MECHANISM OF LOAD TRANSFER ALONG THE BONE-
DENTAL IMPLANT INTERFACE

A Thesis Presented

by

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to

The Department of Mechanical and Industrial Engineering

In partial fulfillment of the requirements

for the degree of

Master of Science

in

Mechanical Engineering

in the field of

Mechanics and Design

Northeastern University

Boston, Massachusetts

August 2009
NORTHEASTERN UNIVERSITY
Graduate School of Engineering

Thesis Title: Mechanism of Load Transfer Along the Bone-Dental Implant Interface

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ACKNOWLEDGEMENT

This thesis could not be possible without the help of the people who made substantial contribution in my graduate study in many ways.

First, my special gratitude goes to Prof. Sinan Müftü, my advisor, for his guidance and inspiration at every step of my graduate study at Northeastern University. His wide knowledge and logical way of thinking have been of great value to me. His understanding, encouraging and personal guidance were substantial keys to make this study happen and make me feel grateful and blessed to have worked with him. I would also like to thank my officemate Mr. Hsuan Yu Chou, for providing me with his substantial knowledge and experiences during this study. I would like to mention my other officemates in 244H FR as well for providing a great working place and my friends for their help and companionship.

Special thanks go to my parents and family for their love and understanding.
ABSTRACT

Endosseous dental implants are used as prosthetic treatment alternatives for treating partial edentulism. Excellent long term results and high success rates have been achieved using dental implants during the past decades. Further improvements in implant protocols will include immediate loading, patient specific implants, applications for patients with extreme bone loss and extreme biting habits such as bruxism. Load transfer from a dental implant to the surrounding bone is believed to be one of the key factors that determine the health of the bone, and thus contributes to the successful survival of the implant system. Load transfer starts along the bone-implant interface, and is affected by the loading type, material properties of the implant and prosthesis, implant geometry, surface structure, quality and quantity of the surrounding bone, and nature of the bone-implant interface.

In the literature, finite element analysis has been used widely to investigate the stress distribution in the bone in the presence of a dental implant. However, a clear statement of how the load is transferred at the bone implant interface seems to be lacking; the effects of implant body-length, implant diameter, implant collar and apex shape, and the effects of presence or lack of screws on the implant body have been studied anecdotally, but not systematically. In this work we tackle the analysis of the fundamental load transfer mechanisms between the implant and the surrounding bone, and analyze the effects of the aforementioned variables along the bone-implant interface, systematically. Finite Element Method was used to model the bone and dental implant systems. We monitor the stresses along the bone implant interface, as well as in the bone and draw
conclusions on the effects of implant design parameters on stresses generated in the bone, and on the bone-implant interface.

A 2D plain strain analysis of the buccal-lingual cross-section is useful in discussing the load-transfer from the implant to the bone. Among the six contour parameters, the slope ($\theta_c$) and length ($L_c$) of the implant collar, and the implant diameter ($D$) influence the interfacial stress levels the most, and the effects of changing these parameters are only significantly noticed in the cortical bone (alveolar ridge) area. Moreover, Use of implants with external screws reduce the stresses in the bone distal to the implant, whereas bone proximal to the implant (along the bone implant interface), is predicted to sustain larger stress values.
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CHAPTER 1

INTRODUCTION

1.1 Dental Implants

A dental implant serves as structural support for dental prosthesis. A dental implant system consists of three main components: the implant, the abutment and the prosthesis as shown in Figure 1.1. The implant is typically made of titanium or the titanium alloy (Ti6Al4V) which has been characterized by excellent biocompatibility and mechanical properties among many clinically tested implant materials [1]. Other implant materials such as aluminum oxide (Al2O3) disappeared from the market because they were under an increased risk of fatigue failure under long-term function, and they were not strong enough to tolerate masticatory forces. The abutment attached to the implant serves to retain the prosthesis. The two types of implant abutment attachment methods commonly used are screwed-in and tapered interference fit [2].

In the past 30 years, the use of dental implants has become a widely accepted treatment alternative for treating fully or partially edentulous patients, and is regarded as a therapeutic advantage over fixed bridge of removable dentures. Excellent long term results and high success rates have been achieved using dental implants during the past decades. A two-stage surgical procedure is required to place an implant in the jaw bone, if there is adequate bone to support dental implants as shown in Figure 1.2.
Figure 1.1 A dental implant system which is composed of three components: crown, abutment and implant.¹

Figure 1.2 Surgical procedures of dental implant treatment. (a) The gum tissue is removed and a dental implant is inserted in the jaw bone. (b) The osseointegration takes place in four to six months. (c) After osseointegration achieved, the abutment is attached to the implant. (d) Finally a prosthetic tooth is placed on the abutment.²

¹ http://www.martinruelas.com/nss-folder/pictures/implant.jpg
² http://www.periodont.com/implants.htm
In the first stage, the gum tissue is removed in order to expose the jaw bone, and an osteotomy is drilled. The implant is placed in the osteotomy and the bone microscopically grows up to and around the dental implant until it firmly anchors into the implant. This phenomenon is called osseointegration, and it was first investigated by the Swedish orthopedic surgeon Per Ingvar Branemark. He discovered the biocompatibility of titanium and applied it to implant dentistry [3].

The osseointegration period takes between four to six months and once it is satisfied the second stage of implant placement begins. An abutment is attached to the implant and a restorative tooth is built over the abutment. [4]

There are two implant placement modalities in implant dentistry known as the submerged and the nonsubmerged approach. Studies were conducted to which approach is more appropriate both in animal [5-8] and clinical studies [9-12]. Both modalities were found applicable in implant patients and offer predictable implant and bone integration. However, the nonsubmerged approach helps clinicians to avoid a second surgical procedure which consequently reduces the treatment time and costs.

1.2 Bone Biomechanics

Since bone and implant are in constant interaction, bone biomechanics plays a crucial role in implant dentistry. According to Wolff’s law of transformation [13], bone responses to its mechanical environment and grows, absorb, and reconstruct accordingly. This law has been used as the source of bone remodeling theories. Bone remodeling is described as changes in the structure of the bone both internally (changes in density) and externally (changes in shape) due to the loads applied on it. Exhibiting this specific biological property, bone interacts with its environment [14]
and responds to the stresses and strain to which it is exposed to. As a result, the mechanism of load transfer along bone implant interface and the stress distribution from an implant to the surrounding bone is of critical importance. Implant design significantly affects the mechanism of load transfer along the bone implant interface and also the stress field transferred to the surrounding bone. Therefore, determining the optimum implant design by considering the clinical and biological constraints is an important issue in bone remodeling [15,16].

1.3 Design Consideration for Bone-Implant Interface

Since the early 1980s, many experimental and clinical studies were carried out investigating various factors that influence the osseointegration of endosseous dental implants. These studies resulted in improving implant anchorage in bone and increasing the treatment of partially edentulous patients with dental implants for more than 20 years. Today, many implants are inserted in areas of reduced bone height and high functional load, such as in posterior segments of mandibular and maxilla jaw bone. Recently, promising results have been observed for cases when implants were subjected to immediate functional load [17-24]. Likelihood of osseointegration varies if an implant is placed in function following a certain period of healing process or immediately after placement of implant.

Based on experimental and clinical studies, the factors influencing osseointegration are determined as follows: implant material, implant placement modality, implant shape, and implant surface. Implant shape determines how osseointegration is achieved and maintained under long-term functional load after implant insertion. The effect of implant shape and design will be the primary topics in the following
chapters. Other than biomechanical factors, the surgical considerations and prosthesis requirements such as alveolar ridge width, bone quality, bone height, restorative tooth dimensions, and degree of implant to bone contact, initial implant stability, prosthetic support and stability and emergence determine the selection of implant [26].

A large amount of implant designs varying in shape, size, materials and surfaces have been developed and tested in the past 30 years. Implant designs were improved by market demands rather than basic scientific research [25]. Currently, there are more than 50 implant designs available in the market. The changing clinical protocol of implant treatments further proves the significance of implant design [21]. The level of stress and strain induced in the bone due to occlusal loading have a profound effect on the reliability and stability of dental implants. Bone is maintained if the strain levels are in the homeostatic range [15, 27]. The load transfer to the bone from a dental implant is influenced by several factors such as the loading type, the length and diameter of implant, the implant shape, the structure of the implant surface, and bone quality [15]. One of the main factors that have a great influence in properly transmitting load from the implant to the bone is contour shape of the implant [28]. The main factor in designing an implant is not just the ability to bear the loads that implant encounters in the course of its lifetime, but also the ability to distribute loads at a desirable level of stress to the surrounding bone. Appropriate stress level results in higher likelihood of osseointegration and preservation of peri implant marginal bone height. Therefore, a preferable implant design should concentrate stress in areas remote to the marginal bone [29].
1.4 Finite Element Analysis of Implant-Bone Interface

The finite element method (FEM) has been used for many years to solve structural engineering problems [30,31]. Finite element method is a method for numerical solution of field problems. It subdivides the structure into smaller elements, and instead of solving the problem for the whole structure, the field problem is sought element by element. By solving a system of simultaneous equations attributed to each element the field quantity will be approximated in each element and by assembling the elements the field problem will be found for the whole structure. The solution can be improved by using more elements to represent the structure [30].

Due to the complex geometry of bone and dental implant system the closed form solutions in stress analysis is not feasible. The finite element method has been increasingly used in this field [32] to analyze the stress distribution in the bone implant interface for different root form implant designs [32-39] prosthesis designs [40-43] and for various clinical scenarios [44-51].

In a study conducted by Privitzer et al [52], it was concluded that for a given implant geometry, mechanical properties affect the stress distribution in the bone slightly. In another study, Winstein et al. [53] investigated a porous rooted dental implant by two dimensional finite element analysis and concluded that high stresses transfers to the apex of the implant in a model with continuously bonded interface. Rieger et al [35] investigated the effect of implant geometry and the elastic modulus of the implant materials on the stress distribution under a 113 N axial load in three different implants. A tapered design made of a material with high elastic modulus was concluded to be the most suitable design in their study. In a two dimensional finite
element analysis carried out by Kitoh et al. [54], it was concluded that the occlusal force applied to the implant was supported entirely by the cortical bone, and trabecular bone experience a slight load level. Siegel and Soltesz [36] compared five implant shapes: cylinder, conical, stepped, screw-type and hollow cylinder. A 100 N normal load and 25 N lateral loads were applied. They concluded that implant shape affects the stress distribution significantly. Their results demonstrated that under vertical load, lower stress level are transferred using implants with smoother shapes such as cylindrical and screw-shaped implants rather than implants with small radii of curvature such as the conical shape and implants with geometric discontinuities such as stepped implant contours. Maximum stress concentration was observed in the bone implant interface of apical area of hollow cylindrical implant and below the uppermost thread for the screw type implants under lateral loading. Holmgeren et al. [39] concluded that oblique load indicates more realistic bite direction and transfers high stress levels to cortical bone. Moreover, they found out that the stepped implant design levels out the stress distribution better than a cylindrical design.

1.5 Use of Wide-Diameter Implants

Since the early 1980s, tremendous efforts have gone into the design of dental implants in order to improve implant anchorage in bone and osseointegration. As a result of various clinical and experimental researches widening and shortening of implant were suggested and tested and proved to be an advantage in implant design. Wide bodied implants offer a greater surface area for osseous contact, and provide higher mechanical strength to avoid implant fractures [55]. In addition, the wider and short implants provide the advantage of avoiding sinus elevations and extensive bone
augmentation procedures in regions of limited bone height due to the existence of alveolar nerve in the mandible and maxillary sinus in the maxilla, and potentially prevent the costs associated with bone grafting procedures [56-59]. Overall advantages of wide diameter implants includes improved prosthetic stability, reduced screw loosening, reduced incidents of implant fracture, and more optimal force distribution in qualitatively and quantitatively poor bone [70].

Wider diameter implants provide increased implant-bone contact area, enable the engagement of the implant to the buccal and lingual (BL) faces of the bone, and have the ability to occupy the tooth socket especially in the posterior regions. These inherent characteristics of wide diameter implants significantly improve initial implant stability, which leads to the increase in likelihood of osseointegration [57,60,61].

In the posterior regions, the dimensions of a molar are much larger than the diameter of the standard implants which are 3.75-4 mm [62]. The difference between the surface area of the standard implants and the root of molar, higher occlusal loads, and poor bone quality are one of the main reasons of implant failure in the posterior regions [63]. Using wide diameter implants provides an improvement in the mentioned situations.

Gerami et al. [64] conducted a finite element analysis comparing displacement of a standard diameter and a wide diameter implant under an occlusal load applied at the distobuccal cusp tip, and concluded that increasing the diameter of the implant will reduce both mesiodistal and buccolingual displacement of the implant system by approximately 50%.
Davarpanah et al. [65] evaluated the resistance to fracture and depth of insertion of wide diameter implants versus standard diameter implants. They found that wider diameter implants demonstrate more resistance to fracture than standard implants due to the fact that the supporting surface of the top area of implants with 5 mm diameter and 5 mm height is increased by 122% and 281% respectively, compared with standard implants. Consequently, implants with higher surface area distribute the occlusal forces more evenly.

Jarvis [66] compared the 3.7 mm and 4.7 mm diameter implants and concluded that wider diameter implants decrease the induced load on the abutment screw which results in reducing implant fracture, and also the vibration of the implant that leads to loosening.

Griffin et al. [67] conducted a clinical study investigating the application of 6×8 mm HA coated screw retained implants in the mandibular and maxillary molar regions and reported a 100% success rate. They observed that significant stress concentration distributed to the crestal cortical bone, at the level of the first few threads and concluded that the use of long implants to provide a larger surface area for stress distribution is not necessary. Instead larger surface area provided by wide diameter implants is deemed to be better.

On the other hand in a retrospective study conducted by Aparicio et al. [68] the success rates of 5 mm- and 3.75 mm-diameter implants were reported to be similar in the maxilla, while higher success rate was observed for 3.75 implants in the mandible. They attributed the high failure rate in the mandible to the overheating during surgical
bone drilling, excessive tightening force during implant placement, and variations of
the remodeling response of the cortical bone caused by extensive drilling.
Mahon et al. [69] evaluated the stress distribution using implants with diameters 3.25,
3.75, 4, 5, and 6 mm under the load of 176N 5 mm off axis. They observed that the
mean stress level was highest for the 3.25 mm-diameter implant and lowest for the 6
mm-diameter implant. High stress levels were located at the necks of the 3.25 mm
implant which was consistent with the high deformation which occurred in these
regions. They observed that stress level for 3.75, 4, and 5 mm diameter implants did
not demonstrate large differences, however, 6 mm diameter implants showed the
most reduction in the stress level. Due to this observation, they concluded that the
implant diameter must be greater than a certain value in order to reduce the stress
significantly.

1.6 Use of Two Narrow Implants

Using two narrow implants to support prosthesis in posterior regions has been an
alternative solution to the wide diameter implant usage [57,62,63]. Two implants
maintain a more natural replacement of the missing tooth in position and direction,
and allow for the preservation of the crestal bone [71]. This approach provides more
appropriate support against buccolingual and mesiodistal bending and decreases the
rotating forces around the implant axis and as a result reduces the loosening of the
restoration under normal or parafunctional forces. Use of two implants offers greater
surface area and better biomechanical properties, and as a result reduces the
possibility of occlusal overload. This approach also maintain prosthesis retrievability
[61,70]. However, there are some restrictions on using two narrow implants in the
posterior regions. One of these is the cone space availability buccolingually (BL) and mesiodistally (MD). There should be 12.5 mm mesial-distal (MD) space available allowing 1.5 mm distance between the implants and between the implants and adjacent teeth for the insertion of two narrow implants [58].

Gerami et al. [64] conducted a finite element analysis comparing use of a wide diameter implant with the use of two implants. They found that using two implants to support the restoration reduces the buccolingual displacement to the same level as the 5 mm-diameter implant. Eckert et al. [71] analyzed the stress distribution for both wide diameter implants and two implant design systems and concluded that the percentage of stress reduction was almost identical for both designs. They observed that stress concentrations were not provoked in the narrow space of bone between the two implants of the two implant design. The two systems illustrated identical biomechanical effects; therefore choosing between the two treatments should be based on anatomic conditions. In a study conducted by Bahat et al. [72], the failure rate of the 5 mm-diameter implants was 2.3% compared to the 1.6% failure rate of the double implants. They suggested using double implants to support restorations rather than a single implant in the molar regions even though there were some disadvantages associated with using double implants such as greater bone loss and higher prosthesis mobility. On the other hand, Sato et al. [73] concluded that using double implants in molar areas does not always reduce loads on the implants however eliminates torque. They observed higher stress levels near the marginal ridge of the superstructure compared to stress field on the wide diameter implants. They considered position and direction of the load as a critical factor in the geometric analysis.
1.7 Threaded Implants

Implants with extended screws are highly recommended in implant dentistry today. There are different types of externally threaded implants available in the market, which vary in thread pitch, shape and depth. The thread pitch is the number of threads per unit length. The thread shape defines the shape of the thread’s cross section such as square, V-shape, or buttress. The difference between the minor and major diameters of the thread is defined as thread depth [74]. Since the morphology of screw threads plays an important role in the load transfer from dental implant to the surrounding bone [80], usage of different thread configurations for different bone qualities have been suggested [75-78].

There are many advantages associated with threaded implants. The implant threads improve primary implant stability during the implant insertion [79] and reduce micromovements of the implant during post insertion healing period until the achievement of osseointegration. This characteristic is of more importance in the regions of low bone density and in the submerged placement modality of implant [80]. Moreover, screw threads positively influence the load transfer from the implant to the surrounding bone since an ordinary screw is able to transmit stresses in any direction. The threads have inclined faces and can carry vertical force in normal stress perpendicular to the interface. Use of cylindrical implant is not suggested anymore due to their incapability of achieving osseointegration and higher failure rate [81]. They also develop micro tension in peri-implant bones which leads to bone resorption [82-84].
In a finite element study, Siegele and Soltesz [36] evaluated the load transfer in the case of several different implant forms (cylindrical, conical, with shoulder, screw-type). They found a high failure rate in the hollow cylindrical implants due to low primary stability and high infection of the bone in the hollow cylinder. Moreover, the conical or shoulder-type implants distributed high stress level at the bone interface. Rounding of the corners of the implant was found to have a significant effect in reducing the stress [36]. Therefore today, screw-type implants with rounded screw threads are highly recommended [86].

In a finite element study carried out by Moser and Nentwig [88], it was observed that using screw threads with an apically increasing screw thread depth reduces tension in the cervical area when implant was apically loaded.

Chun et al. [89] conducted a finite element study to evaluate the stress distribution using different thread design implants under a 100 N applied 15 degree off axis. They observed that the maximum effective stress in the cortical bone was higher in the plateau design compared to the triangular or square designs. Moreover, they found out that screw pitch has a significant effect on stress distribution. In another study carried out by Patra et al. [90], tapered thread design implant were found to distribute higher stress levels in bone rather than the parallel profile thread.

The transosteal region of the implant body has been defined as the ‘crest or collar” module [74]. A majority of implant designs available in the market have smooth face collar rather than screw shaped collar design with the parallel, converging or diverging sides. However, there are some designs that screw threads continue all the way up to the crest. Hansson [33] compared the stress distribution created by these
two sets of implant designs using finite element method. He concluded that the threaded collar implant design transfer lower interfacial shear stresses compared to the smooth collar design.

In a study by Skalak [87], stress transfer at the implant interface was evaluated. They observed that the close apposition of bone to an osseointegrated implant is an important feature in implant survival. Providing the interface with any roughness benefits this close apposition since it helps to resist shear stresses very effectively other than normal stresses. Moreover, their study showed that using screw threads on the implant body helps to transmit stresses any direction without any gross sliding due the presence of threads. Inclined faces of threads allow for normal stress to carry perpendicular to the interface. Transmission of shear stress can benefit from microasperities on the interface which work along each of the faces of a screw in a similar way that the screw threads work. Therefore, using screw threads on implant body with some microscale roughness provides a favorable situation for osseointegration [87]. When a favorable osseointegration is achieved, the stress is spread over a wide area and at a lower level. Therefore, stress distribution improves as the integration between bone and implant improves. In the situations of poor integration, in the regions of large tensile stress, the separation of bone and the implant might occur [87].

A considerable amount of experimental and numerical studies have been performed on understanding the mechanism of load transfer along the bone-implant interface. A significant number of design features were suggested, tested and analyzed. Some of the analyzed systems are currently off the market of have not passed beyond the
experimental design phase, while so many design improvement have taken place in implant systems. While analytical formulas provide a comprehensive interpretation of the problem, finite element studies enables us to create more realistic and complex models; thus more detailed analysis. In Chapters 2-4, a numerical approach, the finite element method, is used in order to investigate the mechanism of load transfer along the bone-implant interface, and enables the interpretation of the experimental results.
CHAPETR 2

ANALYSIS of LOAD TRANSFER MECHANISM USING 2D and 3D FEA

2.1 Introduction

The primary goal of this thesis is to compare the load transfer predictions performed by 3D and 2D plane strain analysis. In this chapter, the fundamental mechanism of load transfer from a dental implant to the surrounding bone is investigated. In Sections 2.4 and 2.5 the effects of the implant diameter and the effect of the implant collar and apex shape are presented respectively. The normal and shear stress variations along a linear path in the BL cross-section of the bone-implant interface are investigated in Section 2.6. Sections 2.7 and 2.8, investigate the stress distributions in 2D models and compare them with their counterparts 3D models.

2.2 Methods

In this chapter, a 3D analysis of the problem is carried out using the finite element method (FEM). The bone is modeled as an elliptical cylinder. The implant and abutment system are modeled as a circular cylinders. A quarter symmetric model of the bone-implant system is used in order to save computational resources, as shown in Figure 2.1.

The overall dimensions of the bone were chosen to be similar to the dimensions of the bone near an incisor, based on a CT image. Therefore, in this idealized configuration the cortical bone is modeled as an ellipse with the major axis of 30 mm and minor axis of 18 mm. The major axis of trabecular bone was 26 mm and minor axis of it was 14 mm. In order to investigate the effect of implant’s diameter three sets of implant systems were modeled with the diameters 3.3, 3.5, and 4 mm. The abutment
width was 2.5 mm. The height of the abutment above the collar region of the implants was kept at 5 mm in all cases.

Modeling and finite element analysis of the above mentioned system was carried out in ANSYS version 11. Element type used in this analysis was Solid 185 which is a 3D 8-Node structural solid element. The model was meshed with this element as shown in Figure 2-1. As it is seen in this figure, the mesh of the implant system is finer than that of the bone. The element size was 0.1 mm for the implant system, 0.5 mm for cortical bone and 0.7 mm for trabecular bone.

![Model meshed with Solid185 of ANSYS](image)

Figure 2.1 Loads applied on the quarter of the model (a) Model meshed with Solid185 of ANSYS (b)

The material properties used in this analysis are given in Table 2.1.

<table>
<thead>
<tr>
<th></th>
<th>Elastic modulus (GPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical Bone</td>
<td>13</td>
<td>0.3</td>
</tr>
<tr>
<td>Trabecular Bone</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Implant</td>
<td>113</td>
<td>0.3</td>
</tr>
<tr>
<td>Abutment</td>
<td>113</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 2.1 Material properties used in analysis.
It is assumed that an occlusal load of 113 N is applied on the prosthesis in the buccal lingual plane oriented at 11 degree with respect to the main axis. This force was transferred to the center of the abutment’s top surface. Therefore, a normal compressive load of $F_N=110.9$ N, a lateral load $F_L=21.56$ N, and a moment of 90 N.mm were applied on the abutment. Since the model is quarter symmetric, the above mentioned loads were applied in three load steps. In the first load step, a quarter of the normal load was applied at the center of the abutment and the Buccolingual (BL) and MesioDistal (MD) cross sections were chosen to be symmetric. In the second load step, a quarter of the lateral load step was applied, and symmetry condition was again defined in BL and MD cross sections. In the third step, half of the moment was applied at the same location. The BL cross section was chosen to be symmetric while the MD cross section was asymmetric. The distal end of the cylindrical bone was constrained in all degrees of freedom for all load steps in the quarter symmetric model. The problem was solved for all load steps and the results were superimposed. Different components of stress distributions of the superimposed results were plotted in Tecplot and presented in Figure 2.2. In this Figure, the implant system was removed from the model in order to better monitor the load transfer characteristics from the implant to the bone. In all the figures stresses are plotted in narrow range in order to observe the more details of the stress distribution.

2.3 Stress Distribution Analysis

Stress components $\sigma_x$, $\sigma_y$, $\sigma_z$, $\tau_{xy}$, $\tau_{xz}$, $\tau_{yz}$ in the bone are plotted for a case containing a 3.5 mm diameter implant as shown in Figure 2.2.
Figure 2.2 Distribution of stress components $\sigma_x$, $\sigma_y$, $\sigma_z$, $\tau_{xy}$, $\tau_{xz}$, $\tau_{yz}$, and $\sigma_{VM}$ (MPa).
2.3.1 Normal Stress in $x$-Direction, $\sigma_x$

Figure 2.2a shows the distribution of the stress component $\sigma_x$. It is observed that a compressive stress in $x$-direction of about -10MPa was transferred from the implant to the coronal region of the bone. This compressive stress decreases in the lower segments of the cortical and trabecular bone, eventually diminishing. It varies in the range 0-0.05 MPa near the lower boundaries both in $x$- and $y$-directions. There is a small stress concentration at the apex region of the implant-bone interface. This tensile stress is about 0.5 MPa, and reaches about 0.05 MPa as it goes a little down into the cortical bone. According to Figure 2.2a, the cortical bone is in compression coronally, which tends to pinch and compress the implant. However, the outward deformation of cortical bone puts the trabecular bone primarily in tension, especially near the implant.

2.3.2 Normal Stress in $y$-Direction, $\sigma_y$

The stress component $\sigma_y$ is shown in Figure 2.2b. It is concluded that the mechanism of stress transfer is the same in $y$-direction as in $x$-direction. Similar to $\sigma_x$ distribution, a compressive stress in $y$-direction of about -10 MPa was transferred to the coronal region of implant, and bone-implant interface due to the applied loads. This compressive stress tends to gradually decrease as going down into both cortical and trabecular bone in all directions. It reaches nearly zero, in the inferior sections of both cortical and trabecular bone (negative $y$-direction). $\sigma_y$ remains compressive in most regions of implant-bone interface, cortical bone and trabecular bone. The only tensile regions are the distal constrained area, where a small stress concentration is seen, and also a small region adjacent to the bone-implant boundary due to the
presence of implant system as discussed above. According to the figures, the cortical bone is in compression primarily dictated by the vertical component of occlusal force. The trabecular bone is also in compression primarily at the apex region of the implant. However, on the lateral side near the collar region of the implant, the bone is in tension due to a combination of the implant pulling it in the inferior direction and the cortical bone moving externally.

2.3.3 Normal Stress in $z$-Direction, $\sigma_z$

Figure 2.2c shows the stress component $\sigma_z$. This component of the stress is controlled, in the cortical section by the bending of the bone, and in the trabecular section by the presence of the implant. Note that the 3D system modeled in this work is in a fixed-fixed beam-like configuration. As a result, the stresses are primarily compressive at the superior aspect, and small but tensile at the inferior aspect of the cortical bone. Note that the transition region from $<+>$ to $<->$ stresses occurs not at the neutral plane of the system, but it is closer to the superior aspect. In the trabecular region, the stresses are tensile. The effect of $\sigma_z$ is almost diminished in the trabecular bone distal to the implant.

2.3.4 Shear Stress in $xy$-Direction, $\tau_{xy}$

Shear stress component $\tau_{xy}$ (MPa) is shown in Figure 2.2d. According to this figure, the maximum shear stress ($\tau_{xy}$) occurs at the bone-implant interface. The magnitude of $\tau_{xy}$ varied from 0.1 MPa to 1 MPa on the interface. It is seen that $\tau_{xy}$ is positive on the BL cross section, while it is negative on the MD cross section. $\tau_{xy}$ is high in the cortical bone as it directly counteracts the vertical force component of the occlusal force. A gradual decrease is monitored in $\tau_{xy}$ as moving further from the implant-bone
interface. The shear stress component $\tau_{xy}$ is nearly diminished on the inferior boundaries of the cortical and trabecular bone. This stress is high in the cortical bone as it directly counteracts the vertical force component of the occlusal force.

### 2.3.5 Shear Stress in $xz$-Direction, $\tau_{xz}$

Distribution of the shear stress component $\tau_{xz}$ is shown in Figure 2.2e. The magnitude of $\tau_{xz}$ at the superior aspect of the bone-implant interface is about 0.05 MPa. Toward the inferior side of the bone-implant interface, the positive shear stress changes to negative and it increases in magnitude at reaching the bottom face of the bone-implant interface where it becomes $\tau_{xz}=0.5$ MPa. Further distally to the implant boundaries, $\tau_{xz}$ decreases toward zero and negative values. The $\tau_{xz}$ is negative on the boundaries on all sides, at the inferior aspect of the bone.

### 2.3.6 Shear Stress Distribution in $yz$-Direction, $\tau_{yz}$

Shear stress component $\tau_{yz}$ is shown in Figure 2.2f. As seen in this figure, $\tau_{yz}$ reaches its maximum at the superior aspect of the bone-implant interface. It tends to decrease as going down inferiorly along the interface, but it slightly increases at the inferior aspect of the bone-implant interface. A gradual decrease in negative $\tau_{yz}$ was observed inside the bone on both coincident $xy$- and $yz$-planes. The effect of $\tau_{yz}$ was very small close to the boundaries of the bone. The shear stress in this direction can be attributed to the bending stresses ($\sigma_z$).

### 2.3.7 Von Mises Stress, $\sigma_{VM}$

A high stress level is transferred to the cervical regions of the bone and implant. The stress gradually decreases as going toward the inferior direction. Von Mises stress is
almost zero at the intersection of cortical and trabecular bones in the inferior region; however, a low stress concentration is observed at the fixed boundaries.

2.4 Effects of Implant Collar Angle on the Load Transfer from Implant to Bone

2.4.1 Introduction

In the second part of this study, the effect of implant collar angle on load transfer is investigated. Keeping the bone geometry the same as in the previous study, an implant with the collar angle of -10 degrees was placed into the bone. The load and boundary conditions are the same as before. The model was meshed with the same element type and the same element size as previous study. The meshed model is shown in Figure 2.3.

![Figure 2.3](image)

Figure 2.3 (a) path on the boundary bone and implant, (b) Model meshed with Solid185

Different components of the internal stresses were plotted in the same way as in the previous study, and a comparison of the results was made. The stress distributions are shown in Figure 2.4.
Figure 2.4 Distribution of stress components $\sigma_x$, $\sigma_y$, $\sigma_z$, $\tau_{xy}$, $\tau_{xz}$, $\tau_{yz}$, $\sigma_{vM}$ (MPa).
2.4.2 Stress Analysis

Figure 2.4 shows that the distribution of the stress components $\sigma_x$, $\sigma_y$, $\sigma_z$, $\tau_{xy}$, $\tau_{xz}$, $\tau_{yz}$ in the model containing the implant with the collar angle of -10 degrees are very similar to those in the model containing cylindrical implant. This brings us to the conclusion that changing the collar’s angle does not significantly affect the bone loading in areas distal to the bone-implant interface.

2.5 Effects of Apex Angle on the Load Transfer from Implant to Bone

2.5.1 Introduction

In this section, the effect of implant apex angle on load transfer was investigated. The same system as in the previous studies was modeled in this part with an implant apex angle of 10 degrees. The meshed model is shown in Figure 2.5.

Figure 2.5 (a) path on the boundary bone and implant, (b) Model meshed with Solid185 of ANSYS
The stress components $\sigma_x$, $\sigma_y$, $\sigma_z$, $\tau_{xy}$, $\tau_{xz}$, and $\tau_{yz}$ are plotted in Figure 2.6, and the results are compared to the previous cases.

![Stress Components](image)

Figure 2.6 Distribution of stress components $\sigma_x$, $\sigma_y$, $\sigma_z$, $\tau_{xy}$, $\tau_{xz}$, $\tau_{yz}$, $\sigma_{vM}$ (MPa).
2.5.2 Stress Analysis

Investigation of $\sigma_x$ and $\sigma_y$ in Figures 2.2, 2.4, and 26 shows noticeable differences in the BL plane, in the trabecular bone. We see that a straight implant surface tends to be in tension in Figures 2.2a,b and 2.4a,b, but the apex angle in Figure 2.6a,b causes more of a compression in the trabecular bone. This could have long term consequences in a) keeping the implant in compression and thus preventing the peel off of the bone implant interface, and b) in remodeling of the bone.

2.6 Stresses Along the Bone-Implant Interface.

In the fourth part of this study, the effect of diameter was investigated. Implants with three different diameters 3.3, 3.5, and 4 mm were placed in the bone with the characteristics and geometries discussed in the previous studies. In each model, a path was defined along the bone-implant interface on the BL cross section, as shown in Figure 2.7. The effect of diameter was also investigated for implants with nonzero collar and apex angles. Figure 2.7a shows the path on the model with cylindrical implant. Figure 2.7b,c show the path in case of the implant with collar angle of -10 degrees and with apex angle of 10 degrees, respectively.

![Figure 2.7 Path on the boundary of bone and (a) cylindrical implant (b) implant with the -10 degree collar angle (c) implant with 10 degree apex angle](image-url)
Normal and shear stresses ($\sigma_{11}, \sigma_{12}$) were obtained by 2D stress-transformations, and plotted along these paths. The plots are shown in Figure 2.8.

Figure 2.8 Normal and shear stress along the bone-implant interface in case of (a) cylindrical implant, (b) implant with -10 degree collar angle, (c) implant with 10 degree apex angle.
For all of the cases considered, both the normal and the shear stresses decreased as the implant diameter increased. Normal stress $\sigma_{11}$ is very similar in case of cylindrical implant (Figure 2.8a) and implant with 10 degree apex angle (Figure 2.8e). The only difference observed is a small jump that occurs at the point $s = 5$ mm in implant with apex angle. This is the point where the angle changes between the body of implant and apex. In the case of the implant with -10 degree collar angle (Figure 2.8c), normal stress is very similar to the other two cases around central section of the body of the implant, while some difference was observed at the collar region; for the 3.3 mm diameter implant, the normal stress increased; for the 3.5 mm diameter implant, the normal stress remained the same; and in case of 4 mm diameter implant, the normal stress decreased significantly.

Shear stress on the path $\sigma_{12}$, was very similar for cases of cylindrical implant (Figure 2.8b) and implant with 10 degree apex angle (Figure 2.8f). The only difference was at the point where the angle changed between implant’s body and apex at point $s = 5$ mm where a slight jump was observed in case of implant with nonzero apex angle. Shear stress noticeably decreased for all implant diameters in case of implant with 10 degree collar angle (Figure 2.8f).

### 2.7 Comparison Between 3D and 2D Systems

#### 2.7.1 Introduction

In this section analysis was carried out by assuming that the bone can be modeled in BL plane by 2D (plane-strain) analysis as shown in Figure 2.9. This assumption reduces the computational complexity of analysis. The shape of the bone was considered to be elliptical. Cortical bone was first modeled as an ellipse with a major
axis of 30 mm and a minor axis of 18 mm. Trabecular bone was modeled as an ellipse with a major axis of 26 mm and a minor axis of 14 mm. All of the components, (implant, abutment, cortical bone, and trabecular bone) were assumed to be perfectly bonded. The loading condition is the same as that in 3D models; however, the bone displacement is restricted in all directions around the bottom periphery of the cortical bone.

2.7.2 Stress Distribution Analysis

Distribution of the stress components $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ are plotted in the BL plane as shown in Figure 2.9.

![Stress distribution figures](image)

Figure 2.9 (a) Normal stress component, $\sigma_x$, (b) Normal stress component, $\sigma_y$, (c) Shear stress component, $\tau_{xy}$, (d) von Mises stress component, $\sigma_{vM}$

2.7.2.1 Normal Stress in x-Direction, $\sigma_x$

Figure 2.9 shows that the cortical bone is in compression in the coronal region causing pinching effect of the implant. Outward deformation of the cortical bone, exerts tensile stress on the trabecular bone on the buccal side.
2.7.2.2 Normal Stress in y-Direction, $\sigma_y$

Both cortical and trabecular bone are primarily in compression due to the vertical component of occlusal force. The small tensile regions at the inferior aspect of the bone is due to the fixed boundary at that region. Moreover, downward movement of implant and outward deformation of the cortical bone put trabecular bone adjacent to the implant in tension.

2.7.2.3 Shear Stress in xy-Direction, $\tau_{xy}$

Vertical force component of the occlusal force exerts a high shear stress in bones which is primarily positive on the lingual side and negative on the buccal side which pushes the bone upward. But high shear stress occurs on the buccal side of the cortical bone.

2.7.2.4 Comparison Between 2D and 3D Systems

The load transfer mechanism in the 2D and 3D models are reasonably close. Differences in the magnitudes of the stresses are due to plain-strain assumption and the boundary conditions, where the 3D models are fixed in all degrees of freedom in the distal ends. Lower stress levels are predicted in the 3D model, as the 2D model is much more restricted at the bottom. The stress concentration near the bottom of the 2D models should, therefore be evaluated with caution.
CHAPTER 3

EFFECT OF IMPLANT CONTOUR ON LOAD TRANSFER IN THE BONE-IMPLANT INTERFACE

3.1 Introduction

This chapter presents the effects of various implant design parameters on the load transfer along the bone-implant interface. A 2D plane strain analysis was performed in the BL plane of the bone. In Section 3.3 the shape of the bone was considered to be elliptical and its size was chosen close to the size of the bone adjacent to an incisor. Implants with different design (contour) parameters were placed into the bone and the stress distributions were analyzed. In section 3.4 the same procedure is followed, for a bone geometry digitized from a CT-scan of an incisor.

3.2 Methods

In order to investigate the effects of the implant geometry various features of the implant describing the implant contour were varied. This analysis was carried out by considering the implant to be composed of the four regions shown in Figure 3.1. These are from top to bottom, designated as the collar, body-1, body-2, and apex regions. In this study the effects of the length, $L_c$, and slope $\theta_c$ of the collar region, the length, $L_{b1}$, and the diameter, $D$, of the body-1 region and the length, $L_{b2}$, and the slope, $\theta_{b2}$, of the body-2 region are investigated. The apex of the implant is assumed to be flat as shown in Figure 3.1. The values used in this report are given in Table 3.1. Note that all 360 combinations of these variables were modeled.
Figure 3.1 The implant system composed of four regions.

Table 3.1 Implant dimensions that were varied in this work. See Figure 1 for the definitions of these variables. Note that $\theta_c$ as drawn in this figure is defined to be a negative angle, whereas $\theta_b$ is defined to be positive.

The abutment width was 3 mm. The height of the abutment above the collar region of the implants was kept at 5 mm in all cases.

The bone cross-section was originally obtained from a CT scan of the incisor area as shown in Figure 3.2. A Matlab script was written to digitize the coordinates of the CT scan, and the width and height of the bone was determined in order to analyze the effect of bone loading independently from the variations of the anatomical features in
the mandible, first the bone cross-section was approximated as an ellipse, with
general dimensions similar to the CT scan. The outer contour of the cortical bone is
defined by an ellipse with 30 mm long major axis and 18 mm long minor axis. The
inner contour of the cortical area has 26 mm and 14 mm in these variables. The inner
region is assumed to have the properties of trabecular bone. The analysis of this
assumed bone shape is presented in Section 3.3. The effect of the original bone
contour as shown in Figure 3.2 was also investigated. This is presented in Section 3.4.
A macro was written in the APDL language of ANSYS (Version 11) to automatically
create the bone and the implant for different configurations. All of the components,
(implant, abutment, cortical bone, and trabecular bone) were assumed to be perfectly
bonded. All of the components were modeled under 2D plane strain assumptions.

The locations of the keypoints of the implant geometry, defined in Figure 3.1, were
programmed to be variable. Note that the coordinate system was placed at the center
of the top surface of the implant as shown in Figure 3.1. The coordinates of the
keypoints in terms of the implant dimension variables given in Table 3.1 are defined
as follows;

\[
x_A = \frac{D}{2} - L_c \times \tan(\theta_c \times \frac{\pi}{180}) \quad (1a)
\]
\[
y_A = 0 \quad (1b)
\]
\[
x_B = \frac{D}{2} \quad (2a)
\]
\[
y_B = -L_c \quad (2b)
\]
\[
x_D = \frac{D}{2} \quad (3a)
\]
\[
y_D = -L_c - L_{b1} \quad (3b)
\]
\[ x_E = \frac{D}{2} - L_{b2} \times \tan(\theta_{b2} \times \frac{\pi}{180}) \]  

\[ y_E = -L_c - L_{b1} - L_{b2} \]  

\[ x_F = \frac{D}{2} + L_{b2} \times \tan(\theta_{b2} \times \frac{\pi}{180}) \]  

\[ y_F = -L_c - L_{b1} - L_{b2} \]  

\[ x_G = -\frac{D}{2} \]  

\[ y_G = -L_c - L_{b1} \]  

\[ x_I = -\frac{D}{2} \]  

\[ y_I = -L_c \]  

\[ x_J = \frac{D}{2} + L_c \times \tan(\theta_c \times \frac{\pi}{180}) \]  

\[ y_J = 0 \]  

The stresses in the bone implant interface were computed in the \((x,y)\) coordinate system of ANSYS and recorded using the *VWRITE command. In order to compute the stresses normal and tangential to the interfacial path (Figure 3.1), the following stress transformation equations were used:

\[ \sigma_{11} = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2} \cos 2\theta + \tau_{xy} \sin 2\theta \]

\[ \sigma_{12} = -\frac{\sigma_x - \sigma_y}{2} \sin 2\theta + \tau_{xy} \cos 2\theta \]

where \(\sigma_{11}\) indicates the stress component normal to the interfacial path and \(\sigma_{12}\) indicates the stress component tangential to the path. The orientation \(\alpha\) of the path with respect to the x-axis is computed from the knowledge of the geometry defined in
Eqns. (1-8). The normal $n_1$ and tangent $n_2$ vectors of the path are oriented as shown in Figure 3.1.

A biting force of 113 N was applied on the prosthesis with the direction of 11 degree with respect to the main axis, as shown in Figure 3.3. This force was transferred to the center of the abutment’s top surface. Therefore, a normal compressive load of 110.9 N and a lateral load of 21.56 N and a moment of 90 N.mm were applied on the abutment as shown in Figure 3-2. The bone displacement is restricted in all directions around the bottom periphery of the cortical bone as shown in Figure 3.3c.

The analysis was carried out in ANSYS version 11, using the 8-node structural solid element PLANE82. The model was meshed with this element as shown in Figure 3.3(b). In order to prevent computational effort, the model was gradually meshed. The lines defining the bone-implant interface and the lines adjacent to the interface were set to have the finest mesh, with an element size of 0.1 mm. All other regions were meshed according to their distance to the bone-implant interface. Closer regions were given an element size of 0.2 mm, and the farther ones 0.4 mm. The material properties used in this analysis are given in Table 3.2.

<table>
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<th>Elastic modulus (GPa)</th>
<th>Poisson’s ratio</th>
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</thead>
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</tr>
<tr>
<td>Trabecular Bone</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Implant</td>
<td>113</td>
<td>0.3</td>
</tr>
<tr>
<td>Abutment</td>
<td>113</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 3.2 Material properties used in analysis.
Figure 3.2 a) CT-scan of the incisor, b) digitized model in MATLAB c) The boundary condition applied on the model

Figure 3.3 (a) Boundary condition and external loads applied on the model, (b) The finite element mesh used in the model, (c) the zoomed-in mesh
3.3 Effect of Implant Contour Design Parameters Using Assumed Bone Shape.

The variation of the normal and shear stress along the bone-implant interface are presented with respect to the interfacial path, \( s \), which starts at point A, as shown in Figure 3-1. The profile of the stress distribution remained similar in all 360 models that were created. We first present the results of a system with parameters \( L_{b1} = 5 \text{ mm} \), \( L_c = 1 \text{ mm} \), \( \theta_c = -10 \text{ degree} \), \( L_{b2} = 3 \text{ mm} \), \( \theta_{b2} = 5 \text{ degree} \), \( D = 3.3 \text{ mm} \). The von Mises stress distribution, in Figure 3.4, shows that the load is mostly carried by the buccal side of the bone, where the cortical bone carries most of the load. The lower boundary and the lingual side of the bone are predicted to have relatively low stresses. Note that the fixed boundary conditions (Figure 3.2) affect this distribution of the load. Comparing the von Mises stress distribution to the results for the 3D system, in Chapter 2, we see that the stress magnitudes are higher in the 2D model, but the general characteristic of the distribution of the stress is similar.
Figure 3.4 von Mises stress distribution on the model for the implant with dimensions of: $L_{b1}=5$ mm, $L_c=1$ mm, $\theta_c=-10$ degree, $L_{b2}=3$ mm, $\theta_{b2}=5$ degree, $D=3.3$ mm
Figure 3.5 Normal stress ($\sigma_{11}$) and shear stress ($\sigma_{12}$) for implant with dimensions of: $L_{b1}=5$ mm, $L_c=1$ mm, $\theta_c=-10$ degree, $L_{b2}=3$ mm, $\theta_{b2}=5$ degree within: (a,b) entire path, (c,d) $s=0-5$ mm, (e,f) $s=8-14$ mm, (g,h) $s=18-22$ mm.
Corresponding normal and shear stresses along the bone-implant interface are plotted in Figure 3.5a,b. This figure shows that the normal stress $\sigma_{11}$ is compressive along the collar region and the apex of the implant, but it is small and tensile along the smooth faces of the body-1 and -2 regions. Figures 3.5c,d,e,f,g, and h show the details of the stress distribution. Various jumps and stress concentrations are seen at the locations with abrupt changes in geometry. For example, a jump is observed at the end of collar region, at point B ($s = 1$ mm), where normal stress jumps from about -40 MPa to about -20 MPa. Significant jumps in normal stress are also observed at the corners of the implants apex at points E and G.

On the lingual side of the bone-implant interface the tensile normal stress has nearly zero magnitude over body-1 and body-2 regions. The collar region on the lingual side, is seen to experience roughly $1/10^{th}$ of the compressive stress experienced on the buccal side.

Figure 3.5e shows the variation of the shear stress $\sigma_{12}$ along the bone implant interface, $s$. Much like the normal stress, the interfacial shear stress also shows stress concentrations jumps near the points where the geometry has abrupt changes. In particular near points B, D,E, G, and I. The largest interfacial shear stresses are seen in the collar area.

Note that Figure 3.5 also shows the effect of implant diameter, for 3.3, 3.5, and 4 mm. The most significant effect is seen in the collar region on the buccal side, where the magnitude of the interfacial normal stress drops on the order of 25% between a narrow diameter and wide diameter implant. The interfacial shear stress also experiences a drop but this is of smaller magnitude.
3.3.1 Effect of Collar Angle ($\theta_c$)

The effect of collar angle ($\theta_c$) of the implant was studied for $\theta_c = -10$, 0, and 10 degrees, and for the three diameters ($D = 3.3, 3.5, 4$ mm). All other dimensions were kept the same.

![Graphs showing the effect of collar angle on stress distribution for different diameters and angles.]

Figure 3.6 Effect of collar angle, $L_{b1}=5$ mm, $L_{b2}=3$ mm, $\theta_{b2}=5$ degrees, $L_c=1$ mm, (a) $\theta_c=-10$ degrees, (b) $\theta_c=0$, (c) $\theta_c=10$ degrees
Figure 3.6 shows the variation of the normal and shear stress components $\sigma_{11}$ and $\sigma_{12}$ along the bone implant interface. This figure shows that changing collar angle $\theta_c$ from -10 to 0 and to 10 deg. results in approximately %16 decrease of the interfacial normal stress level in the collar region. In addition, the jump at point B due to the geometry was removed in case of implant with $\theta_c = 0$ deg, as expected. On the other hand, the shear stress, $\sigma_{12}$ increased in the collar region as a result of the same change. Increase of shear stress level is more abrupt in case of implant with $\theta_c = 10$ deg. than the other two cases. The jump at point B due to the angle change is removed in case of $\theta_c = 0$ deg. similar to normal stress. Normal and shear stress distribution did not change noticeably in other regions of bone-implant interface while changing collar angle, $\theta_c$.

3.3.2 Effect of Collar Length ($L_c$)

The effect of collar’s length defined in Figure 3.1 was investigated for $L_c= 1, 2, \text{ and } 3$ mm, for three different implant diameters. All of the other dimensions kept unchanged. Figure 3.7 shows normal and shear stress components $\sigma_{11}$, $\sigma_{12}$ along bone implant interface.
Increasing collar length $L_c$ resulted in a noticeable decrease in normal stress level in the collar region. Normal stress reduced about $33\%$ while changing $L_c$ from 1 to 3 mm. Change of normal stress level at point C, where $s \sim 1.5$ mm due to the transformation of cortical bone to trabecular bone was more noticeable in case of $L_c=2$ mm than the other two cases. This holds for shear stress level as well. However, the
level of shear stress in collar region did not change noticeably with increasing collar length, $L_c$. Normal and shear stress distribution did not change in other regions of the bone-implant interface while changing collar length.

### 3.3.3 Effect of Length of Body-2 ($L_{b2}$)

The effect of the length of body-2 region of the implant, $L_{b2}$ defined in Figure 3.1 is investigated for $L_{b2} = 3$ and 4 mm and $\theta_{b2} = 0, 5, 10$ deg. During these analyses the implant diameter was varied in the range $D = 3.3, 3.5, 4$ mm, as before, and $L_{b1} = 4$ mm, $L_c = 1$ mm, $\theta_c = -10$ deg. values were kept constant. Figure 3.8 shows the interfacial normal stress; $\sigma_{11}$ variation along the bone-implant interface and Figure 3.9 shows the variation of the shear stress $\sigma_{12}$.

As observed in Figures 3.8 and 3.9 the normal and shear stress distributions did not change significantly in any regions of bone-implant interface with the change of length of body-2, $L_{b2}$ from 3 to 4 mm.
Figure 3.8 Normal stress in cases with the dimensions: $L_b1=4$ mm, $\theta_c=-10$ degree, $L_c=1$ mm, (a) $\theta_{b2}=0$ degree, $L_{b2}=3$ mm, (b) $\theta_{b2}=0$ degree, $L_{b2}=4$ mm, (c) $\theta_{b2}=5$ degree, $L_{b2}=3$ mm, (d) $\theta_{b2}=5$ degree, $L_{b2}=4$ mm, (e) $\theta_{b2}=10$ degree, $L_{b2}=3$ mm, (f) $\theta_{b2}=10$ degree, $L_{b2}=4$ mm.
Figure 3.9 Shear stress in cases with the dimensions: 

- \( L_{b1} = 4 \text{ mm}, \theta_c = -10 \text{ degree}, L_c = 1 \text{ mm} \),
- (a) \( \theta_{b2} = 0 \text{ degree}, L_{b2} = 3 \text{ mm} \),
- (b) \( \theta_{b2} = 0 \text{ degree}, L_{b2} = 4 \text{ mm} \),
- (c) \( \theta_{b2} = 5 \text{ degree}, L_{b2} = 3 \text{ mm} \),
- (d) \( \theta_{b2} = 5 \text{ degree}, L_{b2} = 4 \text{ mm} \),
- (e) \( \theta_{b2} = 10 \text{ degree}, L_{b2} = 3 \text{ mm} \),
- (f) \( \theta_{b2} = 10 \text{ degree}, L_{b2} = 4 \text{ mm} \).
3.3.4 Effect of Angle of Body-2 ($\theta_{b2}$)

The effect of the orientation of the body-2 region is investigated by changing $\theta_{b2}$ defined in Figure 3.1. The results of this change are already reported in Figures 3.8 and 3.9. These results show that increasing $\theta_{b2}$ from 0 to 5 to 10 deg. results in a slight increase in the normal stress level in collar region. As shown in these plots, the normal stress level is about % 8 higher in the case with $\theta_{b2} = 10$ deg. as compared to $\theta_{b2} = 0$ deg. case. Shear stress slightly reduces in the apex region with the increase of $\theta_{b2}$ from 0 to 5 to 10 deg. Normal and shear stresses did not change significantly in other regions with these parameter changes.

3.3.5 Effect of Length of Body-1 ($L_{b1}$)

In order to investigate the effect of length of body-1 region, two cases with $L_{b1} = 4$ and 6 mm were investigated. The other dimensions of the implant were common and they were $L_c = 1$ mm, $\theta_c = -10$ degree, $L_{b2} = 3$ and 4 mm, $\theta_{b2} = 5$ degree, $D = 3.3, 3.5, \text{ and } 4$ mm. Figures 3.10 and 3.11 show the normal and shear stress variations along the bone-implant interface for these systems respectively.
While changing $L_{bi}$ from 4 mm to 6 mm, normal stress $\sigma_{11}$, slightly reduces in collar region. In addition, the change of normal stress level at point C, where bone transforms from cortical to trabecular is more noticeable in case with $L_{bi} = 4$ mm than in case with $L_{bi} = 6$ mm. This also holds for shear stress. However, the level of shear stress did not change in collar region with increasing the length of body-1.

Normal and shear stress did not change significantly in other regions of bone-implant interface while increasing $L_{bi}$ from 4 mm to 6 mm.
Figure 3.11 Shear stress variations along bone-implant interface for the systems: 
\[ \theta_c = -10 \text{ degree}, \quad L_c = 1 \text{ mm}, \quad \theta_b = 5 \text{ degree}, \]
\begin{align*}
  & (a) \quad L_{b2} = 3 \text{ mm}, \quad L_{b1} = 4 \text{ mm}, \\
  & (b) \quad L_{b2} = 4 \text{ mm}, \quad L_{b1} = 4 \text{ mm}, \\
  & (c) \quad L_{b2} = 3 \text{ mm}, \quad L_{b1} = 6 \text{ mm}, \\
  & (d) \quad L_{b2} = 4 \text{ mm}, \quad L_{b1} = 6 \text{ mm}
\end{align*}

3.3.6 Effect of Implant Diameter (D)

In this study, implant diameters of 3.3, 3.5, and 4 mm were considered. In all the cases, it is observed that increasing implant’s diameter resulted in decreasing the normal and shear stress over the whole regions of bone-implant interface.
Figure 3.12 shows the normal and shear stress profile on the implant interface.

![Figure 3.12 Normal and shear stress profile on the implant interface.](image)

### 3.4 Effect of Implant Contour on Load Transfer to Real Bone

In this section the effects of implant contour parameters on the interfacial load transfer are investigated for a bone contour obtained from the CT of the lower incisor region as described in Section 3.2.

#### 3.4.1 Von Mises Stress Distribution in the Bone

von Mises stress distribution for the implant system with dimensions $L_{b_1} = 4$ mm, $L_c = 1$ mm, $\theta_c = -10$ degrees, $L_{b_2} = 3$ mm, $\theta_{b_2} = 5$ mm, $D = 3.3$ mm is shown in Figure 3.13.
This figure shows high stress levels on the buccal side of the cortical bone. This effect is similar to that observed in Figure 2.2 for 3D analysis, and Figure 2.9 for 2D analysis with assumed elliptical shape. As it can be observed in Figure 3.12, the implant is placed in cortical bone on the lingual side. This condition creates a stress concentration region near the apex of the implant around points G and F as shown in Figure 3.12. The trabecular bone bears relatively low levels of stress. Nevertheless, close to the bone-implant interface the von Mises stress is higher as compared to the inferior section of the trabecular region.

**3.4.2 Interfacial Stress Variation**

The normal $\sigma_{11}$ and shear $\sigma_{12}$ stresses along the bone-implant interface were computed and plotted as a function of distance ($s$) defined from point A in Figure 3.13a,b, respectively.
This figure shows that the normal stress is primarily compressive on the buccal side of the collar region and tensile on the lingual side. A small jump in normal stress is observed at point B, where the contour slope changes between the collar and body regions. A stress concentration occurs at point C at \( s = 4 \) mm where the bone transitions from compact to cancellous. Similar stress concentrations are observed at the apical corners of the implant, particularly on the lingual side. Such relatively high levels of interfacial stress could be counterindicative to healthy bone response. It is also interesting to note that the normal stress on the lingual side of the cortical bone is tensile. This behavior is opposite of that observed for the assumed bone shape presented before in Figure 3.4.

Figure 3.14 shows that shear stress is primarily positive in all regions other than in the apex where it is negative due to geometry change, and bone property changes at points F and G. In the collar region shear stress increases gradually. A jump occurs at point B where \( s \sim 1 \) mm due to geometry and at point C, where \( s \sim 4 \) mm, due to bone quality change. Similar observations are made for the collar region on the other side of the interface.

Body-1 and body-2 regions bear a small level of shear stress very close to zero which is continuous and positive.
Figure 3.14 Normal stress ($\sigma_{11}$) and shear stress ($\sigma_{12}$) for implant with dimensions of: $L_{b1} = 5$ mm, $L_{c} = 1$ mm, $\theta_{c} = -10$ degree, $L_{b2} = 3$ mm, $\theta_{b2} = 5$ degree within: (a,b) the whole path, (c,d) $s=0-3$ mm, (e,f) $s=7-14$ mm, (g,h) $s=17-22$ mm.
### 3.4.3 Comparison Between Elliptical Bone and Real Shape Bone

In Figure 3.15 the interfacial stresses of the real bone are compared to those of the hypothetical elliptical bone. The implant dimensions discussed here are the same as those discussed in Section 3.1, $L_{b1} = 5$ mm, $L_c = 1$ mm, $\theta_c = -10$ degree, $L_{b2} = 3$ mm, $\theta_{b2} = 5$ degrees.

![Graphs showing interfacial stresses](image)

a) $\sigma_{11}$, real bone  

b) $\sigma_{12}$, real bone  

c) $\sigma_{11}$, elliptical bone  

d) $\sigma_{12}$, elliptical bone

**Figure 3.15** Normal and shear stress components on the path in case of: (a,b) real shape bone, (c,d) elliptical bone, for the implant system with dimensions of: $L_{b1} = 5$ mm, $L_c = 1$ mm, $\theta_c = -10$ degree, $L_{b2} = 3$ mm, $\theta_{b2} = 5$ degree
3.4.4 Normal Stress $\sigma_{11}$

Figure 3.15 shows differences in stress distributions on the bone-implant interface between the real shape bone and elliptical bone. Normal stress level in collar region decreased significantly in real shape bone compared to elliptical bone. It is about 40 MPa lower in case of real shape bone than that in case of elliptical bone due to higher thickness of cortical bone in case of real shape bone. The jump at point C where bone transformation occurs is much more noticeable in case of real shape bone than that in case of elliptical bone. Normal stress distribution over body-1 and body-2 is similar in both cases which is small, positive, and continuous. On the buccal side of implant’s apex, (point E), stress concentration is slightly lower in case of real shape bone; however, on the lingual side, stress concentration is noticeably higher in the real shape bone due to the combination effects of geometry and bone quality change. Another noticeable difference in stress distribution in the above mentioned cases is the direction of stress over the left collar region which is positive in case of real shape bone and negative in case of elliptical bone. However, the stress magnitudes are close to each other in this region.

3.4.5 Shear Stress $\sigma_{12}$

The overall profile of shear stress distribution is similar in both cases of real shape and elliptical bone, with small differences. In the collar region, shear stress increases in both cases, and reaches its maximum at point B, but it is about 10 MPa smaller in case of real shape bone than that in case of elliptical bone for all cases of implant diameters. After this point, the shear stress gradually decreases and remains close to zero for both cases, until it reaches another jump at point E. This jump is again
smaller in the real shape bone, than in the elliptical bone. On the other hand, the stress concentration on the lingual side of the apex and body-2 is noticeably higher in case of real shape bone due to the combination of the bone geometry and bone property transformation at points F and G, respectively. On the lingual side of the implant system, shear stress $\sigma_{12}$ remains very low and almost constant over the body-1 and body-2 regions in both real shape and elliptical bone cases. Shear stress increases in collar region and a jump occurs at the angle between collar and body-1 (Point I) in both cases. Shear stress was positive in left collar region in case of real shape bone while it turned negative at point H in case of elliptical bone due to bone quality transformation.

Figure 3.16 shows the normal and shear stress profile on the implant interface.

![Normal and shear stress profile on the implant interface](image)

Normal and shear stress profile in this case are very similar to those in case of elliptical bone; however, collar region in the lingual side bears tensile normal stress and positive shear stress which is not in agreement with the direction of stress distribution in case of elliptical bone.
CHAPTER 4

EFFECT OF EXTERNAL THREADS ON LOAD TRANSFER

4.1 The Case of Assumed elliptical bone Shape

4.1.1 Introduction

In this section, the effects of placing external threads over the body of an implants on the stress transfer are presented. Figure 4.1 shows various commercially available and clinically used implants. Cased on investigation of the shapes of the external screws of these (and other) systems four common screw types were identified. The characteristics of these screw types are shown in Figure 4.2.

The geometry of the screw threads is determined by three parameters: screw pitch, $P_t$, screw depth $h_t$ and slope $\theta$. These values were chosen primarily close to the screw dimensions of the screw threads of Noble Biocare system given in Table 4.1. Dimensions used in this study are given in Table 4-2. Note that the thread slopes shown in Figure 4.2 depend on $h_t$ and $p_t$ as shown later.
Figure 4.1 Dental implants of (a) Noble Biocare, Noble Speedy Replace, screw type-1, (b) Astra Tech, thread type-1, (c) Noble Biocare, Noble Active, thread type-2, (d) Ankylos, thread type-2, (e) Noble Biocare, Noble Replace Tapered Groovy, thread type-3, (f) Bicon, thread type-4
Figure 4.2 Screw threads investigated in this work a) Type 1, b) Type 2, c) Type 3, d) Type 4.

<table>
<thead>
<tr>
<th>Type</th>
<th>Diameter (mm)</th>
<th>Thread Depth, ( h_t ) (mm)</th>
<th>Thread Pitch, ( P_t ) (mm)</th>
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<td>0.250</td>
<td>0.5</td>
</tr>
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<td></td>
<td>4.3</td>
<td>0.320</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>0.424</td>
<td>0.8</td>
</tr>
<tr>
<td>Noble Speedy Groovy</td>
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<td>0.5</td>
</tr>
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<td>0.242</td>
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</tr>
<tr>
<td>Noble Speedy Shorty</td>
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<td>0.320</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>0.424</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 4.1 Dimensions of screw threads used in Noble Biocare

The thread depth, $h_t$, is designated 0.32 mm for all three cases of the implant’s body-1 region, whose length $L_{b1} = 4, 5, 6$ mm in this chapter. However, the screw pitch, $P_t$ is designated to be one-seventh of $L_{b1}$ which are given in Table 4.2. The following relationships hold between the slopes $\theta_i$ - $\theta_4$ and $h_t, P_t$ values for the four thread types:

\begin{align*}
h_t & = 0.32 \text{ mm} \quad \text{(9.a)} \\
P_t & = \frac{L_{b1}}{7} \quad \text{(9.b)} \\
\theta_1 & = \text{atan} \left( \frac{2h_t}{P_t} \right) \quad \text{(9.c)} \\
\theta_2 & = \text{atan} \left( \frac{3h_t}{P_t} \right) \quad \text{(9.d)} \\
\theta_3 & = \text{atan} \left( \frac{P_t}{3h_t} \right) \quad \text{(9.e)} \\
\theta_4 & = \text{atan} \left( \frac{3h_t}{P_t} \right) \quad \text{(9.f)}
\end{align*}

Figure 4.3 shows the models of the implants with and without screws with the surrounding cortical and trabecular bone created in ANSYS.
Figure 4.3 implant system with: a) no thread, b) thread type-1, c) thread type-2, d) thread type-3, e) thread type-4.
4.1.2 Methods

The overall geometry of the bone is chosen similar to that in Chapter 3, Section 3.1. The implant systems with all four types of screws are placed into the bone as shown in Figure 4.3. The implants’ dimensions were varied as discussed in Chapter 3. Finite element analysis was carried in ANSYS (version 11) for all of the implant systems. In this section, an implant system with the dimension listed below was analyzed:

\[ L_{b1}=5 \text{ mm}, \ L_{c}=1 \text{ mm}, \ \theta_c = -10 \text{ degrees}, \ L_{b2}=3 \text{ mm}, \ \theta_{b2}=5 \text{ degrees}, \ D = 3.3 \text{ mm} \]

The load and boundary conditions were the same as those in Chapter 3. Therefore, a normal compressive load of 110.9 N, a lateral load of 21.56 N, and a moment of 108 N.mm were applied on the abutment. The model was meshed with plane42, a 4-node structural element in plane strain conditions.

4.1.3 Stress Analysis on Screw Shape Implants

Stress components \( \sigma_x, \ \sigma_y, \ \text{and} \ \tau_{xy} \) are presented for the the implant system with all four types of screws and also for the case of a smooth face in Figure 4.4. Figure 4.5 shows the stress distribution close to the bone-implant interface.
a) Smooth face

b) Thread Type-1

c) Thread Type-2

(ctd.)
Figure 4.4 Stress components $\sigma_x$, $\sigma_y$, $\tau_{xy}$ for an implant with a) no thread, b) type-1, c) type-2, d) type-3, e) type-4 threads.
a) No thread, $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ (MPa)

b) Thread Type-1, $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ (MPa)

c) Thread Type-2, $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ (MPa)
d) Thread Type-3, $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ (MPa)

Figure 4.5 Stress components $\sigma_x$, $\sigma_y$, $\tau_{xy}$ close to the bone-implant interface for an implant with a) no thread, b) type-1, c) type-2, d) type-3, e) type-4 threads.

Stress distribution in other regions remains very similar in all models. Moreover, the presence of the boundary condition in the lower periphery of the bone results in high stress regions of the magnitude of about 10 MPa buccal and lingual sides of the bone. This boundary effect has no physical significance.

Comparing the $\sigma_x$ component of the stress in the bone presented in Figure 4.5 it is seen that use of screw-threads on the implant surface primarily affects the distribution of this stress component in the trabecular bone on the buccal side. The two V-shape geometries of type-1 and-2, in Figure 4.5b and 4.5c experience relatively lower stress
values inside the thread areas, where as the type-3 and-4 experience a more uniform bone loading in the same region. This can be attributed to the increased stiffness of the type-3 and -4 thread shapes to deformation.

Figure 4.5a shows that normal stress component $\sigma_y$ of the magnitude between -30 MPa to -20 MPa is transferred to the cortical bone, in the implant collar region on the buccal side for the smooth faced implant. The magnitude of $\sigma_y$ decreases to about -15 MPa for type-1 thread type. In addition, the stress component $\sigma_y$ is smaller at the apex region of the implant for the models containing external threads. The reduction of maximum stress as described here is attributed to the effective resistance provided by the threads to vertical relative motion of the implants. Distribution of stress component $\sigma_y$ remains otherwise very similar in models containing implants with all four shapes of screws.

Stress component $\tau_{xy}$ of the magnitude of about 30 MPa is transferred to the cortical bone adjacent to the implant’s collar for the smooth faced implant. This stress component decreases to 20 MPa for the implant with thread type-1, and remains the same for the all other thread types.

Comparing the result of the four thread types, it is concluded that while the thread shape does not affect the loading conditions in the bone distal to the implant, use of external threads makes significant changes to the load transfer characteristics, in the bone proximal to the implant.
4.1.4 Normal and Shear Stress Components ($\sigma_{11}$, $\sigma_{12}$) Along the Bone-Implant Interface

A path was defined on the bone-implant interface. This path follows the threads for the threaded implants, but it follows straight line segments for the smooth faced implant along the bone-implant interface. The normal and shear stress components $\sigma_{11}$, $\sigma_{12}$ were computed using the same approach discussed in Chapter 3.

Figure 4.6 Normal and shear stresses along the interface for an implant with a) smooth face, b) type-1 external thread.
Figure 4.6 shows a comparison of the interfacial normal and shear stresses between a smooth faced implant and one with type-1 thread shape. This figure shows that while the presence of threads (Figure 4.6b) causes increase in interfacial stress levels over the threads, the overall load transfer characteristics of the implant are preserved. For example, in the collar region on the buccal side, the $\sigma_{11}$ is compressive, albeit with a smaller magnitude in Figure 4.6b. The general rising trend of $\sigma_{11}$, which is tensile, in body-1 and body-2 regions, is also preserved with the threaded implant. Similarly, the apex region experiences, compressive but smaller normal stresses under threaded implant. Similar observations are made for the variation of shear stress $\sigma_{12}$.

Figure 4.7 shows the variation of $\sigma_{11}$ and $\sigma_{12}$ along the first 10 mm of the interface. This length was chosen because the conclusions reached about the effects of threads are similar when the rest of the interface is considered. Note that the general shapes of the threads were also plotted on these figures in order to identify the causes of stress concentrations, observed. Please refer to Figure 4.2 for the actual thread geometries.
a) smooth

b) type-1

c) type-2

d) Type-3
Figure 4.7 Normal and shear stress components $\sigma_n$, $\sigma_t$ over the bone-implant interface in (a) model 1, (b) model 2, (c) model 3, (d) model 4, and (e) model 5.

The load transfer mechanism from a thread to the bone can be investigated in Figure 4.7 in particular in the trabecular bone.

Type-1 thread shape primarily resists tensile normal stress on the superior face of the threads, and it is nearly zero normal stress on the inferior side of the threads. The shear stress on the threads is primarily in the same direction except at the thread junction points where stress concentration occurs.

Type-2 thread shape displays similar behavior to type-1 in both $\sigma_{11}$ and $\sigma_{12}$ along the thread faces. The shear stress changes directions for a longer segment of the thread junction area.

Type-3 and type-4 thread shapes have flat and sloped thread edges. In type-3 the flat edge faces the superior direction. Figure 4d shows that normal stress on this flat thread edge varies from compression to tensile with high stress concentrations, where as the inferior slope edge is primarily in compression and the side edge is in tension. The shear stress in type-3 thread is lower than types-1 and -2.
Type-4 thread shape, where the flat thread edge is facing the direction of implant apex, the normal stress $\sigma_{11}$ varies similar to type-1 and -2 except at the corner of the flat edge and the lateral edge of the thread, where a stress concentration causes compression. The overall normal and shear stress variations over the screw threads are depicted in Figure 4.8, based on the results of Figure 4.7.

![Normal Stress](image1)

![Shear Stress](image2)

Figure 4.8 Normal and shear stress contour on the screw threads
4.2 The Case of Scanned Bone Shape

In this section, the effects of external threads on the load transfer from implant to bone are investigated for a bone contour digitized from a CT-scan of an incisor as shown in Figure 3.2. A 2D analysis is carried out using finite element method (FEM) in ANSYS. The load and boundary conditions are the same as those in previous sections. The model was meshed with the same element type, which was Plane42, and in the same manner as those in previous studies. Meshed model is shown in Figure 4.9. Stress components $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ were plotted for all five models as shown in Figure 4.10.

![Figure 4.9 Model meshed with Plane42 of ANSYS](image)

![Figure 4.9 Model meshed with Plane42 of ANSYS](image)

![Figure 4.9 Model meshed with Plane42 of ANSYS](image)

![Figure 4.9 Model meshed with Plane42 of ANSYS](image)

![Figure 4.9 Model meshed with Plane42 of ANSYS](image)

![Figure 4.9 Model meshed with Plane42 of ANSYS](image)

![Figure 4.9 Model meshed with Plane42 of ANSYS](image)
Figure 4.10 Stress components $\sigma_x$, $\sigma_y$, $\tau_{xy}$ for an implant with a) no thread, b) type-1, c) type-2, d) type-3, e) type 4 threads.
a) Smooth face, $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ (MPa)

b) Thread type-1, $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ (MPa)

c) Thread type-2, $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ (MPa)
Figure 4.11 Stress components $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ close to the bone-implant interface for an implant with a) no thread, b) type-1, c) type-2, d) type-3, e) type-4 threads.

Comparing the $\sigma_x$ component of the stress in the bone presented in Figure 4.11, it is seen that use of screw-threads on the implant surface reduces the distribution of this stress component in the cortical bone on the buccal side. Stress concentration that is observed in case of smooth implant due to bone transition decreased significantly with threaded implants. However, the two V-shape geometries of types-1 and -2 in Figures 4.9b,c, respectively, experience relatively higher stress values inside the threads. This is not in agreement with the results of the case of elliptical bone.
Comparing the $\sigma_y$ component of the stress, it is observed that use of screw-threads on the implant surface noticeably reduces the distribution of this stress component in the cortical bone on the buccal side. However, higher stress values are observed on the lingual side. In addition, using screw threads increased the distribution of this stress component inside the thread area. It is observed that the shape of the threads does not affect stress distribution significantly.

Comparing the $\tau_{xy}$ component of the stress, it is observed that use of screw-threads on the implant surface reduces the distribution of this stress component in the cortical bone on the buccal side, while stress level on the lingual side is relatively higher in case of threaded implants than in case of smooth implant. Moreover, using screw threads, higher level of shear stress transferred inside the thread areas while the pinching effect on points E and G reduces noticeably. Similar to $y$ component of stress, this component of distribution does not vary with different thread types.

### 4.3 Normal and Shear Stress Components $\sigma_{11}, \sigma_{12}$ on the Bone-Implant Interface

In this section, a path was defined on the bone-implant interface in all of the five models mentioned above. Normal and shear stress components $\sigma_{11}, \sigma_{12}$ were computed over the path using the same approach discussed in Chapter 3.

Figure 4.12 shows a comparison of the interfacial normal and shear stresses between a smooth faced implant and one with type-1 thread shape. It is observed that having the threads on the implant surface results in increase in interfacial stress levels over the threads; however, the overall load transfer characteristics of the implant are preserved. In both cases, the implant collar is in compression on the buccal side while
in tension in the lingual side. Body-1 and body-2 regions experience tensile normal stress $\sigma_{11}$, increasing toward the implant apex. Using threaded implants affects shear stress $\sigma_{12}$ distribution in the collar regions both on the lingual and buccal sides significantly. Shear stress is positive in collar regions in case of smooth face implant, however, adding threads results in negative shear stress on the upper face of the thread and positive shear stress on the other two sides in collar regions.

Figure 4.12 Normal and shear stresses along the interface for an implant with a) no screw, b) type-1 screw

Figure 4.13 shows the variation of $\sigma_{11}$ and $\sigma_{12}$ along the first 10 mm of the interface due to the face that most differences occur in this region with the presence of screw threads.
a) smooth

b) type-1

c) type-2

d) type-3
Figure 4.13 Normal and shear stress components $\sigma_{11}, \sigma_{12}$ (MPa) with respect to the distance over the path in: (a) model 1, (b) model 2, (c) model 3, (d) model 4, (e) model 5.

The mechanism of load transfer from a thread to the bone was investigated in Figure 4.11 where the interfacial stress components $\sigma_{11}, \sigma_{12}$ are plotted for the first 10 mm of the interface on the buccal side.

Type-1 thread shape primarily resist a very low level tensile normal stress on the coronal face of the threads and nearly zero normal stress on the inferior side of the threads. The shear stress on the threads is primarily in the same direction except at the threads junction points where stress concentration occurs. The similar trend of stress distribution was observed in case of elliptical bone; however, the level of stresses was higher in case of elliptical bone.

Type-2 thread shape primarily resists a low compressive stress in all thread edges with noticeable stress concentration on the junction points. It displays similar behavior to type-1 in $\sigma_{12}$ along the thread faces.

Type-3 thread shape with the flat thread edge facing the coronal direction and the sloped edge facing the apical direction experiences compressive stress on all its edges with stress concentrations on the junction points. Shear stress on the threads is...
primarily in the positive direction except at the thread junction points where stress concentrations occur.

Type-4 thread shape with the flat thread edge facing the apical direction and the sloped edge facing the coronal direction resists compressive stress on the coronal and apical edges and almost zero normal stress on the side edge. Noticeable jumps are observed at the junction points due to stress concentrations. Shear stress $\sigma_{12}$ varies similar to type-1. The overall normal and shear stress variations over the screw threads are depicted in Figure 4.14, based on the results of Figure 4.9.

![Diagram of screw threads with normal and shear stress](image-url)

**Figure 4.14 Normal and shear stress contour on the screw threads**
CHAPTER 5

SUMMARY and CONCLUSIONS

5.1 Comparison of Load Transfer Mechanism in 2D and 3D

The load transfer mechanism is observed to be reasonably close in the 2D and 3D models, however differences were observed in the magnitudes of the stresses which were due to plane-strain assumption and the boundary conditions. Lower stress levels were predicted in the 3D model due to the fact that the 3D model is fixed in all degrees of freedom in the distal ends. Therefore, stress concentration observed near the bottom of the 2D model due to the inferior restrictions should be evaluated with caution.

5.2 Effect of Implant Shape on Load Transfer

Implant shape strongly affects the stress distribution characteristics of the implant and the resulting load transfer along the implant-bone interface. Implant failure and bone fracture can occur if stresses exceed the maximum allowable levels. In this study, the effect of implant geometry is investigated by means of dividing the implant into four regions and by changing the variables that define the implant contour. The stresses induced in the bone, and transferred along the bone-implant interface are evaluated for different implant shapes using finite element analysis.

Highest continuous interfacial stresses are encountered in the region where the implant collar engages the cortical bone, and near the apex of the implant in the trabecular bone. Stress concentrations in the interfacial stresses occur near the geometric discontinuities on the implant contour, and discontinuous stresses occur where the elastic modulus of the bone transitions between the values of the cortical
and trabecular bone. Such stress concentrations and discontinuities disrupt the otherwise smoothly varying interfacial stresses, significantly, depending on the geometric parameters.

The interfacial normal stress ($\sigma_{11}$) is generally compressive along the interface with exceptions near the apex and the lingual side of the collar regions. The interfacial shear stress ($\sigma_{12}$) has magnitude comparable to the normal stress in the collar regions, and is generally high in the buccal side of the body-regions. Among the six contour parameters, the slope ($\theta_c$) and length ($L_c$) of the implant collar, and the implant diameter ($D$) influence the interfacial stress levels the most, and the effects of changing these parameters are only significantly noticed in the cortical bone (alveolar ridge) area. Positive collar slope values, larger implant diameters $D$, and longer collar regions (in case the collar region is longer than the cortical bone) reduce the magnitudes of the interfacial stresses in the cortical bone.

5.3 Effect of External Threads on Load Transfer

Using external threads on implant contour strongly affects the stress distribution and the resulting load transfer along the bone-implant interface. Normal and shear stresses induced in the bone and along the bone-implant interface are evaluated and compared in models containing implants with four different thread types. Comparing the result of the four thread types, it is concluded that while the thread shape does not affect the loading conditions in the bone distal to the implant, use of external threads makes significant changes to the load transfer characteristics, in the bone proximal to the implant. Using external threads significantly reduces the stress in the bone away from the interface. On the other hand, it increases the stress transferred inside the thread
areas which helps the bone to generate in those regions and improves the process of osseointegration.

5.4 Suggestions for Future Works

Using finite element method to analyze stress distribution in the above mentioned models; so many assumptions were made such as 100% osseointegration which is very ideal. Modeling the more realistic contact condition of bone and implant is highly recommended for future works.
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APPENDIX-I-3D Quarter Symmetric Model, Cylindrical Implant

/BATCH
/PREP7

! ****************** ET & MP ******************
ET,1,SOLID185 ! Defines element types
KEYOPT,1,2,2 ! Sets element key options.
KEYOPT,1,3,0
KEYOPT,1,6,0
KEYOPT,1,10,0

ET,2,SOLID185
KEYOPT,1,2,2
KEYOPT,1,3,0
KEYOPT,1,6,0
KEYOPT,1,10,0

ET,3,SOLID185
KEYOPT,1,2,2
KEYOPT,1,3,0
KEYOPT,1,6,0
KEYOPT,1,10,0

MPTEMP,,,,,,,, ! Defines material properties
MPTEMP,1,0
MPDATA,EX,1,,113e3 ! Designates elastic modulus
MPDATA,PRXY,1,,0.3 ! Designates poisson's ratio
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,EX,2,,13e3
MPDATA,PRXY,2,,0.3
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,EX,3,,1e3
MPDATA,PRXY,3,,0.3

*DIM,SX,ARRAY,61,1 ! Defines the dimensions of Sx, and so on.....
*DIM,SY,ARRAY,61,1
*DIM,SXY,ARRAY,61,1

*DIM,S11,ARRAY,61,1
*DIM,S12,ARRAY,61,1

*SET,A,1
*SET,d,0

*DO,zz,1,3
*IF,zz,eq,1,THEN
II=3.3
ENDIF
*IF,zz,eq,2,THEN
II=3.5
ENDIF
*IF,zz,eq,3,THEN
II=4
ENDIF

FLST,2,8,6,ORDE,2 ! Specifies data required for a picking operation (GUI).
FITEM,2,5 ! Identifies items chosen by a picking operation (GUI).
VDELE,P51X, ,1

! *********************** CORTICAL BONE Keypoints ***********************

k,19,0.00000,-30.00000,,
k,20,0.50000,-29.97683,,
k,21,1.00000,-29.90712,,
k,22,1.50000,-29.79020,,
k,23,2.00000,-29.62494,,
k,24,2.50000,-29.40968,,
k,25,3.00000,-29.14214,,
k,26,3.50000,-28.81927,,
k,27,4.00000,-28.43710,,
k,28,4.50000,-27.99038,,
k,29,5.00000,-27.47219,,
k,30,5.50000,-26.87317,,
k,31,6.00000,-26.18034,,
k,32,6.50000,-25.37492,,
k,33,7.00000,-24.28099,,
k,34,7.50000,-23.91560,,
k,35,8.00000,-21.87184,,
k,36,8.50000,-19.93007,,
k,37,9.00000,-15.00000,,
k,51,0,0,0

! *********************  TRABECULAR BONE KEYPOINTS *********************

k,54,0,-1.1,0
k,89,0.00000,-28.00000,,
k,90,0.50000,-27.96679,,
k,91,1.00000,-27.86666,,
k,92,1.50000,-27.69802,,
k,93,2.00000,-27.45809,,
k,94,2.50000,-27.14265,,
k,95,3.00000,-26.74560,,
k,96,3.50000,-26.25833,,
k,97,4.00000,-25.66847,,
k,98,4.50000,-24.95782,,
k,99,5.00000,-24.09810,,
k,100,5.50000,-23.04166,,
k,101,6.00000,-21.69602,,
k,102,6.50000,-19.82500,,
k,103,7.00000,-15.00000,,
k,124,1.50000,-1.5,,
k,125,3.50000,-3.74167,
101

k,126,4.00000,-4.33153,,
k,127,4.50000,-5.04218,,
k,128,5.00000,-5.90190,,
k,129,5.50000,-6.95834,,
k,130,6.00000,-8.30398,,
k,131,6.50000,-10.17500,,
k,132,7.00000,-15.00000,,

! ************************* TRABECULAR BONE AREA **********************
FLST,2,24,3
FITEM,2,124
FITEM,2,125
FITEM,2,126
FITEM,2,127
FITEM,2,128
FITEM,2,129
FITEM,2,130
FITEM,2,131
FITEM,2,103
FITEM,2,102
FITEM,2,101
FITEM,2,100
FITEM,2,99
FITEM,2,98
FITEM,2,97
FITEM,2,96
FITEM,2,95
FITEM,2,94
FITEM,2,93
FITEM,2,92
FITEM,2,91
FITEM,2,90
FITEM,2,89
FITEM,2,54

A,P51X                          ! Defines an area by connecting keypoints.

! ************************* CORTICAL BONE AREA ***********************
FLST,2,33,3
FITEM,2,51
FITEM,2,53
FITEM,2,52
FITEM,2,63
FITEM,2,64
FITEM,2,65
FITEM,2,66
FITEM,2,67
FITEM,2,68
FITEM,2,69
FITEM,2,70
FITEM,2,71
FITEM,2,72
FITEM,2,73
FITEM,2,37
FITEM,2,36
FITEM,2,35
FITEM,2,34
FITEM,2,33
FITEM,2,32
FITEM,2,31
FITEM,2,30
FITEM,2,29
ASBA, 2, 1  ! Subtracts areas from areas.

! **************************************** TRABECULAR BONE AREA ****************************************
FLST,2,24,3
FITEM,2,124
FITEM,2,125
FITEM,2,126
FITEM,2,127
FITEM,2,128
FITEM,2,129
FITEM,2,130
FITEM,2,131
FITEM,2,103
FITEM,2,102
FITEM,2,101
FITEM,2,100
FITEM,2,99
FITEM,2,98
FITEM,2,97
FITEM,2,96
FITEM,2,95
FITEM,2,94
FITEM,2,93
FITEM,2,92
FITEM,2,91
FITEM,2,90
FITEM,2,89
FITEM,2,54
A,P51X

! ************** Extruding the bones **************
FLST,2,2,5,ORDE,2
FITEM,2,1
FITEM,2,3
VEXT,P51X, ,0,0,-10,,,, ! Generates additional volumes by extruding areas.(extrudes the area -10
    mm in the z- direction.)

! *********************** Implant Keypoints ******************
K,501,0,0,0,
K,502,0,-9,0,
K,503,0,-9,0,

! *********************** Abutment Keypoints **************
K,505,0,0,5,0,
K,506,1.25,5,0,
K,507,1.25,0,0,
K,508,1.25,-3,0,
K,509,0,-3,0,

! *********************** Implant Area  ***********************
FLST,2,6,3
FITEM,2,507
FITEM,2,501
FITEM,2,502
FITEM,2,503
FITEM,2,509
FITEM,2,508
A,P51X

! ************************ Abutment Area **************************

FLST,2,5,3
FITEM,2,505
FITEM,2,506
FITEM,2,507
FITEM,2,508
FITEM,2,509
A,P51X

! ************************** Rotating implant **********************

FLST,2,1,5,ORDE,1
FITEM,2,63
FLST,8,2,3
FITEM,8,509
FITEM,8,503
VROTAT,P51X, , , , , ,P51X, ,-90, , 
! Generates cylindrical volumes by rotating an area pattern about an
axis.

! ************************ Rotating Abutment ************************

FLST,2,1,5,ORDE,1
FITEM,2,64
FLST,8,2,3
FITEM,8,505
FITEM,8,509
VROTAT,P51X, , , , , ,P51X, ,-90, ,

! ******************* Overlap *************

FLST,2,4,6,ORDE,2
FITEM,2,1
FITEM,2,-4
VOVLAP,P51X

! **************** Glue ****************

FLST,2,8,6,ORDE,2
FITEM,2,5
FITEM,2,-12
VGLUE,P51X

! ******************* Meshing *******************

! Implant # Abutment
TYPE, 1
! designates element type 1 for meshing
MAT, 1
! designates material property for meshing
REAL,
ESYS, 0
SECNUM,
FLST,5,6,6,ORDE,2
FITEM,5,5
FITEM,5,-10
CM,_Y,VOLU
! Groups geometry items into a component.
VSEL, , , ,P51X
! Selects a subset of volumes.
CM,_Y1,VOLU
CMSEL,S,_Y
! Selects a subset of components and assemblies.
! Associates element attributes with the selected, unmeshed volumes.
VATT, 1, 1, 0
CMSELS, Y
CMDELE, Y
CMDELE, Y1
ESIZE,0.2,0,
MSHAPE,1,3D
MSHKEY,0

! Deletes a component or assembly definition.
CMSEL,S,Y
CMDELE,Y
CMDELE,Y1

! Specifies the number of line division. 
ESIZE,0.2,0,

! For elements that support multiple shapes, specifies the element shape to be used.
MSHAPE,1,3D
MSHKEY,0

! Specifies whether free meshing or mapped meshing should be used to mesh a model.
FLST,5,6,6,ORDE,2
FITEM,5,5
FITEM,5,-10
CM,Y,VOLU
VSEL,,P51X
CM,Y1,VOLU
CHKMSH,'VOLU'
CMSELS,Y
VMESH,Y1
CMDELE,Y
CMDELE,Y1
CMDELE,Y2

! Generates nodes and volume elements within volumes.
CM,Y,VOLU
VSEL,,12
CM,Y1,VOLU
CMSELS,Y
CMSELS,Y1
VATT,2,2,0
CMSELS,Y
CMDELE,Y
CMDELE,Y1
ESIZE,0.5,0,
CM,Y,VOLU
VSEL,,12
CM,Y1,VOLU
CHKMSH,'VOLU'
CMSELS,Y
VMESH,Y1
CMDELE,Y
CMDELE,Y1
CMDELE,Y2

! Cortical Bone
CM,Y,VOLU
VSEL,,12
CM,Y1,VOLU
CMSELS,Y
CMSELS,Y1
VATT,2,2,0
CMSELS,Y
CMDELE,Y
CMDELE,Y1
ESIZE,0.5,0,
CM,Y,VOLU
VSEL,,12
CM,Y1,VOLU
CHKMSH,'VOLU'
CMSELS,Y
VMESH,Y1
CMDELE,Y
CMDELE,Y1
CMDELE,Y2

! Trabecular Bone
CM,Y,VOLU
VSEL,,11
CM,Y1,VOLU
CMSELS,Y
CMSELS,Y1
VATT,3,3,0
CMSELS,Y
CMDELE,Y
CMDELE,Y1
ESIZE,0.7,0,
CM,Y,VOLU
VSEL,,11
CM,Y1,VOLU
CHKMSH,'VOLU'
CMSELS,Y
VMESH,Y1
CMDELE,Y
CMDELE_Y1
CMDELE_Y2

!******************** Loads *******************
! Case 1
FLST,2,2,5,ORDE,2
FITEM,2,2
FITEM,2,28
/GO
DA,P51X,ALL,                        ! Defines DOF constraints on areas.
asel,all
FLST,5,8,5,ORDE,8
FITEM,5,77
FITEM,5,81
FITEM,5,87
FITEM,5,90
FITEM,5,96
FITEM,5,98
FITEM,5,103
FITEM,5,107
ASEL,S, , ,P51X
FLST,2,8,5,ORDE,8
FITEM,2,77
FITEM,2,81
FITEM,2,87
FITEM,2,90
FITEM,2,96
FITEM,2,98
FITEM,2,103
FITEM,2,107
DA,P51X,SYMM                         ! designates symmetry condition on the chosen areas
asel,all
FLST,5,8,5,ORDE,8
FITEM,5,61
FITEM,5,61
FITEM,5,78
FITEM,5,82
FITEM,5,86
FITEM,5,95
FITEM,5,97
FITEM,5,102
FITEM,5,105
ASEL,S, , ,P51X
FLST,2,8,5,ORDE,8
FITEM,2,61
FITEM,2,61
FITEM,2,78
FITEM,2,82
FITEM,2,86
FITEM,2,95
FITEM,2,97
FITEM,2,102
FITEM,2,105
DA,P51X,SYMM
FLST,2,1,3,ORDE,1
FITEM,2,505
FLST,2,1,3,ORDE,1
FITEM,2,505
/GO
FK,P51X,FY,-27.72                      ! Applies force of magnitude -27.72 in the y-direction
asel,all
LSWRITE,1,                             ! Writes load and load step option data to a file.
LSCLEAR,ALL                             ! Delete all loads and initialize all load step options and load factors.
! Case 2
asel,all
FLST,2,2,5,ORDE,2
FITEM,2,2
FITEM,2,28
/GO
DA,P51X,ALL,
asel,all
FLST,5,8,5,ORDE,8
FITEM,5,77
FITEM,5,81
FITEM,5,87
FITEM,5,90
FITEM,5,96
FITEM,5,98
FITEM,5,103
FITEM,5,107
ASEL,S,,P51X
FLST,2,8,5,ORDE,8
FITEM,2,77
FITEM,2,81
FITEM,2,87
FITEM,2,90
FITEM,2,96
FITEM,2,98
FITEM,2,103
FITEM,2,107
DA,P51X,SYMM
asel,all
FLST,5,8,5,ORDE,8
FITEM,5,61
FITEM,5,78
FITEM,5,82
FITEM,5,86
FITEM,5,95
FITEM,5,97
FITEM,5,102
FITEM,5,105
ASEL,S,,P51X
FLST,2,8,5,ORDE,8
FITEM,2,61
FITEM,2,78
FITEM,2,82
FITEM,2,86
FITEM,2,95
FITEM,2,97
FITEM,2,102
FITEM,2,105
DA,P51X,ASYM
asel,all
FLST,2,1,3,ORDE,1
FITEM,2,505
/GO
FK,P51X,FX,5.39
asel,all
LWRITE,2,

! Deleting case 2
LSCLEAR,ALL

! Case 3
asel,all
FLST,2,2,5,ORDE,2
ITEM,2,2
ITEM,2,28
/GO
DA,P51X,ALL,
ase,all
FLST,5,8,5,ORDE,8
ITEM,5,77
ITEM,5,81
ITEM,5,87
ITEM,5,90
ITEM,5,96
ITEM,5,98
ITEM,5,103
ITEM,5,107
ASEL,S,,P51X
FLST,2,8,5,ORDE,8
ITEM,2,77
ITEM,2,81
ITEM,2,87
ITEM,2,90
ITEM,2,96
ITEM,2,98
ITEM,2,103
ITEM,2,107
DA,P51X,SYMM
ase,all
FLST,5,8,5,ORDE,8
ITEM,5,61
ITEM,5,78
ITEM,5,82
ITEM,5,86
ITEM,5,95
ITEM,5,97
ITEM,5,102
ITEM,5,105
ASEL,S,,P51X
FLST,2,8,5,ORDE,8
ITEM,2,61
ITEM,2,78
ITEM,2,82
ITEM,2,86
ITEM,2,95
ITEM,2,97
ITEM,2,102
ITEM,2,105
DA,P51X,ASYM
ase,all
FLST,2,1,3,ORDE,1
ITEM,2,506
/GO
FK,P51X,FY,-18
ase,all
LSWRITE,3,

! ****************************************** Solve ***************
FINISH
/SOL
LSSOLVE,1,3,1, ! Reads and solves multiple load steps.(here: load steps from 1 to 3)

! ******** Writing load cases**********
/POST1
SET, FIRST
LCWRITE, 1, , , ! Creates a load case by writing results to a load case file (load case number 1).
SET, LIST, 999
SET, , , 2
LCWRITE, 2, , , ! Performs load case operations (Here: Adds the current load case to load case 1)
LCWRITE, 3, , , ! Reads a load case into the database (Here: load case 3)
LCASE, 3,
LCASE, 1,
LCASE, 2,
LCASE, 3,
LCASE, 1,
SET, LIST, 999
SET, , , 3
LCWRITE, 4, , ,
LCASE, 3,
LCASE, 1,
LCASE, 2,
LCASE, 3,
LCASE, 4,
LCASE, 5,

! ******************* GPP *******************
/POST1
PATH, sa, 3, 30, 30, ! Defines a path name and establishes parameters for the path (name: sa, number of divisions on the path: 30, number of sets of data to be mapped onto the path)
PPATH, 1, 0, II/2, 0, 0, 0, PPATH, 2, 0, II/2, -9, 0, 0, PPATH, 3, 0, 0, -9, 0, 0, AVPRIN, 0, , ! Defines a path by picking or defining nodes, or locations on the currently active working plane, or by entering specific coordinate locations.
PDEF, S, EQV, NOAV ! Interpolates an item onto a path (Here: vonMises stress, Do not average element results across elements.)
AVPRIN, 0, ,
PDEF, S, X, NOAV AVPRIN, 0, ,
PDEF, S, Y, NOAV AVPRIN, 0, ,
PDEF, S, XY, NOAV AVPRIN, 0, ,
PDEF, S, XZ, NOAV AVPRIN, 0, ,
PDEF, S, YZ, NOAV
*CFOPEN, 'C:\Documents and Settings\S.Faegh\Desktop\path2, cylinder\S(\%A\%), txt

*DO, PP, 1, 61
*GET, SS, PATH, 0, ITEM, S, PATHPT, PP ! Retrieves a value and stores it as a scalar parameter or part of an array parameter (Here: node location)
*VWRITE, SS ! Writes data to a file in a formatted sequence.
%G
*ENDDO
*CFCLOSE ! Closes the "command" file.
*CFOPEN, 'C:\Documents and Settings\S.Faegh\Desktop\path2, cylinder\VONMISES(\%A\%), txt

*DO, PP, 1, 61
*GET, SS, PATH, 0, ITEM,SEQV, PATHPT, PP
*VWRITE, SS
%G
*ENDDO
*CFCLOSE

*DO, PP, 1, 61
*GET, SX(PP, 1), PATH, 0, ITEM, SX, PATHPT, PP
*GET, SY(PP, 1), PATH, 0, ITEM, SY, PATHPT, PP
*GET, SXY(PP, 1), PATH, 0, ITEM, SXY, PATHPT, PP
*ENDDO
*CFOPEN, C:\Documents and Settings\S.Faegh\Desktop\path2,cylinder\SX(%A%),txt
*VWRITE, SX(1, 1) (F3.10)
%G
*CFCLOSE
*CFOPEN, C:\Documents and Settings\S.Faegh\Desktop\path2,cylinder\SY(%A%),txt
*VWRITE, SY(1, 1)
%G
*CFCLOSE
*CFOPEN, C:\Documents and Settings\S.Faegh\Desktop\path2,cylinder\SXY(%A%),txt
*VWRITE, SXY(1, 1)
%G
*CFCLOSE
*DO, PP, 1, 30
*SET, S11(PP, 1), SX(PP, 1)
*SET, S22(PP, 1), SY(PP, 1)
*SET, S12(PP, 1), SXY(PP, 1)
*ENDDO
*DO, PP, 32, 61
*SET, S11(PP, 1), SY(PP, 1)
*SET, S22(PP, 1), SX(PP, 1)
*SET, S12(PP, 1), -SXY(PP, 1)
*ENDDO
*CFOPEN, C:\Documents and Settings\S.Faegh\Desktop\path2,cylinder\S11(%A%),txt
*VWRITE, S11(1, 1)
%G
*CFCLOSE
*CFOPEN, C:\Documents and Settings\S.Faegh\Desktop\path2,cylinder\S22(%A%),txt
*VWRITE, S22(1, 1)
%G
*CFCLOSE
*CFOPEN, C:\Documents and Settings\S.Faegh\Desktop\path2,cylinder\S12(%A%),txt
*VWRITE, S12(1, 1)
%G
*CFCLOSE
*SET, A, A+1

FINISH
/PREP7

*ENDDO
APPENDIX-II-2D Model, Elliptical Bone, Type-2 Threaded Implant

/BATCH
/PREP7
! *Preprossor

! *************************** ET & MP ***************************

ET,1,PLANE42
KEYOPT,1,1,0
KEYOPT,1,2,0
KEYOPT,1,3,2
KEYOPT,1,5,2
KEYOPT,1,6,0
ET,2,PLANE42
KEYOPT,1,1,0
KEYOPT,1,2,0
KEYOPT,1,3,2
KEYOPT,1,5,2
KEYOPT,1,6,0
ET,3,PLANE42
KEYOPT,1,1,0
KEYOPT,1,2,0
KEYOPT,1,3,2
KEYOPT,1,5,2
KEYOPT,1,6,0
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,EX,1,,113e3
MPDATA,PRXY,1,,0.3
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,EX,2,,13e3
MPDATA,PRXY,2,,0.3
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,EX,3,,1e3
MPDATA,PRXY,3,,0.3

! ************************** Do Loop ******************************

*SET,d,0
*SET,A,1
*DIM,SX,ARRAY,811,1
*DIM,SY,ARRAY,811,1
*DIM,SXY,ARRAY,811,1
*DIM,S11,ARRAY,811,1
*DIM,S22,ARRAY,811,1
*DIM,S12,ARRAY,811,1

*DO,zz,1,3
  *IF,zz,eq,1,THEN
    II=3.3
  *ENDIF
  *IF,zz,eq,2,THEN
    II=3.5
  *ENDIF
  *IF,zz,eq,3,THEN
    II=4
  *ENDIF
*DO,II,4,6
*DO,KK,1,2
*DO,LL,-10,10,5
*DO,MM,3,4
*DO,NN,5,10,5
! Clear all meshes
FLST,2,6,5,ORDE,3 ! Specifies data required for a picking operation (GUI).
FITEM,2,1 ! Identifies items chosen by a picking operation (GUI).
FITEM,2,3
FITEM,2,-7
ACLEAR,P51X ! clear meshes within area chosen
! Clear all areas
FLST,2,6,5,ORDE,3
FITEM,2,1
FITEM,2,3
FITEM,2,-7
ADELE,P51X, , ,1 ! Delete specified areas

! ************************** CORTICAL BONE Keypoints **************************
    k,-9.00000,-15.00000,; ! generates keypoint number 1, with specified x,y,and z locations.
k,49,-3.50000,-1.18073,,
k,63,3.50000,-1.18073,,
k,64,4.00000,-1.56290,,
k,65,4.50000,-2.00962,,
k,66,5.00000,-2.52781,,
k,67,5.50000,-3.12683,,
k,68,6.00000,-3.81966,,
k,69,6.50000,-4.62508,,
k,70,7.00000,-5.57191,,
k,71,7.50000,-6.70844,,
k,72,8.00000,-8.12816,,
k,73,8.50000,-10.06993,,
k,74,9.00000,-15.00000,,

k,75,-7.00000,-15.00000,,
k,76,-6.50000,-19.82500,,
k,77,-6.00000,-21.69602,,
k,78,-5.50000,-23.04166,,
k,79,-5.00000,-24.09810,,
k,80,-4.50000,-24.95782,,
k,81,-4.00000,-25.66847,,
k,82,-3.50000,-26.25833,,
k,83,-3.00000,-26.74560,,
k,84,-2.50000,-27.14265,,
k,85,-2.00000,-27.45809,,
k,86,-1.50000,-27.69802,,
k,87,-1.00000,-27.86666,,
k,88,-0.50000,-27.96679,,
k,89,0.00000,-28.00000,,
k,90,0.50000,-27.96679,,
k,91,1.00000,-27.86666,,
k,92,1.50000,-27.69802,,
k,93,2.00000,-27.45809,,
k,94,2.50000,-27.14265,,
k,95,3.00000,-26.74560,,
k,96,3.50000,-26.25833,,
k,97,4.00000,-25.66847,,
k,98,4.50000,-24.95782,,
k,99,5.00000,-24.09810,,
k,100,5.50000,-23.04166,,
k,101,6.00000,-21.69602,,
k,102,6.50000,-19.82500,,
k,103,7.00000,-15.00000,,
k,104,-7.00000,-15.00000,,
k,105,-6.50000,-10.17500,,
k,106,-6.00000,-8.30398,,
k,107,-5.50000,-6.95834,,
k,108,-5.00000,-5.90190,,
k,109,-4.50000,-5.04218,,
k,110,-4.00000,-4.33153,,
k,111,-3.50000,-3.74167,,
k,112,-3.00000,-3.15000,,
k,113,-2.50000,-1.5,,
k,114,1.50000,-1.5,,
k,115,3.50000,-3.74167,,
k,116,4.00000,-4.33153,,
k,117,4.50000,-5.04218,,
k,118,5.00000,-5.90190,,
k,119,5.50000,-6.95834,,
k,120,6.00000,-8.30398,,
k,121,6.50000,-10.17500,,
k,122,7.00000,-15.00000,,

! *********************  TRABECULAR BONE KEYPOINTS *********************

! *********************** Implant Keypoints ***********************
K,201,-II,-JJ-kk,,
K,202,-II+II,-JJ-kk,,
K,203,-II,-kk,,
K,204,-II+II-kk,,
K,205,-II+II*K*TAN(LL*3.1415/180),0,,
K,206,-II+II-K*K*TAN(LL*3.1415/180),0,,
K,207,-II+II-MM*TAN(NN*3.1415/180),-MM-JJ-kk,,
K,208,-II+II-MM*TAN(NN*3.1415/180),-MM-JJ-kk,,

! *********************** Abutment Keypoints **************
k,211,-1.25,0,,
k,212,1.25,0,,
k,213,-1.25-kk-JJ/3,,
k,214,1.25-kk-JJ/3,,
k,215,-1.25,5,,
k,216,0,5,,
k,217,1.25,5,,

! *********************  Layers ****************
k,218,1.5,0,,
k,219,-1.5,0,,
k,220,-1.3-MM-JJ-kk+0.5,,
k,221,1.3-MM-JJ-kk+0.5,,
k,222,2.44500,-10.16000,,
k,223,-2.83500,-10.16000,,

! ******** Screw THREAD Keypoints (LINE 1)
*DO,i,1,21
*IF,MOD(i,3),eq,0,THEN
 K,300+i,-II+II-kk-((JJ/21)*i)
*ENDIF
*IF,MOD(i,3),eq,1,THEN
 K,300+i,-II+II+0.32-kk-((JJ/21)*i)
*ENDIF
*IF,MOD(i,3),eq,2,THEN
 K,300+i,-II+II+0.32-kk-((JJ/21)*i)
*ENDIF
*ENDDO

! ******** Screw THREAD Keypoints (LINE 2)
*SET,t,0.02
*DO,i,1,18
*IF,MOD(i,3),eq,0,THEN
 K,400+i,-II-((MM/COS(NN*3.1415/180))*i/18*SIN(NN*3.1415/180))-JJ-kk-
((MM/COS(NN*3.1415/180))*(i/18*COS(NN*3.1415/180))
*ENDIF
*IF,MOD(i,3),eq,1,THEN
 K,400+i,-II+0.32-(t*i)-JJ-kk-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*IF,MOD(i,3),eq,2,THEN
 K,400+i,-II+0.32-(t*i)-JJ-kk-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*ENDDO

! ******** Screw THREAD Keypoints (LINE 3)
*DO,i,1,21
*IF,MOD(i,3),eq,0,THEN
 K,500+i,-II-2-kk-((JJ/21)*i)
*ENDIF
*IF,MOD(i,3),eq,1,THEN
 K,500+i,-II-0.32-kk-((JJ/21)*i)

*ENDIF
*IF,MOD(i,3),eq,2,THEN
   K,500+i,-II/2-0.32,-kk-((JJ/21)*i)
*ENDIF
*ENDDO

! *************** Screw THREAD Keypoints (LINE 4)
*SET,t,0.02
*DO,i,1,18
  *IF,MOD(i,3),eq,0,THEN
  K,600+i,-II/2+(i/18)*SIN(NN*3.1415/180),-JJ-kk-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
  *ENDIF
  *IF,MOD(i,3),eq,1,THEN
  K,600+i,-II/2-0.32+t(i),-JJ-kk-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
  *ENDIF
*END
*IF,MOD(i,3),eq,2,THEN
  K,600+i,-II/2-0.32+t(i),-JJ-kk-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*ENDDO

! *************** IMPLANT AREA ***************
FLST,2,86,3    ! definig Area by keypoints, containing 86 keypoints
FITEM,2,206    ! Identifies items chosen by a picking operation (GUI).
FITEM,2,204
FITEM,2,301
FITEM,2,302
FITEM,2,303
FITEM,2,304
FITEM,2,305
FITEM,2,306
FITEM,2,307
FITEM,2,308
FITEM,2,309
FITEM,2,310
FITEM,2,311
FITEM,2,312
FITEM,2,313
FITEM,2,314
FITEM,2,315
FITEM,2,316
FITEM,2,317
FITEM,2,318
FITEM,2,319
FITEM,2,320
FITEM,2,321
FITEM,2,401
FITEM,2,402
FITEM,2,403
FITEM,2,404
FITEM,2,405
FITEM,2,406
FITEM,2,407
FITEM,2,408
FITEM,2,409
FITEM,2,410
FITEM,2,411
FITEM,2,412
FITEM,2,413
FITEM,2,414
FITEM,2,415
FITEM,2,416
FITEM,2,417
FITEM,2,208
FITEM,2,207
FITEM,2,617
FITEM,2,616
FITEM,2,615
FITEM,2,614
FITEM,2,613
FITEM,2,612
FITEM,2,610
FITEM,2,609
FITEM,2,608
FITEM,2,607
FITEM,2,606
FITEM,2,605
FITEM,2,604
FITEM,2,603
FITEM,2,602
FITEM,2,601
FITEM,2,201
FITEM,2,520
FITEM,2,519
FITEM,2,518
FITEM,2,517
FITEM,2,516
FITEM,2,515
FITEM,2,514
FITEM,2,513
FITEM,2,512
FITEM,2,511
FITEM,2,510
FITEM,2,509
FITEM,2,508
FITEM,2,507
FITEM,2,506
FITEM,2,505
FITEM,2,504
FITEM,2,503
FITEM,2,502
FITEM,2,501
FITEM,2,203
FITEM,2,205
FITEM,2,211
FITEM,2,213
FITEM,2,214
FITEM,2,212
A,P51X

! Defines an area by connecting keypoints.

! ****************** ABUTMENT AREA ******************
FLST,2,7,3
FITEM,2,213
FITEM,2,214
FITEM,2,212
FITEM,2,217
FITEM,2,216
FITEM,2,215
FITEM,2,211
A,P51X
3) Extra abutment area
FLST,2,4,3
FITEM,2,218
FITEM,2,219
FITEM,2,220
FITEM,2,221
A,P51X

4) Extra implant area
FLST,2,8,3
FITEM,2,206
FITEM,2,63
FITEM,2,125
FITEM,2,222
FITEM,2,223
FITEM,2,111
FITEM,2,49
FITEM,2,205
A,P51X

TRABECULAR BONE AREA
FLST,2,45,3
FITEM,2,124
FITEM,2,125
FITEM,2,126
FITEM,2,127
FITEM,2,128
FITEM,2,129
FITEM,2,130
FITEM,2,131
FITEM,2,103
FITEM,2,102
FITEM,2,101
FITEM,2,100
FITEM,2,99
FITEM,2,98
FITEM,2,97
FITEM,2,96
FITEM,2,95
FITEM,2,94
FITEM,2,93
FITEM,2,92
FITEM,2,91
FITEM,2,90
FITEM,2,89
FITEM,2,88
FITEM,2,87
FITEM,2,86
FITEM,2,85
FITEM,2,84
FITEM,2,83
FITEM,2,82
FITEM,2,81
FITEM,2,80
FITEM,2,79
FITEM,2,78
FITEM,2,77
FITEM,2,76
FITEM,2,75
FITEM,2,105
FITEM,2,106
FITEM,2,107
CORTICAL BONE AREA

FLST,2,61,3
FITEM,2,206
FITEM,2,63
FITEM,2,64
FITEM,2,65
FITEM,2,66
FITEM,2,67
FITEM,2,68
FITEM,2,69
FITEM,2,70
FITEM,2,71
FITEM,2,72
FITEM,2,73
FITEM,2,37
FITEM,2,36
FITEM,2,35
FITEM,2,34
FITEM,2,33
FITEM,2,32
FITEM,2,31
FITEM,2,30
FITEM,2,29
FITEM,2,28
FITEM,2,27
FITEM,2,26
FITEM,2,25
FITEM,2,24
FITEM,2,23
FITEM,2,22
FITEM,2,21
FITEM,2,20
FITEM,2,19
FITEM,2,18
FITEM,2,17
FITEM,2,16
FITEM,2,15
FITEM,2,14
FITEM,2,13
FITEM,2,12
FITEM,2,11
FITEM,2,10
FITEM,2,9
FITEM,2,8
FITEM,2,7
FITEM,2,6
FITEM,2,5
FITEM,2,4
FITEM,2,3
FITEM,2,2
FITEM,2,1
FITEM,2,39
FITEM,2,40
FITEM,2,41
FITEM,2,42
FITEM,2,43
FITEM,2,44
FITEM,2,45
FITEM,2,46
FITEM,2,47
FITEM,2,48
FITEM,2,49
FITEM,2,205
A,P51X

! ********************************** Substracting Areas **********************************
FLST,3,5,5,ORDE,2
FITEM,3,1
FITEM,3,-5
ASBA, 6,P51X ! Subtracts areas from areas.

! ********************************** TRABECULAR BONE KEYPOINTS *************************
k,75,-7.00000,-15.00000,,
k,76,-6.50000,-19.82500,,
k,77,-6.00000,-21.69602,,
k,78,-5.50000,-23.04166,,
k,79,-5.00000,-24.09810,,
k,80,-4.50000,-24.95782,,
k,81,-4.00000,-25.66847,,
k,82,-3.50000,-26.25833,,
k,83,-3.00000,-26.74560,,
k,84,-2.50000,-27.14265,,
k,85,-2.00000,-27.45809,,
k,86,-1.50000,-27.69802,,
k,87,-1.00000,-27.86666,,
k,88,-0.50000,-27.96679,,
k,89,0.00000,-28.00000,,
k,90,0.50000,-27.96679,,
k,91,1.00000,-27.86666,,
k,92,1.50000,-27.69802,,
k,93,2.00000,-27.45809,,
k,94,2.50000,-27.14265,,
k,95,3.00000,-26.74560,,
k,96,3.50000,-26.25833,,
k,97,4.00000,-25.66847,,
k,98,4.50000,-24.95782,,
k,99,5.00000,-24.09810,,
k,100,5.50000,-23.04166,,
k,101,6.00000,-21.69602,,
k,102,6.50000,-19.82500,,
k,103,7.00000,-15.00000,,
k,104,7.00000,-15.00000,,
k,105,6.50000,-10.17500,,
k,106,6.00000,-8.30398,,
k,107,5.50000,-6.95834,,
k,108,5.00000,-5.90190,,
k,109,4.50000,-5.04218,,
k,110,4.00000,-4.33153,,
k,111,3.50000,-3.74167,,
k,112,3.00000,-3.15000,,
k,113,2.50000,-2.63000,,
k,114,2.00000,-2.15000,,
k,115,1.50000,-1.72500,,
k,116,1.00000,-1.35000,,
k,117,0.50000,-1.02500,,
k,118,0.00000,-0.75000,,
k,119,-0.50000,-0.52500,,
k,120,-1.00000,-0.35000,,
k,121,-1.50000,-0.22500,,
k,122,-2.00000,-0.15000,,
k,123,-2.50000,-0.10000,,
k,124,-3.00000,-0.07500,,
k,125,-3.50000,-0.06250,,
k,126,-4.00000,-0.05625,,
k,127,-4.50000,-0.05000,,
k,128,-5.00000,-0.04688,,
k,129,-5.50000,-0.04375,,
k,130,-6.00000,-0.04167,,

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! *********************** Implant Keypoints **********************
K,201,-II/2,-JJ-kk,,
K,202,-II/2+II,-JJ-kk,,
K,203,-II/2,-kk,,
K,204,-II/2+II,-kk,,
K,205,-II/2+II*K*TAN(LL*3.1415/180),0,,
K,206,-II/2+II-KK*TAN(LL*3.1415/180),0,,
K,207,-II/2+MM*TAN(NN*3.1415/180),-MM-JJ-kk,,
K,208,-II/2+II-MM*TAN(NN*3.1415/180),-MM-JJ-kk,,

! *********************** Abutment Keypoints **********************
K,211,-1.25,0,,
K,212,1.25,0,,
K,213,-1.25,-kk-JJ/3,,
K,214,1.25,-kk-JJ/3,,
K,215,-1.25,5,,
K,216,0,5,,
K,217,1.25,5,,

! *********************  Layers ****************
K,218,1.5,0,,
K,219,-1.5,0,,
K,220,-1.3,-MM-JJ-kk+0.5,,
K,221,1.3,-MM-JJ-kk+0.5,,
K,222,2.44500,-10.16000,,
K,223,-2.83500,-10.16000,,

! ******** THREAD LINE 1
*DO,i,1,21
*IF,MOD(i,3),eq,0,THEN
K,300+i,-II/2+II,-kk-((JJ/21)*i)
*ENDIF
*IF,MOD(i,3),eq,1,THEN
K,300+i,-II/2+II+0.32,-kk-((JJ/21)*i)
*ENDIF
*IF,MOD(i,3),eq,2,THEN
K,300+i,-II/2+II+0.32,-kk-((JJ/21)*i)
*ENDIF
*ENDDO

! ******** THREAD LINE 2
*SET,t,0.02
*DO,i,1,18
*IF,MOD(i,3),eq,0,THEN
K,400+i,-II/2+II-((MM/COS(NN*3.1415/180))*i/18*SIN(NN*3.1415/180))-JJ-kk-
((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*IF,MOD(i,3),eq,1,THEN
K,400+i,-II/2+II+0.32-(*i),-JJ-kk-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*IF,MOD(i,3),eq,2,THEN
K,400+i,-II/2+II+0.32-(*i),-JJ-kk-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*ENDDO

! ******** THREAD LINE 3
*DO,i,1,21
*IF,MOD(i,3),eq,0,THEN
K,500+i,-II/2,-kk-((JJ/21)*i)
*ENDDO
*SET,t,0.02
*DO,i,1,18
*IF,MOD(i,3),eq,0,THEN
  K,600+i,-II/2+((MM/COS(NN*3.1415/180))*i/18*SIN(NN*3.1415/180)),JJ-kk-
  ((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*IF,MOD(i,3),eq,1,THEN
  K,600+i,-II/2-0.32+(t*i),-JJ-kk-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*IF,MOD(i,3),eq,2,THEN
  K,600+i,-II/2-0.32+(t*i),-JJ-kk-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*ENDDO

! ******************* IMPLANT AREA ******************
FLST,2,86,3
FITEM,2,206
FITEM,2,204
FITEM,2,301
FITEM,2,302
FITEM,2,303
FITEM,2,304
FITEM,2,305
FITEM,2,306
FITEM,2,307
FITEM,2,308
FITEM,2,309
FITEM,2,310
FITEM,2,311
FITEM,2,312
FITEM,2,313
FITEM,2,314
FITEM,2,315
FITEM,2,316
FITEM,2,317
FITEM,2,318
FITEM,2,319
FITEM,2,320
FITEM,2,202
FITEM,2,401
FITEM,2,402
FITEM,2,403
FITEM,2,404
FITEM,2,405
FITEM,2,406
FITEM,2,407
FITEM,2,408
FITEM,2,409
FITEM,2,410
FITEM,2,411
FITEM,2,412
FITEM,2,413
FITEM,2,414
FITEM,2,415
FITEM,2,416
FITEM,2,417
FITEM,2,208
FITEM,2,207
FITEM,2,617
FITEM,2,616
FITEM,2,615
FITEM,2,614
FITEM,2,613
FITEM,2,612
FITEM,2,611
FITEM,2,610
FITEM,2,609
FITEM,2,608
FITEM,2,607
FITEM,2,606
FITEM,2,605
FITEM,2,604
FITEM,2,603
FITEM,2,602
FITEM,2,601
FITEM,2,201
FITEM,2,520
FITEM,2,519
FITEM,2,518
FITEM,2,517
FITEM,2,516
FITEM,2,515
FITEM,2,514
FITEM,2,513
FITEM,2,512
FITEM,2,511
FITEM,2,510
FITEM,2,509
FITEM,2,508
FITEM,2,507
FITEM,2,506
FITEM,2,505
FITEM,2,504
FITEM,2,503
FITEM,2,502
FITEM,2,501
FITEM,2,203
FITEM,2,205
FITEM,2,211
FITEM,2,213
FITEM,2,214
FITEM,2,212
A,P51X

A ************* ABUTMENT AREA  ***************
FLST,2,7,3
FITEM,2,213
FITEM,2,214
FITEM,2,212
FITEM,2,217
FITEM,2,216
FITEM,2,215
FITEM,2,211
A,P51X
! ********************************** 3) Extra abutment area *************
FLST,2,4,3
FITEM,2,218
FITEM,2,219
FITEM,2,220
FITEM,2,221
A,P51X

! ********************************** 4) Extra implant area *************
FLST,2,8,3
FITEM,2,206
FITEM,2,63
FITEM,2,125
FITEM,2,222
FITEM,2,223
FITEM,2,111
FITEM,2,49
FITEM,2,205
A,P51X

! ********************************** TRABECULAR BONE AREA *************
FLST,2,45,3
FITEM,2,124
FITEM,2,125
FITEM,2,126
FITEM,2,127
FITEM,2,128
FITEM,2,129
FITEM,2,130
FITEM,2,131
FITEM,2,103
FITEM,2,102
FITEM,2,101
FITEM,2,100
FITEM,2,99
FITEM,2,98
FITEM,2,97
FITEM,2,96
FITEM,2,95
FITEM,2,94
FITEM,2,93
FITEM,2,92
FITEM,2,91
FITEM,2,90
FITEM,2,89
FITEM,2,88
FITEM,2,87
FITEM,2,86
FITEM,2,85
FITEM,2,84
FITEM,2,83
FITEM,2,82
FITEM,2,81
FITEM,2,80
FITEM,2,79
FITEM,2,78
FITEM,2,77
FITEM,2,76
FITEM,2,75
FITEM,2,105
FITEM,2,106
FITEM,2,107
! ************************ Subtracting areas *************************
FLST,3,4,5,ORDE,2
FITEM,3,1
FITEM,3,-4
ASBA, 5,P51X

! ************************** Implant Keypoints *********************
K,201,-II/2-JJ-kk,,
K,202,-II+II-JJ-kk,,
K,203,-II-kk,,
K,204,-II+II-kk,,
K,205,-II+KK*TAN(LL*3.1415/180),0,,
K,206,-II+KK*TAN(LL*3.1415/180),0,,
K,207,-II+MM*TAN(NN*3.1415/180)-MM-JJ-kk,,
K,208,-II+II-MM*TAN(NN*3.1415/180)-MM-JJ-kk,,

! ************************** Abutment Keypoints ***************
k,211,-1.25,0,,
k,212,1.25,0,,
k,213,-1.25-kk-JJ/3,,
k,214,1.25-kk-JJ/3,,
k,215,-1.25,5,,
k,216,0,5,,
k,217,1.25,5,,

! ******************* Layers *********************
k,218,1.5,0,,
k,219,-1.5,0,,
k,220,-1.3-MM-JJ-kk+0.5,,
k,221,1.3-MM-JJ-kk-0.5,,
k,222,2.44500,-10.16000,,
k,223,-2.83500,-10.16000,,

! ******** THREAD LINE 1
*DO,i,1,21
*IF,MOD(i,3),eq,0,THEN
  K,300+i,-II/2+II,-kk-((JJ/21)*i)
*ENDIF
*IF,MOD(i,3),eq,1,THEN
  K,300+i,-II/2+II+0.32,-kk-((JJ/21)*i)
*ENDIF
*IF,MOD(i,3),eq,2,THEN
  K,300+i,-II/2+II+0.32-kk-((JJ/21)*i)
*ENDIF
*ENDDO

! ******** THREAD LINE 2
*DO,i,1,18
*IF,MOD(i,3),eq,0,THEN
  K,400+i,-II/2+II-((MM/COS(NN*3.1415/180))*i/18*SIN(NN*3.1415/180))-JJ-kk-
  ((MM/COS(NN*3.1415/180)*i/18*COS(NN*3.1415/180)))
*ENDIF
*IF,MOD(i,3),eq,1,THEN
  K,400+i,-II/2+II+0.32-(t*i)-JJ-kk-((MM/COS(NN*3.1415/180)*i/18*COS(NN*3.1415/180)))
*ENDIF
*IF,MOD(i,3),eq,2,THEN
  K,400+i,-II/2+0.32-((t*i)-JJ-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*ENDDO

! ********** THREAD LINE 3
*DO,i,1,21
  *IF,MOD(i,3),eq,0,THEN
    K,500+i,-II/2,-kk-((JJ/21)*i)
  *ENDIF
  *IF,MOD(i,3),eq,1,THEN
    K,500+i,-II/2-0.32,-kk-((JJ/21)*i)
  *ENDIF
  *IF,MOD(i,3),eq,2,THEN
    K,500+i,-II/2-0.32,-kk-((JJ/21)*i)
  *ENDIF
*ENDDO

! ************** THREAD LINE 2
*SET,t,0.02
*DO,i,1,18
  *IF,MOD(i,3),eq,0,THEN
    K,600+i,-II/2+((MM/COS(NN*3.1415/180))*i/18*SIN(NN*3.1415/180)),JJ-kk-
    ((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
  *ENDIF
  *IF,MOD(i,3),eq,1,THEN
    K,600+i,-II/2-0.32+(t*i),JJ-kk-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
  *ENDIF
  *IF,MOD(i,3),eq,2,THEN
    K,600+i,-II/2-0.32+(t*i),JJ-kk-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
  *ENDIF
*ENDDO

! ******************* IMPLANT AREA ******************
FLST,2,86,3
FITEM,2,206
FITEM,2,204
FITEM,2,301
FITEM,2,302
FITEM,2,303
FITEM,2,304
FITEM,2,305
FITEM,2,306
FITEM,2,307
FITEM,2,308
FITEM,2,309
FITEM,2,310
FITEM,2,311
FITEM,2,312
FITEM,2,313
FITEM,2,314
FITEM,2,315
FITEM,2,316
FITEM,2,317
FITEM,2,318
FITEM,2,319
FITEM,2,320
FITEM,2,322
FITEM,2,401
FITEM,2,402
FITEM,2,403
! ****************** ABUTMENT AREA ******************
FLST,2,7,3
FITEM,2,213
FITEM,2,214
FITEM,2,212
FITEM,2,217
FITEM,2,216
FITEM,2,215
FITEM,2,211
A,P51X

! **************** Extra abutment area *************
FLST,2,4,3
FITEM,2,218
FITEM,2,219
FITEM,2,220
FITEM,2,221
A,P51X

! ************ Extra implant area ************
FLST,2,9,3
FITEM,2,206
FITEM,2,63
FITEM,2,125
FITEM,2,305
FITEM,2,304
FITEM,2,303
FITEM,2,302
FITEM,2,301
FITEM,2,204
A,P51X
FLST,2,74,3
FITEM,2,305
FITEM,2,125
FITEM,2,222
FITEM,2,223
FITEM,2,111
FITEM,2,505
FITEM,2,506
FITEM,2,507
FITEM,2,508
FITEM,2,509
FITEM,2,510
FITEM,2,511
FITEM,2,512
FITEM,2,513
FITEM,2,514
FITEM,2,515
FITEM,2,516
FITEM,2,517
FITEM,2,518
FITEM,2,519
FITEM,2,520
FITEM,2,201
FITEM,2,601
FITEM,2,602
FITEM,2,603
FITEM,2,604
FITEM,2,605
FITEM,2,606
FITEM,2,607
FITEM,2,608
FLST,2,9,3
FITEM,2,205
FITEM,2,203
FITEM,2,501
FITEM,2,502
FITEM,2,503
FITEM,2,504
FITEM,2,505
FITEM,2,111
FITEM,2,49
A,P51X

! ********** Subtracting Areas **************
FLST,3,2,5,ORDE,2
FITEM,3,2
FITEM,3,-3
ASBA, 1,P51X
! *********************** Abutment Keypoints ***************
k,211,-1.25,0,,
k,212,1.25,0,,
k,213,-1.25,-MM-JJ-kk+1,,
k,214,1.25,-MM-JJ-kk+1,,
k,215,-1.25,5,,
k,216,0,5,,
k,217,1.25,5,,

! *********************  Layers ****************
k,218,1.5,0,,
k,219,-1.5,0,,
k,220,-1.3,-MM-JJ-kk+0.5,,
k,221,1.3,-MM-JJ-kk+0.5,,

! ************************ 2) Abutment Area *******************
FLST,2,7,3
FITEM,2,213
FITEM,2,214
FITEM,2,212
FITEM,2,217
FITEM,2,216
FITEM,2,215
FITEM,2,211
A,P51X

! ************************ 3) Extra abutment area *************
FLST,2,4,3
FITEM,2,218
FITEM,2,219
FITEM,2,220
FITEM,2,221
A,P51X

ASBA, 2, 1

! *********************** Abutment Keypoints ***************
k,211,-1.25,0,,
k,212,1.25,0,,
k,213,-1.25,-MM-JJ-kk+1,,
k,214,1.25,-MM-JJ-kk+1,,
k,215,-1.25,5,,
k,216,0,5,,
k,217,1.25,5,,

! ************************ 2) Abutment Area *******************
FLST,2,7,3
FITEM,2,213
FITEM,2,214
FITEM,2,212
FITEM,2,217
FITEM,2,216
FITEM,2,215
FITEM,2,211
A,P51X

! **************** Glue all******************
FLST,2,8,5,ORDE,3
FITEM,2,1
FITEM,2,3
FITEM,2,-9
AGLUE,P51X ! Generates new areas by "gluing" areas.
! **************** Meshing****************

! IMP. & Abut.
TYPE,  1  ! choosing element type 1
MAT,    1  ! choosing material type 1
REAL,
ESYS,  0
SECNUM,
FLST,5,86,4,ORDE,6  ! choosing lines for Line Set option
FITEM,5,1
FITEM,5,-81
FITEM,5,92
FITEM,5,-94
FITEM,5,146
FITEM,5,-147
CM,_Y,LINE  ! groups geometry items into a component.
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,. Y  ! selects a subset of components and assemblies.
LESIZE,Y1,0.0125, , , , ,1  ! setting element edge length 0.0125
FLST,5,3,4,ORDE,3  ! choosing lines for Line Set option
FITEM,5,82
FITEM,5,-83
FITEM,5,88
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,. Y
LESIZE,Y1,0.025, , , , ,1  ! setting element edge length 0.025 and so on......
FLST,5,3,5,ORDE,3
FITEM,5,95
FITEM,5,-103
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,. Y
LESIZE,Y1,0.025, , , , ,1
FLST,5,4,4,ORDE,2
FITEM,5,84
FITEM,5,-87
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,. Y
LESIZE,Y1,0.05, , , , ,1  ! For elements that support multiple shapes, specifies the element shape to
MSHAPE,0,2D  ! be used for !meshing.
MSHKEY,0  ! Specifies whether free meshing or mapped meshing should be used to
mesh a model.
FLST,5,3,5,ORDE,3
FITEM,5,1
FITEM,5,3
FITEM,5,9
CM,_Y,AREA
ASEL, , , ,P51X
CM,_Y1,AREA
CHKMSH,'AREA'  ! Checks area and volume entities for previous meshes
CMSEL,S,. Y  ! Selects a subset of components and assemblies
AMESH,. Y1  ! Generating mesh within areas
CMDELE,. Y
CMDELE,. Y1
CMDELE,. Y2
! Cortical bone
TYPE,  2
MAT,    2
REAL,
ESYS,  0
SECNUM,
FLST,5,2,3,ORDE,2
FITEM,5,4
FITEM,5,8
CM,  Y,AREA
ASEL, , , ,P51X
CM, Y1,AREA
CHKMSH,'AREA'
CMSEL,S,Y
AMESH,Y1
CMDELETE,Y
CMDELETE,Y1
CMDELETE,Y2
TYPE,  2
MAT,    2
REAL,
ESYS,  0
SECNUM,
FLST,5,80,4,ORDE,4
FITEM,5,109
FITEM,5,-140
FITEM,5,153
FITEM,5,-200
CM, Y,LINE
LSEL, , , ,P51X
CM, Y1,LINE
CMSELECT,Y
LESIZE,Y1,0.4, , , ,1
FLST,5,20,4,ORDE,8
FITEM,5,104
FITEM,5,-108
FITEM,5,141
FITEM,5,-145
FITEM,5,148
FITEM,5,-152
FITEM,5,201
FITEM,5,-205
CM, Y,LINE
LSEL, , , ,P51X
CM, Y1,LINE
CMSELECT,Y
LESIZE,Y1,0.1, , , ,1
CM, Y,AREA
ASEL, , , , 7
CM, Y1,AREA
CHKMSH,'AREA'
CMSEL,S,Y
AMESH,Y1
CMDELETE,Y
CMDELETE,Y1
CMDELETE,Y2
! Trabecular bone
TYPE,  3
MAT,    3
REAL,
ESYS,  0
SECNUM,
! ******************** Loads ********************
FLST,2,27,3,ORDE,2
FITEM,2,6
FITEM,2,-32
/GO
DK,P51X,,0,ALL,, , , , , ,                           ! Defines DOF constraints at keypoints. (constraints all dof.)
FLST,2,1,3,ORDE,1
FITEM,2,216
/GO
FK,P51X,FY,-110.9                                      ! Defines force loads at keypoints. (applies -110.9 in y-direction)
FLST,2,1,3,ORDE,1
FITEM,2,216
/GO
FK,P51X,FX,21.56
FLST,2,1,3,ORDE,1
FITEM,2,217
/GO
FK,P51X,FY,-36
FLST,2,1,3,ORDE,1
FITEM,2,215
/GO
FK,P51X,FY,36

! ******************** GPP  ***************
*SET,t,0.05
/POST1
PATH,sa,82,30,10,                                       ! Defines a path name and establishes parameters for the path.
PPATH,1,0,-II/2+II-KK*TAN(LL*3.1415/180)+d,0,,0,         ! Defines a path by picking or defining nodes, or locations on the
currently active !working plane, or by entering specific coordinate
locations.
*DO,i,1,21
*IF,MOD(i,3),eq,0,THEN
  PPATH,i+2,0,-II/2+II+d,-kk-((JJ/21)*i),0,0,              ! Defines path
*ENDIF
*IF,MOD(i,3),eq,1,THEN
  PPATH,i+2,0,-II/2+II+0.32+d,-kk-((JJ/21)*i),0,0,        ! Defines path
*ENDIF
*IF,MOD(i,3),eq,2,THEN
  PPATH,i+2,0,-II/2+II+0.32+d,-kk-((JJ/21)*i),0,0,        ! Defines path
*ENDIF
*ENDDO
*SET,t,0.02
*DO,i,1,17

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*IF,MOD(i,3),eq,0,THEN
  PPATH,i+23,0,-II/2+(MM/COS(NN*3.1415/180))*i/18*SIN(NN*3.1415/180),d,-JJ-kk-
  ((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*IF,MOD(i,3),eq,1,THEN
  PPATH,i+23,0,-II/2+II+(t*i)+d,-JJ-kk-(MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*IF,MOD(i,3),eq,2,THEN
  PPATH,i+23,0,-II/2+II+(t*i)+d,-JJ-kk-(MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*ENDDO

PPATH,41,0,-II/2+II-MM*TAN(NN*3.1415/180)+d,-MM-JJ-kk-d,,0,
PPATH,42,0,-II/2+MM*TAN(NN*3.1415/180)-d,-MM-JJ-kk-d,,0,

*DO,i,17,1,-1
*IF,MOD(i,3),eq,0,THEN
  PPATH,60-i,0,-II/2+(MM/COS(NN*3.1415/180))*i/18*SIN(NN*3.1415/180)-d,-JJ-kk-
  ((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*IF,MOD(i,3),eq,1,THEN
  PPATH,60-i,0,-II/2-0.32+(t*i)-d,-JJ-kk-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*IF,MOD(i,3),eq,2,THEN
  PPATH,60-i,0,-II/2-0.32+(t*i)-d,-JJ-kk-((MM/COS(NN*3.1415/180))*i/18*COS(NN*3.1415/180))
*ENDIF
*ENDDO

*DO,i,21,1,-1
*IF,MOD(i,3),eq,0,THEN
  PPATH,81-i,0,-II/2-d,-kk-((JJ/21)*i)
*ENDIF
*IF,MOD(i,3),eq,1,THEN
  PPATH,81-i,0,-II/2-0.32-d,-kk-((JJ/21)*i)
*ENDIF
*IF,MOD(i,3),eq,2,THEN
  PPATH,81-i,0,-II/2-0.32-d,-kk-((JJ/21)*i)
*ENDIF
*ENDDO

AVPRIN,0,,
PDEF,,S,EQV,NOAV
AVPRIN,0,,
PDEF,,S,X,NOAV
AVPRIN,0,,
PDEF,,S,Y,NOAV
AVPRIN,0,,
PDEF,,S,XY,NOAV

*SET,Q,LL*3.1415/180
*SET,n1,COS(Q)
*SET,n2,SIN(Q)
*SET,m1,-SIN(Q)
*SET,m2,n1

! Line 1
*SET,Q,ATAN(6.72/JJ)
*SET,np1,COS(Q)
*SET,np2,SIN(Q)
*SET,mp1,-SIN(Q)
*SET,mp2,np1
*SET,np3,COS(Q)
*SET,np4,-SIN(Q)
*SET,mp3,SIN(Q)
*SET,mp4,np3
! Line
*SET,Q,ATAN(18*0.32-t/MM)
*SET,np5,COS(Q)
*SET,np6,SIN(Q)
*SET,mp5,-SIN(Q)
*SET,mp6,np5
*SET,Q,3.1415/2-(ATAN(MM/(18*(MM/6)*TAN(NN*3.1415/180)+0.32-t)))
*SET,np7,COS(Q)
*SET,np8,-SIN(Q)
*SET,mp7,SIN(Q)
*SET,mp8,np7

! Line4
*SET,Q,3.1415-ATAN((18*0.32-(t))/MM)
*SET,np9,COS(Q)
*SET,np10,SIN(Q)
*SET,mp9,-SIN(Q)
*SET,mp10,np9
*SET,Q,3.1415-3.1415/2-(ATAN(MM/(18*(MM/6)*TAN(NN*3.1415/180)+0.32-t)))
*SET,np11,COS(Q)
*SET,np12,SIN(Q)
*SET,mp11,-SIN(Q)
*SET,mp12,np11

! Line 3
*SET,Q,3.1415-ATAN(6.72/JJ)
*SET,np13,COS(Q)
*SET,np14,SIN(Q)
*SET,mp13,-SIN(Q)
*SET,mp14,np13
*SET,Q,3.1415-LL*3.1415/180
*SET,a17,COS(Q)
*SET,a18,SIN(Q)
*SET,m17,-SIN(Q)
*SET,m18,a17
*CFOPEN,C:\Documents and Settings\S.Faegh\Desktop\Ellipse SCREW,Plane strain\ScrewT2\screwT2,Fine
closemesh\Path\S(%A%)\,txt
*DO,PP,1,811
*GET,SS,PATH,0,ITEM,S,PATHPT,PP   ! Retrieves a value (here: location of node on the path) and stores it
*VWRITE,SS                      ! Writes data to a file in a formatted sequence.
%G
*ENDDO
*CFCLOSE                        ! Closes the "command" file.
*CFOPEN,C:\Documents and Settings\S.Faegh\Desktop\Ellipse SCREW,Plane strain\ScrewT2\screwT2,Fine
closemesh\Path\VONMISES(%A%)\,txt
*DO,PP,1,811
*GET,SS,PATH,0,ITEM,SEQV,PATHTPT,PP
*VWRITE,SS
%G
*ENDDO
*CFCLOSE
*DO,PP,1,811
*GET,SX(PP,1),PATH,0,ITEM,SX,PATHTPT,PP
*GET,SY(PP,1),PATH,0,ITEM,SY,PATHTPT,PP
*GET,SXY(PP,1),PATH,0,ITEM,SXY,PATHTPT,PP
*ENDDO
*CFOPEN,'C:\Documents and Settings\S.Faegh\Desktop\Ellipse SCREW,Plane strain\ScrewT2\screwT2,Fine mesh\Path\SX(%A%)',txt
*VWRITE,SX(1,1)
%G
*CFCLOSE
*CFOPEN,'C:\Documents and Settings\S.Faegh\Desktop\Ellipse SCREW,Plane strain\ScrewT2\screwT2,Fine mesh\Path\SY(%A%)',txt
*VWRITE,SY(1,1)
%G
*CFCLOSE
*CFOPEN,'C:\Documents and Settings\S.Faegh\Desktop\Ellipse SCREW,Plane strain\ScrewT2\screwT2,Fine mesh\Path\SXY(%A%)',txt
*VWRITE,SXY(1,1)
%G
*CFCLOSE
*DO,PP,1,10
*SET,S11(PP,1),n1*n1*SX(PP,1)+2*n1*n2*SXY(PP,1)+n2*n2*SY(PP,1)
*SET,S22(PP,1),m1*m1*SX(PP,1)+2*m1*m2*SXY(PP,1)+m2*m2*SY(PP,1)
*SET,S12(PP,1),m1*ml*SX(PP,1)+(n2*m1+n1*m2)*SXY(PP,1)+n2*m2*SY(PP,1)
*ENDDO
! Line 1
*DO,PP,12,220
*IF,MOD(NINT((PP-5)/10),3),eq,1,THEN
  *SET,S11(PP,1),np1*np1*SX(PP,1)+2*np1*np2*SXY(PP,1)+np2*np2*SY(PP,1)
  *SET,S22(PP,1),mp1*mp1*SX(PP,1)+2*mp1*mp2*SXY(PP,1)+mp2*mp2*SY(PP,1)
  *SET,S12(PP,1),np1*np1*SX(PP,1)+(np2*np1+np1*np2)*SXY(PP,1)+np2*np2*SY(PP,1)
*ENDIF
*IF,MOD(NINT((PP-5)/10),3),eq,2,THEN
  *SET,S11(PP,1),SX(PP,1)
  *SET,S22(PP,1),SY(PP,1)
  *SET,S12(PP,1),SXY(PP,1)
*ENDIF
*IF,MOD(NINT((PP-5)/10),3),eq,0,THEN
  *SET,S11(PP,1),np3*np3*SX(PP,1)+2*np3*np4*SXY(PP,1)+np4*np4*SY(PP,1)
  *SET,S22(PP,1),mp3*mp3*SX(PP,1)+2*mp3*mp4*SXY(PP,1)+mp4*mp4*SY(PP,1)
  *SET,S12(PP,1),np3*np3*SX(PP,1)+(np4*mp3+np3*mp4)*SXY(PP,1)+np4*np4*SY(PP,1)
*ENDIF
*ENDDO
! Line 2
*DO,PP,222,400
*IF,MOD(NINT((PP-5)/10),3),eq,1,THEN
  *SET,S11(PP,1),np5*np5*SX(PP,1)+2*np5*np6*SXY(PP,1)+np6*np6*SY(PP,1)
  *SET,S22(PP,1),mp5*mp5*SX(PP,1)+2*mp5*mp6*SXY(PP,1)+mp6*mp6*SY(PP,1)
  *SET,S12(PP,1),np5*mp5*SX(PP,1)+(np6*mp5+np5*mp6)*SXY(PP,1)+np6*np6*SY(PP,1)
*ENDIF
*IF,MOD(NINT((PP-5)/10),3),eq,2,THEN
  *SET,S11(PP,1),SXY(PP,1)
  *SET,S22(PP,1),SY(PP,1)
  *SET,S12(PP,1),SXY(PP,1)
*ENDIF
*IF,MOD(NINT((PP-5)/10),3),eq,0,THEN
  *SET,S11(PP,1),np7*np7*SX(PP,1)+2*np7*np8*SXY(PP,1)+np8*np8*SY(PP,1)
  *SET,S22(PP,1),mp7*mp7*SX(PP,1)+2*mp7*mp8*SXY(PP,1)+mp8*mp8*SY(PP,1)
  *SET,S12(PP,1),np7*np7*SX(PP,1)+(np8*mp7+np7*mp8)*SXY(PP,1)+np8*np8*SY(PP,1)
*ENDIF
*ENDDO
*DO,PP,402,410
*SET,S11(PP,1),SY(PP,1)
*SET,S22(PP,1),SX(PP,1)
*SET,S12(PP,1),-SXY(PP,1)
*ENDDO

! Line 4
*DO,PP,412,590
  *IF,MOD(NINT((PP-5)/10),3),eq,1,THEN
    *SET,S11(PP,1),np9*np9*SX(PP,1)+2*np9*np10*SXY(PP,1)+np10*np10*SY(PP,1)
    *SET,S22(PP,1),mp9*mp9*SX(PP,1)+2*mp9*mp10*SXY(PP,1)+mp10*mp10*SY(PP,1)
    *SET,S12(PP,1),np9*mp9*SX(PP,1)+(np10*np9+np9*np10)*SXY(PP,1)+np10*mp10*SY(PP,1)
  *ENDIF
  *IF,MOD(NINT((PP-5)/10),3),eq,0,THEN
    *SET,S11(PP,1),SX(PP,1)
    *SET,S22(PP,1),SY(PP,1)
    *SET,S12(PP,1),-SXY(PP,1)
  *ENDIF
  *IF,MOD(NINT((PP-5)/10),3),eq,2,THEN
    *SET,S11(PP,1),np11*np11*SX(PP,1)+(np12*np11+np11*np12)*SXY(PP,1)+np12*np12*SY(PP,1)
    *SET,S22(PP,1),mp11*mp11*SX(PP,1)+(mp12*mp11+mp11*mp12)*SXY(PP,1)+mp12*mp12*SY(PP,1)
    *SET,S12(PP,1),np11*mp11*SX(PP,1)+(np12*mp11+np11*mp12)*SXY(PP,1)+np12*mp12*SY(PP,1)
  *ENDIF
*ENDDO

! Line 3
*DO,PP,592,800
  *IF,MOD(NINT((PP-5)/10),3),eq,1,THEN
    *SET,S11(PP,1),np13*np13*SX(PP,1)+2*np13*np14*SXY(PP,1)+np14*np14*SY(PP,1)
    *SET,S22(PP,1),mp13*mp13*SX(PP,1)+2*mp13*mp14*SXY(PP,1)+mp14*mp14*SY(PP,1)
    *SET,S12(PP,1),np13*mp13*SX(PP,1)+(np14*mp13+np13*mp14)*SXY(PP,1)+np14*mp14*SY(PP,1)
  *ENDIF
  *IF,MOD(NINT((PP-5)/10),3),eq,0,THEN
    *SET,S11(PP,1),SX(PP,1)
    *SET,S22(PP,1),SY(PP,1)
    *SET,S12(PP,1),-SXY(PP,1)
  *ENDIF
  *IF,MOD(NINT((PP-5)/10),3),eq,2,THEN
    *SET,S11(PP,1),np15*np15*SX(PP,1)+2*np15*np16*SXY(PP,1)+np16*np16*SY(PP,1)
    *SET,S22(PP,1),mp15*mp15*SX(PP,1)+2*mp15*mp16*SXY(PP,1)+mp16*mp16*SY(PP,1)
    *SET,S12(PP,1),np15*mp15*SX(PP,1)+(np16*mp15+np15*mp16)*SXY(PP,1)+np16*mp16*SY(PP,1)
  *ENDIF
*ENDDO

*DO,PP,802,811
  *SET,S11(PP,1),n17*n17*SX(PP,1)+2*n17*n18*SXY(PP,1)+n18*n18*SY(PP,1)
  *SET,S22(PP,1),m17*m17*SX(PP,1)+2*m17*m18*SXY(PP,1)+m18*m18*SY(PP,1)
  *SET,S12(PP,1),n17*m17*SX(PP,1)+(n18*m17+n17*m18)*SXY(PP,1)+n18*m18*SY(PP,1)
*ENDDO

*CFOpen,'C:\Documents and Settings\S.Faegh\Desktop\Ellipse SCREW,Plane strain\ScrewT2\screwT2,Fine mesh\Path\S11(%A%)',txt
*VWRITE,S11(1,1)
%G
*CFCLOSE

*CFOpen,'C:\Documents and Settings\S.Faegh\Desktop\Ellipse SCREW,Plane strain\ScrewT2\screwT2,Fine mesh\Path\S22(%A%)',txt
*VWRITE,S22(1,1)
%G
*CFCLOSE
*CFOPEN,'C:\Documents and Settings\S.Faegh\Desktop\Ellipse SCREW,Plane strain\ScrewT2\screwT2,Fine mesh\Path\S12(\%A\%),txt
*VWRITE,S12(1,1)
%G
*CFCLOSE

*ENDDO
*ENDDO
*ENDDO
*ENDDO
*ENDDO
*ENDDO
*ENDDO
APPENDIX-III-MATLAB Procedure to Digitize the Bone

In order to digitize a CT data in MATLAB the following steps should be taken:

I) The CT data should be saved as a graphics file and be read into MATLAB by the command: 
   \[ A = \text{imread}(\text{filename}, \text{fmt}) \]

II) The graphics file will be displayed in MATLAB using the command:
    \[ \text{image}(A) \]

III) Then the command “ginput” should be used which enables to select points from the figure using the mouse for cursor positioning and returns the \( x \) and \( y \) coordinates of the selected points into a matrix.

IV) The scales should be adjusted in order to model the real dimensions.