

Prediction of Stress Shielding Around Implant Screws Induced by Three-Point and Four-Point Bending

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INTRODUCTION

Orthopedic screws are primarily responsible for the stability of the fracture fixation device. Screw loosening to be a major concern in implant failure mainly associated with the pull-out loading (Ramtani & He, 2014). It can cause complication such as graft failure, loss of range of motion, nerve injury, bone tunnel confluence and surgical site infection (Helito et al., 2014). Besides that, the high-stress concentration causes the loosening of the screw that can results implant failure and infection occurs on the fracture site. Screw loosening studies are well reported in the literature (Gefen, 2001; Gefen, 2002). However, studies concerning the bone-screw interactions involving the reduction of stress shielding remained unclear. Fracture healing is commonly categorized by the three-phase of responses which are inflammation, repair, and remodelling phase (Haase & Rouhi, 2013). They have reported the better knowledge of bone healing simulation including the conceptual modeling and biomechanical modelling.

In bone healing simulation, many researchers have focused only on fixed callus geometry to represent a certain level of bone growth (Sun & Swain, 2017). Some studies focused on the effect of the treatment outcome and the factors that influence fracture healing process are external loading, type and duration of fixation, and the morphology of fracture among others (Ghiasi et al., 2017; Shibata et al., 2015). This modelling simulation covers only geometry of initial bone fracture structure and does not include the structural remodeling or directional properties in bone. However, the interface between implant can be varied based on material properties at a certain level of bone remodeling phase.

Some researchers have purposed bone remodelling theory in 2D axisymmetric configuration that represented the implant, cortical and trabecular bone region (Vanegas et al., 2011; Chou & Muftu, 2013). They made an assumption that the osteotomy gap to be filled with callus tissue either immature or matured bone. Since the interaction between implant and bone created while external load applied. There are stresses distributed along the implant screw and directly transfer to the neighbouring bone. A simple model of the screws with the threads are used as an anchorage in cortical and trabecular bone. The threaded screw has been a model to represented through interfacial bone-implant contact conditions as shown in Figure 1.

Stress shielding can be described by parametric study in form of stress transfer parameter (STP) and strain energy design transfer parameters (SEDTP). The aimed of approaches used to calculate the effective stresses at the defined points in the trabecular bone and screw threads (Haase & Rouhi, 2013). Loosening of bone screws caused by stress shielding, and subsequent unbalanced bone

remodelling processes, results in bone loss around the screws, which can ultimately lead to bone fixation failure. Thus, it is necessary to investigate the interaction of orthopedic screw and bone using FEA. The objective of this study is to analyze the bone-implant fixator stress-strain behavior subjected to three point and four-point bending. It became an essential to understand the effect of bending load on the stress-strain behavior of the bone and screws that can cause breakage and give pain to the outpatient.

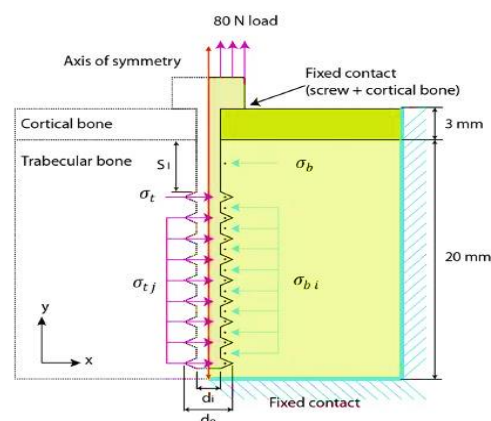


Fig. 1: Parameters studies of stress shielding analysis (Haase & Rouhi, 2013)

FINITE ELEMENT MODELLING

The three-dimensional model of the bone fracture fixation and femur bone structure was developed using Solidworks Software 2013. The finite element analysis is developed by using ANSYS Workbench 18 and the optimized mesh using appropriated setting and values in order to have a small element a number on proximities and curvatures for the model. The converge number of element, 1058958 used for the bone fracture fixation model.

Table 1 describes the details of bone fracture fixation for conventional cortex screw and compression plate based on Synthes product. In this study, the screw length is set at 36 mm, and two types of material (i.e. Stainless Steel and Titanium) were used. These types of bone fracture fixation chose based upon the fracture type suggested based on AO Foundation (Colton & Pape, 2017). Table 2 represents the information regarding the material properties of bone; cortical bones were assumed to be orthotropic, homogeneous, and linearly elastics as were the others' materials used in this study.

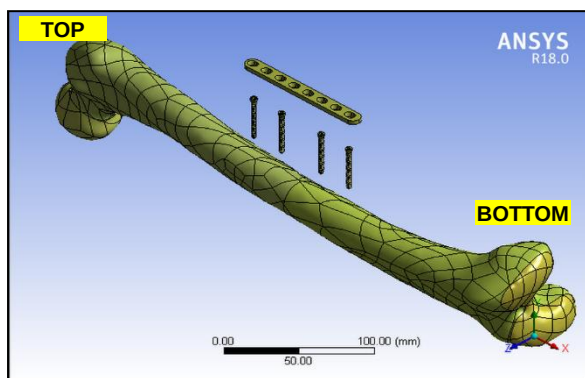
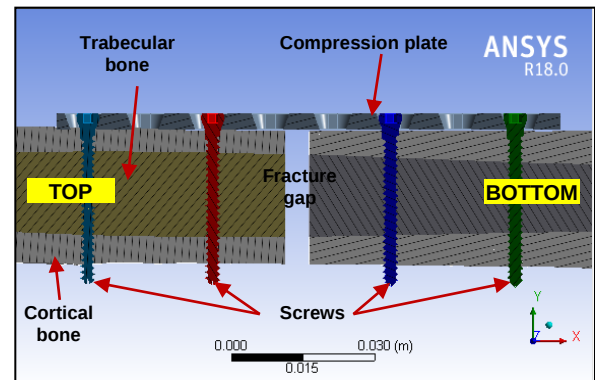
Table 1 Dimensional parameters for bone fracture fixation (Colton & Pape, 2017).

Conventional Cortex Screw (mm)		8-holes compression plate (mm)	
Diameter of thread, d_o	3.5	Width	11.0
Thread pitch	1.25	Thickness	3.3
Diameter of core, d_i	2.4	Center-to-hole distance	13.0
Diameter of head	6.0		

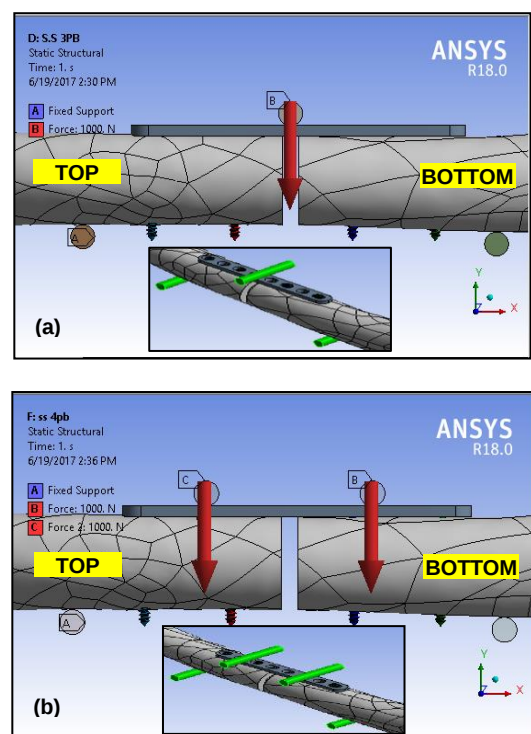
Table 2 Mechanical properties of bone structure and implant materials

Bone material	Young's modulus, E (GPa)	Poisson's ratio (ν)	Shear modulus (GPa)
Trabecular	$E_{Tb} = 1.1$	$\nu_{Tb} = 0.3$	-
Cortical Bone (Longitudinal transverse)	$E_3 = 20.0$	$\nu_{12} = 0.376$	$G_{12} = 4.53$
	$E_1 = 12.0$	$\nu_{23} = 0.235$	$G_{23} = 4.53$
	$E_2 = 12.0$	$\nu_{23} = 0.376$	$G_{13} = 4.53$
Stainless Steel	$E_{s.s} = 200$	$\nu_{s.s} = 0.3$	-
Titanium	$E_{Ti} = 113.8$	$\nu_{Ti} = 0.34$	-

The bone fracture fixation model comprised compression plate and four internal conventional cortex screw (full threaded) anchored along the diaphysis shaft as shown Fig. 2 (a). The fixation or implant was placed in the middle of the fracture line. The fracture gap created at 5 mm) and the screws orientation at 90° also used based on the fracture angle. Fig 3 shows the crosssectional view along the femur bone model. Each screws implanted through the bone (i.e pass through an average of 4.4 mm thickness of cortical bone and cavity filled with trabecular bone).

**Fig. 2** Bone fracture fixation model**Fig. 3** Crosssectional view bone fracture fixation model

There are two type of bending applied to the model which are three-point and four-points bending as shown in Fig. 4. There are pins of fixator for bending simulation. Fig. 4(a) shows the Pin A and Pin C as fixation point while Pin B loading point crossed to the implant for bending simulation. Fig. 4(b) shows four point bending model where Pin A and Pin D setup up as fixation point and Pin B and Pin C as loading point. An uniaxial compression load of 1000 N along y-component is applied on the upper cylindrical beam where is placed directly on the implant crossing between fracture gap. The model is supported by two cylindrical beam below the bone model with gap 186 mm. Thus, the results of von-Mises stress are investigated to determine the critical screw failure.

**Fig. 4** Boundary condition of (a) three-point and (b) four point bending

The interactions between bone and screw are analyzed by using stress shielding approach whereas the two-dimensional of cross section view is used. Shielding analysis is focused on the critical screw while the stress in a proximal thread and distal thread on screw and bone are determined. In order to classify these stresses, stress transfer parameter (STP) and strain energy design transfer parameter (SEDTP) are calculated using the effective stresses at the defined

points in the trabecular bone and screw threads. Stress transfer parameters are defined as

$$STP \alpha = \sigma_b / \sigma_t \quad (1)$$

$$STP \beta = \sum_{i=j=2}^N (\sigma_{bi} / \sigma_{tj}) \quad (2)$$

$$STP_{total} = STP \alpha + STP \beta \quad (3)$$

and strain energy design transfer parameter (SEDTP) are expressed as

$$SEDTP \alpha = \sigma_b \varepsilon_b / \sigma_t \varepsilon_t \quad (4)$$

$$SEDTP \beta = \sum_{i=j=2}^N (\sigma_{bi} \varepsilon_{bi} / \sigma_{tj} \varepsilon_{tj}) \quad (5)$$

$$SEDTP_{total} = SEDTP \alpha + SEDTP \beta \quad (6)$$

where $STP \alpha$ and $STP \beta$ are the ratios of equivalent stress transfer to the bone (σ_b) and neighboring screw thread (σ_t). SEDTP are defined to determine the stress transfer involving stress-strain behavior of the model, von-Mises stress (σ) and von Mises strain (ε) and subscript b and t refer to bone and threads respectively.

RESULTS AND DISCUSSION

Table 3 represents the tabulated data of maximum von-Mises stress of screw for both materials and bending loads. The results showed the Stainless Steel had a higher stress in comparison with Titanium for both bending loads. The reason for this is Stainless Steel had higher elastic modulus compared to Titanium that Stainless Steel led to the optimum failure strength. The modulus obtained by three-point and four-point bending was different but had the 1% value corresponds to the stress-strain slope. Although had different of modulus between these loads, small values did correspond to the same method. The critical screw stress was investigated after the bending load applied. Critical stresses were focused on the bone and screws model while the compression plate was ignored. This is because the presence of compression plate acts as the real case of implant devices were used in bone-implant fixation.

Table 3 Maximum von-Mises stress of stainless steel and titanium screws at two type bending load.

Bending type	Materials	von-Mises stress (MPa)
3-point bending	Stainless steel (S.S)	160
	Titanium (Ti)	125.44
4-point bending	Stainless steel (S.S)	183.08
	Titanium (Ti)	162.63

Fig. 5(a) and Fig. 5(b) shows the results of the 3-points and 4-points bending respectively. Critical stress present on the screw near the fracture site for both bending loads. The stress distributions in bone and screw from the bending load were determined using two-dimensional of the cross section view along the diaphysis shaft.

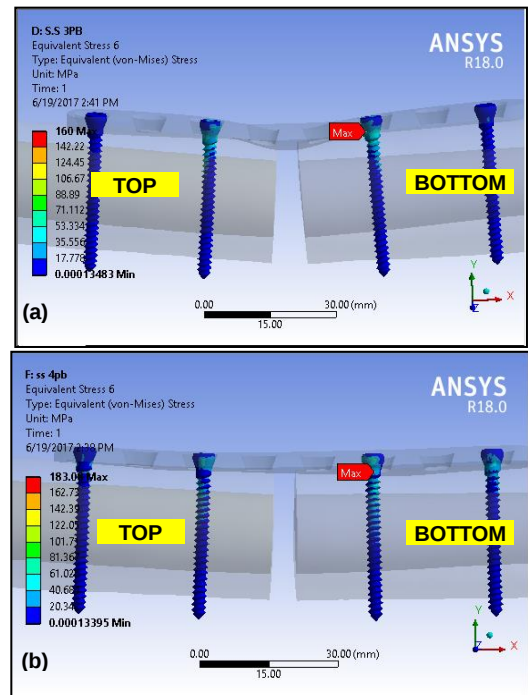


Fig. 5 Maximum von-Mises stress found the screws near the fracture site.

Using the defined parameters in Eqs (1)-(6), STPs and SEDTPs values stress were determined on the screw shaft and the neighbouring bone as shown in Fig. 6. The results show maximum von-Mises stress existed in the intersection of the screw head and the profile. The stress shows reduction as the lowering readings to the screw tip. The first or proximal thread shows to have higher than distal thread (following thread). Similar to the von-Mises strain obtained in the screw thread has a critical strain on the first thread. However, maximum Von-mises were determined, in order to obtain the stress transfers to neighbouring bone. Fig. 7 shows the results of maximum von-Mises stress obtained in the bone at the neck interfaces.

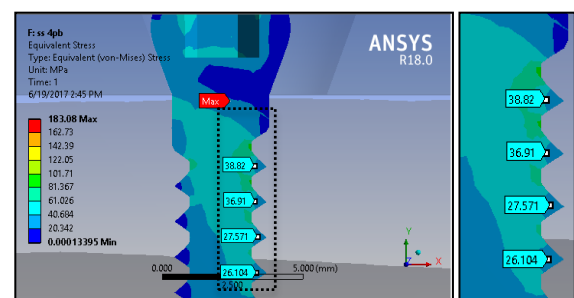


Fig. 6 Enlargement of stress contour of the screw as defined parameters the STP and SEDTP

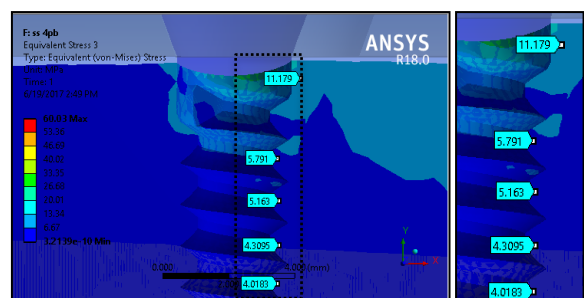


Fig. 7 Enlargement of stress contour of the neighboring bone as defined parameters of the STP and SEDTP

The stress shows reduction along the screws profile. Together correlate to the von-Mises strain obtained in the bone thread has a critical strain on the first thread. These critical stress found in the screw neck was expected to have the largest shear stress in vitro (Vijayalakshmi et al., 2012; Sugiura et al., 2000). The statement was supported by the stress contour results that shows the thread closest to the cortical bone region shows higher stresses concentration. Consequently, the stresses measured on the both proximal thread (α) and distal thread (β) were used to obtain stress transfer parameters from implant screw to bone hole inner surface. The results obtained significant greater stress transfer on STP α compare to the STP β for both loads as shown in Fig. 8(a) and 8(b).

Besides that, STP total of Stainless Steel screws shows less stress transfer to the bone compares to Titanium for both bending loads. It was due to the stainless steel had higher of elastic modulus compare to the titanium for both bending loads. It found that the titanium screws have a good mechanical stimulus, in term of stress transfer that expected to have the high level of stability to promote in the bone remodelling process. Also, SED transfer parameter was very important for initiation and bone remodeling process.

The overall average results of STPs and SEDTPs under three-point bending higher than four-point bending. These might be the contact zone between implant model and cylindrical supports. The total deflections involve the axial forces along the beam that causes the different level flexural strength. Since the bending moment deformed distribute stresses on the screw thread and bone interfaces. Thus, significant differences in the first thread and distal thread based on the STPs and SEDTPs criterion were shown in Fig. 8(a) and 8(b). SEDTP β under three-point bending shows a linear decrease in correlate with STP β , compare with SEDTP α shows highly affect to the SEDTPs values in both loads. These results obtained due to adjacent force or pull out loading existed in adjacent to the screw head and distributed the strain energy along the screw shaft. The varied of elastic modulus (E) of the screws materials, 200 GPa (stainless steel) and 113.8GPa (titanium) results increasing the total stress transferred, STPs between screw and bone interface. Increment on average STPs of 26% (stainless steel) and 31% (titanium) for three-point and four-point bending load respectively. It also observed that both types of loads show the increases the average of STPs on the simulated titanium screws, in comparison to the stainless steel screws as shown in Fig. 9(a) and Fig. 9(b). This result shows an agreement with literature wherein stated that increase of elastic modulus of the screws causes increasing of stress shielding (Gefen, 2001).

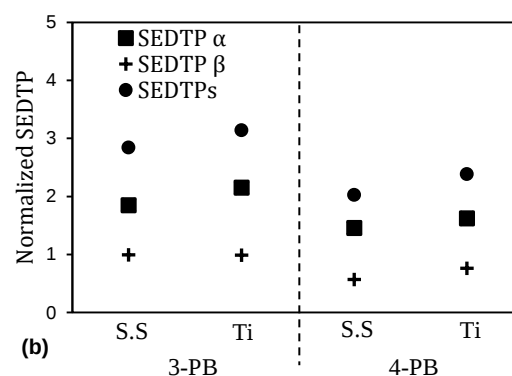
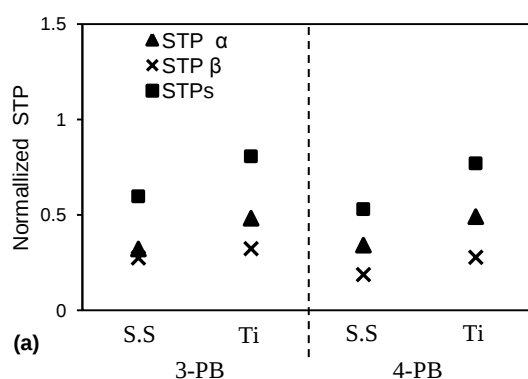


Fig. 8 The effect of material of screws on average STPs/ SEDTPs (a) three-point (3-PB) and (b) four-point bending load (4-PB)

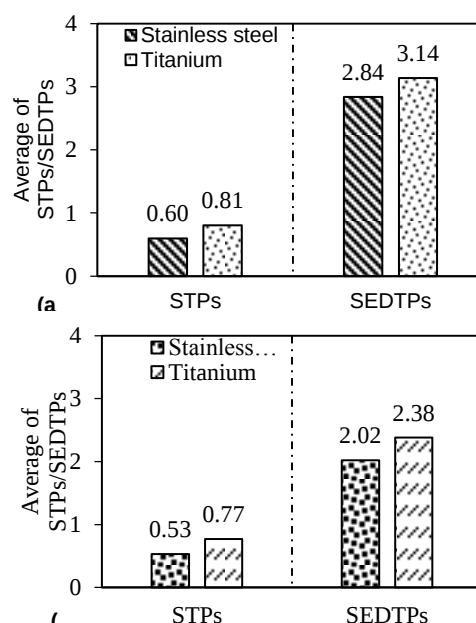


Fig. 9 The effect of material of screws on average STPs/ SEDTPs (a) 3-point bending load (3-PB) and (b) 4-point bending load (4-PB)

Increasing the screw's elastic modulus had a significant effect on the average SEDTPs. Increment about 10% and 15% of the average of SEDTPs for three and four-point bending loads respectively. These results were contrary to the previous studies stated that elastic modulus had no effect on average (SEDTPs) (Haase & Rouhi, 2013). However, the results obtained were dependent on the varied geometric parameters and materials properties.

CONCLUSION

The stainless steel has higher stress shielding compare to the titanium under three-point and four-point bending. The result obtained based on the stress transfer STPs (α and β) and strain energy density transfer SEDTPs (α and β) parameters. The screw at closest to the fracture site had found highest stress that concentrated on the screw neck. This study provided meaningful differences exist between stress and strain energy density in the bone under two type of bending loading, which can ultimately assist the bone remodelling rate and stress shielding for different materials.

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