MICROMECHANICAL ANALYSIS OF DENTIN ELASTIC ANISOTROPY

[1] Anil Misra, [2] Paulette Spencer, [1] Orestes Marangos, [2] Yong Wang, [1, 2] J. Lawrence Katz
[1] Civil Engineering, [2]Oral Biology, University of Missouri-Kansas City
email: misraa@umkc.edu

INTRODUCTION

Stress-strain relationships for materials have been traditionally established through direct phenomenological modeling based upon experimental observations. However, it is widely accepted that the material stress-strain behavior critically depends upon the underlying mechanisms that occur at scales smaller than the material sample scale. Modeling methodologies that account for the underlying mechanisms governing the material behavior and explicitly model material microstructure are expected to provide better insight to the material stress-strain behavior and bridge the scale between continuum and discrete representations. For instance, micromechanical models considering particle interactions have been successfully used for describing stress-strain behavior of granular materials [1]. The objectives of this work are: (1) to develop a micromechanical model that relates the anisotropic elastic properties to the microstructure of dentin using a virtual bond idealization, and (2) to study the average force constants and anisotropy parameters utilizing the developed model in order to understand how the dentin elasticity is affected by the presence of water.

Along this approach, we consider the material-scale to be composed of nano-scale grains (representing molecular bonds) whose centroids represent material points. Similar granular or discrete microstructure models have been considered in the past for developing constitutive relations, such as the virtual internal bond model developed by Gao and Klein [2], the higher order constitutive relationships developed by Chang and co-workers (see among other publications [3]), and the micromechanics models [1,4]. In analogy with atomistic-scale interactions, these nano-scale grains are viewed as interacting with each other through pseudo-bonds.

METHODS

The underlying material microstructure is conceptualized as a collection of interacting grains modeled by virtual bonds. With the view of bridging behavior at nano and micro-scales, the virtual bond force-displacement relationships are formulated taking inspiration from atomic-bond interactions. The force-displacement relationships are formulated for both central and non-central interactions, denoted by the force constants K_n and K_w, respectively. The dentin microstructure is characterized by a virtual bond directional distribution function modeled by first-term of the spherical harmonic expansion denoted by anisotropy parameter a_{20}. Considering the kinematic assumption that the bond displacement is linearly related to the overall strain, the pseudo-bond force-displacement relationships may be combined with its orientation to derive the incremental stress and stiffness tensors. Alternatively, utilizing a static assumption that relates the virtual-bond force to the stress tensor, the pseudo-bond force-displacement relationships may be combined with its orientation to derive the incremental strain and compliance tensors.

RESULTS AND DISCUSSION

Closed form expressions of the transverse isotropic stiffness tensor are obtained for the case of linear inter-granular interactions. These expressions are utilized to compute the stiffness and anisotropy parameters for dry and wet dentin [5] utilizing an optimization method. The stiffness parameters are defined as follows: $A_1 = L_o^2 N_p K_n$ and $C_1 = L_o^2 N_p K_w$, where L_o is the bond length, and N_p is the bond density per unit volume. The stiffness parameters A_1 and C_1, (in GPa) respectively are as follows: 183.2, 0.0 (dry dentin), 199.7, 0.0 (wet dentin) based upon kinematic approach, and 196.5, 45.7 (dry dentin), 243.2, 38.3 (wet dentin) based upon static approach. The anisotropy parameter a_{20} are as follows 0.0 (dry dentin), -0.234 (wet dentin) based upon kinematic approach, and 0.0 (dry dentin), -0.218 (wet dentin) based upon static approach. Measured elastic moduli for dry dentin are isotropic, while those for wet dentin are transversely isotropic with the isotropy plane perpendicular to the tubule direction being stiffer. Consequently, the anisotropy parameter a_{20} vanishes for dry dentin and takes a negative value for wet dentin.

CONCLUSIONS

The force constant for wet dentin is higher than that of dry dentin indicating that the presence of water results in the stiffening of bonds that contribute to the mechanical stiffness at the sample scale. Moreover, the anisotropy parameter of wet dentin indicates that the bond density becomes higher in the isotropy plane in the presence of water.

REFERENCES

1. Misra A, Chang CS *Intl J Sol Strucs*, **30**, 2547-2566, 1993.
2. Gao H, Klein P *J Mech Phys Solids*, **46(2)**, 187-218, 1998.
3. Chang CS, Askes H, Sluys LJ. *Engr Frac Mech*, **69(17)**, 1907-1924, 2002.
4. Thiagarajan G, Misra A *Intl J Sol Strucs*,, **41**, 2919-2938, 2004.
5. Kinney JH *J Biomech*, **37,** 437-441, 2004.

ACKNOWLEDGEMENTS

Supported in part by grant NIH/NIDCR DE014392.