation is also a BIG challenge to material scientists.

Physics (Micromechanics) of Ductile Failure Is Extremely Complicated



The relative importance of each of these factors varies from material to material