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A Discussion on Plating Factors that Affect Stress Shielding Using Finite Element Analysis*

Kristina HAASE** and Gholamreza ROUHI**,***
**Department of Mechanical Engineering, University of Ottawa
161 Louis Pasteur, Ottawa, Canada
E-mail:grouhi@uottawa.ca
***Faculty of Biomedical Engineering, Amirkabir University of Technology, Iran

Abstract

Fixation plates and screws are commonly used to promote stability and stiffness to fractures through the compression of bone fragments. However, the difference between the rigidity of an implant and the bone causes stress shielding, and can lead to excessive resorption in the vicinity of implants, thereby causing subsequent implant loosening and failure of fixation. In this study, finite element analysis (FEA) software is employed to generate a simplified three-dimensional model of a transverse femoral fracture affixed with a plate. The first model discussed in this paper is a validation study, proving the qualitative accuracy of using FEA, while the second model is one of increased fidelity and is used in a parametric study to delve into the effects of plate and screw parameters on the level of resultant stress shielding in bone underlying the plate. The models discussed reveal insight into the nature of applied fixation plates. Direct compression plating, although inherently stable, will cause stress shielding in bone and can result in bone loss, screw avulsion, and fixation failure. However, as seen in the parametric study, which is in agreement with previous works, a decrease in implant flexural rigidity, through a decrease in plate thickness and angle, will decrease the level of stress shielding present in a bone-implant system. As well, the importance of screw placement, implant materials, and the future use of FEA as a prospective tool is discussed.

Key words: Finite Element Analysis, Bone Fracture, Remodeling, Fixation, Stress Shielding

1. Introduction

Internal fixation of long bones with plates and screws dates back over half of a century and although many advances have been made since their early development, compression plating still remains one of the most conventional plating techniques. However, the major disadvantages involved with the use of direct compression plates, wherein primary healing is promoted through direct compression of the plate to bone, include: the bending required prior to surgical insertion; the damage caused to vascular tissue adjacent to the bone; and most importantly stress shielding in the underlying bone (1).

With the application of internal plating devices, unevenly distributed loads are introduced into the bone-plate system, because of the large difference between bone and implant moduli of elasticity and also flexural rigidities, which disrupts the normal level of mechanical stimuli transmitted to bone. This phenomenon, known as stress shielding, invokes a negative rate of bone remodeling which can lead to bone loss and subsequent implant loosening when the implant is left *in vivo* (2).

Limiting the difference in flexural rigidities between implants and bone through a change in material properties is the most well known method for reducing stress shielding.

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As early as 1970, Allgower et al.(3) tested the biocompatibility of titanium alloy dynamic compression plates, and found that in conjunction with spherical screw holes they are advantageous in their resistance to corrosion. They also found that titanium alloy dynamic compression plates are more malleable for surgical bending, and they have an elastic modulus closer to that of bone which causes a reduction in stress shielding. In a later study, Woo et al.(4) proved that decreasing the rigidity of implants alone causes a significant decrease in stress shielding. Experimental evidence (5; 6; 7; 8) that proves the effectiveness of this method has provoked an increasing trend towards the general acceptance and use of more flexible plating systems (i.e. titanium alloys). However, controversy still exists over the optimal level of implant flexibility; one that will limit stress shielding while maintaining a sufficient level of stability (9). It has been hypothesized that a small amount of micro-motion at the fracture site will promote more rapid fracture healing; as in this case, a combination of primary and secondary healing occurs (10; 11). Considering that stable fixation is crucial for the union of fracture segments immediately following implantation, an ideal bone-implant system will gradually transform from one of rigid stability to increased flexibility as fracture healing progresses.

Since flexural rigidity is dependent both on the material properties and the cross-sectional area of the plating device, we postulate that any change to the implant geometry, while maintaining the same material properties, should result in changes in the stress transfer to the underlying bone. Although research(6) has shown that a reduction in the thickness of fixation plates reduces the amount of stress shielding of bone, research into other geometric factors has not been considered. The main focuses of our parametric study (12), in which the cross-sectional area of the plate is altered, is to determine the level of influence the plate geometry would have on stress shielding.

The success of fracture fixation is dependent on many factors, some of which include: the proper placement of the device, the quality of bone into which it is inserted, and choosing the most appropriate device for a particular type of fracture. From a biomedical engineering standpoint, the first two factors cannot be controlled; however parameters involving the design of the fixation device in question can be analyzed and controlled prior to implementation. The use of finite element analysis (FEA) is a well recognized tool for performing *in situ* research in this area and allows researchers to gain further insight into the behaviour of complex systems which would otherwise rely on trial-and-error type methods, mostly that of *in vitro* experiments (13; 14)(15).

The primary focus of this paper is to compare our FEA studies (16; 12) with other work in the field (17; 18) in an effort to draw conclusions on ways to reduce the effects of stress shielding through manipulation of plate structural and material properties. An outline of the methods used in our FEA analyses of both a primary validation study (16) and a parametric study (12) of a fracture fixation plate will be presented.

2. Materials and Methods

2.1 Predicting bone stresses using composite beam theory

As a preliminary theoretical method, composite beam theory is used to predict the stress in bone underlying plates, as modeled in our two FE studies. In the case of our first model, the plate is rigidly affixed to the bone, so we are able to consider the model as a rough approximation of a two-material composite beam. We are able to predict the stresses in bone at the fracture site using the following equation (19):

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

Using Eq. (1) we can calculate the stresses in bone (σ_B) at a distance (t_b) from the neutral axis of the composite structure (19). We are interested in the region of bone directly beneath the plate; therefore we calculate the stresses in bone between the range of $r_i \geq t_b \leq r_o$ (where r_i and r_o are the inner and outer radii of bone, respectively). This measure (t_b) is effectively the distance away from the point of application of the load (P), as shown in Fig. 1 (a). The moduli of elasticity of the bone (E_B) and plate (E_P) and their respective second moment of areas (I_B) and (I_P) are calculated using material properties of that of Plexiglas and stainless steel in order to compare with our validation FE model (16). For the case of our validation model, the cross-sectional area of bone (A_B) remains constant, however, that of the plate (A_P) is changed to reflect a change in plate design; i.e. a change in plate thickness and plate angle, for our parametric model (12). The moment (M) about the neutral axis, which is caused by the application of the applied load (P), can be calculated as follows:

$$M=P\left(d-\hat{y}\right) \tag{2}$$

From Eq. (2) we can also calculate the moment (M) that develops in the plated-bone construct from an axial and eccentric axial load that is applied at a distance (d) away from the neutral axis of the plated bone construct (where $\hat{y}$ is the composite's neutral axis).

2.2 The validation model

In our first model, ANSYS FEA software is used to characterize the resultant stress fields for a geometrically idealized compression plate system (16). A total of 195 linear isotropic SOLID186 elements make up the mesh of the tube, and 24 for the plate. Specified contact and target elements produce the bonded contact surface between the plate and tube. As seen in Fig. 1, a range of static loading conditions, i.e. a compressive axial load, pure bending moment, and eccentric axial load, are applied simultaneously to a bone-plate model, which is comprised of a self-compressing stainless steel plate attached to an intact tube with the material properties of Plexiglas (representative of bone post-union). A comparison to our theoretical results demonstrates the importance of the bone-plate interface conditions when using FEA. In addition, comparisons with strain gage results from studies done by Cheal et al.(18) are used as a validation of the FE methods used.

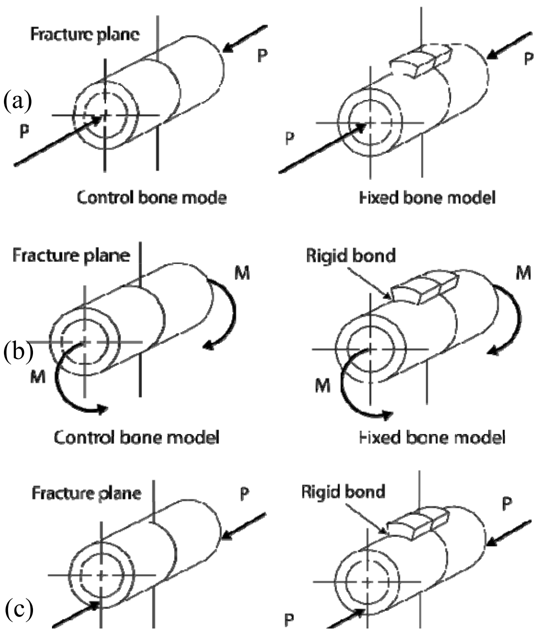
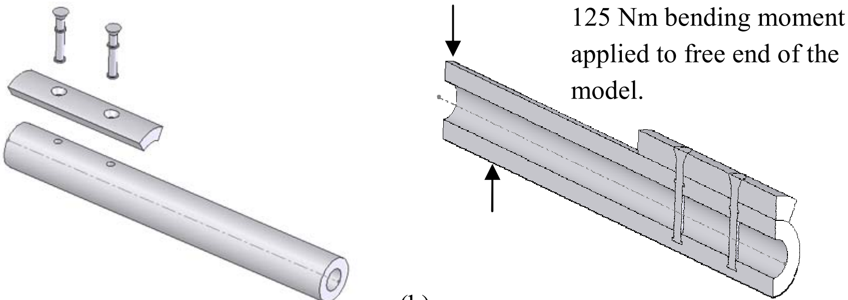


Fig. 1 Centric axial load (a), pure bending (b), eccentric axial load (c) (23)

2.3 The parametric model

While other researchers have focused their attention on the material selection of implants, our parametric model (12) explores changes in the cross-sectional geometry of the plate. The model is comprised of a hollow cylinder representative of cortical bone, a stainless steel plate, and four titanium screws, as depicted in Fig. 2. A patch conforming mesher generates an all-tetrahedral mesh of Solid187 linear isotropic solid elements (a total of 6637 elements for the first configuration). This particular model relies on the screw forces for compression, and allows for stress-free separation of the plate and bone, i.e. a sliding contact condition is employed. It is used to investigate the stress in bone underlying the plate through a parametric change in plate thickness from 3.0 to 4.5 mm; a change in the radial bone-plate contact area from 60 to 90°; and a change in the distance of the distal screw from the fracture site between 15 to 30 mm. Employing a small deflection and strain analysis, a 4-point 125 Nm bending moment is applied to the model in order to investigate the resulting stress levels in bone for each plate configuration.



(a) (b)

Fig.2 Parametric model geometry (a) Exploded view, (b) Cross-sectional view (12)

3. Results

3.1 Validation model

In order to validate our FE methods, we outline the theoretically predicted bone stresses in Section 3.1.1 and then compare them to our FE model results in Section 3.1.2.

3.1.1 Theoretically predicted bone stresses

Using Eq. (1), we calculate the stress in the top cortice of bone, i.e. from just below the plate to the bottom of the cortice. Due to the high flexural rigidity of the modeled plate (plate: EI=2.476 x10^{-6} Nm^2) in comparison to that of modeled bone (bone: EI=1.761 x10^{-7} Nm^2), the neutral axis of our bone-plate system lies in the region of the plate. Since the axial load is applied at the centroid of the bone, below the composites neutral axis, a bending moment is created and the bone below the plate is compressed. From our theoretical calculations, for an axially applied load, a linear decrease in bone stress is predicted, from directly beneath the plate to the outer edge of the top cortice (see Fig. 3). A similar behaviour is demonstrated by the application of an eccentric load, wherein the compressive stresses in bone are higher (due to a larger induced bending moment). The bending moments induced by the axial and eccentric axially applied loads, at the centroid of the bone, are 4.73 Nm, and 5.28 Nm, respectively. In the case of pure bending, a 9.34 Nm bending moment is applied, and in the absence of any axial compression there is less total bone stress.

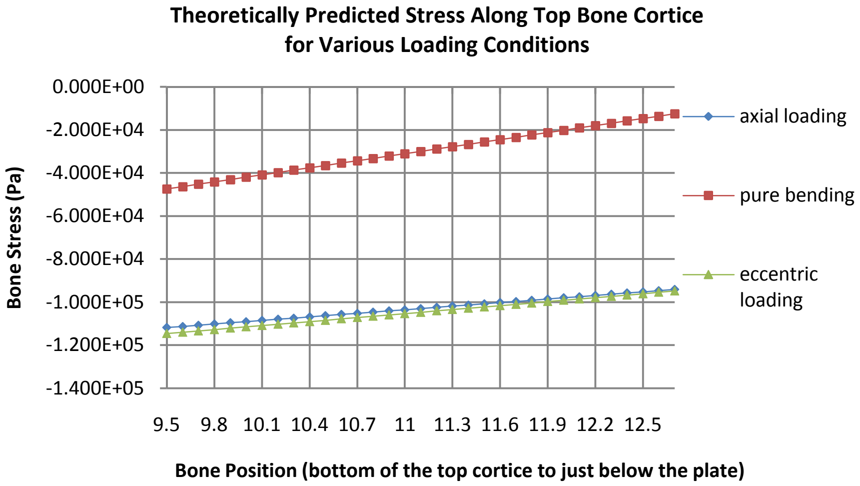


Fig. 3 Theoretical prediction of stress in bone below the plate

3.1.2 Comparison of predicted bone stresses with FE model results

In Fig. 4 we compare the longitudinal principal stresses resulting from our FE model (along the top cortice of the bone) to our predicted stresses. The results from the FE model produce much larger compressive stresses at the bottom of the cortice in comparison to the top, which is expected, however, the stresses are significantly higher than those calculated using composite beam theory.

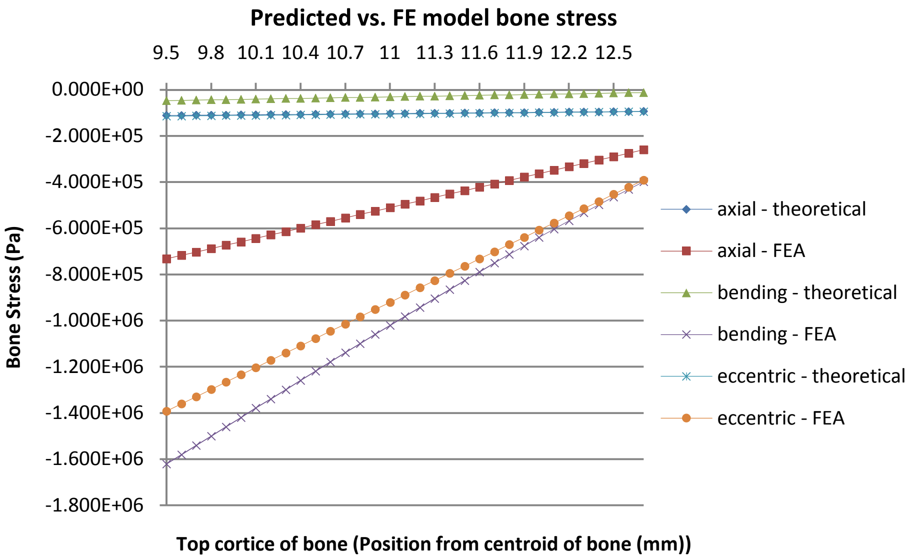


Fig.4 Axial loading of a simple direct contact bone-plate model

With the application of both a compressive axial load and an eccentric axial load to the plated model, a bending moment results (see Fig.5). This is in agreement with our theoretical prediction wherein a bending moment exists due to the application of compressive axial load at a distance away from the composite's neutral axis. As seen in the figure, as is intuitively expected, maximum stress levels occur in the proximity of the fracture site.

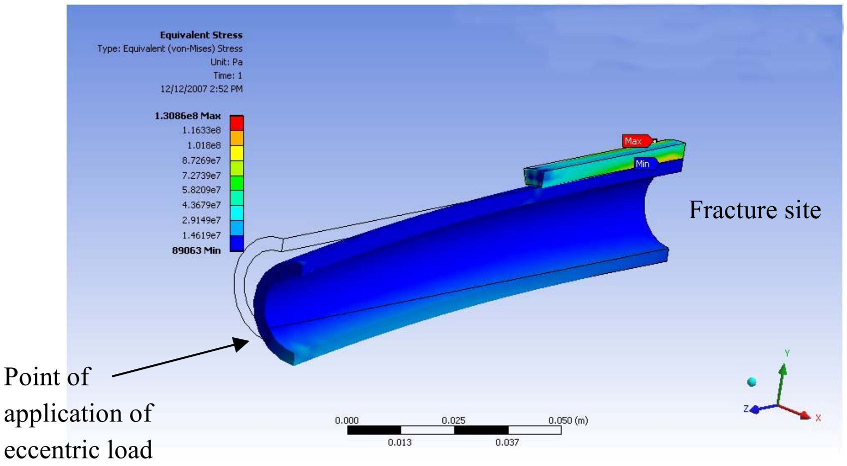


Fig.5 Highly eccentric axial loading of the plated-bone model

In the case of pure bending, as seen in Fig. 6, the maximum region of stress in the plate acts at the bone-plate interface, located distally from the fracture site. This is the expected result due to the direct contact region that is modeled between the plate and bone. As the composite is bent, the much stiffer plate resists the bending motion, therefore resulting in a high stress concentration where the plate would likely separate from the bone.

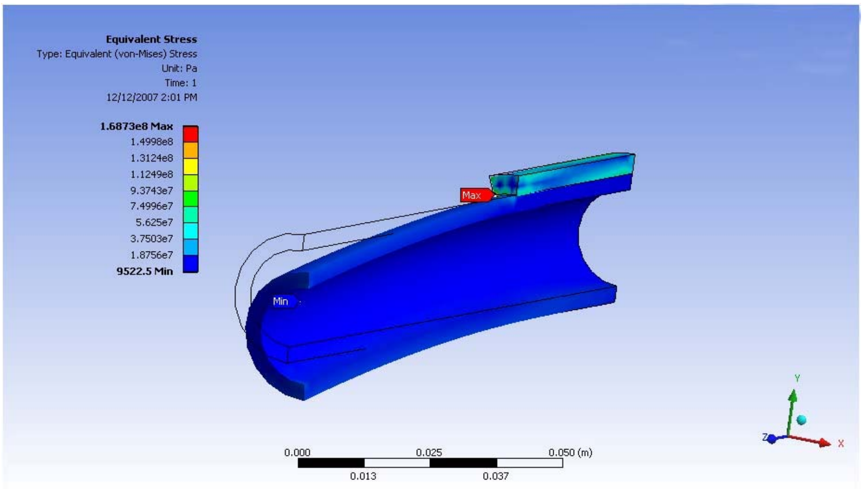


Fig.6 Pure bending loading of the plated-bone model

Results from the validation model, correspond well with previous experimental results performed by Cheal et al.(18; 17), and demonstrate the effectiveness of plate application in reducing bone strain, and the subsequent reduction in longitudinal bone stresses. Figure 7 demonstrates the differences between longitudinal stresses for the control and plated models. Reductions in stress range between 71-92%, 85-95%, and 18-90% for the axial, pure bending, and applied eccentric axial loads.

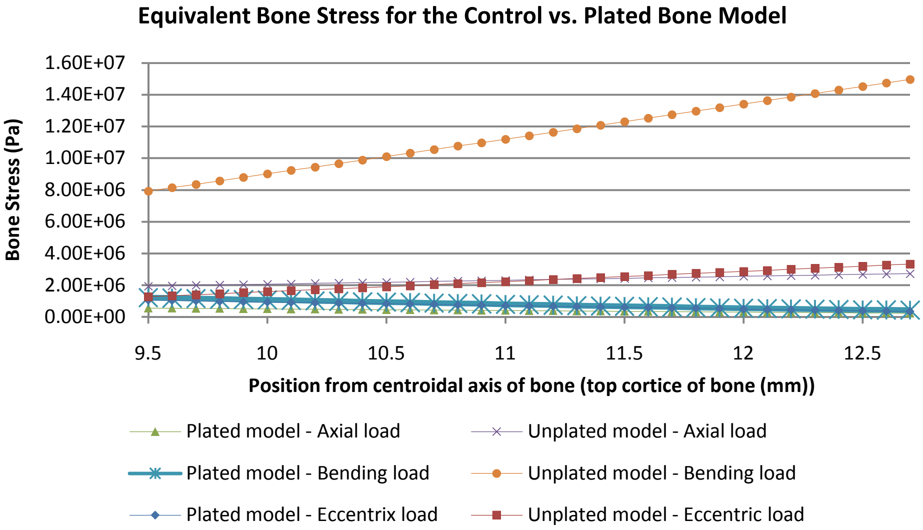


Fig.7 Comparison of bone stresses for the control and the fixed bone model

The difference in predicted versus FE model results is due to the simplifying nature of the composite beam theory, which does not account for the sliding contact surfaces between the plate and bone. The theory is only accurate for predicting the axial stress component in the cross section at the center of the plate where little sliding occurs (the smallest difference between predicted and FE results are just below the plate, i.e. at 12.7 mm in Fig. 4). The limitations of using composite beam theory to accurately predict the stresses in bone-plate constructs is noted by other researchers (8; 18) and demonstrates the usefulness of computational methods for these analyses.

3.2 Parametric model

In an effort to create a more realistic situation, the parametric study incorporates simplified screws into the model and also allows for sliding to occur at the bone-plate interface. Our theoretical predictions of resultant bone stresses (immediately underlying the plate) are compared to our FE model results below, in order to demonstrate the limitations of using the composite beam theory for predicting stresses in bone-plate constructs.

3.2.1 The effect of plate thickness on bone stress

Using the geometry and material properties modeled in our parametric study in Eq. (1), it is predicted that at the smallest plate thickness, i.e. 3.0 mm, the stress in bone just below the plate is tensile (see Fig. 8). While maintaining a plate angle of 60˚, as the thickness of the plate increases, the neutral axis of the bone-plate system moves further upward towards the plate causing a decrease in compressive stresses in bone below the plate until a plate thickness of 3.7 mm is used, wherein bone stress then becomes compressive. This compressive stress increases as the thickness of the plate increases from 3.7 to 4.5 mm.

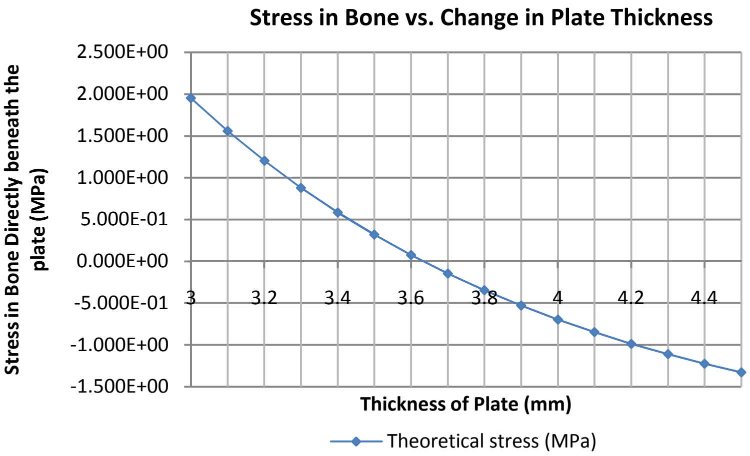


Fig.8 Theoretical predictions of stress in bone underlying a plate of changing thickness

As seen in Fig. 9, our FE results demonstrate a decrease in bone stress for an increase in plate thickness. The variation between the theoretical prediction of stress and our FE results can be explained by the boundary conditions used. For our theoretical calculations, it is assumed that the bone and plate are rigidly affixed, which is a poor approximation of the bone-plate interface, where sliding motion exists.

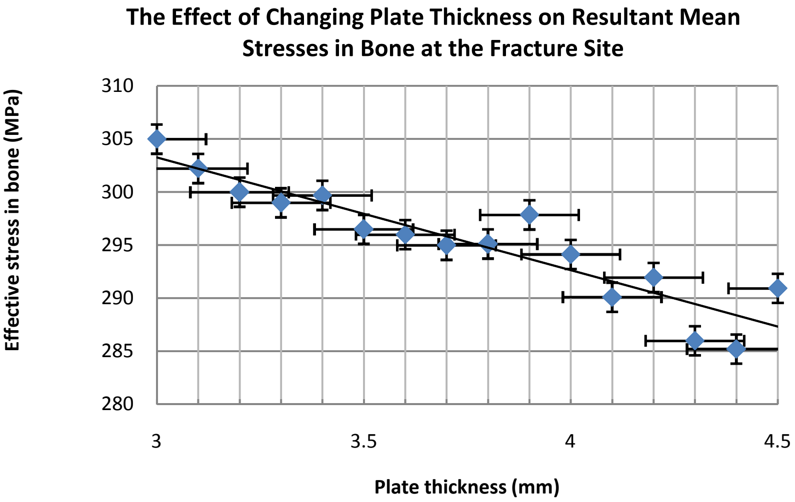


Fig.9 A decrease in effective stress along the bone-plate interface occurs when the thickness of the plate is increased

3.2.2 The effect of plate angle

The theoretical prediction of bone stress due to an increase in plate area is shown in Fig. 9. At a plate angle of 60˚ the bone is under compressive stress which decreases until the plate angle is modeled as 67˚, wherein the bone experiences an increase in tensile stress up to the modeled plate angle of 90˚. While maintaining a thickness of 4.5 mm, an increase in the plate angle effectively moves the neutral axis of the bone-plate towards the centre of the bone, thereby creating tensile stresses in the top cortice of the bone when a plate angle of 67˚ or larger is modeled.

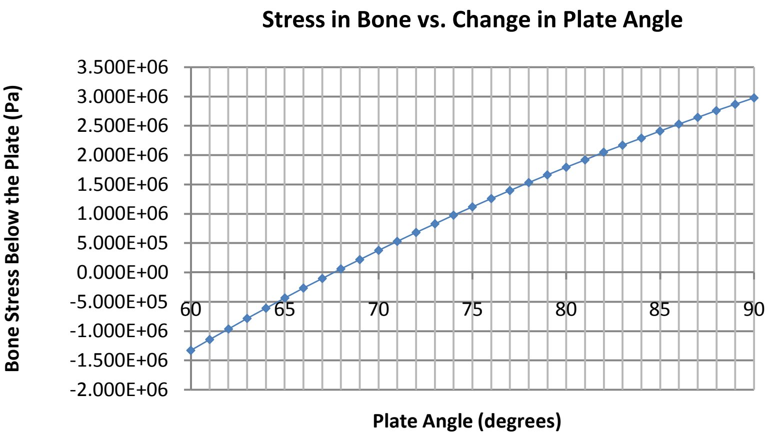


Fig.10 Predicted change in bone stress below the plate with a change in plate angle

Results from our FE model (see Fig. 11) indicate that an increase in plate angle will cause a decrease in stress in the underlying bone, i.e. a higher degree of stress shielding develops in the neighbouring bone. The variation between the theoretical prediction of bone stress and our FE results is quite prominent here, and can once again be explained by the assumptions made about the bone-plate interface. In the FE model, because of the sliding contact between the bone and plate, the majority of the bending moment is effectively transferred to the plate.

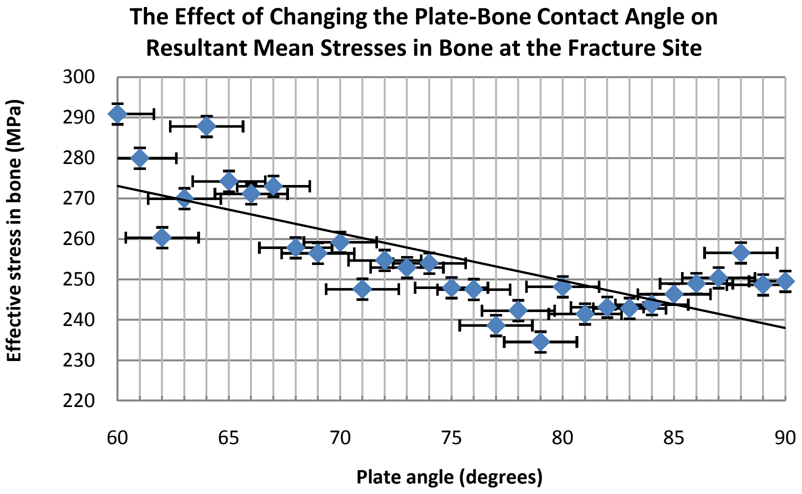


Fig.11 A decrease in effective stress in the bone at the bone-plate interface occurs with an increase in plate-bone contact area

3.2.3 The effect of screw position

Experimental research has highlighted some of the geometric factors responsible for the pullout strength of bone screws (20; 21). However, little information involving the stress distribution between screws and bone exists. Our parametric study reveals an important consideration involving bone screw stresses; the distal screw is the highest region of concentrated stress, which is in agreement with previous works (18). Stress and strain reductions in bone are seen to be the most apparent in between the two innermost screws, near the fracture site (see Fig. 12). This indicates that stress shielding is most prominent in the vicinity of the fracture. According to other researchers (15), this is beneficial upon initial fracture reduction; however, in the post-union phase, the reduction of load will affect the rate of remodeling and can cause subsequent bone loss.

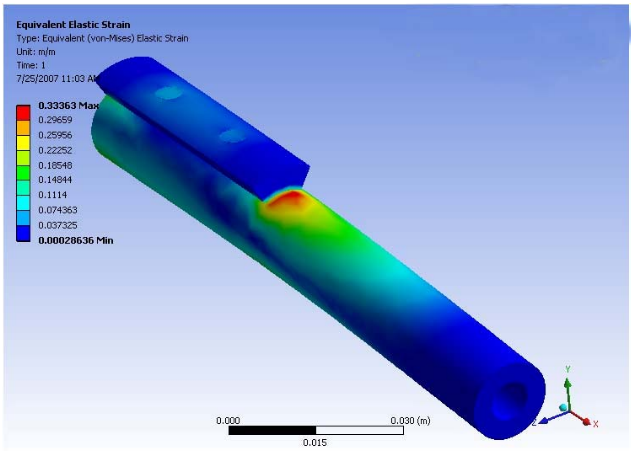


Fig.22 Parametric model equivalent strain

4. Discussion

A comparison of our FE models' results, to those predicted theoretically, demonstrates the limitations of using the composite beam theory to predict stress-shielding in a bone-plate system. From our validation model (16), we notice that axially compressive loads applied away from the composites' neutral axis will cause bending of the plated-bone construct, which was predicted by our theoretical calculations. This suggests that composite beam theory does work well for predictions in the mid-shaft of the composite during axial and bending loading when a fixed contact region is considered between the bone and plate. The theory does not take into consideration the importance of relative motion between the plate and bone, and therefore considerable differences between the theoretical model and the parametric model (which allows for sliding motion at the bone-plate interface) can be seen. Moreover, the complex nature and geometry of actual bone-plate systems with screws is reliant upon FEA for investigative analysis of their non-linear behaviour.

In order to observe the stresses in bone underlying the plate, in our validation model we used compressive axial and eccentric axial loads, as well as pure bending. Under all loading conditions, the application of a rigidly fixed plate to a fractured bone reduces the levels of bone strain and longitudinal stresses immediately below the plate (in comparison to the control bone under the same load). This stress shielding effect is in agreement with experimental evidence by researchers such as Claes and Woo (2; 6), whom demonstrate that bone loss is exacerbated by the use of stiff plates (2; 6). Although the loads modeled are simplifications of the complex physiological loads that occur *in vivo*, we notice that, in both theory and our FE model, axially compressive loads generates higher overall bone stresses. Since less axial compressive loading will be present in the long bones of upper extremities, in comparison to those of the lower extremities (22), it is likely that stress shielding is more pronounced in these cases of fracture. A quantitative experimental comparison of stress shielding between the two fracture types is greatly needed.

Using the composite beam theory we predicted that bone stress is dependent on the geometry of the plate and will transform between tensile and compressive stresses in relation to the composites' neutral axis. However, since the theory relies on a fixed interface between the bone and plate, we observe some variances with our FE results. For the range of thicknesses analyzed, our FE model indicates that an increase in plate thickness results in a relatively linear decrease in effective bone stress immediately below the plate. Since the angle of the plate is not changed in these cases, the neutral axis of the bone-plate construct will shift upwards towards the plate causing an increase in bone compression (for all points that lie below the neutral axis). Since Von Mises' stresses are considered in our FE model, the results will represent the combination of equivalent stresses (both tensile and compressive) at the point in question, i.e. in bone just below the plate.

According to Woo and co-workers (5) the plate axial stiffness is the dominant factor that alters bone stresses; however, they do not consider the natural geometry of the plate, or the pre-surgical bending of implants in their models. Bone plates are generally designed to include a curved cross-sectional area in order to conform to the cylindrical-like characteristics of long bones. For this reason, in this study, we analyzed the effect of plate angle in relation to stress shielding. An overall increase in stress shielding is demonstrated by an increase in plate angle, however unlike plate thickness, this parameter does not demonstrate a linear relationship with observed bone stress. When increasing the plate angle, the type of stress in bone is more complex due to the altered load distribution caused by the limitations of the geometry. Radiological assessment has shown that limiting the contact area between plate and bone reduces the amount of visible stress shielding as well as the amount of damage to the blood supply (23), so we postulate that the plate angle should be limited.

It is also noted that special attention should be paid to the placement of screws in the plate-bone system (12). Cheal and co-workers reported that the screw nearest the fracture site is at risk for failure during the early stages of fracture healing; however, the most distal screw is at risk for prolonged fixation (18). Our results demonstrate that the outermost screw is most likely to fail (12), which corresponds to results by Simon et al.(15) that consider a similar FE model (in the post-union phase of fracture healing). Based on our findings, an arrangement that reduces the likelihood of stress shielding near the fracture site and screws, without interfering with initial reduction, should be sought. Our future models explore the effects of screw geometry on the stress distributions in neighbouring bone.

Although some researchers, such as Perren et al.(24), suggest that necrosis associated with vascular insufficiency is the main cause of increased bone porosity, most researchers (10; 5; 6; 7; 8), attribute increased levels of stress shielding to a reduction in mechanical stimuli caused by implants. As is the case in all other FEA works referenced (18; 25; 14), and for the sake of simplicity, we consider a standard compression plate and neglect the effects of soft tissues in our models. Although interstitial tissues have an overall effect on the stress distribution of the system (13), their significance is minimal in comparison to the distributions resulting from variances in implant material and geometry. Clinically, the alleviation of decreased vascularity and soft tissue damage can be achieved with devices such as the Less Invasive Stabilization System (LISS) and the Point-Contact Fixator (PC-Fix) (26; 27; 28).

Although three-dimensional models can be used to predict screw stresses and contact stresses (15), their predictive capabilities is questionable, as even radiological and clinical testing methods, when used alone, are inaccurate in predicting fracture healing (11). A combination of FE and experimental evidence would be ideal to accurately predict the outcomes of fracture healing for various implant designs. The lack of a universally accepted and comprehensive bone remodeling theory (29) is a main reason for not being able to fully analyze stress shielding effects in a bone-implant system to date. Although, many researchers have incorporated adaptive remodeling theories into simple FE bone models (14; 30; 31), none of the present models can fully capture all aspects of the very complex bone remodeling process (32; 33; 34). Along with the incorporation of a universal bone remodeling theory into bone-implant systems, improvements to the realism of geometries, material properties, and boundary conditions will increase the accuracy of predictive bone-implant interaction models.

5. Conclusions

Results from our studies indicate that FE models are useful in qualitatively analyzing the effects of stress and strain distributions in simplified bone-plate constructs resulting from different loading conditions. The application of a plate to a bone causes a significant reduction in bone stresses, most importantly at the fracture site (16). This is shown experimentally by others (24; 7). We have shown that one method to reduce stress shielding, besides the selection of more flexible plating materials, is to reduce the implant flexural rigidity through limiting plate thickness and angle. A reduction in stresses in and around the fracture site is also noted by a change in the distal screw position, which demonstrates the importance of screw placement.

Acknowledgements

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