Osteosynthesis metal plate system for bone fixation using bicortical screws: numerical modelling

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ABSTRACT

This work describes the numerical modelling of an immobilization system currently used to repair long bone fractures. The referred system was employed to ensure the mechanical stabilization of an oblique bone fracture by means of a dynamic compression plate (DCP) and bicortical screws. The numerical characterization of the fixation system was performed to obtain stress and strain fields in cortical bone tissue. The validation of the numerical model was performed using experimental data previously obtained in other work. Since the experimental characterization indorsed the visualization of the screw pull-out phenomenon during the loading process, damage parameters (trapezoidal law) were measured experimentally in this region. These parameters were introduced in the finite element model (FEM) to simulate the initiation and propagation of damage in bone tissue. A mixed-mode (I+II) damage law was used to mimic the mechanical behaviour of the bone fracture and the screw-bone interface.

Keywords: Cortical bone, bone fracture, osteosynthesis plate, mechanical tests, finite element analysis.

INTRODUCTION

The cortical bone is an anisotropic, hierarchical tissue composed of macromolecules, water, and mineral content [1]. Bone is commonly exposed to external loads that can exceed its strength, causing numerous fractures (e.g., oblique, transverse, and comminute-type). The repair of these injuries is performed using many mechanical fixation systems that employ wires, screws, grids, and/or plates, which are truly important to optimize. Osteosynthesis metal plates and bicortical screws are frequently used to promote bone regeneration, ensuring the required mechanical stabilization and fracture alignment. Since the disposition of bicortical screws may induce important stress fields in the screw-bone interface [2], the evaluation of damage parameters in this region is fundamental. In fact, it has been found that this interface impacts considerably on the local stress-strain fields near the screws, leading to different mechanical responses of bone damage or screw loosening [3]. The fracture process analysis also involves the crack initiation and propagation along the longitudinal direction, which motivated the evaluation of damage parameters in those regions. Thus, it is intended to reproduce numerically the non-linear behaviour of the bone through the implementation of a mixed-mode (I+II) damage law. It is possible to evaluate the stress and strain fields in bone tissue resulting from the application of mechanical loading through numerical models [2,4]. The strengthening effect of a prophylactic internal fixation system has been demonstrated using sheep tibia models [2]. By applying a strain criterion, the most suitable plate for the model stabilization was a 3.5 mm stainless dynamic compression plate (DCP) with bicortical screws [2]. In this study, the biomechanical performance of a DCP to stabilize an oblique fracture in the central diaphysis was performed through finite element analysis (FEA).

MATERIALS AND METHODS

Three mechanical tests were previously executed: (a) three-point bending (TPB) to evaluate the elastic modulus of the goat cortical bone tissue along the longitudinal direction, (b) screw pull-out strength (POS) performed in four goat femoral sections to identify damage parameters essential to the screw-bone interface characterization, and finally, (c) four-point bending (FPB) experiments on the femoral shafts. The experimental data was required to undergo finite element analysis (FEA) aiming to evaluate the mechanical behaviour of a reinforced cortical bone structure submitted to FPB loading tests. The boundary conditions implemented in numerical models were defined in coherence with the experimental tests.

RESULTS AND DISCUSSION

FEA of both POS (Figure 1a) and FPB (Figure 2) tests were executed, combining damage parameters (DP) and contact pairs (CP). DP were introduced to simulate the initiation and propagation of damage occurring in the cortical bone structure (crack propagation) during the experimental tests. CP have allowed establishing the connection between elements of different model components. Numerical characterization of POS was achieved within four bone femoral sections, reproducing the experimental responses. Figure 1b shows the numerical-experimental agreement for one of those four bone sections.

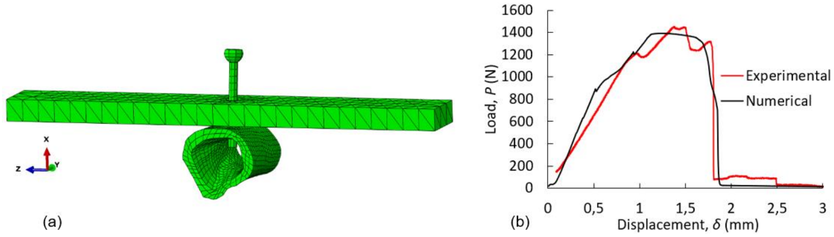

Figure 1. (a) Finite element mesh and (b) P-δ (load-displacement) curves of the POS test (one femoral section).

Figure 2 (a) and (b) represent the normal stress field of the FPB test in bone longitudinal direction (σ_{xx}), in which the normal stress gradient is coherent with the force and boundary conditions employed in the numerical model. The crack propagation in both parts of the bone is also illustrated (Figure 2b).

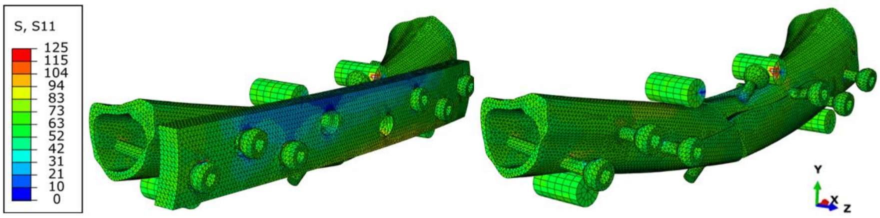

Figure 2. Normal stress field (σ_{xx}) of the FPB finite element model with (a) and without (b) the reinforcing plate.

The numerical-experimental agreement for the FPB tests is then reported through P-δ (load-displacement) curves (Figure 3). The numerical curve replicates the global behaviour observed experimentally, reproducing the initial stiffness and the first loading peaks satisfactorily.

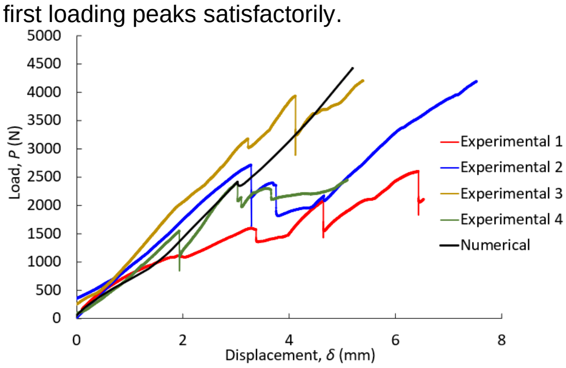

Figure 3. P-δ (load-displacement) curves of the FPB tests (numerical-experimental agreement).

CONCLUSIONS

Numerical characterization of a fixation system (DCP and bicortical screws) used to stabilize an oblique femur fracture was performed, allowing to reproduce the mechanical behaviour observed in cortical bone tissue in the vicinity of the employed screws and fracture lines.

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