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Experimental poromechanics of trabecular bone strength: Role of Terzaghi's effective stress and of tissue level stress fluctuations

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ABSTRACT

In the 1920s and 1930s, Terzaghi and coworkers realized that the failure of various porous geomaterials under internal pore pressure is given through evaluating the failure function for the same materials at zero pressure, with 'total stress plus pore pressure' instead of 'total stress alone' as argument. As to check, probably for the first time, the relevance of this ('Terzaghi's') failure criterion for trabecular bone, a series of poromechanical and ultrasonic tests was conducted on bovine and human trabecular bone samples. Evaluation of respective experimental results within the theoretical framework of microporomechanics showed that (i) Terzaghi's effective stress indeed governs trabecular bone failure, (ii) deviatoric stress states at the level of the solid bone matrix (also called tissue level) are primary candidates for initiating bone failure, and (iii) the high heterogeneity of these deviatoric tissue stresses, which increases with increasing intertrabecular porosity, governs the overall failure of trabecular bone. Result (i) lets us use the widely documented experimental results for strength values of bone samples without pore pressure, as to predict failure of the same bone samples under internal pore pressure. Result (ii) suggests a favorable mode for strength modeling of solid bone matrix. Finally, result (iii) underlines the suitability of microfinite element simulations for trabecular bone microstructures.

1. Introduction

Trabecular bone is a porous material subjected to loads which are large enough as to result in non-negligible changes in its porosity. This, in turn, may lead to pore pressure built-up and potential fluid flow. Hence, this material has often been studied in the framework of *poromechanics* (Coussy, 1995, 2004; Cowin, 1999). Accordingly, numerous experimental (Bryant, 1983, 1988; Hong, 2004; Knothe Tate et al., 2000; Kumar et al., 1979; Lim and Hong, 2000; Ochoa et al., 1991b) and theoretical (Fornells et al., 2007; Gururaja et al., 2005; Hellmich and Ulm, 2005; Smit et al., 2002; Steck et al., 2000, 2003; Swan et al., 2003) studies of poromechanical properties of bone have been launched, being mainly focused on the load-induced fluid transport problem (Dillaman et al., 1991; Fornells et al., 2007; Grimm and Williams, 1997; Gururaja et al., 2005; Hellmich and Ulm, 2005; Hong, 2004; Knothe Tate et al., 2000; Ochoa et al., 1991a; Smit et al., 2002; Steck et al., 2000, 2003; Tami et al., 2002; Qin et al., 2003; Swan et al., 2003) and on the 'hydraulic stiffening and strengthening problem' (Bryant, 1983, 1988; Kumar et al., 1979; Lim and Hong, 2000; Ochoa et al., 1991b). We here concentrate on the latter problem, recalling the discussions on strength of porous media, namely of soils, which in the 1910s–1940s, set the very starting point to what is nowadays called 'poromechanics', with Terzaghi (1943) as the prominent pioneer. What was found out at that time is that, rather than the total stress acting on a piece of porous material, 'Terzaghi's effective stress' (de Buhan and Dormieux, 1996), i.e. 'macroscopic stress plus pore pressure [times unity tensor]', governs material failure of porous rocks and soils. Terzaghi's effective stress relevant for porous material *failure* has to be clearly distinguished from Biot's effective stress in *poroelasticity* (Biot, 1955). The latter is defined as 'macroscopic stress plus Biot coefficient' (or a respective tensor in the anisotropic case, Dormieux et al., 2002; Hellmich and Ulm, 2005; Hellmich et al., 2009). Thereby, the Biot coefficient ranges between 0 and 1, and the latter number, where the Biot and the Terzaghi effective stresses formally coincide, relates to an incompressible solid skeleton, a case which is not encountered in bone (Cowin, 1999; Hellmich and Ulm, 2005; Hellmich et al., 2009). Interestingly, it took around six decades until a theoretical understanding of the aforementioned experimental relevance of Terzaghi's stress for the *strength* of fluid-filled media was presented: This was done by de Buhan and Dormieux (1996, 1999), in the form of a yield design approach applied to a micromechanical system consisting of a solid skeleton and of a fluid-filled pore space.

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