A PRESSURE DEPENDENT BONE REMODELING MODEL FOR APPLICATION IN ORTHODONTICS.

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INTRODUCTION

The goal of this work is to provide a constitutive model able to represent bone remodeling, accounting for the pressure dependency observed macroscopically on alveolar bone remodeling during tooth movement in orthodontic treatments. For most types of bones, remodeling processes take place in order to adjust the amount of tissue and its topology according to long term loading conditions, following what is called ``Wolff's law'' of bone adaptation [1]. Bone resorption/apposition occurs when disuse/overuse is observed. The bone therefore adapts its density in such a way as to achieve an homeostatic state of stresses. Besides the density change, remodeling also occurs to modify the bone topology, mainly in cancellous bone for which the trabeculae tend to align along the principal stresses directions. However, alveolar bone remodeling seems on a macroscopic scale to depend mainly on the pressure state [2]. One can observe apposition on the tension side of a tooth when loaded with an abnormal mechanical environment, such as the one obtained with orthodontic appliances, as well as resorption on the compression side.

The present work concentrates on the bone behavior during remodeling. We assume the pressure state of the bone matrix as the key stimulus to differentiate apposition and resorption in overloaded conditions.

METHODS

The original model which is proposed in this work is built on a damage/repair model, first proposed by Doblaré and co-workers [3]. The damage variable is a measure of the bone density; it is not an actual damage of the bone matrix. The model is here extended in order to be used for the alveolar bone. It therefore takes into consideration the pressure state of the tissue, and not only the pressure intensity, as one of the stimuli for bone remodeling. It is also enhanced to be coupled to an elasto-plastic material behavior. It can therefore capture permanent strains of the tissue beyond the ones due to density variation.

We therefore propose an anisotropic damage/repair model within the framework of the strain equivalence approach in continuum damage mechanics [4]. An equivalent stress tensor, $\tilde{\sigma}$, is defined from an objective stress tensor, σ, and two damage variables : a damage measure tensor, H, and a scalar value, η, measuring the degree of anisotropy. One can write, according to [4]:

$$\tilde{\sigma} = dev(HsH) + \frac{p}{1 - \eta/3\, D_{kk}} I$$

where p and s are the hydrostatic (scalar) and deviatoric (tensor) parts of the stress tensor and $D = I - H^2$ is the damage tensor as defined within the continuum damage framework. The damage measure tensor H can be related to the microstructure through the use of a fabric tensor $\hat{H}$. The damage evolves in order to achieve an homeostatic level of a given stimuli in such a way that

$$\dot{H} \propto -\dot{r}\frac{\rho_0}{\rho} J : W$$

where J is the tensor value thermodynamically associated to damage, W is a fourth order unit anisotropic tensor and $\dot{r}$ is a remodeling rate function (the dot accounts for an objective time derivative). The remodeling rate is here written to account for the pressure state of the alveolar bone so that repair will occur in the case of tissue formation, for overloaded tension conditions and damage will increase in the case of tissue resorption, both in the case of overloaded compression conditions and underloaded conditions.

This work also proposes an integration procedure for the coupling of anisotropic continuum damage and a visco-plastic material (inspired from [5]), proposing a consistent tangent operator used in a large strains home made finite element code, Metafor [6].

RESULTS AND DISCUSSION

The proposed model gives the possibility of a macroscopic description of the alveolar bone remodeling. A tooth submitted to orthodontic forces will transfer tension and compression stresses that will allow bone remodeling. This will be done so that the tooth moves along the line force, bone resorption occurring on the compression side and apposition on the tension one. If a non pressure dependent model was applied, one would observe only resorption or apposition on all sides of the tooth if no other non-linearities were to be considered. As the damage accounting for a density measure is anisotropic, the remodeling will allow for a change of both the damage value and its spatial distribution. One can therefore model a change of the trabeculae density as well as their orientation due to bone remodeling.

The constitutive model proposed is used on ideal plane geometries of a tooth and its surrounding tissues. It will nevertheless be applied on a 3D model of a jaw obtained from pre-treatment CT-scan images.

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