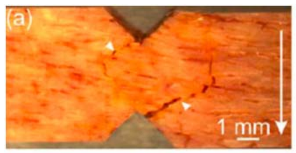
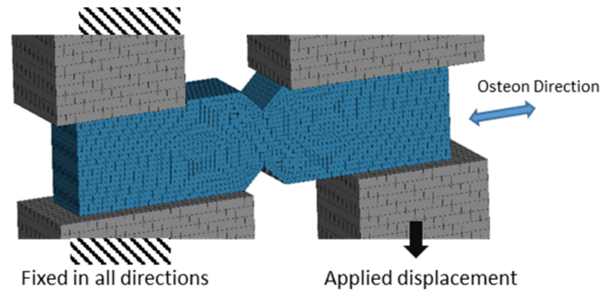
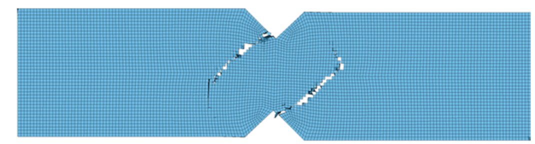


Tang 2015





HONDA
The Power of Dreams

Hard Tissue Fracture Assessment in Human Body Models

RCCADS Research Consortium for Crashworthiness in Automated Driving Systems

May 25, 2023

DS Cronin PhD, PEng, FCAE, Professor

Tier 1 Canada Research Chair in Trauma Biomechanics and Injury Prevention
Professor, Department of Mechanical and Mechatronics Engineering

Director, Impact Mechanics and Material Characterization Group

Fellow, Canadian Academy of Engineering

UNIVERSITY OF WATERLOO

IMMC Impact Mechanics and Material Characterization

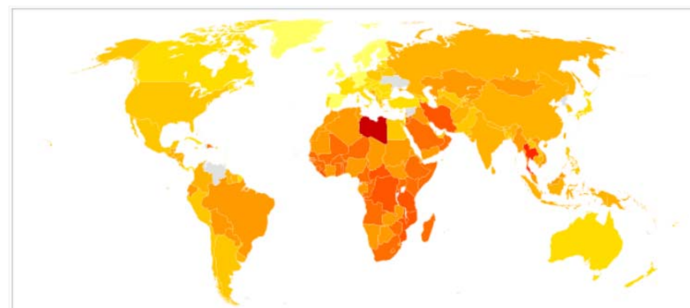
tBIP Trauma Biomechanics and Injury Prevention

Introduction

Why Human Body Models (HBMs)?

- Human response risk for omni-directional loading.
- Assessment of vulnerable populations
  - Aged persons, female, varying anthropometrics.
  - Understanding population variability.
- Tissue-level injury risk
  - Assess injury at the tissue level where injury occurs.

Critical to achieving goals of reduced injury and fatality (zero road fatalities).



Death rates from road traffic accidents by country, per 100,000 inhabitants, world map (WHO 2022).[1][nb 1]

fewer than 5
5–10
10–15
15–20
20–25
25–30
30–35
35–40
more than 40
Data unavailable

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Introduction

- Finite element Human Body Models (HBM) have the potential to predict injury risk in impact scenarios, with the aim to predict tissue-level injury.
- Prediction of loading, fracture initiation, and post-fracture response of hard tissues are critical to evaluate injury risk to adjacent or underlying soft tissues.
  - Existing cortical bone constitutive models are often limited to tension-based fractures.

Gierczycka 2021

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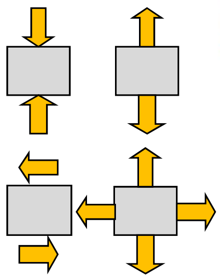
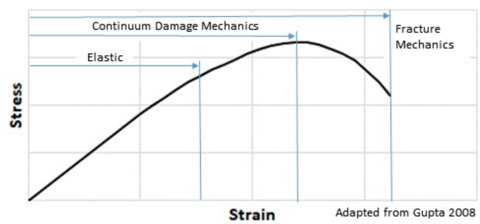
Introduction – FE Model Requirements

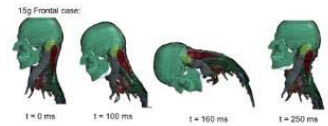
A balanced approach is required.

- Material properties
- Constitutive models





Adapted from Gupta 2008



Model Scale

Response
Kinetic/Kinematic

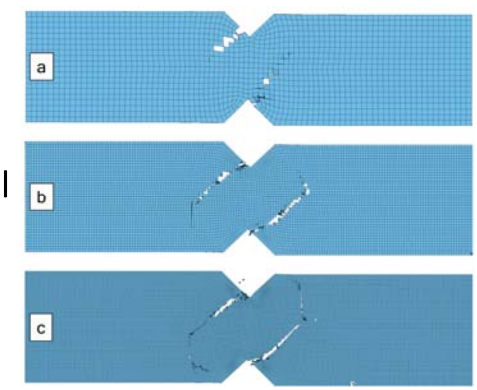
Potential for Injury

Material Properties

Geometry/ Anatomy

Loading (BC's)

- Mesh refinement
- Relevant anatomical structures



- Force, Deformation or related quantities
- Representative
- Coupling

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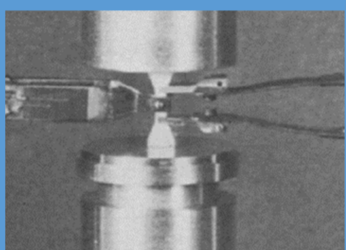
Introduction – FE Model Requirements

Measured mechanical properties

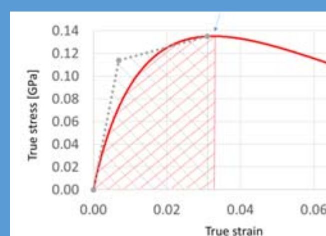


Reilly 1975

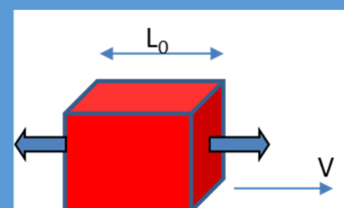
Constitutive model selection and fitting

$$\sigma = f(\varepsilon', \dot{\varepsilon})$$

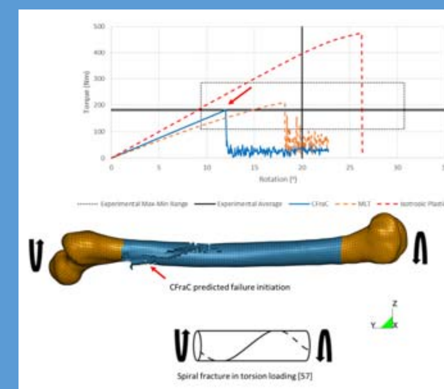
$$p = f(\varepsilon_V)$$



Numerical implementation



Verification and validation



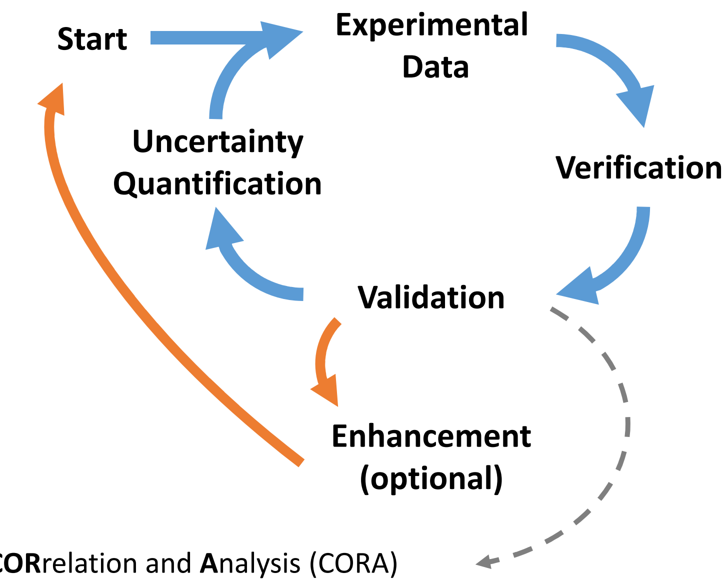
V&V and UQ

ASME V&V 10-2006, "Guide for Verification and Validation in Computational Solid Mechanics"

- Verification, Validation and Uncertainty Quantification (V&V and UQ)
- Assessment using existing data sets

VERIFICATION	VALIDATION
Mathematical accuracy	Represent real world scenarios

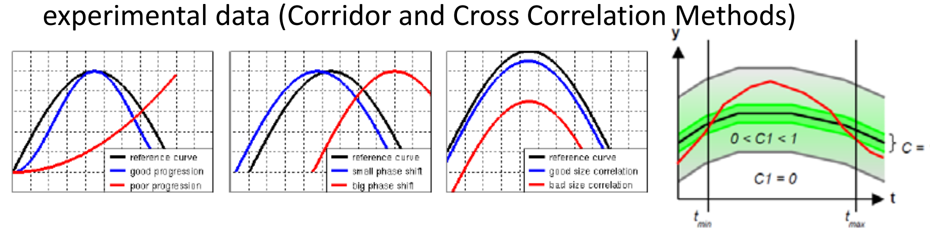
CALIBRATION	UNCERTAINTY
Adjust material properties and model parameters	Quantify and reduce uncertainty



CORrelation and **A**nalysis (CORA)

Partnership for Dummy Technology and Biomechanics, Ingolstadt, Germany http://www.pdb-org.com/en/information/18-cora-download.html

- Provides an objective rating between model prediction and experimental data (Corridor and Cross Correlation Methods)



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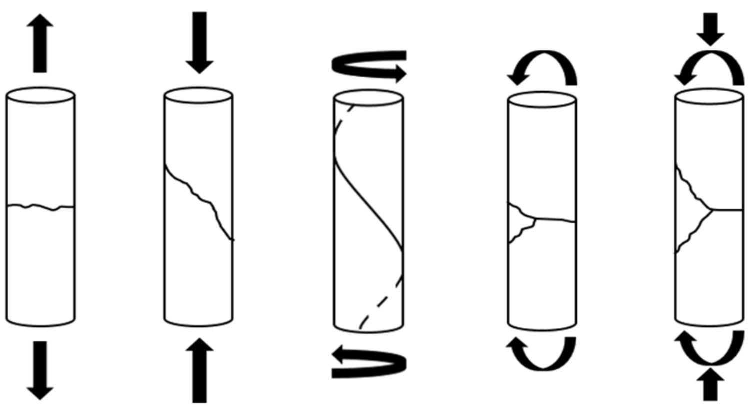
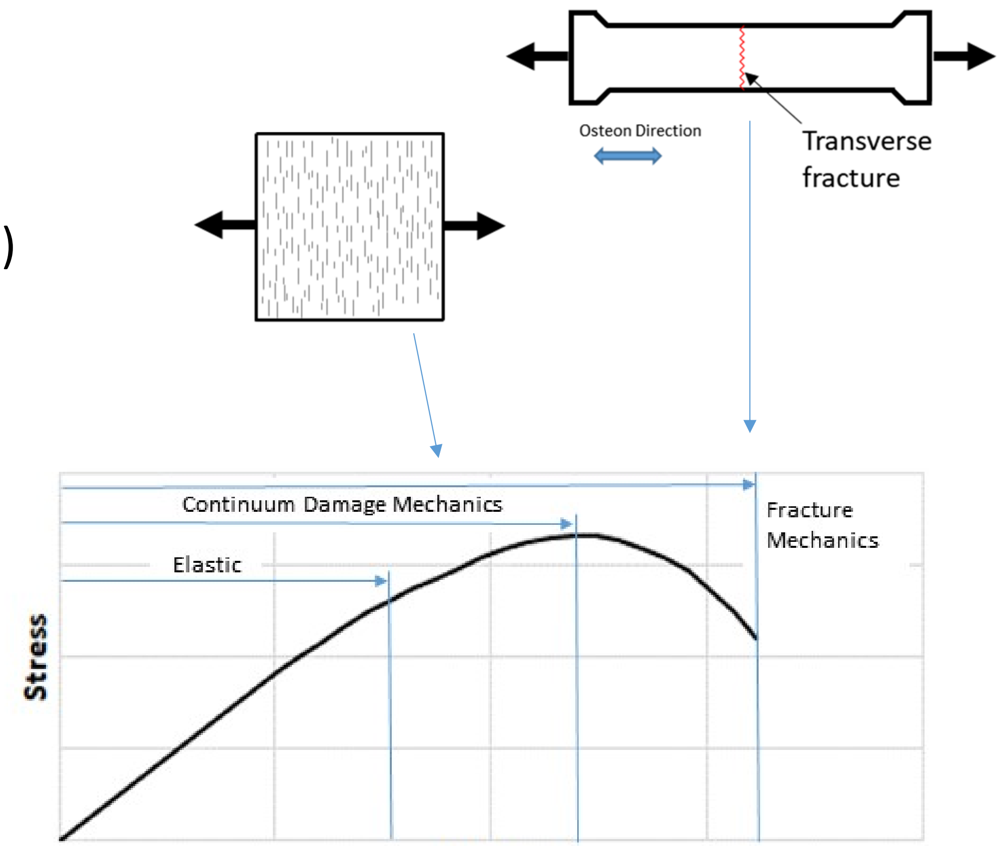
Introduction

- Mechanical properties
  - Orthotropic (osteon vs transverse directions)
  - Deformation rate effects (compression)
  - Tension/compression asymmetry
  - Damage accumulation, fracture

- Fracture patterns
  - Correspond to mode of loading

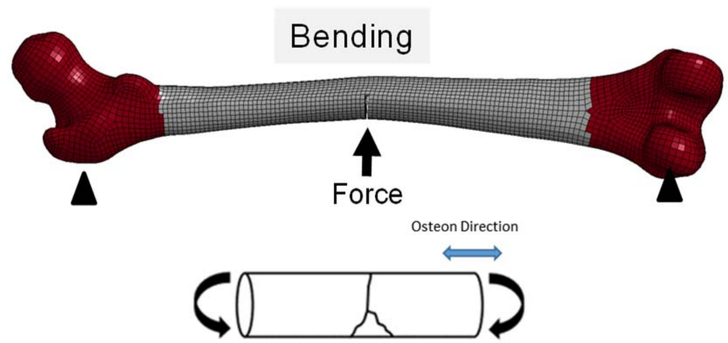


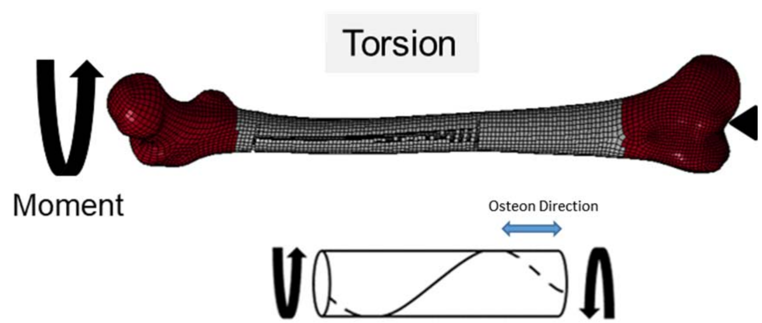


Constitutive Models

- Metal plasticity models - most common:
  - Shear properties/strength are related to tension properties through yield surface and flow rule.
  - Can predict tension-based failure, but not shear or mixed mode.

- Cortical bone is transversely isotropic with asymmetric properties in tension and compression.





Khor F, Cronin DS, Watson B, Gierczycka D, Malcolm S. (2018) "Importance of Asymmetry and Anisotropy in Predicting Cortical Bone Response and Fracture Using Human Body Model Femur in Three-Point Bending and Axial Rotation". Journal of the Mechanical Behavior of Biomedical Materials 87:213-229.

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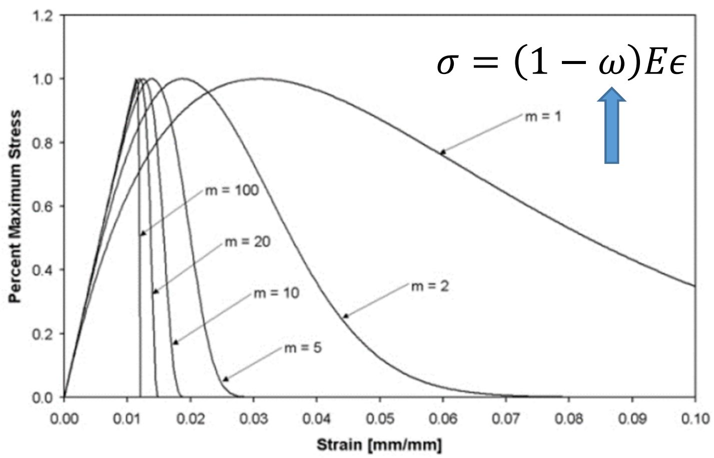
Constitutive Models

- MLT anisotropic continuum damage mechanics model
  - Includes: orthotropy, asymmetry, damage (ω)



$$\sigma = (1-\omega)E\epsilon$$

$$\sigma = H^{-1}\varepsilon$$

$$H = \begin{bmatrix} \frac{1}{(1-\omega_{11})E_{11}} & \frac{-\nu_{21}}{E_{22}} & \frac{-\nu_{31}}{E_{33}} & 0 & 0 & 0 \\ \frac{-\nu_{12}}{E_{11}} & \frac{1}{(1-\omega_{22})E_{22}} & \frac{-\nu_{32}}{E_{33}} & 0 & 0 & 0 \\ \frac{-\nu_{13}}{E_{11}} & \frac{-\nu_{23}}{E_{22}} & \frac{1}{(1-\omega_{33})E_{33}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{(1-\omega_{12})G_{12}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{(1-\omega_{23})G_{23}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{(1-\omega_{31})G_{31}} \end{bmatrix}.$$

H^{-1} gives coupling of damage modes in all directions

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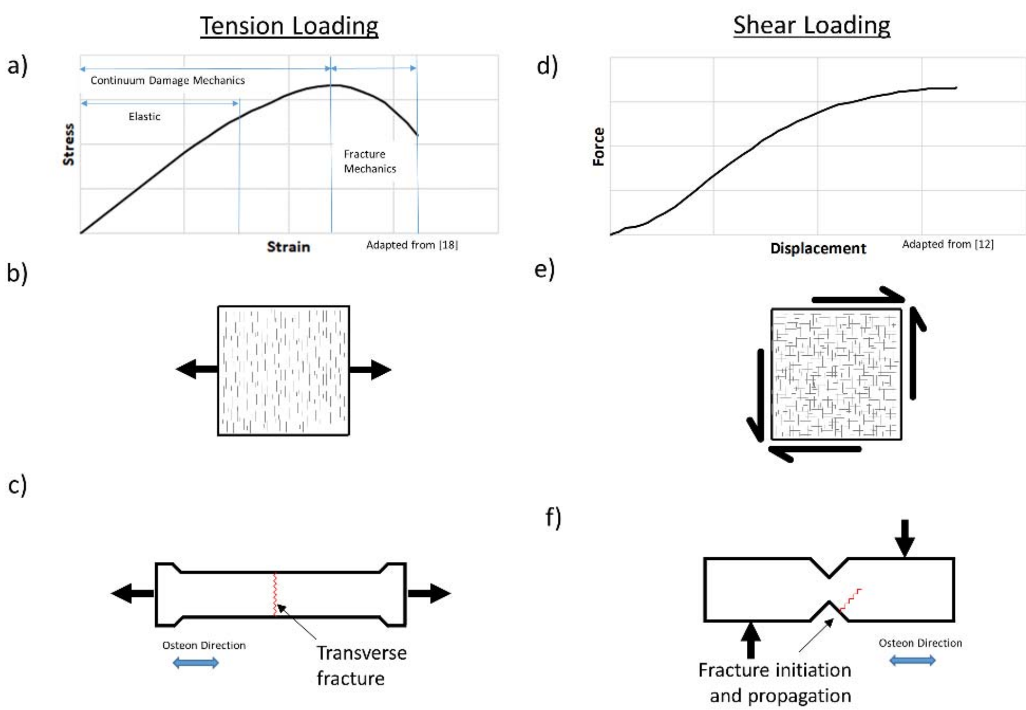
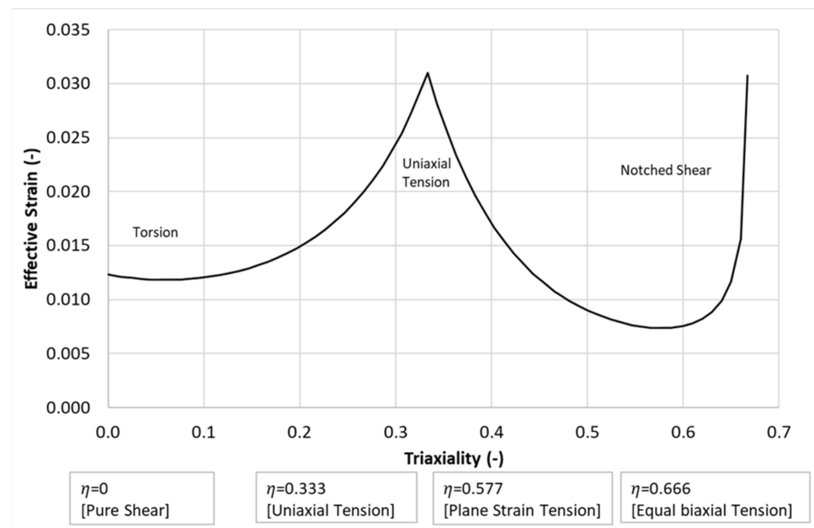
Constitutive Models

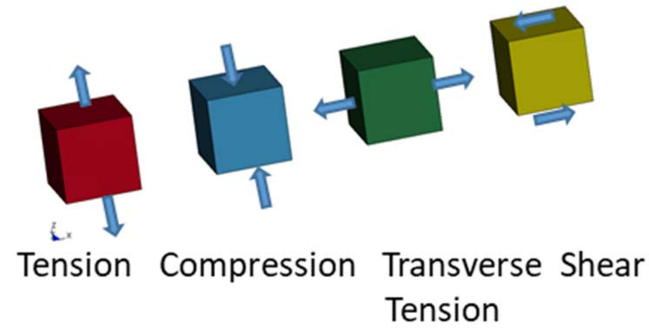
- MLT anisotropic continuum damage mechanics model
  - MMC effective strain to predict the onset of fracture



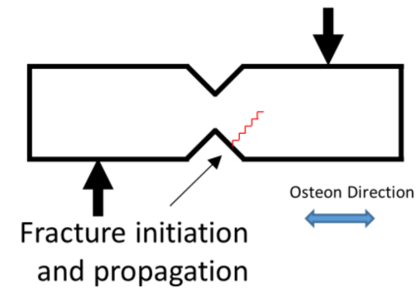


Bone Model V&V

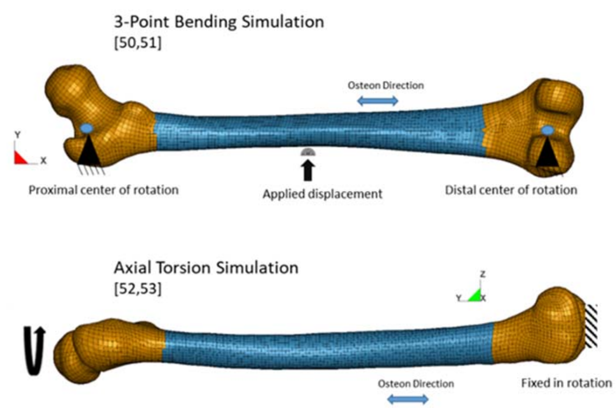
- The material models were verified with single element simulations (metal plasticity, MLT).



- The Iosipescu sample was investigated, based on experimental data for cortical bone from Tang (2015).



- The material model was applied to a HBM femur model in 3-point bending and torsion.



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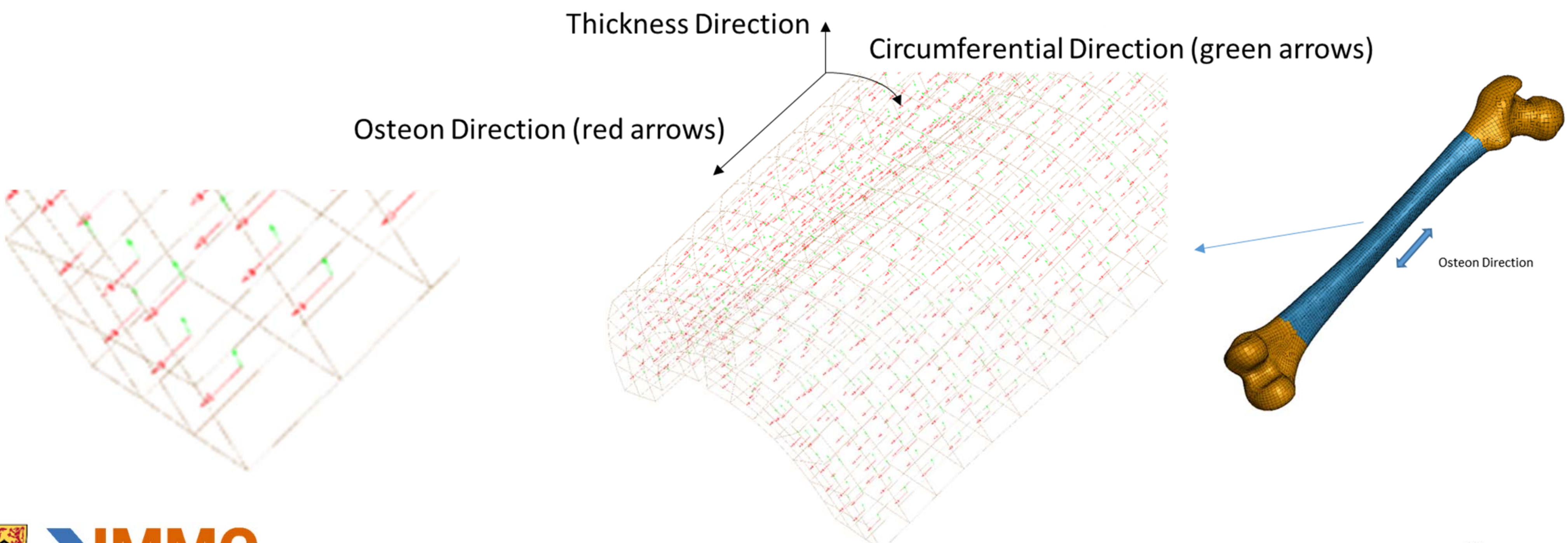
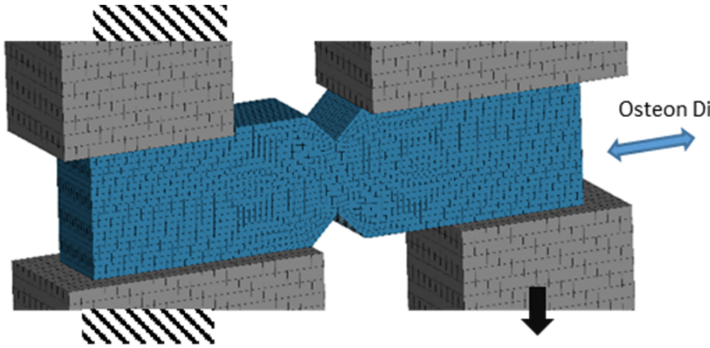
Material Directions

- Anisotropic model requires definition of material directions.
- Using nodal directions (node numbering) with invariant node numbering option.



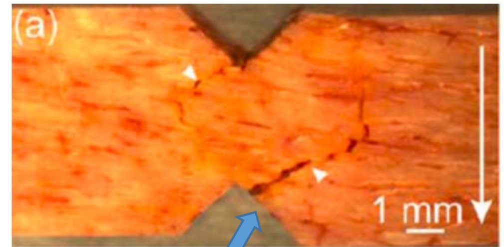
Results and Discussion



Osteon Direction

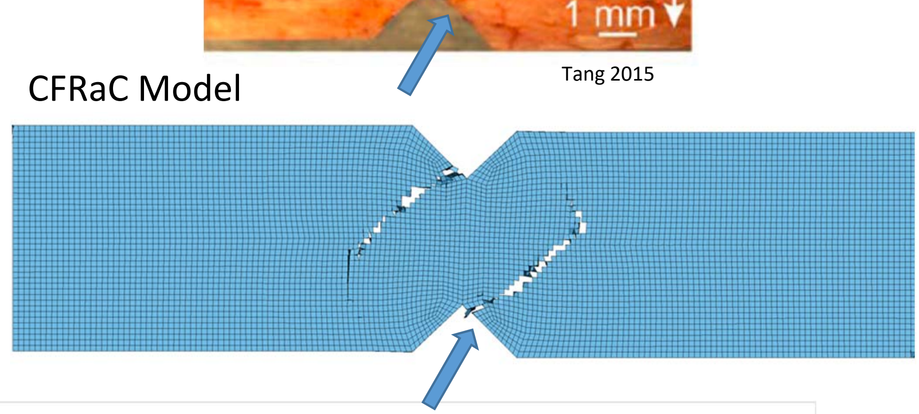
Fixed in all directions

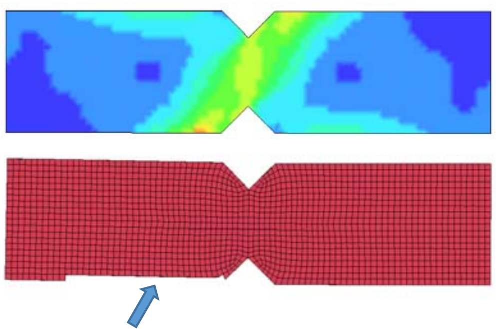
Applied displacement



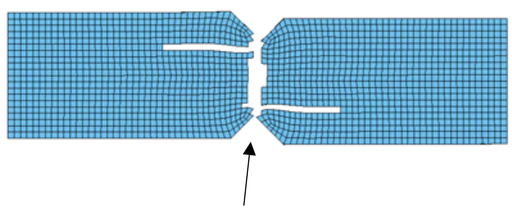
Tang 2015

CFRaC Model

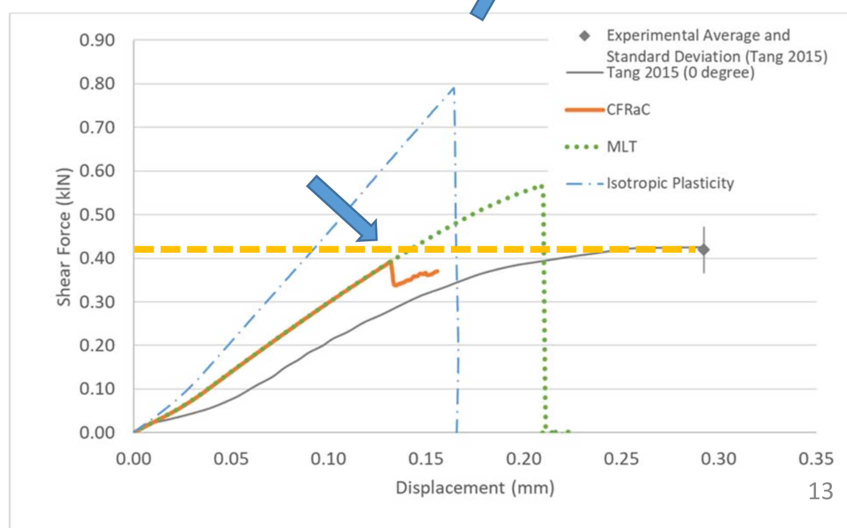




Plasticity model predicted failure a load application location

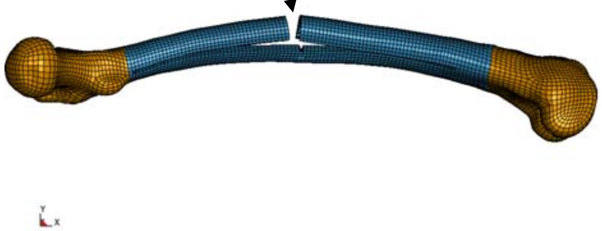


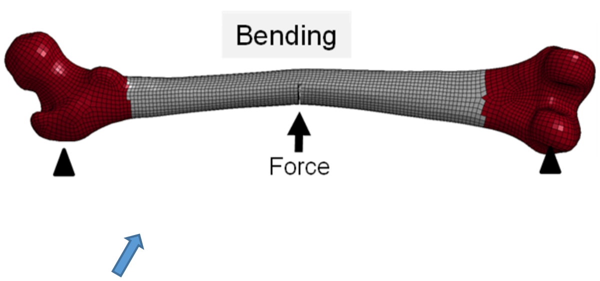
MLT only model - Fracture initiation location



Results and Discussion: 3-Point Bending

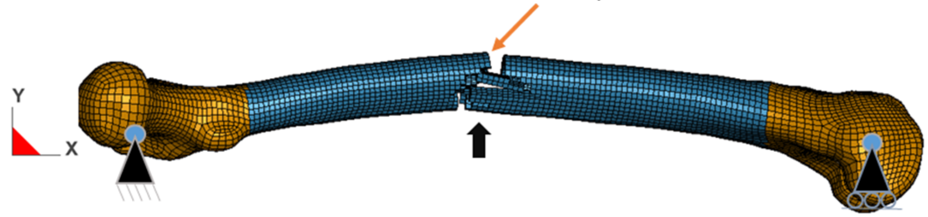
MLT Fracture initiation location

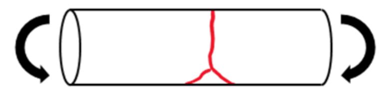




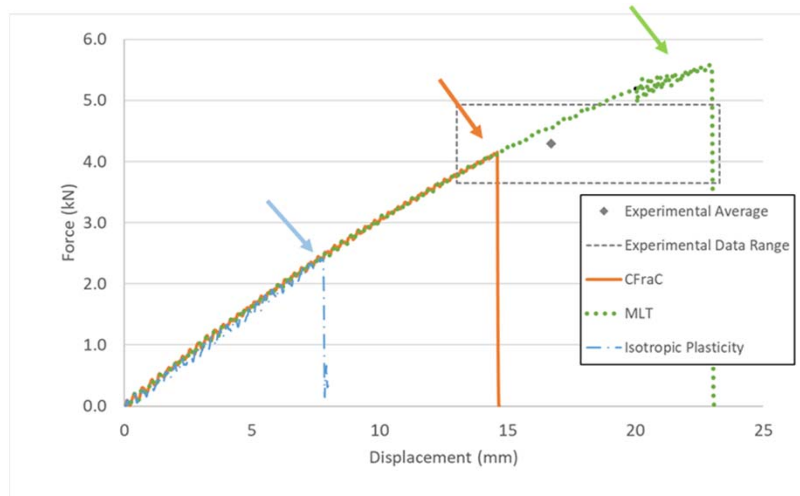
Plasticity model predicted failure a load application location

CFraC predicted failure initiation

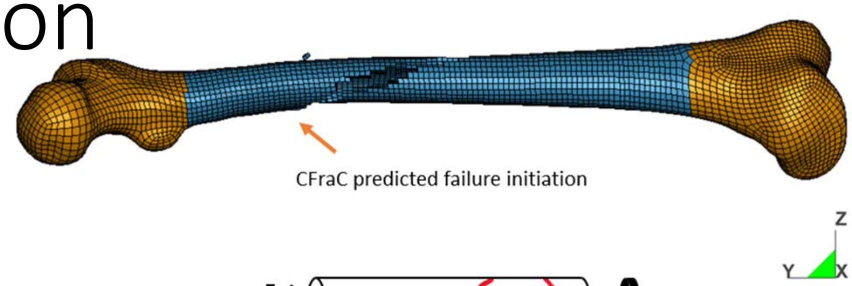


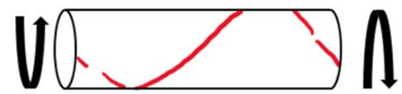


Tension-wedge or butterfly fracture [redrawn from Carter & Spengler, 1982]

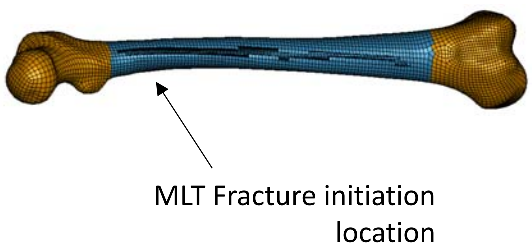


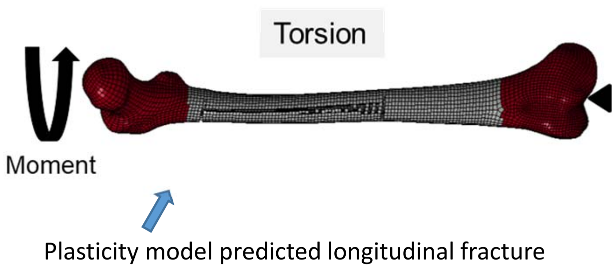
Results and Discussion: Torsion

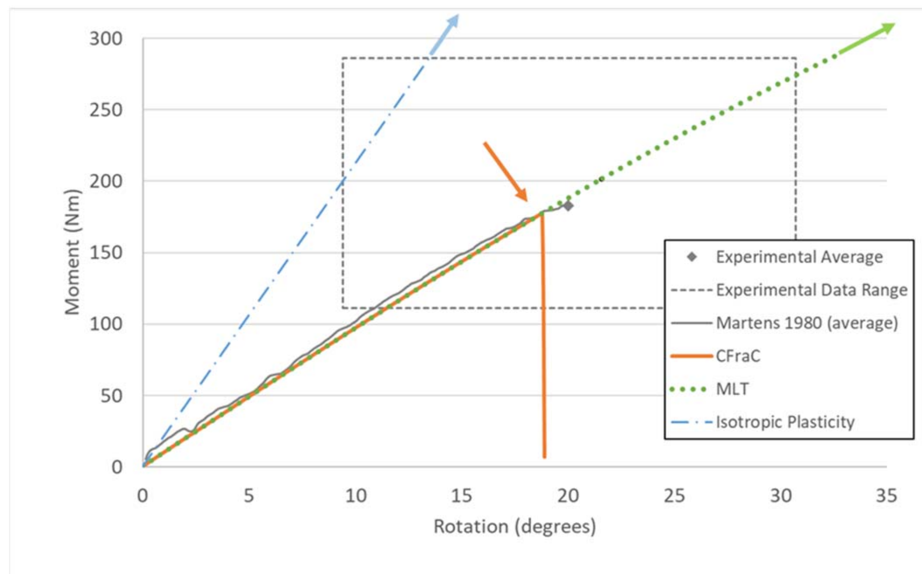




Spiral fracture in torsion loading [redrawn from Carter & Spengler, 1982]



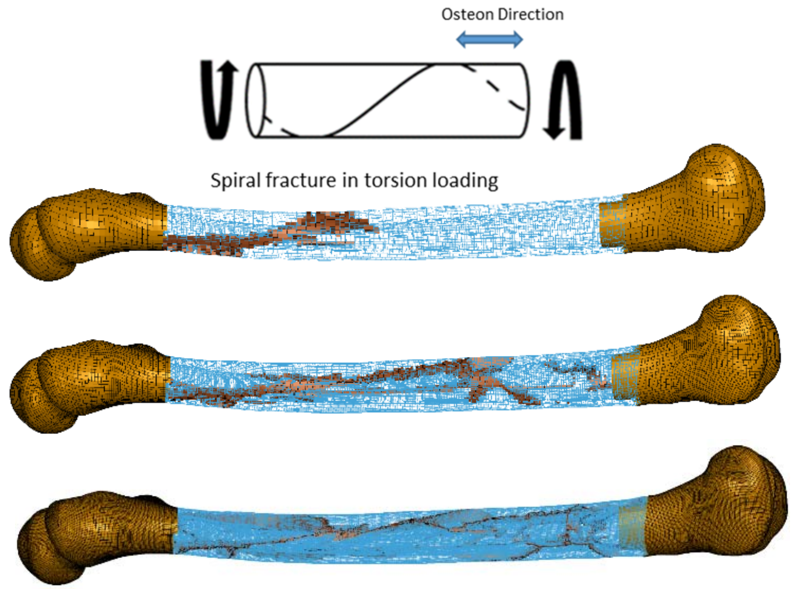


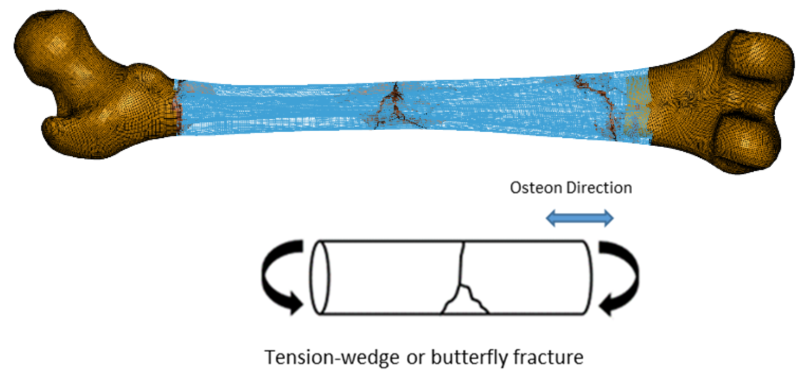


Results and Discussion

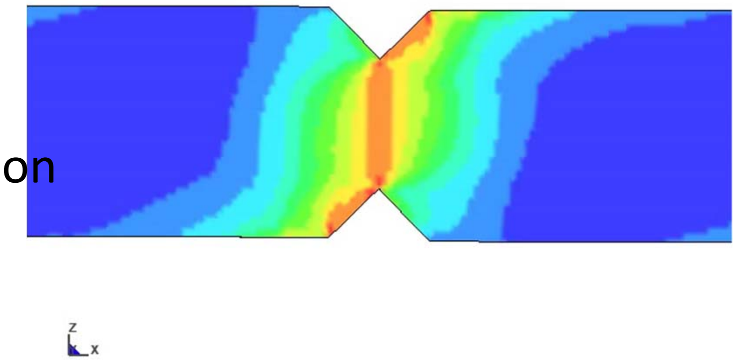
- CDM approach can provide a reasonable approximation to loading, fracture initiation and fracture pattern.
- Feasible for implementation in HBM.
- Careful consideration of meshing required to represent material directions.

- Limitations
  - More mixed mode experimental data needed.
  - Mesh size dependency.
  - Deformation rate effects.

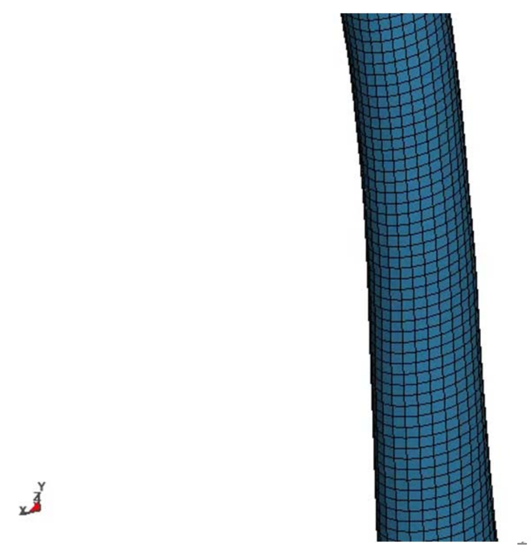




Summary and Contribution



- Contemporary HBMs using isotropic/plasticity material models may predict tension-based fracture initiation.
  - Lack of asymmetry can result in unphysical compression failure.
  - Limited for other modes of loading (shear).
- CFraC constitutive model
  - CDM model with triaxiality-based fracture initiation.
  - Includes anisotropy and asymmetry.
  - Predicted failure initiation, location, pattern.
- Potential for general applicability in hard tissue fracture simulation.



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Constitutive Model Availability

- The CFraC constitutive model is implemented as a User Material (UMAT) in LS-DYNA.
- The model is available as a shared library, that can be integrated with current versions of the commercial code.
- Please contact the author for more information.