FINITE ELEMENT ANALYSIS OF A FRACTURE FIXATION PLATE: A PARAMETRIC STUDY

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INTRODUCTION

Internal fixation plates and screws are often required to promote union and primary healing of fractured bone. Primary healing bypasses callus formation, therefore reducing healing time [1-5]. Rigid plate fixation systems provide the initial support and stability necessary for successful healing of this nature. However, differences in stiffness between the plate and bone causes an alteration of the normal bone loading conditions. This stress shielding effect causes a reduction in the rate of bone remodelling [2].

Bone remodelling is an adaptive process involving the resorption and deposition of bone tissue in response to mechanical, chemical, and biological stimuli [1, 6]. The rate of remodelling is partly dependent on the physiologic loading conditions applied to a region of bone [2-5, 7-12], which is inherent to its anisotropic behaviour. A reduction in bone remodelling can lead to implant loosening and subsequent improper fracture healing [2].

This study employs ANSYS finite element analysis software to investigate the level of stress shielding of two simplified bone-plate models; a validation model; and a parametric model. The validation model employs a range of static loading conditions on a three-dimensional model of a self-compressing stainless steel plate applied to an intact Plexiglas tube (representative of bone post-union) to analyze stress concentrations. Comparisons made to results using composite beam theory, in addition to results from studies done by Cheal et al. [2-3] validate the model. Subsequent parametric models involve changes in plate thickness, plate-bone coverage, and screw position in an attempt to find an optimal condition where stress shielding is reduced.

Initial observations reveal that an increase in plate thickness and angle results in stress reductions in the underlying bone. Through employment of composite plate materials, that reduce plate stiffness, an attempt to reduce the effects of stress shielding is in development.

METHODS

Validation Models

Two models provide a comparison for FEA validation in this study: a control bone and fixed bone model. The fixed bone model is modelled as a direct contact model wherein nodal constraints directly connect the plate surface to the bone surface. The imposition of direct contact between the plate and bone eliminates the possibility of plate-bone separation, allowing the transfer of normal and shear stresses to occur. This approach affords the observation of Von Mises' stresses (a conservative failure theory) and allows for a comparison of these values to yield strengths of the respective materials modelled.

A self-compressing 316L stainless steel plate and a Plexiglas tube (representative of bone) are modelled using ANSYS Design Modeller. The material properties used in this study are as follows: (1) Plexiglas tube: E = 3.1 GPa, and $\nu = 0.2$. The use of Plexiglas, results in a tendency for higher bending and lower axial rigidities, and is most comparable to the canine femur [2]. (2) Plate: E = 196 GPa, and $\nu = 0.3$.

Displacement constraints on the nodes maintain symmetry therefore only one quarter of each model is required to be analyzed, thereby reducing the solution time. The model is representative of the fracture post-union; therefore a fixed boundary applied to the mid-plane negates any deformation at the fracture site.

The analysis includes three loading conditions: a compressive axial load of 342 N (Fig.1); an applied moment of 9.34 Nm (Fig.2); and an eccentric axial load of 342 N (Fig.3). Each of these conditions acts on the surface opposing the fracture site and is representative of a normal physiological loading condition of a femur.

The validation models compare stress and strain results with strain gage data from a FEA model analyzed by Cheal et al. [2], as well as a solution using composite beam theory (Eq.1) wherein the plate is assumed to be rigidly fixed to the bone [2-4]. The stress in the bone at a distance t_B from the neutral axis of the composite structure can be written as:

$$\sigma_B = -\frac{PE_B}{E_B A_B + E_P A_P} - \frac{E_B M t_B}{E_B I_B + E_P I_P} \quad (1)$$

Where $M = P(\alpha r_0 - \hat{y})$ and αr_0 is the distance from the neutral axis where P is applied.

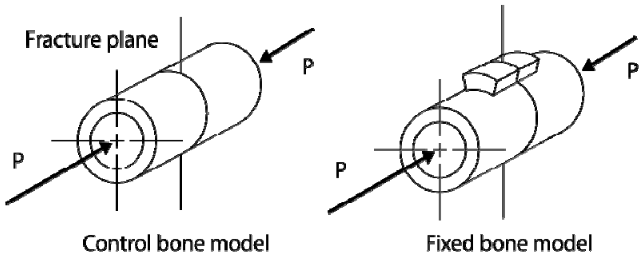

Figure 1: Loading case A

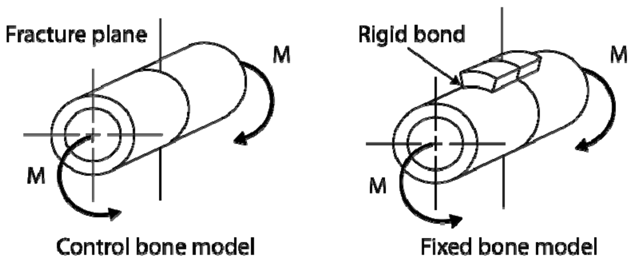

Figure 2: Loading case B

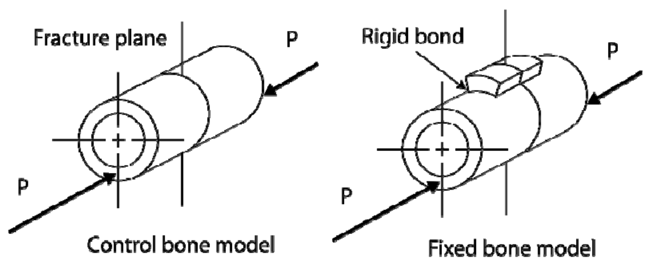

Figure 3: Loading case C

Parametric Models

In actuality, the plate is not rigidly bonded to the bone, but rather is compressed to the tensile side of one cortical layer by means of screw forces. In order to produce realistic results, a parametric model is created incorporating a stainless steel plate with 4 titanium screws. The geometry (Fig.4) is representative of a transverse radius fracture post union. The parameters include: a change in plate thickness from 3.0 to 4.5mm in thickness analysed in 1mm increments; a change in the angular plate coverage from 60 to 90° analysed in 1° increments; and an increase in the distance of the distal screw from the fracture site from 15 to 30mm.

A 4-point bending moment of 125 Nm produces high levels of equivalent stress for comparative purposes. Due to symmetry, only one half-model is required and is analyzed in order to reduce solution time.

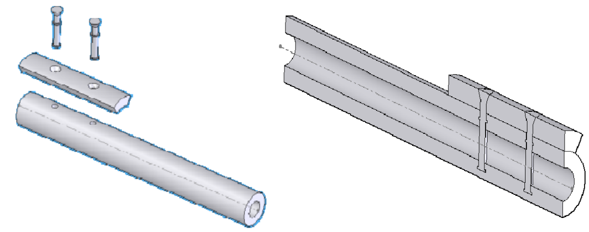

Figure 4: Parametric model geometry

RESULTS

Validation Models

A comparison of Von Mises' stresses, resulting from FEA, to results calculated using composite beam theory produces a large discrepancy. This is due to the bonded contact region between the plate and bone. Composite beam theory is only accurate for predicting the axial stress component in the cross-section at the center of the plate for externally applied axial and bending loads. The determination of static stress fields due to plate and screw pre-tension requires more complex models [3]. Figures 5 through 7 display the resulting equivalent stresses from the FEA for each loading condition.

Application of a compressive axial load results in a bending moment of the composite fixed bone model (Fig. 5) with maximum stresses occurring in proximity to the fracture site.

A bending moment applied to the free end increases the equivalent stress at the outer edge of the plate-bone contact region (Fig. 6).

Equivalent stress increases in the plate and bone when an eccentric axially compressive load is applied, however, the increase is not as predominant as for applied bending (Fig.7).

All three loading conditions result in increased levels of stress with application of the plate; however, the maximum stress values do not cause initial yielding of the plate. All three loading conditions also result in a decrease in longitudinal stresses directly below the plate.

A comparison of the total strain deformations for both the control and fixed plate models demonstrates an increase in longitudinal strain for an axially applied load. Application of a bending moment and an eccentric axial load results in a strain reduction with an affixed plate. The strain level will, most likely, dictate the rate of bone remodeling on the bone-implant interface [1, 7]. For this reason, attempts should be made to increase the level of strain in the underlying bone to increase the bone remodelling rate, and subsequently decrease the stress shielding effect.

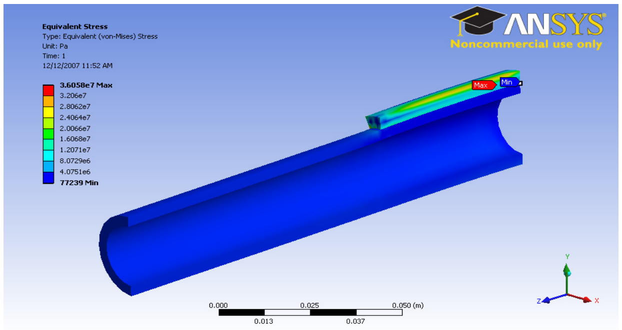

Figure 5: Equivalent stress – Axial compressive load

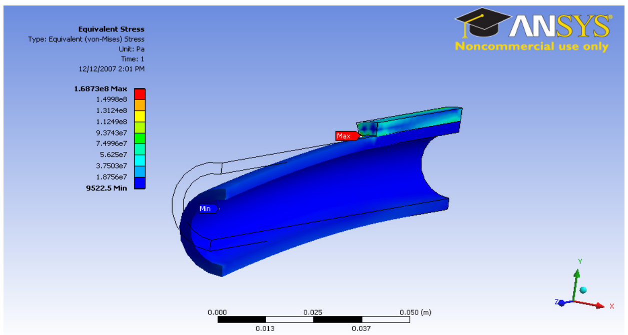

Figure 6: Equivalent stress – Bending load

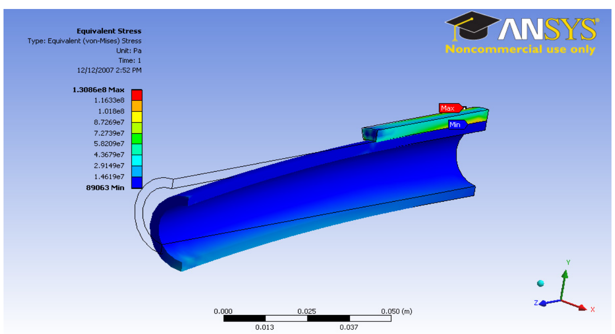

Figure 7: Equivalent stress – Eccentric load

Parametric Models

Initial results indicate that an increase in plate stress and a decrease in underlying bone stress develop due to an increase in plate thickness. This result is consistent with previous studies [13] and indicates the importance of reducing plate stiffness over time during fracture healing. An increase in the angle of plate coverage also increases the equivalent stress level in the plate and produces higher levels of stress shielding on the underlying bone as indicated in Figure 8.

Current results indicate that the distal screw is consistently a higher region of concentrated stress. This result is consistent with the indication of a higher tendency for plate-bone separation at the outer plate end seen in the fixed plate validation model and Figure 9.

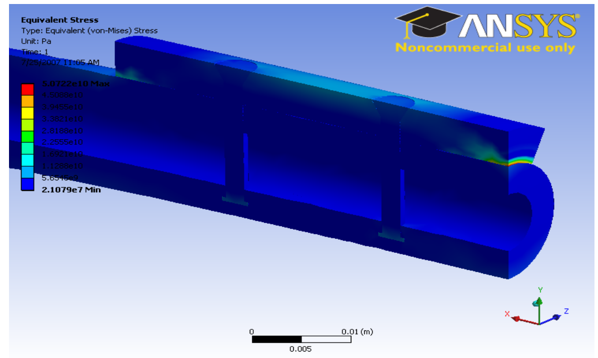

Figure 8: Equivalent stress resulting from applied bending moment

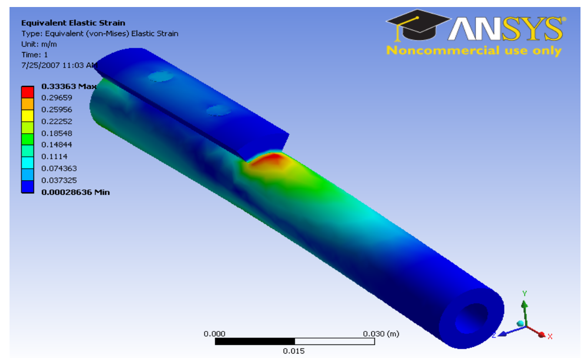

Figure 9: Strain Resulting From Applied Bending Moment

DISCUSSION

Validation Models

This study's results are consistent with the results found by Cheal et al. [3] for longitudinal strain deformations during both axial compression and bending. The results did, however, vary from those of the composite beam theory, demonstrating the importance of relative motion between the plate and the tube.

Results from the validation models include: (1) An upward shift of the neutral axis towards the plate due to the plate application; (2) A change from a constant stress state to a combination of axial and bending stress (for uniform axial loading); (3) A minimized combination of loading for an off-center axial load; (4) An increase in stress at the plate/tube interface for a highly eccentric axial load; (5) A reduction of the longitudinal stresses (between 80 to 95%), especially directly beneath the plate, except for a slight increase in the region for off-center axial loads; (6) A tendency for plate separation with applied eccentric axial loading; and (7) An increase in tensile stresses in the region beneath the outer end of the plate.

Parametric Models

The theory that a reduction in mechanical loading of bone is the primary cause of decreased bone remodelling rates is a topic of much debate amongst researchers [3-5]. The decrease may also be attributed to vascular insufficiency, also referred to as plate induced osteopenia [2]. In order to further investigate the stress shielding developed by plate application a model involving stress-free plate separation using screws is modeled. Stress in the plate-bone contact area is of particular interest as the occurrence of stress shielding in underlying bone will cause a decrease in bone remodelling and may result in increased porosity [16].

Initial observations reveal that stress reduction is most evident between the innermost screws. The normal stresses in the regions of the middle and outer screws increase with the application of a plate when compared to the control bone model. Previous studies, in correlation with these results, also dictate that the outermost screw should experience the highest level of loading and result in a significant region of stress concentration [3, 14-16].

Longitudinal stress reductions of 25% or less result in the underlying bone with plate application due to an applied bending moment, which is consistent with previous research [3].

Parametric studies indicate that stress shielding effects can be reduced by limiting the plate angle and thickness, which reduces the stiffness of the fixation.

Advanced simulations performed using this simplified approach will lead to further insight on the effects of stress shielding. Future studies include the application of pre-tensioned screws, which significantly raise stress in the geometry. Moreover, current investigations using composite plate materials employing the parametric model are in progress in an effort to substantiate the goal of optimizing plate fixation techniques by a reduction of plate stiffness.

ACKNOWLEDGEMENTS

University of Ottawa for providing the Start-Up funds and IRND.

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