# APPLICATION OF COMPOSITE FRACTURE MECHANICS TO BONE FRACTURE ANALYSIS USING ABAQUS XFEM

Presenter: David Reid

*Dassault Systemes UK Ltd – SIMULIA*

*david.reid@3ds.com – 01925 885971 – 07825 308031*

Work by: Xiaoliang Qin; Xiangyi (Cheryl) Liu; Zhenzhong Du

*Dassault Systemes Simulia Corp, Providence/Rhode Island, USA*

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# Introduction

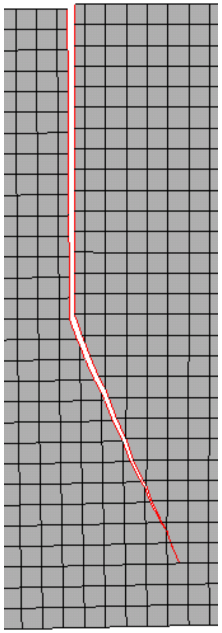
***Bone Fracture***

- **Predicting and preventing bone fractures is an important topic in orthopedics**
  - High rate of incidences
    - e.g.: 1.66 million hip fracture world-wide in 1990
  - Result in serious complications
    - e.g.: infections and nonunion
  - The impact is more severe for elderly
    - Loss of mobility and independence
    - Blood clots may develop
  - Understanding the fracture behavior of bone will help researchers find proper bone strengthening treatment
    - To prevent such traumatic failure

# Introduction

*Abaqus XFEM*

- **Finite element analysis has been instrumental in understanding various aspects of bone mechanics**
- **Modelling bone fracture had been difficult with traditional FEA**
  - The crack propagation path had to be defined before the analysis
  - The finite element mesh had to conform to geometric discontinuities
- **Abaqus introduced eXtented Finite Element Method (XFEM) from version 6.9**
  - Permits a crack to be located in the element interior
  - The crack location is independent of the mesh
  - Simulate initiation and propagation of a discrete crack along an arbitrary, solution-dependent path without the requirement of remeshing in the bulk materials



# Introduction

## *Abaqus XFEM*

- **Damage initiation criteria**
  - Built-in criteria
    - Maximum principal stress
    - Maximum principal strain
    - Maximum nominal stress
    - Maximum nominal strain
    - Quadratic nominal stress
    - Quadratic nominal strain
  - User-defined damage initiation criterion (available in 6.10EF)
    - Provides users with access to the damage initiation criterion and the direction of the crack propagation
    - Allows the specification of competing failure mechanisms
      - Multiple crack initiation mechanisms in composite material
    - Great tool to study bone fracture properties
      - Which failure criterion best predicts when a crack will initiate





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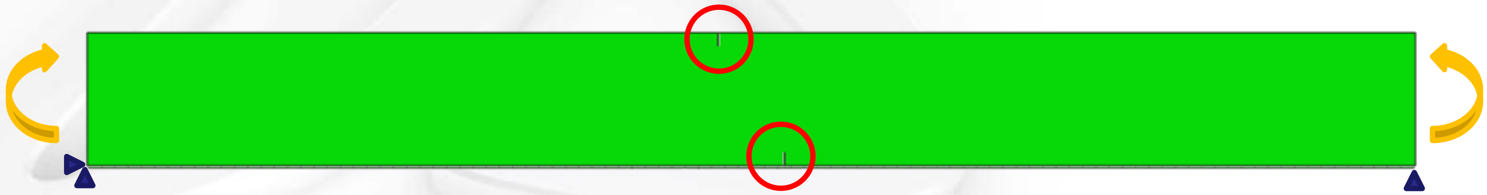
# Methods

*Example 1: Beam Bending*

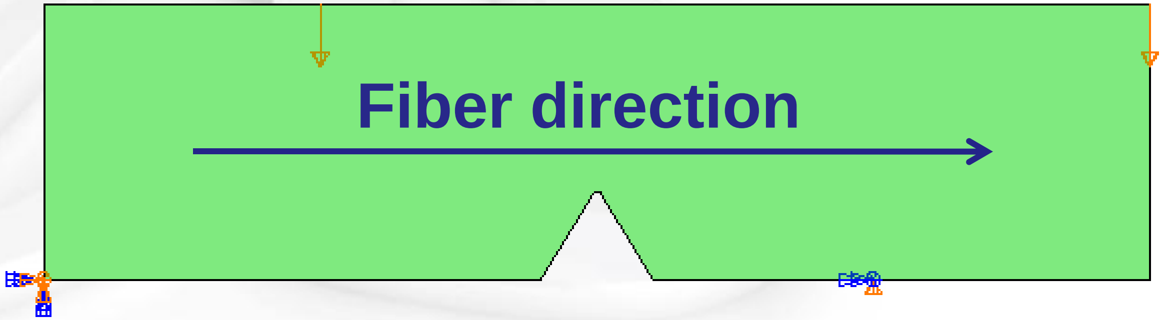
- **Objective**
  - Demonstrate effect of different damage initiation criteria on a simple model
- **FEA model**
  - 2D plane strain elements
  - Linear elastic material
  - Pure bending loading conditions applied
- **XFEM**
  - Two initial cracks of the same size placed in both tension and compression side
  - Three damage initiation criteria analyzed
    - Built-in maximum principal stress criterion
    - User-defined compressive only damage initiation criterion
    - User-defined combined tension and compression damage criteria



# Methods

*Example 2: Mode II Fracture of Cortical Bone*

- **Objective**
  - Demonstrate how composite fracture criteria could be applied to predict cortical bone fracture using XFEM and user defined damage initiation criteria
- **FEA model**
  - 3D model of a notched bone under asymmetric four point bending
  - Assuming fiber runs along the axis of the specimen
- **XFEM**
  - Two damage initiation criteria analyzed
    - Built-in maximum principal stress criterion
    - Composite fracture criterion with two competing failure mechanisms



# Methods

*Example 2: Mode II Fracture of Cortical Bone*

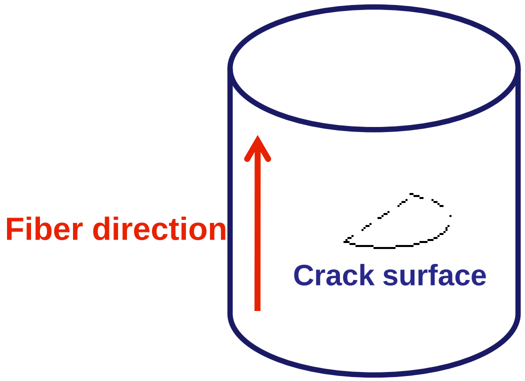
- **Fiber failure mechanism**
  - The fiber direction is based on the material orientation
  - Fiber failure stresses:

    $\sigma_f = 133$ MPa

    $\tau_f = 68$ MPa
  - Fiber failure criterion

$$\bar{\sigma} = \sqrt[2]{\frac{\sigma_{11}{}^2}{\sigma_f{}^2} + \frac{\tau_{12}^2}{\tau_f{}^2} + \frac{\tau_{13}^2}{\tau_f{}^2}} \geq 1$$

  - Crack surface is always perpendicular to the fiber direction





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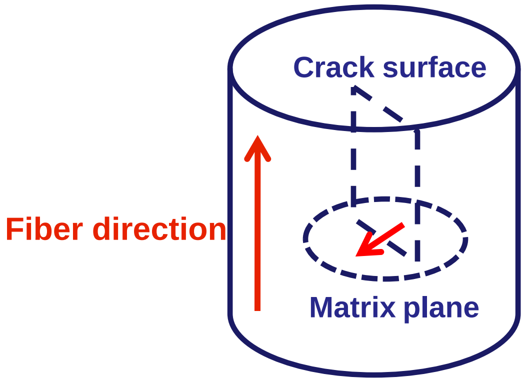
# Methods

*Example 2: Mode II Fracture of Cortical Bone*

- **Matrix failure mechanism**
  - Matrix plane: any plane perpendicular to the fiber direction
  - The in-plane maximum principal stress and its direction within the matrix plane is used to determine the crack initiation and propagation direction
  - Matrix failure stress:

$$\sigma_f = 51 \text{ MPa}$$

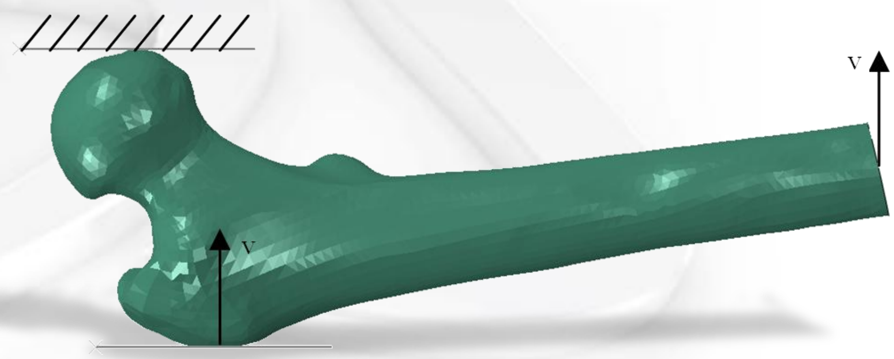
  - Crack surface is the plane that perpendicular to the maximum in-plane principal direction and parallel to the fiber direction



# Methods

***Example 3: Femur Fracture***

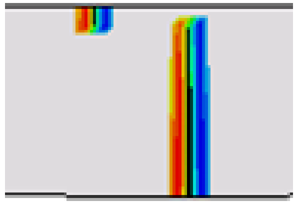
- **Objective**
  - Demonstrate how user-defined damage criteria could be applied to whole bone fracture simulation
- **FEA model**
  - A femur fracture test is simulated
  - Apparent bone density implemented as a field variable
  - Bone elastic and damage properties defined as functions of bone density through field variable dependent material properties
- **XFEM**
  - Two damage initiation criteria analyzed
    - Built-in maximum principal strain criterion
    - User-defined combined tension and compression damage criteria



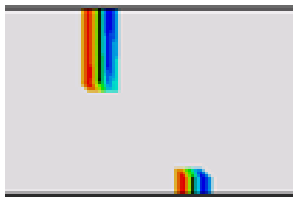
# Results

*Example 1: Beam Bending*

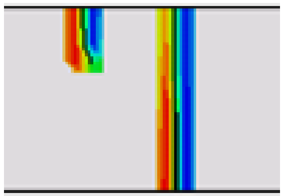
- **Built-in maximum principal stress criterion**
  - Only crack on the tension side propagated



- **User-defined compressive only damage initiation criterion**
  - Only crack on the compressive side propagated
  - Crack propagation stopped at neutral axis due to the stabilizing effect of contact at the crack surfaces



- **User-defined combined tension and compression damage criteria**
  - Both cracks propagated
  - Crack on the compressive side stopped at neutral axis







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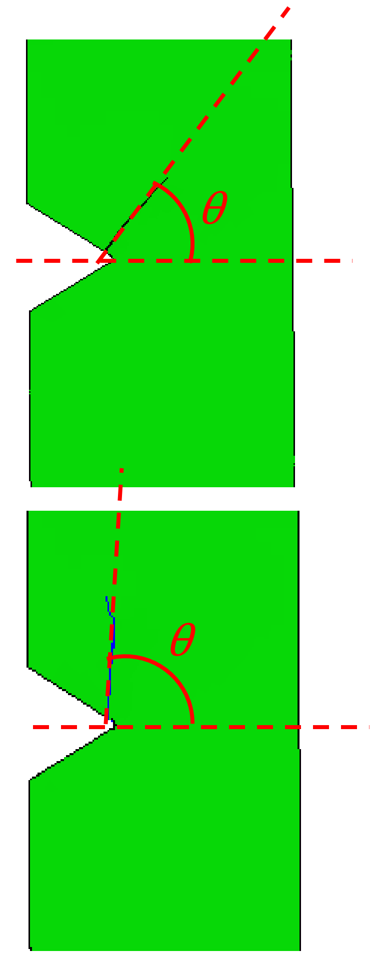
# Results

*Example 2: Mode II Fracture of Cortical Bone*

- **Built-in maximum principal stress criterion**
  - Crack deflection angle $\theta \sim 65°$
    - Close to analytical solution
- **Composite fracture criterion**
  - Crack deflection angle $\theta \sim 90°$
    - Similar results were observed in experimental study on human cortical bone fracture[1]

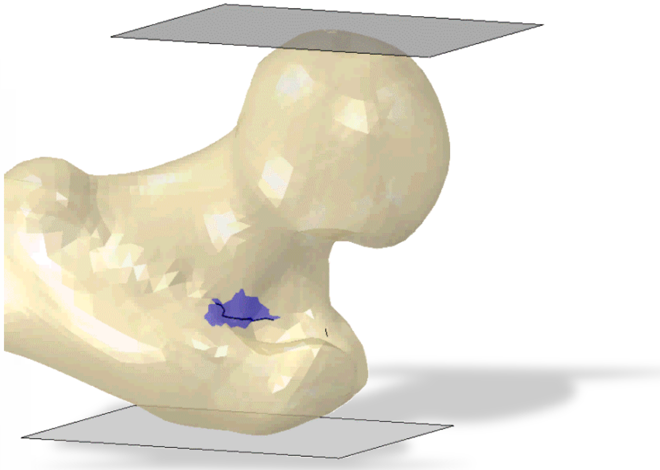



1. Zimmermann, et al. "Mixed-mode Fracture of Human Cortical Bone, Biomaterial, 2009, 30: 5877-5884

# Results

*Example 3: Femur Fracture*

- **Built-in maximum principal strain criterion**
  - Crack initiated from posterior side of the femur neck
  - Right underneath the femur head
  - Crack propagated mostly along the surface
    - Did not extend deep into the femur neck
- **User-defined combined tension and compression damage criteria**
  - Crack initiated from the anterior side of the femur neck
  - Next to the greater trochanter
  - Crack propagated along the surface and into the femur neck







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# Summary

*Abaqus XFEM for Bone Fracture Study*

- **Bone is a very complex material**
  - Hierarchical: multilevel structure complexity
  - Inhomogeneous: material property varies spatially
  - Orthotropic: stronger in the load carrying direction
  - Asymmetric: stronger in compression than in tension and shear
  - Living tissue that is capable of repairing and remodelling itself
- **Fracture mechanics property is one of the most important aspects of bone that concerns millions of people's wellbeing**
  - It is not yet fully understood
  - Abaqus XFEM is another unique powerful tool for researchers to:
    - Better understand bone fracture and failure behavior
    - Develop strengthening treatment