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THE MICROPOLAR BEHAVIOUR OF CORTICAL BONE: SIZE AND SURFACE EFFECTS IN 3 POINT BENDING

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SUMMARY

The complex hierarchical nature of the microstructure in cortical bone has an important influence on the macroscale material properties. We have investigated whether micropolar or Cosserat elasticity may be an appropriate continuum theory by which this microstructure is modelled. Numerical models demonstrate that the nature of the surface greatly influences the macroscale material behaviour. Experimental results on bovine cortical bone have shown that the material behaviour follows the predictions of the numerical study. Therefore, this suggests micropolar elasticity may be an appropriate material model with which to analyse the stresses around prosthetic implants.

INTRODUCTION

Cortical bone is a complex heterogeneous material characterised by various levels of hierarchical microstructure (Figure 1). This microstructure has a fundamental influence on the macroscopic material properties. Orthopaedic implants and surrounding bone are typically modelled using classical or Cauchy continuum elasticity however the lack of microstructural characterisation of the bone may not adequately describe periprosthetic stress concentrations, with a concomitant reduced ability in predicting failure. A material model which incorporates microstructural features may more accurately describe the material behaviour under loading [1].

Micropolar elasticity is a higher order generalised continuum theory which includes a couple stress, in addition to the direct stresses, in its formulation. Micropolar materials exhibit a size effect in bending or torsion tests, where smaller specimens of similar geometry are relatively stiffer. Importantly, cortical bone has previously been shown to follow trends associated with micropolar behaviour [2, 3]. We aim to include idealised Haversian canal microstructures into a FE model of bone to numerically assess potential micropolar behaviour and compare the theoretical mechanical behaviour with experimental behaviour of cortical bone as specimen size decreases

METHODS

Finite Element (FE) modelling (ANSYS 12.1) was used to create an array of structural units containing repeated, axially aligned voids in beams with (Figure 2a) and without (Figure 2b) surface microstructural features, mimicking cortical bone’s Haversian canal microstructure. By applying three-point-bending loading constraints the stiffness of each beam was compared over a range of depths, with stiffness variation indicating the presence of a size effect in the material.

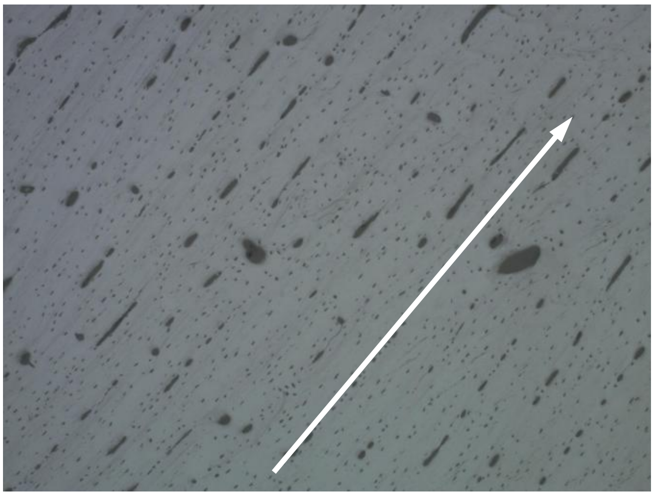
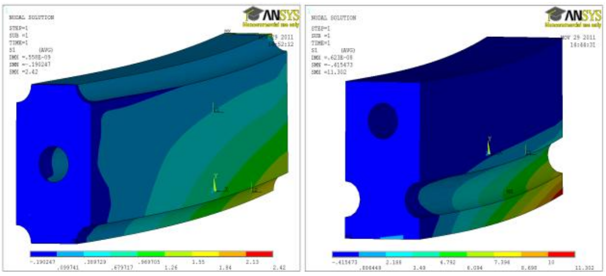


Figure 1: A view through a longitudinal cross section showing the microstructure in cortical bone. The white arrow indicates the direction of the long axis of the bone.



(a) (b)

Figure 2: The stress distribution for structural units with (a) and without (b) surface voids in three point bending.

In addition to the numerical modelling a series of three point bending experiments were carried out in order to determine the degree of observable size effect present in bovine cortical bone. Ten specimens were prepared from the anterior region of the mid diaphysis of five bovine femurs. Specimens were prepared using a diamond bladed sectioning saw and with incrementally increasing grades of silicon carbide paper up to 2400 grit, under irrigation with PBS. All ten specimens were orientated along the long axis of the femur. Each specimen was tested in a water bath at 37 °C in phosphate buffered saline (PBS) to a strain of 0.005 at a strain rate of $0.0025s^{-1}$. After testing a cutting was removed in order to analyse the surface roughness and constitutive properties. Each specimen was then re-prepared to a new depth and the above process was repeated. In total, eleven unique depths (5, 4, 3, 2.1, 1.5, 1.3, 1.2, 1, 0.9, 0.7, 0.5mm) were experimentally tested. An aspect ratio (length:depth) of 10 was maintained for every test.

RESULTS AND DISCUSSION

The numerical modelling of idealised heterogeneous materials revealed that the presence of surface voids has an important influence on the nature of the size effect present in the material. Where the surface is continuous the material follows the predicted size effect trend associated with micropolar elasticity. On the other hand, where the surface is corrugated by voids from the internal microstructure the material follows an opposite size softening trend (Figure 3).

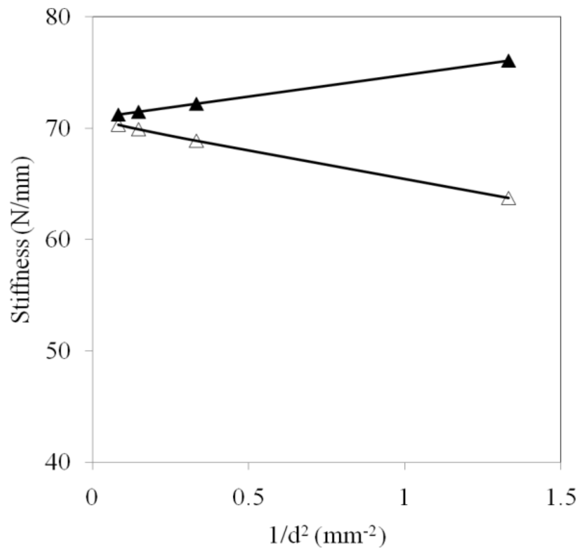


Figure 3: Computational results for beams with a void fraction of 8.2% and normalized void radius of 0.12. Continuous beams with a micropolar size effect are shown with solid triangles. Corrugated beams with surface voids are shown with hollow triangles.

Experimental results from three point bending tests revealed an anti-micropolar size softening trend (Figure 4). This suggests the surface of the specimens is perforated by the internal microstructure (as depicted in Figure 1). As the continuous and perforated numerical models represent the extremes of the idealised material behaviour it is possible to extract the micropolar material properties of bovine cortical bone from the anti-micropolar trend. In doing so, the micropolar characteristic length matched the approximate diameter of a Haversian canal suggesting that at the macroscopic level the Haversian system is of fundamental importance to the mechanical behaviour of cortical bone.

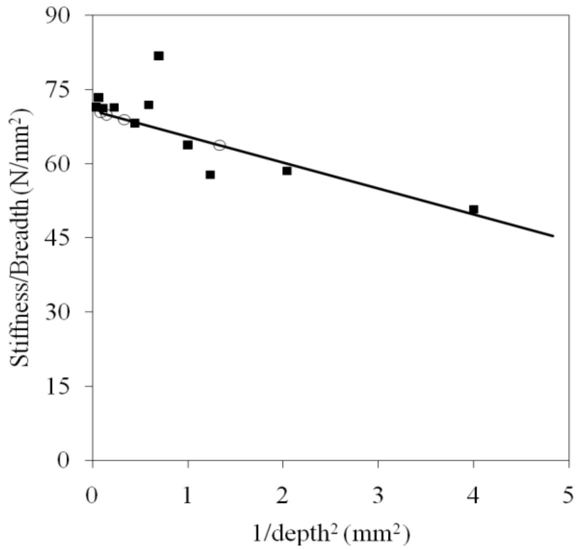


Figure 4: The experimental size effect (solid squares) plotted with the numerical size effect trendline produced with a void fraction of 8.2% and normalized void radius of 0.12 (hollow circles).

CONCLUSIONS

Numerical modeling of idealised heterogeneous materials, mimicking the structure of cortical bone, revealed the importance of surface artifacts in determining the nature of micropolar size effects.

By matching and comparing the observed experimental size effect in bone with the numerical studies it has been possible to ascertain an important micropolar material property of bovine cortical bone. The ramifications of this are that the Haversian system is of fundamental importance in understanding size effects, and thus stress concentrations, in cortical bone. Further tests are required to build up an anisotropic micropolar depiction of cortical bone in order to fully appreciate the implications for the design of bone prostheses.

ACKNOWLEDGEMENTS

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