NON LINEAR MICROMECHANICAL MODELING OF HEMP CONCRETES

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Abstract

This paper deals with a non-linear micromechanical modeling of hemp and lime concretes based on a iterative multi-scale method derived from the differential scheme and including FEM solving procedures for local problems. The ability of the model to account for the influence of the morphology of shives thanks to FEM simulations is first tested in a linear context. Then the iterative multi-scale approach is extended to a non-linear context due to the apparition of damage in the matrix, and several solving algorithms are discussed. The first corresponding digital results obtained are presented, analyzed and compared to experimental data found in the literature.

1 Introduction

Building materials reinforced with vegetal aggregates allow to build sustainable and yet affordable housing. Vegetal granules are indeed renewable and biodegradable materials predominantly extracted from agricultural by-products. Vegetal concretes are also highly porous soundproof media, with high heat insulation properties, allowing substantial energy savings. On the other hand, they exhibit poor mechanical performances, which explains why they are currently only used as filling materials in association with wooden load-bearing structures. Project managers aim at reducing those load-bearing structures with the help of vegetal concrete manufacturers. Their common goal is to improve the mechanical resistance of vegetal concretes while preserving the insulation properties of the latter. Building norms are in the meantime required to enable a wide use of this new type of materials.

In order to obtain these results at low-cost, the development of comprehensive constitutive models is required. Those models should indeed allow to perform a collection of numerical simulations (so called "digital experiments") with varying parameters such as particle size or thermal/mechanical properties of the constituents, in the frame of a large optimization and certification campaign. In this context, a collaboration between Institut Jean le Rond d'Alembert and CSTB (French scientific and technical building center) has been recently settled with the aim of developing a micromechanical approach that would provide an accurate constitutive modeling for hemp and lime concretes, including genuine non linear behavior of the constituents and multiphysic couplings.

After a short presentation of the mechanical properties of hemp and lime concretes and corresponding modeling issues, the main ingredients of the iterative multi-scale approach when carried out in a linear context are listed. Corresponding results of the simulations are then presented and compared with experimental references. In the fourth section, the several attempts to extend the iterative multiscale technique to a non-linear context are presented and discussed thanks to the corresponding numerical simulations.

2 Mechanical properties of Hemp and Lime Concretes (HLC) and corresponding modeling issues.

2.1 Microstructure specificities

Hemp and Lime Concretes (HLC) are produced by mixing hydraulic, air-slaked, and pozzolanic lime with thin bar-shaped vegetal particles, called hemp shives, cut in the wooden core of hemp stems. In general the forming process of HLC also includes a compaction stage, during which shives tend to collect in strata Fig.3. In that case, the alignment of shives induces an anisotropic behavior.

Figures 1, 2 & 3: 1: Exemple of HLC breezeblock, 2: Random distribution of shives embedded in lime within HLC before compaction (measure in cm), 3: Micrograph of shives within a compacted HLC (cross section).

HLC are considered as materials highly-filled with shives but porosity may actually represent a larger part of their volume (up to 80% according to [10] & [6]. See also Fig.2). Voids are indeed present at both meso and microscales. In addition to mesopores appearing during the concrete drying phase, microvoids can be observed in shives and in the lime matrix. The porosity of hemp shives was itself evaluated to 57% [6].

2.2 Non linear behavior of the constituents

Experimental results of uniaxial loading tests on HLC prove that the behavior of this type of material is strongly non-linear as evidenced on series of tensile compression tests [6], [7], [8]. Several sources of non-linearity can be identified such as damage appearing in the matrix, or voids nucleation and closure inducing residual strains. Multicoupled phenomena have also been evidenced in HLC [11], [12]. Water diffusion and thermal expansion occurring at microscopic scale have also proved to impact significantly on global mechanical, thermal and hydric behavior [9].

In order to construct HLC constitutive laws in a rigorous and progressive framework, it has been chosen to incorporate the various sources of non-linearity in the model separately. Thus each contribution to the global behavior can be tested, and its implementation carefully validated. Every single enhancement of the model is nevertheless performed with the aim of combining all those influences on the global behavior in a forthcoming version of the model.

Two sources of non-linearity have been recently treated in the context of this study, namely the introduction of damage in the matrix phase and void closure in shives during compression tests. In the present paper only the results concerning the damaging behavior of the matrix are reported and detailed in Section 4.

3 Iterative multi-scale approach in a linear context

When quantifying the effects of the microstructure on the global behavior is at stake, multiscale approaches have proved to be particularly efficient. For instance the relationship between the slenderness ratio (or other morphological features such as the spatial distribution of shives in the material) and the anisotropic properties of the material can be taken into account in a direct manner. A model based on a homogenization technique has consequently been chosen to describe the behavior of HLC.

In order to cope with the high heterogeneity rates under consideration in HLC the modeling technique chosen is more precisely based on a specific iterative micromechanical approach. This type of approach derived from the differential scheme [16] has recently been put into practice to predict the behavior of highly-filled polydisperse composites with spherical inclusions as well as several porous media such as clays [1], [2], [3], [4]. The approach is here extended with numerical features allowing to take into account the specific morphology of shives and their spatial distribution. This way the anisotropic behavior of HLC can be exhibited. The iterative procedure is also put into practice in a non-linear context to account for damage in the matrix phase. Salient features of the method aforementioned are collected and described in the following paragraphs.

3.1 Iterative multiscale approach

The iterative method under consideration consists in a progressive introduction of small volume fractions of heterogeneities within a matrix phase, followed by a homogenization stage. The equivalent homogenized medium (EHM) thus obtained is then considered as the matrix phase for the introduction of another heterogeneity and the sequence is repeated until the final rate of heterogeneity is reached. In the case of HLC the inclusions at each step can be a small fraction of shives as well as voids.

Although the final material may be highly-filled, each homogenization step is treated as a single-inclusion problem performed within the area of application of direct effective moduli homogenization schemes. As a consequence any of those may actually be chosen to perform the homogenization stages, and the method has been previously tested with several analytical schemes (dilute, self-consistent,...) [1], [4]. The specific morphology of shives (close to rectangular strips) prevents yet from using analytical scale transition techniques that are easy to put into practice and less consuming in terms of few CPU-time; hence the development of a specific numerical solving procedure. More precisely, each local problem is solved thanks to finite element simulations on representative volume elements (RVE) including real bar-shaped particles. Rough estimates of local fields and their fluctuations can moreover be obtained with such simulations, which is another advantage of the method.

Considering that 3D FEM simulations, including several sources of non-linearity are envisioned, special attention has been given to computational efficiency. In particular a single reference mesh made of an unique bar shaped heterogeneity representative of the average real shive or polyhedral void embedded in a matrix phase is here used for each homogenization step, leading to orthotropic EHM (see Fig. 5). In a linear context, any type of anisotropy can then be described by multiplying the stiffness tensors by high order rotation matrices and performing discrete weighted averages so that each orientation of the aggregate brings its proper representative contribution to the global behavior. In the case of a random distribution of phases (i.e. for slightly or non compacted HLC) when the effective behavior is isotropic, the resultant constitutive tensor of the final EHM is first multiplied by rotation matrices, and then integrated on the unit sphere given that each orientation is encountered with the same probability in the material [13], [15]. A recapitulative scheme of the iterative method coupled with the rotation process is presented on Fig.4.

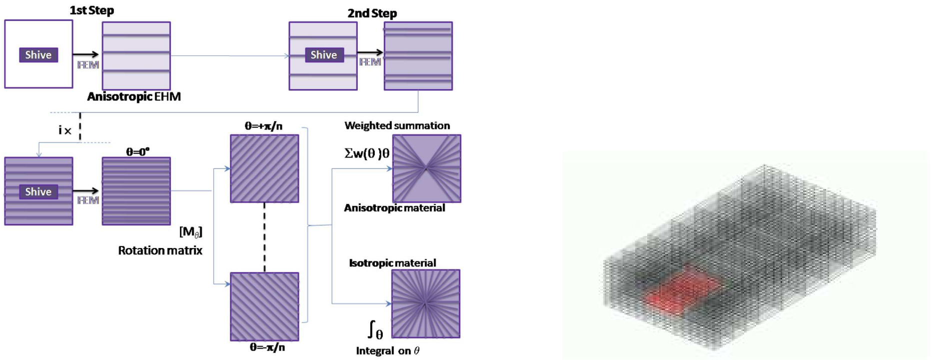

Figure 4 & 5: 4: Recapitulative scheme of the iterative multiscale modeling procedure, general process in a linear framework. 5: Cross section of a sample of 3D mesh for intermediate problem solving. Cutting plane is the one at the front, bar-shaped shive in red in the center.

3.2 Taking into account the anisotropic behavior of HLC in a linear framework.

The iterative multiscale method –as described on Fig.4- has been tested in a linear framework to estimate the anisotropic global properties of HLC. Simulations have been performed with the finite element code Cast3M on 3D meshes. The method was tested on the entire range of conceivable densities for HLC, and the mechanical effective properties (Young moduli) obtained for different compositions of HLC are presented on Fig.6&7.

The results stemming from the iterative procedure are compared to experimental data collected by Cerezo [5] for slightly compacted (i.e. quasi isotropic) HLC. The model seems to provide reliable estimates of HLC rigidity, as did the self-consistent estimates obtained by Cerezo on spherical inclusions [5], which proves that the influence of shives morphology on global behavior is rather weak. On the other hand a compression test on a given highly-filled strongly compacted HLC has been performed by Nguyen [7] and the corresponding results are presented on Fig.7. Longitudinal and transversal young moduli for the various compactnesses measured have been estimated thanks to the iterative numerical method with some success. The good accordance between experimental and numerical estimates certainly relies on the fact that anisotropy is correctly accounted for in the modeling. One must note that the numerical results presented here also take into account the evolving non linear behavior of squeezed shives with respect to compaction that cannot be described in detail in this very article.

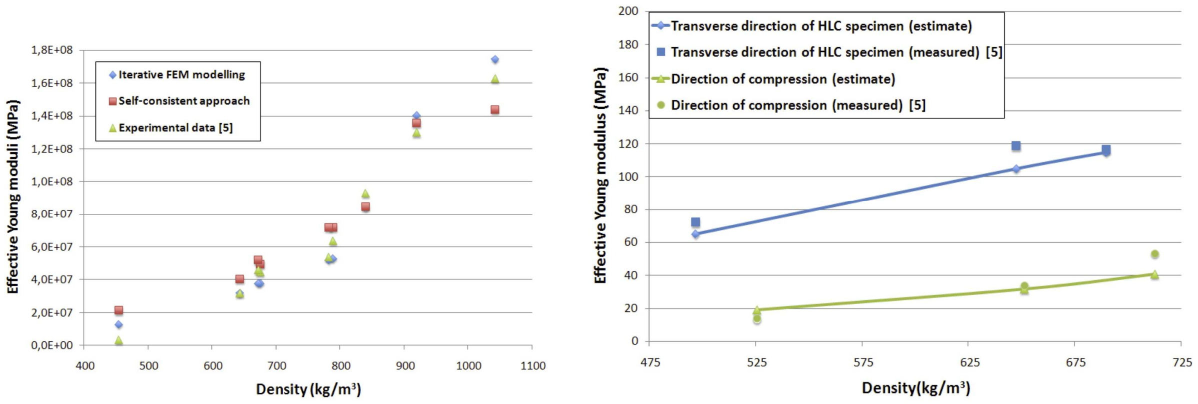

Figure 6 & 7: 6: Evolution of Young Moduli of isotropic HLC (slight compaction state). 7: Evolution of longitudinal and transverse Young moduli of a cylindrical specimen of strongly compacted HLC during a compression test.

4 Iterative multi-scale approach in a non-linear framework

4.1 Modeling damage in the matrix phase

The first stages of the actual non-linear response of HLC during experimental compression tests as evidenced by Nguyen [7] are here supposed to correspond to the apparition of damage in the matrix phase. It has been chosen to describe this evolution of the mechanical properties of the binder thanks to damage modeling based on Mazars' work. This type of non-symmetrical damage law is indeed commonly used to describe the mechanical response of regular concretes [17]. In this model the rigidity tensor is affected by a simple scalar damage variable D which depends on an equivalent strain $\tilde{\varepsilon}$ depending itself on the three main strains. Damage in the matrix phase is consequently diffuse, homogeneous, and isotropic, and appears when the equivalent strain reaches a critical value $\tilde{\varepsilon} > \varepsilon_{crit}$ (see [17] for more details).

$$\bar{\bar{\sigma}} = \left(1 - D(\tilde{\varepsilon})\right)\boldsymbol{A} : \bar{\bar{\varepsilon}} \tag{1}$$

The relationship between the damage variable D and the equivalent strain $\bar{\bar{\varepsilon}}$ depends on the type of loading (tensile/compression), hence the non-symmetrical property, and on four parameters in addition to the critical strain ε_{crit}, namely A_T, B_T, A_C, B_C. The latter are expressed with respect to parameters that can be identified on a tensile/compression response curve such as the elasticity limit, maximum stresses, stresses at failure…

4.2 Coupling with a linearization process: iterative procedure used on a linear comparison composite.

When trying to determine the response of a non-linear material to a certain loading linear comparison composites (LCC) are commonly used. More precisely the equivalent stiffness tensor of the non linear phase (here the matrix) is taken as the secant stiffness estimated for an effective strain in the phase (generally the average of local strains). Then linear simulations can be carried out on this equivalent medium until a convergence point is reached as far as the dependence of the stiffness tensor with respect to the effective strain is concerned.

The simplest way to incorporate the iterative method in this classical procedure is to implement the iterative algorithm in the linearization loop. The materials at stake are indeed linear within the loop and the iterative process as depicted in a linear framework in Section 3.1 can be directly put into practice. Simulations were performed on HLC following this algorithm and compared to experimental results obtained by [5]. The materials at stake are three phase media (lime matrix, shives and voids) with randomly distributed bar-shaped inclusions leading to an isotropic behavior of the material (slightly to non compacted HLC). Mechanical properties of pure lime and more precisely damage model parameters were not available and were consequently identified thanks to an inverse method in order to fit the experimental results of A3-2 HLC samples (shives 33.3%, lime matrix 39.2% and air 27.5%) as presented on Fig. 8. Simulations were then performed to obtain the response of A3-1 HLC specimens (shives 44.3%, lime matrix 24.4%, and air 31.3%).

If the linear part is successfully simulated (good accordance of Young moduli), when damage appears the experimental and digital curves split. There are probably many reasons to explain this discrepancy. First the evolution of porosity (and correlated variation of the mechanical properties of the constituents) is not taken into account in the simulations. Second of all the mechanical properties of the lime matrix may have changed from one sample to another. In particular the inner porosity of this phase may have changed which could imply that the identification of the parameters of the damage model for this new phase is inaccurate. Eventually one must notice that with this solving algorithm the non-linear behavior of the constituents is only accounted for at first step in the iterative procedure and as a consequence cannot impact the final global simulated behavior of the material in its full extent. It can be moreover proved that an immediate consequence of this fact is that the position of the minimum stress cannot vary from one curve corresponding to a HLC formulation to another and is correlated to the position of the minimum stress on the response of pure lime matrix. In order to circumvent this flaw of the model another modeling technique is currently tested and is presented in the following section.

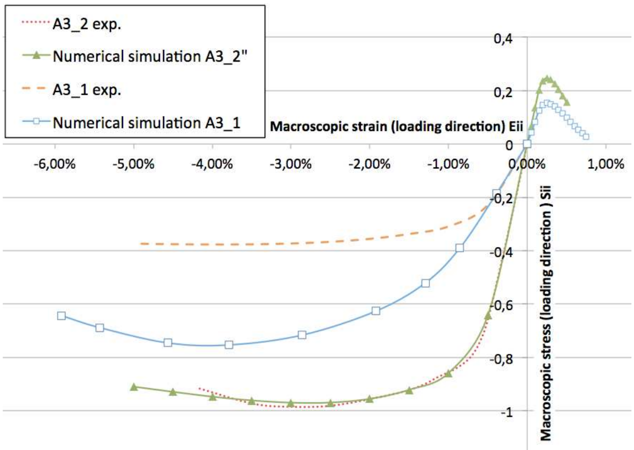

Figure 8: Comparison between the experimental and simulated resposnses of two different isotropic HLC formulations during an unconfined unidirectional compression test.

4.3 Coupling with a linearization process: iterative procedure put into practice on actual non-linear constituents.

Another way of putting the iterative modeling technique into practice in a non-linear context is indeed currently investigated. It consists in nesting the linearization loop inside the iterative one in order to overcome the difficulties spotted in the former section.

In a linear framework the complete stiffness tensor can be obtained at the end of each homogenization stage thanks to the computation of a series of elementary tests. In the case of non-linear constituents the expression of the non linear dependence of the stiffness tensor with respect to strains is in general not explicitly exhibited. This is an issue in the case of the iterative modeling technique since the behavior of the EHM at the end of each stage is required as input data for the next homogenization step. The iterative multiscale modeling is consequently adapted as follows:

1- the determination of the stiffness tensor of each EHM, usually performed thanks to elementary tests in a linear framework is replaced by a comprehensive simulation of the response of each EHM. These simulations are classically carried out on LCC with the equivalent stiffness tensors taken as the secant stiffness of the phases of the actual non linear composite estimated for the average strain over the corresponding phase.

2 -The parameters required to model the non-linear behavior of the EHM are then identified on the curve just obtained and the updated behavior of the matrix phase can be used for next homogenization step.

Here are presented the first results obtained with the iterative mutliscale modeling loop outside the linearization one. In order to keep interpretations simple, simulations have been performed so far in a two dimensional context on microstructures with a hexagonal pattern containing circular inclusions leading to an isotropic global behavior (See Fig 9). A test material previously identified and used by [3] has been chosen to perform the simulations. It has only two different phases (sand aggregates and damaged matrix), a target volume fraction of aggregate of 10%, and above all the contrast between the mechanical properties of both constituents is lower than for HLC in which shive squeezing can be exhibited.

The response of a specimen submitted to an unconfined unidirectional compression loading under periodic boundary conditions is reported on Fig.10. The results have been obtained thanks to two different approaches. On the one hand a direct non-linear simulation including a linearization stage but without the iterative procedure is carried out (curve with cross markers). On the other hand the iterative procedure in its full extent has been used to perform a two steps simulation (0% to 5% and 5% to 10%), with an update of the non-linear behavior of the matrix phase in between. The response of the intermediary EHM obtained after the first step (curve with diamond shaped markers) is used for identification of the Mazars parameters of the matrix phase of the step second step simulations. Final response of the specimen is drawn as a dot line on Fig.10.

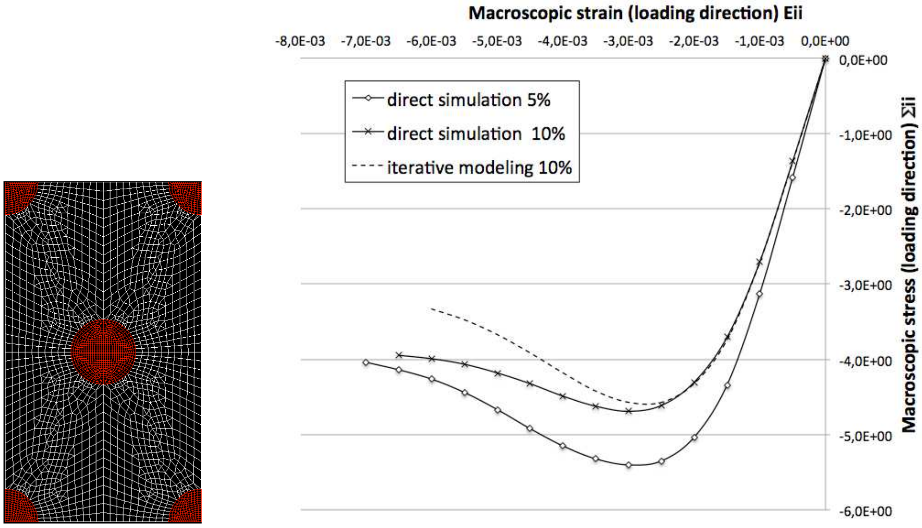

Figure 9 & 10: Hexagonal 2D model with circular inclusion and periodic limited conditions. Simulation of an unconfined unidirectional compression test of an isotropic HLC containing 10% of shives. Comparison between direct and iterative modeling techniques.

First it can be observed that, as expected, both simulation techniques lead to the same response during the elastic phase. The minimum stresses are also approximately the same whether the response of the material has been obtained in a direct manner or not. Only the residual stress varies from one simulation to the other. The origin of this discrepancy could be the incorrect identification of the parameters of the damaged matrix during the second step of the second simulation. As stated before these are the very first results obtained, and simulations are currently run in order to enhance this particular stage, which could allow to perform simulations on composites with much higher filling rates.

5 Conclusion

In this paper an iterative multiscale modeling technique has been enhanced to model the behavior of highly-filled hemp and lime concretes. Two aspects have been more precisely investigated. On the one hand the ability of the model to account for the influence of the morphology of shives on global behavior in a linear context has been tested. It relies on a FEM solving of the local problem coupled with the application of rotation matrices on the stiffness tensors at stake. It has been proved that in the case of slightly to non compacted HLC, in which shives are randomly distributed, the geometrical shape of the inclusions does not impact significantly the global behavior whereas it is a crucial aspect when modeling the behavior of anisotropic highly compacted HLC is under consideration.

On the other hand attempts have been made to extend the iterative modeling procedure to a non-linear context in order to take into account the damaging behavior of the matrix. Several solving algorithm have been tested showing that the iterative loop which allows to model the behavior of highly-filled materials has to be implemented outside the linearization process.

Further investigation should consist in an enhancement of the simulation process in presence of damage. The introduction of other sources of non-linearity such as the evolution of porosity is also currently developed and should be coupled with the modeling of damage. The study of the influence of the nature of the shives/lime interfaces is also planned thanks to the introduction of jump relations between phases or by the direct introduction of an extra phase.

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