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Variational asymptotic micromechanics modeling of heterogeneous porous materials

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ABSTRACT

This paper presents a numerical technique to predict the effective elastic properties of heterogeneous fluid-filled porous media where the heterogeneity may result from dissimilar solid and fluid phase properties or due to mismatch in porous microstructure. The technique is based on the variational asymptotic method of homogenization where finite element method is employed for discretization. Biot's theory of poroelasticity is used to describe porous media where both solid and fluid phase motions ($u - U$ formulation) are considered with associated strain measures. The method estimates the poroelastic constitutive law in single analysis which makes it very efficient compared to other finite element based homogenization techniques. The method is also general enough to compute all 28 elements of an anisotropic constitutive matrix. Other than estimating the effective properties the micro-stress/strain distribution is also obtained at no additional cost.

The method is successfully applied for homogenization of porous media, fluid-filled cavity and finally for effective property estimation of bone lamella. In absence of any other direct method of porous media homogenization, the present technique is compared with classical homogenization methods with fluid approximated as solid of very high Poisson's ratio. The suitability of this approximation and various other alternatives are also discussed. It is shown that the present homogenization method can be an efficient tool for bone property estimation where fluid-filled porous hierarchical micro-/nanostructure must be respected at all steps.

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1. Introduction

Heterogeneous porous media in nature appear in the form of geomaterials like rocks and biomaterials like bones. The inhomogeneity of porous material constituents at the microlevel, spatial variation of their microstructure and the resulting variation in the porosity distribution indicate that modeling of these media is computationally expensive if one is interested in capturing the effect of these variations on the system response. Thus, one can take recourse to detailed (expensive) microstructure based modeling where the microstructure data can be obtained by different experimental methods (e.g., CT and MRI scan for bone tissue) and analyzed by standard numerical methods (e.g., finite element method). Alternatively, one can look for effective property estimation of these porous media and then use them judiciously to have an estimate of the average response. It is to be noted that the second approach is computationally many orders of magnitude more efficient in capturing the average response. Moreover, the microscale response (fluctuation) can be obtained from the macroscale response with minimal computational effort.

One of the predominant methods of modeling geomaterials is Biot's theory of poroelasticity, which successfully represents the coupled nature of solid and fluid deformation in a fluid-filled porous media (Biot, 1955a,b).

Although the theory was originally developed for modeling soil consolidation process in geomechanics (where gradual deformation of porous solid skeleton occurs with fluid coming out of the pores) it can aptly describe the deformation of porous composite microstructure with solid and fluid phase. For example, the "undrained" case referred in geomechanics is same as having a composite porous structure with sealed boundaries so that no pore fluid can escape. Similarly, the "drained" case is akin to having a porous microstructure with empty pores. Thus, Biot's consolidation theory can be considered to be a suitable instrument to describe the deformation of porous composite. Over almost a period of four decades this theory has also been applied to bone modeling (see the survey article by Cowin (1999)). While there are several other methods including the theory of mixture, which are suitable for porous media modeling, Biot's theory enjoys an unparalleled advantage over other methods because of its simplicity, proven accuracy, firm theoretical basis, strong connection to other homogenized theories and ease of implementation. In the present work, we restrict ourselves to the framework of Biot's theory and various

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