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Image-based Micromechanics Analysis Using Level Sets and the Extended Finite Elements Method

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With the emergence of novel ways of characterizing complex material microstructures, computational methods to correspond in versatility are developed and evolve. This paper presents the advantages of using a numerical method that couples the level set method with the extended finite element method (X-FEM) applied to solving problems of micromechanics from a digital image representation of the microstructure.

The use of level sets techniques in the context of image segmentation leads to a precise representation of the geometry, the advantage of this technique being that changes in topology are handled implicitly. A user initialized contour is evolved based on image features such as grayscale intensity, gradient magnitude or image edges. The present application uses the Insight Toolkit (ITK) [1] for building the image segmentation application tailored to the specific needs of treating images of material microstructures. For each image the user has to specify the threshold of intensity values and an initial level set model. The level set solution is calculated to subpixel precision [7], and interpolated at pixel level. For a two phase material, the level set value corresponds to the distance to the material interface, with a positive or negative sign according to the phase.

The X-FEM method is used to solve the mechanical problem posed on the microstructure. One of the very attractive features of the X-FEM, especially when tackling complex geometry problems, is that the formulation does not require a conforming mesh. Rather, a regular mesh is constructed independent of the geometry and the physical boundaries read into the X-FEM algorithm in the level set form such that the elements intersected by the physical interface(s) are enriched. The enrichment function is chosen to express a strain jump at the interface, and is defined from the level-sets nodal values.

The capabilities of the coupling between the X-FEM and the level set method for micromechanics applications have been shown in [2], but the applications were restricted to microstructures with material interfaces that can be described by analytical level sets. This work advances the method one step further, presenting the process of obtaining the level set information corresponding to a digital image of a material structure and using it in setting up and solving an X-FEM problem, as illustrated in Fig. 1.

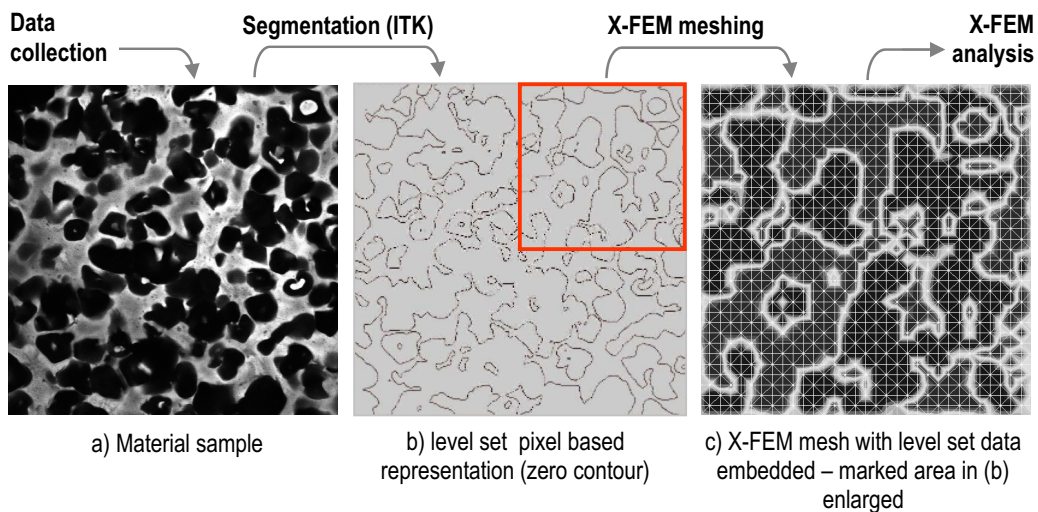


Fig. 1 : Numerical algorithm: the digital image (a) is digitized and segmented using a level set threshold based segmentation filter (b) and the X-FEM mesh is constructed incorporating the level set data in the enriched elements (c).

In this work, this numerical framework is used to obtain the overall elastic properties of an heterogeneous material, solving a homogenization problem posed on its microstructure. Since the materials studied here can not be considered as periodic media, their effective properties are computed using an homogenization scheme with homogeneous kinematic boundary conditions.

In order to illustrate the present approach, starch based organic composite sample is studied. In addition to determining the effective properties of the structure, the question of the size of the representative volume element (RVE) arises. Following the method described in [3], subdivisions of the original sample are considered and the effective properties are determined for each sample; regular subdivisions of the image in 4, 16, and 64 samples are analyzed: the pixel based level set data is obtained using a threshold level set filter based on the image intensity and the X-FEM mesh is constructed, after an initial assessment of the sensitivity of the results with elements' size. The evolution of the Young's modulus with sample size is recorded in Fig. 2b. Given the small disparity between the two phases a rapid convergence is obtained. The iso-values of the Von-Mises stresses for a shear macro-strain are shown Fig. 2a, for a mesh with two elements per pixel.

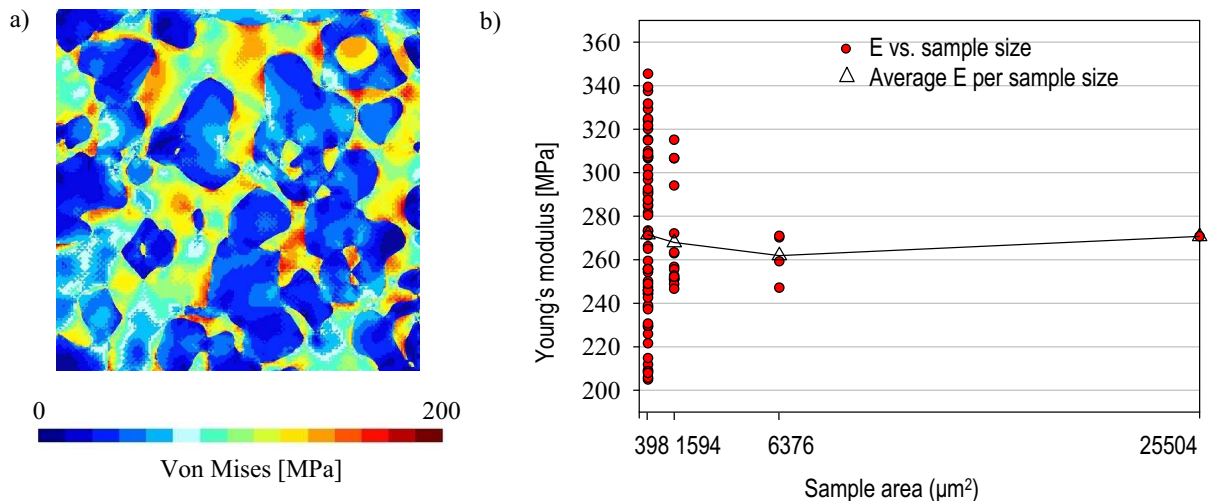


Fig. 2: a) Von Mises stresses corresponding to the shearing micro-mode for a $\frac{1}{4}$ area sample of the original; b) Young's modulus variation as a function of sample size.

In summary, this study demonstrates the feasibility of using level sets and the X-FEM for treating problems of micromechanics. The method offers a direct way to treat problems of complex microstructures taking advantage of the versatility of level sets and the non-conforming meshing algorithm of X-FEM. It can be applied equally well to two- or three- dimensional imaging data. Our ongoing effort is directed towards implementing an adaptive octree mesh algorithm, such that the element size will be dictated by the distance to the material interface.

Main references

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- [2] Moës, N., Cloirec, M., Cartraud, P., and Remacle, J.-F., 2003, "A computational approach to handle complex microstructure geometries", *Computer Methods in Applied Mechanics and Engineering*, 192, pp. 3163-3177.
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