Reducing the Mesh-burden and Computational Expense in Multi-scale Free Boundary Engineering Problems

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AICES Graduate School
RWTH-Aachen University
I3MS Seminar Series
20140512

279578 - REALTCUT - Towards real time multiscale simulation of cutting in non-linear materials with applications to surgical simulation and computer guided surgery
• A small, young, dynamic university
• 3 languages (English, German, French); bilingual and trilingual degrees
• Strong mathematics and Comp. Sc.
• RUES: 3 professors in computational mechanics, 30 collaborators
• Computational sciences priority 1
• Strong local industry
• Strong and supportive national funding
• 7 EU projects in engineering, of which RealTcut: ERC Starting Grant (Bordas)

• A large, established university (1883)
• 95% 3 or 4* at RAE2008 in Civil
• Over 100 EU projects awarded of which ITN: INSIST
• Mechanics Research: 40 researchers, 14 faculty members
• Advanced manufacturing and characterisation

NUMERICAL ANALYSIS / CAE
We develop a 3D generalised isogeometric Analysis formulation based on CAD shape functions. Also we study hybrid methods that exploit the advantages of isogeometric Analysis and standard finite elements. Moreover, we explore mortar methods based on structured and unstructured discretisations and 3D XFEM formulations based on level-set functions that describe the boundary of the domain. Finally, we develop adaptive refinement algorithms and model reduction techniques.

erc INSIST
The institute
- 6 professors, 6 lecturers/senior lecturers
- 10 post-doc fellows
- 17 PhD students
- ~ £1.0M funding annually
Motivation: multiscale fracture/cutting

Practical early-stage design simulations (interactive)

- Discretise

- Surgical simulation

Reduce the problem size while controlling the error (in QoI) when solving very large (multiscale) mechanics problems
Motivation: multiscale fracture - Example

Solder joint durability (microelectronics), Bosch GmbH
• Efficient numerical prediction of material and structural failure

[Kerfriden et al., 2010]

L. Beex S.P.-A. Bordas P. Kerfriden

• Characterisation and optimisation of composites

[Initial crack distribution]

[Final fracture]

[Sutula et al., 2013]

[Silani et al., 2013]
• Interactive simulations of biological structures

• Simplified Link between CAD/CT scans and analysis

[Scott et al., 2013]

[Courteouisse et al., 2013]

[Nguyen et al., 2013]
• Advanced discretization techniques for complex PDEs

- XFEM/meshfree

  [Bordas et al., 2008]  
  Taylor bar problem  
  (dynamic fragmentation)

- Isogeometric analysis

  Model simplification  
  (CAD)  
  IGA

  [Tornincasa et al., 2013]
• Multilevel methods to reduce CPU time by orders of magnitude and devise robust, efficient code/model coupling

- HPC Adaptive multiscale models/solvers with controlled accuracy

[Kerfriden et al., 2010]

[Akbari et al., 2013]
• Multilevel methods to reduce CPU time by orders of magnitude and devise robust, efficient code/model coupling

- Virtual chart with controlled accuracy via ROM for multiscale modelling and real-time optimisation

[Hoang et al., 2013]
Discretization

- partition of unity enrichment
- (enriched) meshless methods
- level sets

- isogeometric analysis
- implicit boundaries

Model reduction

- multi-scale & homogenisation
- algebraic model reduction (using POD)
- Newton-Krylov, “local/global”, domain decomposition

Error control

- XFEM: goal-oriented error estimates
  - used by CENAERO (Morceo XFEM)
- meshless methods for fracture
- error estimation for reduced models
Part 0. An adaptive method for fracture - application to polycrystalline failure

Ahmad Akbari, Pierre Kerfriden, Spaß

Faculty of Sciences, Technology and Communication
Multiscale modelling

- Bottom-up view: replace heterogeneous subscale model by an equivalent, smoother, model at the scale where predictions are required (i.e. macroscopic scale)

- When is scale-bridging necessary?
  - Derive predictive macroscopic models that are difficult to obtain using phenomenological approaches
  - Optimise subscale properties to obtain better overall characteristics
  - Observations at microscale but approximations required away from region of interest to remain tractable

[Chen et al. 2011]

Figure 3. Microstructure of the A2024 alloy shown in Figure 1 after being extruded at 400°C for 1 hour.
Examples

Approximation of the behaviour of polycrystalline materials away from macroscopic cracks

Optimisation of fiber content in sandwich beams to minimise interfacial stress in
Mathematical formulation

- Knowing the governing equations at the microscale, can we find homogeneous governing equations at the macroscale s.t.:
  - The solution of the macroscale problem converges to the solution of the microscale problem when the scale ratio tends to zero

- Hopefully: the solution of the macroscale problem is a good approximation of the solution of the microscale problem (in some sense) even when the scale ratio is not very small.

Error in QoI macroscopic $<$ Tolerance
Cost of solving macromodel $<<$ subscale model
Classical homogenisation in linearised elasticity

- Heterogeneous microstructure undergoing moderate deformations, observations at macroscale, slow loading, scale separability

- Macroscale candidate model: lin. elasticity
  - Equilibrium
    \[ \text{div} \sigma^M + f = 0 \quad \text{in } \Omega \]
    \[ \sigma^M \cdot n = 0 \quad \text{in } \partial \Omega_f \]
  - Kinematic equations
    \[ u^M = U_d \quad \text{in } \partial \Omega_u \]
    \[ \varepsilon^M = \frac{1}{2} \left( \text{grad} u^M + \text{grad} u^M^T \right) \quad \text{in } \Omega \]
  - Constitutive relation by classical micromechanics
    \[ \sigma^M = S^M \left( \varepsilon(u^M) \right) \quad \text{in } \Omega \]
Classical homogenisation in linearised elasticity

- Attach a representative volume element to the material point: volume of material large enough to represent the statistics of the distribution of material properties (unit cell in periodic case)
  \[ \sigma^m = D(y) : \varepsilon^m \]

- Suppose that the RVE is mechanically equilibrated: \[ \text{div} \sigma^m = 0 \]

- The effective constitutive law the/a relationship between average stress and average strain
  \[ < \sigma^m > = S^M ( < \varepsilon^m > ) \]
Computational homogenisation

- Obtain \( <\sigma^m> = S^M ( <\varepsilon^m> ) \) by solving RVE problem numerically

\[ \bar{u}(y) = \varepsilon^M \cdot y + \tilde{u}(y) \]

- Ill-posed, requires BC for fluctuation compatible with \( <\varepsilon(\tilde{u}(y)> \)
- One possibility: Dirichlet problem, fluctuation vanishes on boundary

→ Very expensive too solve
Multiscale methods for Fracture

- Non-concurrent
  
  Damage zone is modelled by a macroscopic cohesive crack that homogenises the failure zone.

  \[ \frac{L}{l} >> 1 \]

- Concurrent
  
  Damage zone is modelled directly at the microscale and coupled to the coarse scale.

  \[ \frac{L}{l} > 1 \]

V.P. Nguyen 2012
Ways to reduce the fracture models

- Homogenisation (FE^2, etc.) - Hierarchical
- Concurrent (bridging domain, ARLEQUIN, etc.)
- Enrichment (PUFEM, XFEM, GFEM)
- Model reduction
Fine Scale: micro-structure

➢ Microscale problem:

\[
\int_{\Omega/\Gamma_c} \sigma(u) : \delta \varepsilon \, d\Omega + \int_{\Gamma_c} \mathbf{T} \cdot [\delta \mathbf{u}] \, d\Omega = \int_{\partial \Omega} \mathbf{f} \cdot \delta \mathbf{u} \, d\Gamma
\]

■ Orthotropic grains

\[\forall \mathbf{x} \in \Omega/\Gamma_c, \quad \sigma = \mathbf{C} : \varepsilon\]

■ Cohesive interface

\[\forall \mathbf{x} \in \Gamma_c, \quad \mathbf{T}|_t = T \left( ([\mathbf{u}]|_T)_{T \leq t} \right)\]
Macroscale problem:

- FE$^2$ Method
  Based on averaging theorem
  (computational homogenisation)

- Adaptive mesh refinement
  Error estimation by Zienkiewicz-Zhu-type recovery technique
Coarse Scale: FE$^2$

- The FE$^2$ Method

RVE

- Shortcoming of the FE$^2$ Method:
  - Lack of scale separation
  - RVE cannot be found in the softening regime

Lack of scale separation
RVE cannot be found in the **softening regime**
Error control in multiscale modelling

Domain Decomposition Method

FE² method

Critical size

Critical level of error

Homogenisation error

Discretization error

error

Coarse Element size
Fine-Coarse scales Coupling

Solution beyond $\text{FE}^2$: “Hybrid Multiscale Method”

- $\text{FE}^2$ for non-critical region (hierarchical multiscale)
- Domain decomposition for critical region (concurrent multiscale)

$$u_f = u_c$$
Adaptive multiscale method: A Concurrent approach

Strategy:
• control the coarse scale discretization error
• control the modelling error

Mesh refinement
Hybrid method
$\Omega_f$
$\Gamma_{cf}$

$FE^2$
$FE^2$
$FE^2+ Domain Decomposition Method$
Coarse Scale: Adaptive mesh refinement

- Coarse scale Adaptive mesh refinement
  - Error estimation by Zienkiewicz-Zhu-type recovery technique

\[
\|e\| = \int_{\Omega_c} (\sigma^* - \sigma) : \left( \frac{\partial \sigma}{\partial \varepsilon} \right)_{u^c}^{-1} : (\sigma^* - \sigma) \, d\Omega
\]

• Convergence criterion: \[ \frac{\|e\|}{\|\sigma\|} < Tol \]

Error due to the discretisation of neglected
Results: L-shape
Results: L-shape

Direct Numerical Solution

Adaptive Multiscale method
Results: uni-axial tension

_sizes are in mm_
Results: uni-axial tension

von Mises stress (Pa)

❖ 100X (magnification of displacement)
Results: uni-axial tension

von-Mises stress (Pa)

❖ 100X (magnification of displacement)
Results: uni-axial tension

von-Mises stress (Pa)

❖ 100X (magnification of displacement)
Results: uni-axial tension

von-Mises stress (Pa)

❖ 100X (magnification of displacement)
Results: uni-axial tension

von-Mises stress (Pa)

- 100X (magnification of displacement)
Verification

(a) DNS

(b) The adaptive multiscale method

\[ W_{\text{ext}} \]
\[ D = W_{\text{ext}} - W_{\text{int}} \]

Energy (J)

0 0.5 1 1.5

0 8 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120

Time steps

\[ W_{\text{int}} \]

\[ \text{total dissipated energy, } D, (J) \]

0 0.2 0.4 0.6 0.8 1

0 1 2 3 4 5

\[ w_A^m \text{ (mm)} \times 10^{-3} \]

DNS

adaptive multiscale method
Verification

a) DNS

b) The adaptive multiscale method

The adaptive multiscale method

DNS
Perspectives

• coarsening once the crack is open
• molecular dynamics at the fine scale

• real-life problems! :) 
• coupling with algebraic model reduction (POD)
Link with algebraic model reduction
(Proper Orthogonal Decomposition)
Parametric / stochastic multiscale fracture mechanics

First realisation

Highly correlated solution fields

Second realisation

Localisation of fracture, uncorrelated

➡ Direct numerical simulation: efficient preconditioner?
➡ Reduced order modelling?
➡ Adaptive coupling?
Reduced DDM-POD

- Decompose the structure into subdomains
- Perform a reduction in the highly correlated region
- Couple the reduced to the non-reduced region by a primal Schur complement
Publications

http://hdl.handle.net/10993/16347

http://orbuilu.uni.lu/handle/10993/14475

http://orbuilu.uni.lu/handle/10993/10207

http://orbuilu.uni.lu/handle/10993/10066

http://orbuilu.uni.lu/handle/10993/12454

http://orbuilu.uni.lu/handle/10993/16323

http://orbuilu.uni.lu/handle/10993/12012

http://orbuilu.uni.lu/handle/10993/12014
Part I. Streamlining the CAD-analysis transition

Part II. Some advances in enriched FEM

Part III. Application to H cutting of Si wafers

Part IV. Interactive cutting sim.
Part I. Streamlining the CAD-analysis transition

Coupling, or decoupling?
Motivation: free boundary problems - mesh burden

FEM

XFEM
CAD to Analysis

iterate

80%

mesh

calculate

20%

vM stress distribution
One would like to be able to use such a mesh.
Superimpose the geometry onto an arbitrary background mesh.
Compute interactions between the geometry and the mesh.
Perform the analysis

Figure 5.27 – Approximation géométrique d'une microstructure contenant des inclusions lenticulaires. (a) maillage grossier de l'approximation EF. (b) Raffinement par un sous-maillage gradué (SMG) de niveau (n = 7) à l'intérieur de chaque élément de frontière \( EB \). (c) approximation de la géométrie indépendamment de la taille \( h \) du maillage.

Figure 5.28 – Champs de contraintes (a) et de déplacements (b).

Figure 5.29 – Approximation géométrique d'une microstructure contenant des inclusions en forme de tore indépendamment de la taille du maillage EF.
Paradigm 1: Separate field and boundary discretisation

- Immersed boundary method (Mittal, et al. 2005)
- Fictitious domain (Glowinski, et al. 1994)
- Embedded boundary method (Johansen, et al. 1998)
- Virtual boundary method (Saiki, et al. 1996)
- Cartesian grid method (Ye, et al. 1999, Nadal, 2013)

✓ Easy adaptive refinement + error estimation (Nadal, 2013)
✓ Flexibility of choosing basis functions
- Accuracy for complicated geometries? BCs on implicit surfaces?
⇒ An accurate and implicitly-defined geometry from arbitrary parametric surfaces including corners and sharp edges (Moumnassi, et al. 2011)
Objectives

- insert surfaces in a structured mesh
  - without meshing the surfaces (boundary, cracks, holes, inclusions, etc.)
  - directly from the underlying CAD model
  - model arbitrary solids, including sharp edges and vertices
- keep as much as possible of the mesh as the CAD model evolves, i.e. reduce mesh dependence of the implicit boundary representation
- maintain the convergence rates and implementation simplicity of the FEM

Pixel/Voxel-based FEA on Cartesian grids (Valencia)

Geometry-based refinement

H-adaptive refinement based on error estimation
Pixel/Voxel-based FEA on Cartesian grids (Valencia)

- **FEM**
- **SPR-C**
- **SPR-C–FEM**

Quad8 uniform refinement

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<th>Processing time</th>
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- T6 ANSYS 11
- Q8 ANSYS 11
- Q8 DIMM SPR-C
- Q8 DIMM SPR

Institute of Mechanics and Advanced Materials

EXTENSION TO IMAGE TO MESH TRANSITION UNDER WAY
How can we move from an image...
...or perhaps a series of images...
to a full mechanical analysis?
Pipeline to analysis

Traditional

Acquire images

Segment images

Mesh Surfaces

Mesh Volume

Perform analysis
Each voxel $j$ is a 32-bit floating point measurement.
Soft segmentation

\[ 0 < m_k(j) < 1 \quad \forall j, k \]

\[ \sum_{k=1}^{K} m_k(j) = 1 \quad \forall j \]
Hard segmentation

\[ \Omega = \bigcup_{k=1}^{K} S_k \]

\[ S_k \cap S_j = \emptyset \quad \forall k \neq j \]
Hard Segmentation at 0.2f

float / class unknown
30 x 50 x 60 / voxel size 3.943 (ScaleMap)
22,490 active voxels
Hard Segmentation at 0.2f with CGAL and OpenVDB
Visible Human

Stephane Lanteri (INRIA) and France Telecom
Problems

• **Core problem**: Geometry is tightly coupled with discretisation.

• How will we deal with:
  
  • Dynamic topology eg. cutting.
  
  • Clinical environments.
  
  • Refinement.
  
  • Complex microstructures.
Pipelines to analysis

Traditional

1. Acquire images
2. Segment images
3. Mesh Surfaces
4. Mesh Volume
5. Perform analysis

Implicit Boundary

1. Acquire images
2. Segment images
3. NURBS
4. Explicit
5. Perform analysis
6. Implicit

Explicit
The method
1-irregular mesh/2:1 balance

Octree data structure
Nested Octree

Discretisation

Geometry

$O_d$  $M$  $O_g$
How to transfer geometric information back to the discretisation?

\[ V_{h_d}^{p_d}(\mathcal{O}_d) \oplus E[V_{h_g}^{p_g}(\mathcal{O}_g)] \]

- \( V_{h_d}^{p_d}(\mathcal{O}_d) \)
- \( p_d > p_g \)
- \( h_d > h_g \)
- \( V_{h_g}^{p_g}(\mathcal{O}_g) \)
- \( p_g = 1 \)
For each enriched cell in the discretisation...
generate local Delaunay triangulation…
Case 1: boundary

finite cell method, implicit boundary method...
Case 2: inclusion

\[ u_h(x) = \sum_{i=1}^{N} N_i u_i + \sum_{i=1}^{N} N_i \sum_{j=1}^{M} \psi_j(x)a_i^j \]
Case 3: Dirichlet Boundary

Nitsche’s method, Lagrange multipliers…
Paradigm 2 : IGA

Couple Geometry and Approximation
Isogeometric analysis (with BEM)

Approximate the unknown fields with the same basis functions (NURBS, T-splines ...) as that used to generate the CAD model.

- Exact geometry.
- High order continuity.
- \textit{hpk}-refinement.

Direct calculation

Meshing
1. Generate a **volume** discretization using the **surface** geometry only?

2. Realistic solids can in general not be represented by only one volume (patch) and multiple **patches** must be **glued** together to avoid “leaks” (Nitsche, T-splines, PHT-splines, RL/LR-splines)

3. Refinement must be done everywhere in the domain (T, PHT… splines)

**3 KEY QUESTIONS FOR IGA**
Isogeometric Analysis with BEM

1. IGABEM with NURBS for 2D elastic problems (Simpson, et al. CMAME, 2011).


Difficulties in dealing with nonlinear problems and non-homogeneous materials.
**Knot vector**

A non-decreasing set of coordinates in the parametric space.

\[ \Xi = \{\xi_1, \xi_2, \ldots, \xi_{n+p+1}\} \]

**B-spline basis function**

\[
N_{a,0}(\xi) = \begin{cases} 
1, & \text{if } \xi_a \leq \xi < \xi_{a+1} \\
0, & \text{otherwise.}
\end{cases}
\]

\[
N_{a,p}(\xi) = \frac{\xi - \xi_a}{\xi_{a+p} - \xi_a} N_{a,p-1}(\xi) + \frac{\xi_{a+p+1} - \xi}{\xi_{a+p+1} - \xi_{a+1}} N_{a+1,p-1}(\xi).
\]

**NURBS basis function**

\[
R_{a,p}(\xi) = \frac{N_{a,p}(\xi) w_a}{W(\xi)} = \frac{N_{a,p}(\xi) w_a}{\sum_{\hat{a}=1}^{n} N_{\hat{a},p} w_{\hat{a}}},
\]
Properties of NURBS

- Partition of Unity

\[ \sum_{i=1}^{n} R_{i,p}(\xi) = 1 \]

- Non-negative

- \( p-1 \) continuous derivatives

- Tensor product property

\[
S(\xi, \eta) = \sum_{i=1}^{n} \sum_{j=1}^{m} R_{i,p}(\xi) R_{j,q}(\eta) B_{i,j} \\
\sum_{i=1}^{n} \sum_{j=1}^{m} R_{i,p}(\xi) R_{j,q}(\eta) = \left( \sum_{i=1}^{n} R_{i,p}(\xi) \right) \left( \sum_{j=1}^{m} R_{j,q}(\eta) \right)
\]
NURBS to T-splines

(NURBS geometry)

NURBS
- No watertight geometry
- No local refinement scheme

(T-splines geometry)

T-splines
- Local knot vector (as Point-based splines)
- Global topology

Propeller: NURBS would require several patches - single patch T-splines

Isogeometric boundary element analysis using unstructured T-splines
MA Scott, RN Simpson, JA Evans, S Lipton, SPA Bordas, TJR Hughes, TW Sederberg
Part II. Some recent advances in enriched FEM
Handling discontinuities in isogeometric formulations

with Nguyen Vinh Phu, Marie Curie Fellow
Discontinuities modeling

### PUM enriched methods

- IGA: link to CAD and accurate stress fields
- XFEM: no remeshing

### Mesh conforming methods

- IGA: link to CAD and accurate stress fields
- Apps: delamination
PUM enriched methods (XIGA)

\[ u^h(x) = \sum_{I \in S} R_I(x) u_I + \sum_{J \in S^c} R_J(x) \Phi(x) a_J \]

NURBS basis functions \hspace{1cm} enrichment functions


Delamination analysis with cohesive elements (standard approach)

\[ \int_{\Omega} \delta \mathbf{u} \cdot \mathbf{b} \, d\Omega + \int_{\Gamma_t} \delta \mathbf{u} \cdot \mathbf{t} \, d\Gamma_t = \int_{\Omega} \delta \mathbf{\epsilon} : \mathbf{\sigma}(\mathbf{u}) \, d\Omega + \int_{\Gamma_d} \delta \mathbf{[u]} \cdot \mathbf{t}^e(\mathbf{[u]}) \, d\Gamma_d \]

- No link to CAD
- Long preprocessing
- Refined meshes
Isogeometric cohesive elements


2. V.P. Nguyen, P. Kerfriden, S. Bordas. Isogeometric cohesive elements for two and three dimensional composite delamination analysis, 2013, Arxiv.
Isogeometric cohesive elements: advantages

- Direct link to CAD
- Exact geometry
- Fast/straightforward generation of interface elements
- Accurate stress field
- Computationally cheaper

- 2D Mixed mode bending test (MMB)
- 2 x 70 quartic-linear B-spline elements
- Run time on a laptop 4GBi7: 6 s
- Energy arc-length control

Isogeometric cohesive elements: 2D example

- Exact geometry by NURBS + direct link to CAD
- It is straightforward to vary:
  (1) the number of plies and
  (2) # of interface elements:
- Suitable for parameter studies/design
- Solver: energy-based arc-length method (Gutierrez, 2007)
Isogeometric cohesive elements: 2D example
Rotation free B-splines shell elements (Kiendl et al. CMAME)
Two shells, one for each lamina
Bivariate B-splines cohesive interface elements in between
Isogeometric cohesive elements: 3D examples

- cohesive elements for 3D meshes the same as 2D
- large deformations
Isogeometric cohesive elements

- singly curved thick-wall laminates
- geometry/displacements: NURBS
- trivariate NURBS from NURBS surface (*)
- cohesive surface interface elements

Future work: model selection (continuum, plate, beam, shell?)

Model selection
- Model with shells
- Identify “hot spots” - dual
- Couple with continuum
- Coarse-grain

Nitsche coupling - NURBS-NURBS

1/2 concurrent

level 0 global

level 1 local

thesis A. Akbari
thesis O. Goury
Part III. Application to multi-crack propagation

with Danas Sutula, President Scholar
Numerical Modeling of SOI Wafer Splitting
Physical process

Manufacturing process: SmartCut\textsuperscript{TM}

- H\textsuperscript{+} ionization of a thin surface of Si
- Bonding to a handle-wafer (stiffener)
- High temperature thermal annealing
- Nucleation and growth of cavities filled with H\textsubscript{2}
- Pressure driven micro crack growth
- Coalescence and post-split fracture roughness

![Diagrams showing the manufacturing process with annotations:](image-url)
Objectives

Determine:
- micro crack nucleation points and direction
- multiple crack paths until coalescence
- time to complete fracture
- final surface roughness
Modeling cavities by zero thickness surfaces
• discontinuities in the displacement field

Linear elastic fracture mechanics (LEFM)
• infinite stress at crack tip, i.e. *singularity*

- Cohesive interface with variation in surface energy
- Fracture criterion at the discontinuity tip
- Statistically distributed discontinuities
- Discontinuity subjected to H$_2$ pressure
Extended Finite Element Method (XFEM)

- Introduced by Ted Belytschko (1999) for elastic problems

Fracture of “XFEM” using XFEM
Plate with 300 cracks - vertical extension BCs
Vertical extension of a plate with 300 cracks

Example #1

Post-split roughness
Example #2

Mechanical splitting of a wafer sample
- Post-split roughness as a function of micro crack distribution
Mechanical splitting of a wafer sample

- Discretisation ($\approx$1mln. DOF, $h_e = 150$ nm)

Fracture control parameters
- initial cracked length: $\rho_{crk} = \{10, 30, 50, 70\}$ ($\%$)
- damage thickness: $t_{dmg} = \{100, 300, 500\}$ (nm)
Fracture roughness results:

- Case example:

Example #2

Roughness vs. Percentage cracked (mechanical splitting)

RMS roughness of profile, $R_q$ (µm)

- $t_{dmg} = 100$ (nm)
- $t_{dmg} = 300$ (nm)
- $t_{dmg} = 500$ (nm)
Application to Si-wafer splitting

Mechanical splitting of a wafer
- Post-split roughness as a function of micro crack distribution
- Consider a representative material sample
- BC: blade loading = fixed displacements (RHS)
- 20 initial micro cracks within the damage zone

Physical experiment
Application to Si-wafer splitting

Mechanical splitting of a wafer
• Fracture path comparison: max-hoop crit. VS. energy min.
• NOTE: non-uniform scaling of axis, y / x = 400

Si-wafer splitting using a wedge blade
(comparison of two growth criteria)
Part IV. Application to surgical simulation

with Institute of Advanced Studies (iCube, University of Strasbourg, France: Hadrien Courtecuisse), INRIA, SHACRA Team (Stéphane Cotin, Christian Duriez); Karol Miller, UWA.
The ERC RealTcut project

Surgical simulation (real time/interactivity)

- Reduce the problem size while controlling error in solving very large multiscale mechanics problems

Courteixse et al. PBMB 2011
**Concrete objective:** compute the response of organs during surgical procedures (including cuts) in real time (50-500 solutions per second)

**Two schools of thought**
- constant time
  - accuracy often controlled visually only
- model reduction or “learning”
  - scarce development for biomedical problems
  - no results available for cutting

**Proposed approach:** maximize accuracy for given computational time. Error control

First implicit, interactive method for cutting with contact

[Courtecuisse et al., MICCAI, 2013]
Collaboration INRIA
 offline

**GENERATE** particular solutions

compute asymptotics

instrument action

online: interactive

**sorting** preop

patient-specific mapping

cut-tip enrichment

**POD**

reduced space of small dimension

~10^3 snapshots

~10^6 snapshots

**reduction**

global POD approximation

représentation locale

representing locale
A semi-implicit method for real-time deformation, topological changes, and contact of soft tissues

Paper ID : 269
Acknowledgements
TWO POST DOCS
TWO FACULTY POSITIONS AVAILABLE

OPEN SOURCE CODES

PERMIX: Multiscale, XFEM, large deformation, coupled 2 LAMMPS, ABAQUS, OpenMP - Fortran 2003, C++

MATLAB Codes: XFEM, 3D ISOGEOMETRIC XFEM, 2D ISOGEOMETRIC BEM, 2D MESHLESS

DOWNLOAD @ http://cmechanicsos.users.sourceforge.net/

COMPUTATIONAL MECHANICS DISCUSSION GROUP
Request membership @
http://groups.google.com/group/computational_mechanics_discussion/about
Application to Si-wafer splitting

Mechanical splitting of a wafer

• Comparison of total (potential) energy
Publications - model reduction

- http://orbilu.uni.lu/handle/10993/12024
- http://orbilu.uni.lu/handle/10993/12012
- http://orbilu.uni.lu/handle/10993/10207
- http://orbilu.uni.lu/handle/10993/12454
- http://orbilu.uni.lu/handle/10993/12453
- http://orbilu.uni.lu/handle/10993/14475
- http://orbilu.uni.lu/handle/10993/10206
Mesh-burden reduction

- http://orbi.lu/uni.lu/handle/10993/12159
- http://orbi.lu/uni.lu/handle/10993/14135
- http://orbi.lu/uni.lu/handle/10993/13847
- http://orbi.lu/uni.lu/handle/10993/12157
- http://orbi.lu/uni.lu/handle/10993/11850
Demos

• Surgical simulation
  • http://www.youtube.com/watch?v=KqM7rh6sE8s
  • http://www.youtube.com/watch?v=DYBRKbEiHj8

• Multi-crack growth
  • http://www.youtube.com/watch?v=6yPb6NXnex8
  • http://www.youtube.com/watch?v=7U2o5bFvj8E
Demos

- http://www.youtube.com/watch?v=90NAq76mVmQ
- Solder joint durability
  - http://www.youtube.com/watch?v=Ri96Wv6zBNU
  - http://www.youtube.com/watch?v=1g3Pe_9XN9I
Damage tolerance assessment directly from CAD

- http://www.youtube.com/watch?v=RV0gidOT0-U
- http://www.youtube.com/watch?v=cYhaj6SPLTE
- http://orbilu.uni.lu/handle/10993/12159
- http://orbilu.uni.lu/handle/10993/14135
- http://orbilu.uni.lu/handle/10993/13847
- http://orbilu.uni.lu/handle/10993/12157
Damage tolerance analysis directly from CAD

http://orbilu.uni.lu/handle/10993/11850
Isogeometric analysis


Isogeometric boundary element analysis using unstructured T-splines
MA Scott, RN Simpson, JA Evans, S Lipton, SPA Bordas, TJR Hughes, TW Sederberg


TWO POST DOCS
TWO FACULTY POSITIONS AVAILABLE

OPEN SOURCE CODES

PERMIX: Multiscale, XFEM, large deformation, coupled 2 LAMMPS, ABAQUS, OpenMP - Fortran 2003, C++

MATLAB Codes: XFEM, 3D ISOGEOMETRIC XFEM, 2D ISOGEOMETRIC BEM, 2D MESHLESS
DOWNLOAD @ http://cmechanicsos.users.sourceforge.net/

COMPUTATIONAL MECHANICS DISCUSSION GROUP
Request membership @ http://groups.google.com/group/computational_mechanics_discussion/about
Publications - model reduction

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  • http://www.youtube.com/watch?v=DYBRKbEiHj8

• Multi-crack growth
  • http://www.youtube.com/watch?v=6yPb6NXnex8
  • http://www.youtube.com/watch?v=7U2o5bFvj8E
Demos

- [http://www.youtube.com/watch?v=90NAq76mVmQ](http://www.youtube.com/watch?v=90NAq76mVmQ)
- Solder joint durability
  - [http://www.youtube.com/watch?v=Ri96Wv6zBNU](http://www.youtube.com/watch?v=Ri96Wv6zBNU)
  - [http://www.youtube.com/watch?v=1g3Pe_9XN9l](http://www.youtube.com/watch?v=1g3Pe_9XN9l)
Damage tolerance assessment directly from CAD

- http://www.youtube.com/watch?v=RV0gidOT0-U
- http://www.youtube.com/watch?v=cYhaj6SPLTE
- http://orbilu.uni.lu/handle/10993/12159
- http://orbilu.uni.lu/handle/10993/14135
- http://orbilu.uni.lu/handle/10993/13847
- http://orbilu.uni.lu/handle/10993/12157
Damage tolerance analysis directly from CAD

• http://orbilu.uni.lu/handle/10993/11850
Peer reviewed
ORBi viewed: 21 (2 UL); downloaded: 1 — WOS: - — SCOPUS®: -
IF last: 1.383; IF5: 1.216 — EigenF last: 0.0028 — Article Infl. last: 0.2163

Peer reviewed
ORBi viewed: 128 (7 UL); downloaded: 19 (1 UL) — WOS: - — SCOPUS®: -
IF last: 2.432; IF5: 2.314 — EigenF last: 0.0107 — Article Infl. last: 1.0463

Peer reviewed
ORBi viewed: 27 (1 UL); downloaded: 0 — WOS: - — SCOPUS®: 0
IF last: 1.509; IF5: 2.000 — EigenF last: 0.0134 — Article Infl. last: 0.9159
http://hdl.handle.net/10993/15781
Peer reviewed
ORBilu viewed: 15 (1 UL); downloaded: 30 (2 UL) — WOS: - — SCOPUS®: -

http://hdl.handle.net/10993/14452
Peer reviewed
ORBilu viewed: 17 (2 UL); downloaded: 6 — WOS: 0 — SCOPUS®: 0
IF 2014: ?; last: 2.06; IF5: 2.295 — EigenF: — Article Infl.: ?; last: 1.0545

http://hdl.handle.net/10993/12316
Peer reviewed
ORBilu viewed: 283 (4 UL); downloaded: 134 (1 UL) — WOS: 1 — SCOPUS®: 1

http://hdl.handle.net/10993/15809
Peer reviewed
ORBilu viewed: 112 (4 UL); downloaded: 69 (1 UL) — WOS: 0 — SCOPUS®: 0

http://hdl.handle.net/10993/15814
Peer reviewed
ORBilu viewed: 7 (2 UL); downloaded: 1 — WOS: - — SCOPUS®: -
IF 2014: ?; last: 1.212; IF5: 1.425 — EigenF: — Article Infl.: ?; last: 0.6648

http://hdl.handle.net/10993/12317
Peer reviewed
ORBilu viewed: 32 (1 UL); downloaded: 2 — WOS: - — SCOPUS®: 0
IF 2014: ?; last: 2.331; IF5: 2.550 — EigenF 2013: ?; last: 0.0182 — Article Infl. 2013: ?; last: 0.6988

http://hdl.handle.net/10993/12379
Peer reviewed
ORBilu viewed: 30 (1 UL); downloaded: 2 — WOS: 0 — SCOPUS®: -
IF 2013: ?; last: 2.231; IF5: 2.550 — EigenF 2013: ?; last: 0.0182 — Article Infl. 2013: ?; last: 0.6988

http://hdl.handle.net/10993/12117
Peer reviewed
ORBilu viewed: 15; downloaded: 14 — WOS: - — SCOPUS®: -

http://hdl.handle.net/10993/13772
Peer reviewed
ORBilu viewed: 15 (1 UL); downloaded: 8 — WOS: 10 — SCOPUS®: 10
IF 2013: ?; last: 2.331; IF5: 2.550 — EigenF 2013: ?; last: 0.0182 — Article Infl. 2013: ?; last: 0.6988
Peer reviewed
ORBilu viewed: 377 (9 UL); downloaded: 207 (4 UL) — WOS: — SCOPUS®: 1

Peer reviewed
ORBilu viewed: 126 (14 UL); downloaded: 38 (3 UL) — WOS: — SCOPUS®: 3

Peer reviewed
ORBilu viewed: 9; downloaded: 2 — WOS: — SCOPUS®: 0

Peer reviewed
ORBilu viewed: 18; downloaded: 36 — WOS: — SCOPUS®: 0

Peer reviewed
ORBilu viewed: 11; downloaded: 11 — WOS: — SCOPUS®: 0

Peer reviewed
ORBilu viewed: 8 (1 UL); downloaded: 2 — WOS: — SCOPUS®: 0

Peer reviewed
ORBilu viewed: 51 (5 UL); downloaded: 57 (5 UL) — WOS: 4 — SCOPUS®: 6

Peer reviewed
ORBilu viewed: 15 (2 UL); downloaded: 5 — WOS: — SCOPUS®: 0

Peer reviewed
ORBilu viewed: 39 (2 UL); downloaded: 2 — WOS: — SCOPUS®: 2
Peer reviewed
ORBilu viewed: 22 (2 UL); downloaded: 27 (1 UL) — WOS: - — SCOPUS®: 1

Peer reviewed
ORBilu viewed: 23 (1 UL); downloaded: 5 (2 UL) — WOS: 0 — SCOPUS®: 1

Peer reviewed
ORBilu viewed: 15 (1 UL); downloaded: 24 — WOS: - — SCOPUS®: -
IF: 2013: ?; last: 2.143; IFS: 2.466 — EigenF: — Article Infl.: — WOS: — SCOPUS®: -

Peer reviewed
ORBilu viewed: 7; downloaded: 2 — WOS: 3 — SCOPUS®: 4

Peer reviewed
ORBilu viewed: 42 (7 UL); downloaded: 8 — WOS: - — SCOPUS®: 0
IF: 2013: ?; last: 2.432; IFS: 2.314 — EigenF: — Article Infl.: — WOS: 0 — SCOPUS®: 0

Peer reviewed
ORBilu viewed: 63 (1 UL); downloaded: 60 — WOS: 2 — SCOPUS®: 3

Peer reviewed
ORBilu viewed: 11 (3 UL); downloaded: 4 (2 UL) — WOS: - — SCOPUS®: 0

Peer reviewed
ORBilu viewed: 84 (6 UL); downloaded: 25 (1 UL) — WOS: 8 — SCOPUS®: 15

Peer reviewed
ORBilu viewed: 13; downloaded: 5 — WOS: 2 — SCOPUS®: 3

Peer reviewed
ORBilu viewed: 5 ; downloaded: 4 — WOS: 10 — SCOPUS®: 10


Peer reviewed
ORBilu viewed: 10 ; downloaded: 15 — WOS: 0 — SCOPUS®: 0
IF 2013: ?; last: 2.315; IF5: 2.598 — EigenF 2013: ?; last: 0.0419 — Article Infl.: 10 — WOS: 0 — SCOPUS®: 0


Peer reviewed
ORBilu viewed: 23 (1 UL) ; downloaded: 9 — WOS: 0 — SCOPUS®: 0
IF 2013: ?; last: 2.432; IF5: 2.314 — EigenF: — Article Infl.: 15 — WOS: 0 — SCOPUS®: 0


Peer reviewed
ORBilu viewed: 15 (2 UL) ; downloaded: 13 — WOS: 0 — SCOPUS®: 0
IF 2013: ?; last: 3.406; IF5: 3.746 — EigenF: — Article Infl.: 35 — WOS: 0 — SCOPUS®: 0


Peer reviewed
ORBilu viewed: 4 ; downloaded: 3 — WOS: 1 — SCOPUS®: 4
IF 2012: 1.214; last: 1.214; IF5: 1.286 — EigenF: — Article Infl.: 36 — WOS: 0 — SCOPUS®: 0


Peer reviewed
ORBilu viewed: 12 ; downloaded: 3 — WOS: - — SCOPUS®: 0
IF 2012: 1.882; last: 1.659; IF5: 1.608 — EigenF: — Article Infl.: 37 — WOS: - — SCOPUS®: -


Peer reviewed
ORBilu viewed: 45 (4 UL) ; downloaded: 21 — WOS: 8 — SCOPUS®: 11
IF 2012: 2.068; last: 2.068; IF5: 2.295 — EigenF: — Article Infl.: 38 — WOS: - — SCOPUS®: -


Peer reviewed
ORBilu viewed: 50 ; downloaded: 24 — WOS: - — SCOPUS®: -
IF 2012: 1.486; last: 1.917; IF5: 2.307 — EigenF: — Article Infl.: 39 — WOS: - — SCOPUS®: -


Peer reviewed
ORBilu viewed: 9 ; downloaded: 0 — WOS: 0 — SCOPUS®: 0

Peer reviewed

ORBilu viewed: 7 ; downloaded: 5 — WOS: - — SCOPUS®: 0


Peer reviewed

ORBilu viewed: 10 ; downloaded: 8 — WOS: - — SCOPUS®: 0


Peer reviewed

ORBilu viewed: 6 ; downloaded: 0 — WOS: 18 — SCOPUS®: 22

IF 2012: 2.617; last: 2.617; IF5: 2.738 — EigenF: — Article Infl.: 1


Peer reviewed

ORBilu viewed: 4 ; downloaded: 0 — WOS: 8 — SCOPUS®: 9

IF 2011: 0.675; last: 0.460; IF5: 0.668 — EigenF 2011: 0.0033; last: 0.0033 — Article Infl. 2011: 0.4159; last: 0.4159


Peer reviewed

ORBilu viewed: 4 ; downloaded: 0 — WOS: 33 — SCOPUS®: 35

IF 2011: 2.009; last: 2.068; IF5: 2.295 — EigenF: — Article Infl.: 1


Peer reviewed

ORBilu viewed: 4 ; downloaded: 0 — WOS: 33 — SCOPUS®: 35

IF 2011: 2.009; last: 2.068; IF5: 2.295 — EigenF: — Article Infl.: 1


Peer reviewed

ORBilu viewed: 27 (3 UL) ; downloaded: 10 — WOS: 17 — SCOPUS®: 24

IF 2011: 2.651; last: 2.617; IF5: 2.738 — EigenF 2011: 0.0041; last: 0.0041 — Article Infl. 2011: 1.327; last: 1.327


Peer reviewed

ORBilu viewed: 8 ; downloaded: 0 — WOS: 15 — SCOPUS®: 17

IF 2011: 2.651; last: 2.617; IF5: 2.738 — EigenF 2011: 0.0041; last: 0.0041 — Article Infl. 2011: 1.327; last: 1.327


Peer reviewed

ORBilu viewed: 3 ; downloaded: 0 — WOS: 18 — SCOPUS®: 17

IF 2011: 2.240; last: ; IF5: - — EigenF: — Article Infl.:
http://hdl.handle.net/10993/11865
Peer reviewed
ORBilu viewed: 3; downloaded: 0 — WOS: 6 — SCOPUS®: 8
IF 2011: 1.874; last: 1.509; IF5: 2.000 — EigenF 2011: 0.0134; last: 0.0134 — Article Infl. 2011: 0.9159; last: 0.9159

http://hdl.handle.net/10993/13773
Peer reviewed
ORBilu viewed: 7 (2 UL); downloaded: 0 — WOS: 7 — SCOPUS®: 3
IF 2010: 1.928; last: 0.849; IF5: 0.956 — EigenF 2010: 0.0061 — Article Infl. 2010: 0.4402

http://hdl.handle.net/10993/11866
Peer reviewed
ORBilu viewed: 11; downloaded: 0 — WOS: 80 — SCOPUS®: 80
IF 2010: 1.722; last: 1.509; IF5: 2.000 — EigenF 2010: 0.0154; last: 0.0134 — Article Infl. 2010: 0.9105; last: 0.9159

http://hdl.handle.net/10993/12116
Peer reviewed
ORBilu viewed: 10; downloaded: 1 (1 UL) — WOS: 18 — SCOPUS®: 19
IF 2010: 1.928; last: 0.849; IF5: 0.956 — Article Infl. 2010: 0.9159

http://hdl.handle.net/10993/12327
Peer reviewed
ORBilu viewed: 13; downloaded: 0 — WOS: 0 — SCOPUS®: 0

http://hdl.handle.net/10993/11873
Peer reviewed
ORBilu viewed: 7; downloaded: 0 — WOS: 25 — SCOPUS®: 30
IF 2010: 1.928; last: 0.849; IF5: 0.956 — Article Infl. 2010: 0.9159

http://hdl.handle.net/10993/15307
Peer reviewed
ORBilu viewed: 2; downloaded: 0 — WOS: 27 — SCOPUS®: 30
IF 2010: 2.085; last: 2.617; IF5: 2.738 — EigenF 2010: 0.0403; last: 0.0401 — Article Infl. 2010: 1.2625; last: 1.327

http://hdl.handle.net/10993/12115
Peer reviewed
ORBilu viewed: 8; downloaded: 0 — WOS: 35 — SCOPUS®: 43
IF 2009: 2.025; last: 2.068; IF5: 2.295 — EigenF: — Article Infl.: 0.9105

http://hdl.handle.net/10993/15308
Peer reviewed
ORBilu viewed: 3; downloaded: 0 — WOS: 33 — SCOPUS®: 37
IF 2008: 2.229; last: 2.068; IF5: 2.295 — EigenF: — Article Infl.: 0.9105
http://hdl.handle.net/10993/15333
Peer reviewed

ORBilu viewed: 2 — WOS: 18 — SCOPUS®: 0

http://hdl.handle.net/10993/13726
Peer reviewed

ORBilu viewed: 29 (1 UL); downloaded: 36 — WOS: 202 — SCOPUS®: 240
IF 2008: 0.930; last: 0.836; IF5: 1.033 — EigenF 2008: 0.0052; last: 0.0068 — Article Infl. 2008: 0.3584; last: 0.4252

http://hdl.handle.net/10993/15234
Peer reviewed

ORBilu viewed: 146 (1 UL); downloaded: 92 — WOS: 73 — SCOPUS®: 85
IF 2007: 1.612; last: 2.068; IF5: 2.295 — EigenF: — Article Infl.: —

http://hdl.handle.net/10993/14470
Peer reviewed

ORBilu viewed: 6 ; downloaded: 7 — WOS: 68 — SCOPUS®: 77
IF 2006: 1.390