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Evgeniia Lapina, Paul Oumaziz, Robin Bouclier. Isogeometric LaTIn method for non-linear simulation with multiple frictional contacts. 25ème Congrès Français de Mécanique, Aug 2022, Nantes, France. hal-03774136

HAL Id: hal-03774136

<https://hal.science/hal-03774136v1>

Submitted on 9 Sep 2022

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Isogeometric LaTIn method for non-linear simulation with multiple frictional contacts

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Résumé :

Avec le développement des techniques d'imagerie volumique, on peut désormais construire des modèles mécaniques d'un matériau à l'échelle de sa microstructure à partir des images 3D d'un échantillon. Cependant, le calcul de tels modèles pour des applications réelles reste un défi. L'objectif de ce travail est de présenter une approche numérique pour simuler les matériaux composites renforcés en fibres avec un comportement non-linéaire à l'interface. La contribution de ce travail est l'utilisation de la méthode de décomposition de domaine mixte appelée LaTIn avec des techniques de frontières immergées (méthode de domaine fictif) dans le cadre de l'IGA. L'algorithme proposé permet d'éviter une phase de maillage délicate de telles structures géométriquement complexes. L'algorithme présente des résultats précis sur un problème académique, où une matrice avec une inclusion est considérée avec un comportement de contact sur l'interface. Au cours de la présentation, des exemples de telles inclusions multiples et des lois cohésives aux interfaces seront présentés pour démontrer l'efficacité de l'algorithme dans des contextes plus généraux.

Abstract :

With the development of volume imaging techniques, one can now build mechanical models of a material at the microstructure scale from 3D images of a sample. However, computation of such models for real applications is still challenging. The aim of this work is to present a numerical approach to simulate fibre-reinforced composite materials with non-linear interface behaviour. The contribution of the present work is the use of the mixed domain decomposition method called LaTIn together with immersed boundary techniques in the framework of IGA. The proposed algorithm avoids a delicate meshing phase of such geometrically complex structures. It exhibits accurate results on an academic problem, where a matrix with one inclusion is considered with contact behaviour on the interface. During the presentation, examples of such multiple inclusions and cohesive laws on the interfaces will be presented to demonstrate the efficiency of the algorithm in more general contexts.

Mots clefs : LaTIn method, IGA, Frictional contact, Nonconforming interface, Parallel computing

1 Introduction

The development of volume imaging techniques (MRI, scanner, ultrasound, optical coherence tomography, etc.) now makes it possible to obtain 3D images of a sample at the scale of its microstructure. One can then build mechanical models from these images. With such models, characterization of the mechanical properties of materials at their microstructure scale becomes feasible. For instance, imaged-based models have recently been used in material science to simulate foam-like structures [10]. On the experimental side, these models are used to regularize field measurement from image registration [8]. Moreover, they have been used in biomedical domain for patient-specific simulation [3, 11, 10].

However, the computation of the image-based models still seems out of reach for real mechanical applications. Indeed, these models are associated with massive data and need to incorporate complex non-linear behaviours. The present work aims to simulate fibre-reinforced composite materials. In this context, since numerous irregularly-shaped inclusions can be present, meshing becomes a challenging task.

As a first step towards High-Performance Computing (HPC), the present work utilizes IsoGeometric Analysis (IGA). Introduced by Hughes ([5]), IGA proposes to use splines Non-Uniform Rational B-Splines (NURBS) not only for the representation of the geometry, but also for the solution fields approximation (see, e.g. [1] for a recent review). A distinctive feature of IGA is the smoothness of its basis functions. Indeed, NURBS are $C^{(p-1)}$ regular between elements for a polynomial degree p , while Lagrange polynomials, which are used in FEM, attain only C^0 regularity at these locations. As a result, IGA exhibits a better approximation per number of degrees of freedom than the FEM to capture smooth solution. Thus, IGA is of a particular use when HPC is requested.

However, modelling geometrically complex objects can be challenging. To tackle the geometrical complexity of 3D objects, IGA is used in combination with immersed boundary approaches [10, 11, 12]. Indeed, immersed techniques allow to benefit from regular Cartesian meshes and alleviate cumbersome meshing process while modelling geometrically complex objects. In recent works IGA has been combined with the fictitious domain approach to compute, for instance, the effective elastic properties of a microstructure sample [11]. As another example, immersed IGA has been used to model fiber-reinforced composites in the context of linear elasticity [12].

Another hindrance in composite modelling is related to the computation of strongly non-linear behaviours. As a preliminary stage, contact behaviour on the matrix/fibre interface is considered in this work while materials are supposed linear elastic. In order to model contact behaviour, LaTIn-based solvers have been used in a wide range of mechanical problems. For instance, together with an immersed approach (CutFEM), LaTIn has been recently used to model multiple body contact [4]. The LaTIn method has also been implemented in a noninvasive way to simulate 3D structure involving many interfaces with frictional contact [7]. But so far and up to our knowledge, the works have considered the LaTIn within the framework of Finite Element Method (FEM) and it has not been developed in the context of IGA. It is important to note that the LaTIn method lend itself to parallel computation. This trait is of a paramount importance since HPC is requested for massive data models of composite materials with numerous fibres.

Finally, coupling of matrix and fibre models is severely non-conformal. In the present work, non-conformal coupling is performed through Nitsche's approach. It has shown optimal convergence behaviour for global/local analysis [2]. Moreover, in contrast to its Lagrange counterpart, Nitsche's method does not require additional degrees of freedom and avoids numerical instabilities, such as mesh locking [9].

2 Methodology

We aim to simulate a composite with fibrous reinforcements. As mentioned above, non-linear fibre-matrix interface and non-conformal coupling are of particular difficulty in microstructure simulation. To solve the problem, we propose a pragmatic strategy that consists of separating the non-linear and non-conforming difficulties. To illustrate our method, we start by considering only one fibre in a matrix. We follow here the idea put forward in [12]; that is, two conformal layers are built around the non-linear matrix-fibre interface Γ , see FIGURE1. Interface Γ_i (respectively Γ_m) is a but non-conforming perfect interface inside inclusion (resp. matrix) model.

We emphasize that even though interfaces Γ_i and Γ_m are non-conformal, they do not perform any non-linear behaviour. In contrast, the matrix/fibre interface Γ is conformal; however, non-linear behaviour is allowed. This conformal coupling is done with the use of the LaTIn method so that multiple inclusions can be calculated in parallel.

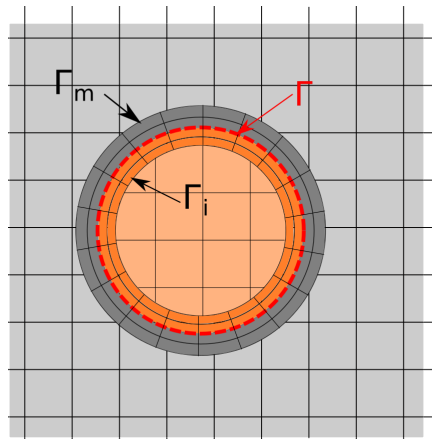


FIGURE 1 – An inclusion and matrix model with two conformal layers. Grey colour corresponds to the matrix, tangerine - to the inclusion.

In this context, the LaTIn method relies on the two following principles.

1. The equations are separated into two groups: local non-linear equations that describe the matrix/fibre interface contact behaviour and global linear equations relative to a subdomain (matrix or fibre model). This results in two spaces of partial solutions: space \mathcal{A} of the solutions that verify the equilibrium of subdomains, space \mathcal{L} of the solutions that verify the interface behaviour.
2. A two-stage iterative approach is applied, where the first stage is local non-linear and the second is global linear. The scheme is characterized by two search directions: k^+ to go from \mathcal{A} to \mathcal{L} , k^- to go from \mathcal{L} to \mathcal{A} .
 - (a) Local non-linear stage: for a known solution $S_i \in \mathcal{A}$ find a solution $\hat{S}_i \in \mathcal{L}$ following the search direction k^+ .
 - (b) Global linear stage: for a known solution $\hat{S}_i \in \mathcal{L}$ find a solution $S_{i+1} \in \mathcal{A}$ following the search direction k^- .

FIGURE2 depicts a graphical representation of the LaTIn method. As we noted previously, the LaTIn method favours parallel computation. Indeed, since the model is decomposed into subdomains, the global stage can be solved in parallel for each subdomain. Non-linear stage equations are solved locally and explicitly; therefore, can also be very efficiently parallelized. It should be noted that in a FEM framework

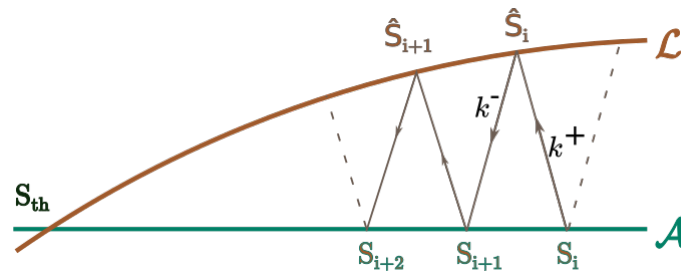


FIGURE 2 – Graphical representation of the LaTIn method.

local equations can be written directly in the model nodes. However, for spline models this strategy is not possible since the control points do not live on the structure. Thus, in the present work, local non-linear equations describing contact interface behaviour are solved at integration points.

As mentioned above, the layers are coupled through Nitsche's method with the matrix or fibre models (non-conformal interfaces Γ_m and Γ_i respectively). These models use the fictitious domain approach. The key idea is to embed a geometrically complex physical domain in a larger, simpler one. In order to take into account in a precise way physical boundaries, specific quadrature rules are used for building stiffness operators (such based on the quad-tree scheme [8]).

3 Numerical results

In this section, we study an academic problem. We consider a matrix with one inclusion; see FIGURE3 for the problem setting. Both matrix and inclusion materials are linear elastic, and we assume plane stress state and small deformations. Contact behaviour without friction is considered on the matrix/inclusion interface. Due to the symmetry of the problem, only one quarter of the area can be modelled with corresponding symmetrical boundary conditions.

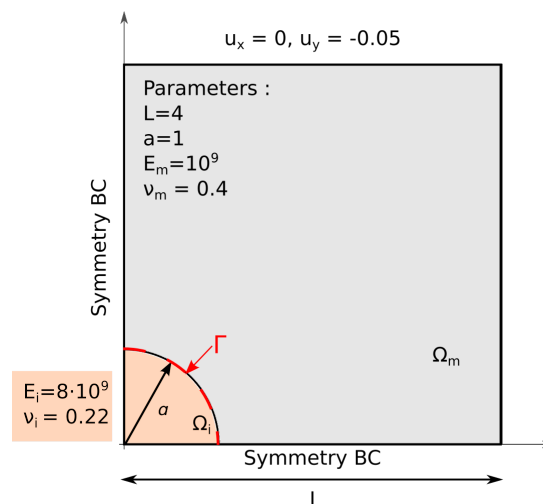


FIGURE 3 – problem settings.

We decompose the model into two independent subdomains corresponding to the matrix and to the inclusion. Then, following [12], in each model we add two conformal layers on the matrix/inclusion interface (see FIGURE4). Thus, each subdomain consists of two parts: a conformal layer and a regular

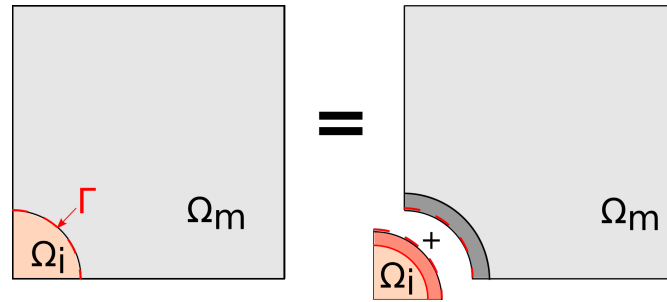


FIGURE 4 – model decomposition

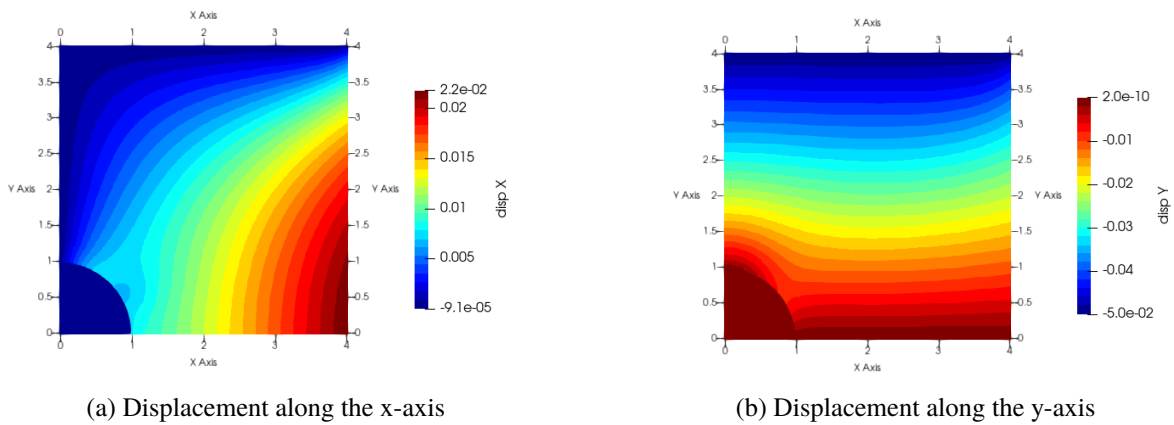


FIGURE 5 – Displacement components for the problem of a matrix with a circular inclusion.

background mesh. Each layer is coupled through Nitsche's method with its corresponding model (matrix or inclusion). Together, the subdomains are connected through the LaTin method by the boundary Γ . We recall that this technique precludes us from simultaneous treatment of non-conformal interface and contact behaviour.

Each layer contained 32×32 elements, each fictitious domain model - 80×80 elements. NURBS of degree 2 have been used. FIGURE5 shows obtained displacement. It can be noticed that, since the displacements are not continuous everywhere, interface Γ is not entirely in contact. FIGURE6 depicts vertical displacement near the inclusion on a deformed geometry with a scale factor of 10.

In order to validate the algorithm, we compare our solution to a reference one. To this end, we have performed a finite element simulation with the use of Salome Meca software. FE mesh contained 158497 linear

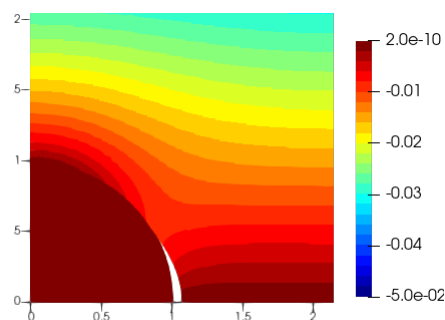


FIGURE 6 – Vertical displacement near the inclusion. Deformed geometry with a scale factor of 10.

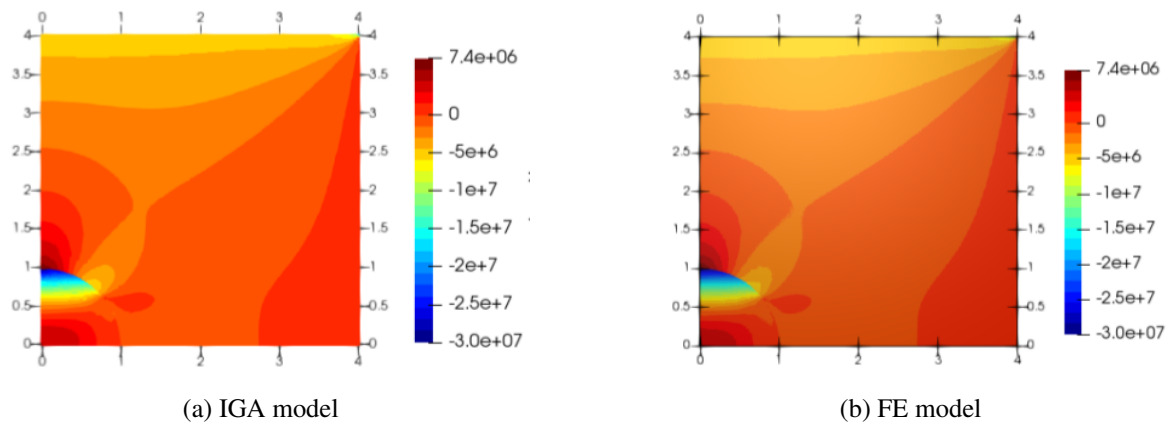


FIGURE 7 – normal stress σ_{xx} for the problem of a matrix with a circular inclusion.

elements. Stresses obtained by our algorithm and FE simulation are depicted in FIGURE7a and FIGURE7b respectively. Results of our algorithm are in a good agreement with the FE results.

4 Conclusion and perspectives

We have presented an approach to treat contact problems with the use of the LaTIn method in the framework of IGA. The proposed approach benefits from the fictitious domain method along with the immersed boundary technique. Thus, it alleviates the cumbersome meshing process and avoids dealing with non-linear behaviour and non-conformal coupling concurrently. Moreover, the LaTIn method lends itself to parallel computations. Therefore, the presented approach can be parallelized in case of a model with multiple inclusions. The proposed algorithm exhibits accurate results on an academic problem, where a matrix with one inclusion is considered with contact behaviour on the interface. During the presentation, examples with multiple inclusions and cohesive laws on the interfaces will be presented.

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