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An efficient multi-scale method for non-linear analysis of composite structures

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ABSTRACT

The use of multi-scale procedures is encouraged by the continuous increase of computational capacity, but it is still a challenge performing a non-linear analysis of real composite structures without the aid of large computers. This work proposes a strategy to conduct non-linear multi-scale analysis in an efficient way. The proposed method considers that in a large structure, in general, material non-linear processes only take place in a localized region (or in a reduced number of finite elements, if a FE method is used). The strategy determines the elements that require a non-linear analysis defining of a non-linear activation function that accounts for the failure of the most critical point in the microstructure. The procedure conserves the dissipated energy through the scales, being mesh independent as the mesh objectivity concept is extended to the microstructure. The validity of the strategy proposed is proved with the analysis of academic examples showing not only the mesh independency but also the reduction of computational cost. Finally, an industrial composite component is solved using a standard computer, showing that the proposed strategy is capable of reducing the computational cost from 32 days and 14 hours (required by a classical multi-scale method) to less than 12 hours.

1. Introduction

Composite materials are not like simple materials because they are internally a complex structure. Therefore, composites required specific formulations that the ones used in single materials. For a linear analysis or a study of maximum load it is enough with one orthotropic material characterization and a law with some complexity to predict the break of the structure (such as, maximum strain criterion [1], tsai-wu criterion [2], etc). However, numerical methods have allowed the simulation of structures beyond their elastic limit, and then it is possible obtain the post critic behavior of the structure and its tenacity and structural integrity can be estimate.

The complexity of composites has promoted that different formulations appear to predict their behavior, which are more o less suitable according to computational cost available, the accuracy in the results desired or even the expected failure type. In the following, some of the most relevant formulations are described.

One possibility to simulate structures of composite materials which have complex microstructures is to use phenomenological homogenizations. The most common method is the classical mixing theory, which obtains the behavior of the composite from the mechanical performance of the composite components, these are simulated with its own constitutive law [3]. Afterward, Oller [4] generalizes the theory to enable the resolution of any composite with reinforced matrix, without the limitation required by the compatibility equation. On the other hand, in the SP [5] continuum approach the mechanic characteristic of the composite are obtained using the properties of each component and taking into account its topological distribution. This serial/parallel (SP) mixing theory assumes a serial-parallel self-adjusting behavior to the topological distribution of fiber embedded in the matrix of the composite material. Recently, one extension of the mixing theory for the study of matrices reinforced with nanotubes has also been developed [6]. All these theories have proved to be able to reproduce not only mechanic properties of composites but to solve non-linear problems also [7–9]. It is necessary to say that in some particular cases, when the damage is located in one lamina, how in a delamination process, the SP theory may lack accuracy [10].

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List of acronyms

DDM	Discrete Damage Mechanics	RVE	Representative Volume Element
FE	Finite Element	SFS	Smart First Step
NLAF	Non-Linear Activation Function	SP	Serial Parallel
NLS	Non-Linear Strategy		
POD	Proper Orthogonal Decomposition		

To simulate laminated composites, one alternative to the previous methodologies described is the Discrete Damage Mechanics (DDM) models [11,12]. The stiffness reduction due to transverse matrix cracking in laminates with symmetric but with arbitrary laminate stacking sequence, subject to in-plane stress, is obtained for the laminae [11]. The properties of the damaged laminates only depend of the crack densities of the damaged laminae. The crack density evolution is derived in term of the strain energy release rate. This procedure showed that it can predict the initiation and evolution of the matrix cracking, and the stress redistribution in the laminae. Recently, the described method was extended to predict the laminate failure throughout including fiber failure [13]. A Weibull statistical distribution is used to characterize fiber failure and it is incorporated to [11] using a simple fiber damage model. Therefore, the laminate properties now depend of the fiber damage in the laminae too.

On the other hand, Sanchez-Palencia [14] and Suquet [15] laid the foundation of what today is known as first-order homogenization methods. The macroscopic deformation gradient tensor is used to solve the problem at the microstructural scale and then the macroscopic stress tensor is obtained using the averaging equation [16,17]. Later, Suquet uses the method of average described to solve and extend the problem of two scales to non-linear range [18]. Over time, thanks to the work to several authors, the method was extended to large deformations with arbitrary non-linear material behavior at the microsctructural scale [19–24].

Geers and Kouznetsova proposed what is called second-order homogenization [25–27], which is an extension of the first-order theory. In this case, the macroscopic deformation gradient tensor and its Lagrangian gradient is used to solve the boundary value problem at the microstructural scale. The second-order approach allows solve problems in the presence of localization phenomena without loss of precision in the solution because the Lagrangian tensor is taken into account. The main drawbacks of this method are its computational cost and complex implementation.

Continuous–discontinuous homogenization method has been developed in the context of masonry [28]. The methodology incorporates a localization band in the macrostructural scale and using the first-order homogenization concepts solve the damaged zone (in the localization band) and the undamaged zone. However, the localization band has a fixed size and need to be located at the beginning. Besides, the approach loses the benefits of the homogenization ideas and it is more similar to a domain decomposition with a refined subscale. Other phenomenological and homogenization models specifically applied to masonry can be found in references [29–31].

Computational homogenization approach is adopted to solve interface volume with cohesive zone [32]. The cohesive zone (using a traction-opening concept) is coupled with a microstructural scale with finite dimension. The boundary value problem at the microstructure is solved using the macrostructural scale kinematics (interface opening vector).

The approach used in current work is a multi-scale homogenization based on a Representative Volume Element (RVE) or unit cell concept. The RVE has a microstructural subregion geometry which is representative of the entire microstructure. The boundary value problem on the structural scale and in the microstructural scale (RVE) is solved by the Finite Element (FE) method (see Appendix A). With this approach, it is necessary to solve the RVE each time that the macrostructural model requires information about its performance, this is why this kind of solution procedure is known as FE^2.

Most of the work on FE^2 multi-scale procedures are done on analyzing the numerical performance of RVE [33,34] or on connecting different scales [35]. In general, in this kind of homogenization methods the elastic properties of the microstructure are obtained solving the microstuctural problem at the beginning of the structure problem. However, the problem with these methods is their computational cost for a non-linear analysis because it is required solving the RVE in every integration point at the macrostructural problem and for every time step to know the non-linear limit and then the behavior of the microstructure in non-linear range. Non-linear performance has also the problem that the dissipated energy of both scales is not always related [36].

In order to improve the computational cost of the multi-scale homogenization some strategies use model-order reduction techniques [37–39]. These methods use the Proper Orthogonal Decomposition (POD) to obtain the reduced set of empirical shape functions. Besides, [39] proved that the common approach of replacing the non-affine term by an interpolant constructed taking only POD modes arrives to ill-posed formulations. An enriched approximation space with the span of the gradient of the empirical shape functions is proposed to avoid this ill-posedness. However, these kind of procedures do not solve the complete structure.

Here it is proposed a new procedure to reduce computational cost of multi-scale simulation. The paper looks also into the problem of localization and energy dissipation across the scales, as the proposed method must be consistent [40]. It is important to note that the procedure developed takes and extends the two-scale homogenization proposed by Otero et al. [10] (see Appendix A).

In the following the formulation and algorithm schemes of the proposed procedure is described. Afterwards, Section 3 presents theoretical framework and its extension to multi-scale methods of the consistent energy dissipation problem. The numerical validation and one industrial application using the developed method is shown in Section 4. Finally in last section the conclusions of this work are exposed.

2. New procedure to reduce the computational cost of a multi-scale analysis

The main advantage of the FE^2 method related to a micro model is the reduced computer memory requirements. To solve the same problem, the amount of memory required by the classical FE micro model method is substantially larger than FE^2 procedure [10]. This difference is found because the memory used is proportional to the FE mesh size and, while the FE micro model has to solve a problem with a very small discretization, the FE^2 procedure only requires memory for the macrostructural problem and the RVE that is being solved. However, if the material reaches non-linear behavior, the computational cost of FE^2 method becomes as large as the one