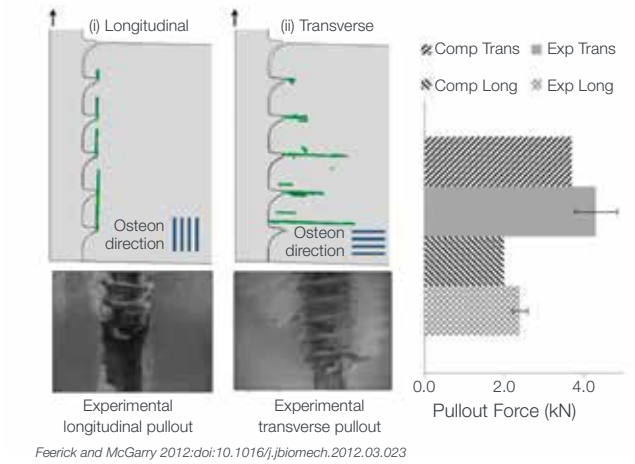
National University of Ireland Galway Models Cortical Bone Fracture Using the eXtended Finite Element Method

Eighty percent of a human's skeletal weight comes from cortical bone—a compact type of bone tissue mostly present in the shaft of long bones found in the arms and legs and on the outer shells of smaller bones such as vertebral bodies. As a naturally engineered strong composite material, cortical bones provides the strength individual bones need to support body weight, facilitate movements, and protect internal organs. In many cases, when orthopaedic trauma devices that use bone screws as their primary mode of fixation are implanted, cortical bone is the main supporting structure that prevents the screw from pulling out of the bone.

To evaluate device design, researchers at the National University of Ireland Galway are using realistic simulation with advanced modeling techniques for cortical bone fracture caused by pull-out forces applied on the screws. The eXtended Finite Element Method (XFEM) and the UDMGINI user subroutine were implemented to model the fracture of cortical bone. As the microstructure of cortical bone is analogous to a composite, consisting of a fiber and a matrix, Hashin damage-based criteria were developed to simulate the fracture patterns of cortical bone. In addition to defining the initiation criteria, the direction of crack growth was also defined for each criterion. These were based upon experimental observations of cortical bone fracture.

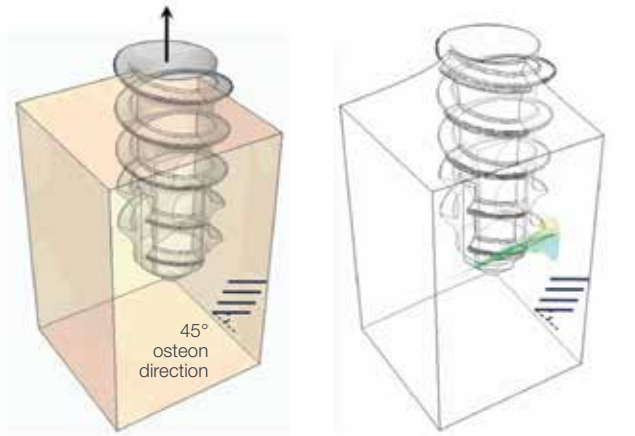
Cortical bone was modeled using anisotropic elasticity. Axial failure strengths were defined for tensile and compressive loading as well as shear failure strengths for each of the criteria developed. A material orientation assigned to the models represented the aligned osteon microstructure. Once damage was initiated, it evolved according to the XFEM-based cohesive segment. Once a defined critical strain energy release rate was reached, the two fragments of the split element were free to displace away from each other. Surface interactions were also applied to the newly exposed surfaces to prevent unphysical over-closure of split elements with a friction coefficient of 0.3.

The criteria developed were applied to the fracture of cortical bone during screw pullout in 2D and 3D. Previous experimental studies revealed that during screw pullout cracks propagate parallel to the osteon direction. Higher pullout forces were observed for cortical bone with osteons aligned perpendicular to the central axis of the orthopaedic screw (transverse). Simulating screw pullout from cortical bone, using the developed failure criteria and the XFEM method, accurately predicted the failure loads and fracture patterns that were observed for experimental screw pullout. Cracks were predicted generally parallel to the direction of osteon alignment during longitudinal and transverse screw pullout, with the latter requiring a significantly higher pullout force.



Feerick and McGarry 2012:doi:10.1016/j.jbiomech.2012.03.023

2D screw pullout model for longitudinal and traverse osteon orientation



3D screw pullout application for 45° osteon orientation

Previously, models had been developed to simulate fracture of cortical bone at the micro scale that required explicit representation of the micro-structural geometry of cortical bone. Incorporating detailed geometries of the microstructure of cortical bone into macro scale simulations of cortical bone fracture (e.g. during screw pullout) would be too computationally expensive. The possibility of lowering computational demand using simplified material models, with assigned orientations and anisotropic damage initiation criteria, offers an advance on previous models that were limited to the micro scale.

Application of the developed damage criteria using XFEM to predict screw pullout highlights the potential for both device design evaluation and cortical bone fracture fixation studies. A simplified macro scale representation of cortical bone, which accurately predicts both the fracture toughness and crack patterns, offers a level of complexity essential to fracture fixation studies. This complexity is achieved using XFEM without elevating computational demand beyond a viable threshold.

For More Information

www.nuigalway.ie
www.3ds.com/SCN-October2012