

Finite element analysis of functionally graded bone plate at femur bone fracture site

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Abstract. This paper focuses on the analysis of fractured Femur bone with functionally graded bone plate. The Femur bone is modeled by using the data from the CT (Computerized Tomography) scan and the material properties are assigned using Mimics software. The fracture fixation plate used here is composed of Functionally Graded Material (FGM). The functionally graded bone plate is considered to be composed of different layers of homogeneous materials. Finite element method approach is adopted for analysis. The volume fraction of the material is calculated by considering its variation along the thickness direction (z) according to a power law and the effective properties of the homogeneous layers are estimated. The model developed is validated by comparing numerical results available in the literature. Static analysis has been performed for the bone plate system by considering both axial compressive load and torsional load. The investigation shows that by introducing FG bone plate instead of titanium, the stress at the fracture site increases by 63 percentage and the deformation decreases by 15 percentage, especially when torsional load is taken into consideration. The present model yields better results in comparison with the commercially available bone plates.

1. Introduction

Femur fracture may be classified into transverse fracture, oblique fracture, and comminuted fracture. In order to promote the healing of the fractured bone different fracture fixation techniques has been used. The most common type of treatments used are intramedullary canalizing (IM), external fixation device and internal fixation device (plates and screws) based on the geometry and location of fracture. Researchers developed various methods and techniques for the fitment of the bone fracture. For example Lenz et al. [1] investigated the comparison between trochanteric hook plate and subtrochanteral bicortical locking plate fixation technique for periprosthetic femur fractures. The experimental results indicated that in comparison with hook plate fixation, Subtrochanterically placed LAP produced better fixation strength under cyclic loading. Papers are available concerning the comparison between different bone plate material in order to improve the strength of the bone plate and betterment of the stress shielding. Das et al. [2] carried out FE analysis of femur fracture fixation plates considering titanium and other metallic biomaterials, and drew conclusion that stress at the fracture site significantly increases when the former is used as bone plate material compared with the later. Mehboob et al. [3] made a comparative investigation between composite flexible bone plates and conventional high modulus metallic plates. They depicted superior performance of fiber reinforced composite flexible bone plates. Kim et al. [4] applied finite element analysis to know the possible use



of composite bone plates for the healing of fracture tibia subjected to different contact conditions and time dependent material properties of calluses. Mehboob et al. [5] performed an extensive literature survey on design and optimization of orthopedic composite prostheses for effective bone healing. Miramini et al. [6] presented how the geometry of both oblique and transverse fracture affecting bone healing under plate fixation environment.

Study of FG material for the bone plate fixation has been carried out by different researchers. H. Fouad [7] adopted finite element method to function-graded (FG) fracture fixation bone plates which was subjected to both compressive and torsional loading at different healing stage with tibia bone. The results revealed that the torsional load has notable effects on the resultant stress of the fracture fixation bone-plate system. Apart from this, it is found that stress shielding at the fracture site significantly decreases when FG bone plates used in place of other alloys. Enab [8] employed two dimensional finite element approach to investigate the biomechanical behavior of knee implant subject to different loading conditions.

Generally bone plates are made up of stainless steel, titanium alloys and cobalt chromium molybdenum etc. For the bones in growth, Titanium as bone plate is the most suitable material. But recently with the use of coating material like Hydroxyapatite (HA), the growth rate of the bone has been improved. Due to its bioactivity, it encourages the bones to grow and restore the effect. But the major drawback includes wear and tear and the sharp change of material properties at the interface between the two adjacent layers that causes large inter-laminar shear stresses. Such detrimental effect can be mitigated by grading the properties of both Titanium and Hydroxyapatite in a continuous manner across the thickness direction which is incorporated in the present investigation.

2. Finite Element Modeling

The morphology of femur bone is asymmetric and curved in three planes; hence it is difficult to generate a 3-D model. In order to model the femur bone, Computer Tomography (CT) scan data are imported into the MIMICS software (Materialise Interactive Medical Image Control System) in DICOM format (Digital Imaging and Communications in Medicine). 0.5 mm slice thickness is chosen for better geometrical accuracy. The 3D model of femur bone is imported into the Solid works CAD software and intramedullary canal is created by using a cut function. The bone plate and screws are modeled and the bone plate system is assembled. Commercially available ANSYS software is used for the analysis. The *solid 186* layered structural solid element is used for discretization of the model. This Solid 186, a higher order 3D, 20-noded solid element that exhibits quadratic displacement type behavior and each node is having three degrees of freedom. The total number of nodes and elements for the bone plate system are found to be 63,749 and 30,040 respectively. Grid independence test has been conducted for the optimum mesh and further change in mesh has no considerable effect on the results. Tetrahedral mesh has been employed for the model and the quality of the mesh is checked by the orthogonal quality of the elements and their skewness.

2.1 Material Properties and Boundary conditions

In the present study, the material properties are shown in Table 1. Cortical bone is considered for the analysis. Titanium and FG material are used for the bone plate. Titanium is also used for the screw material. The material properties for the entire bone plate system are assumed to be linearly elastic and isotropic in nature.

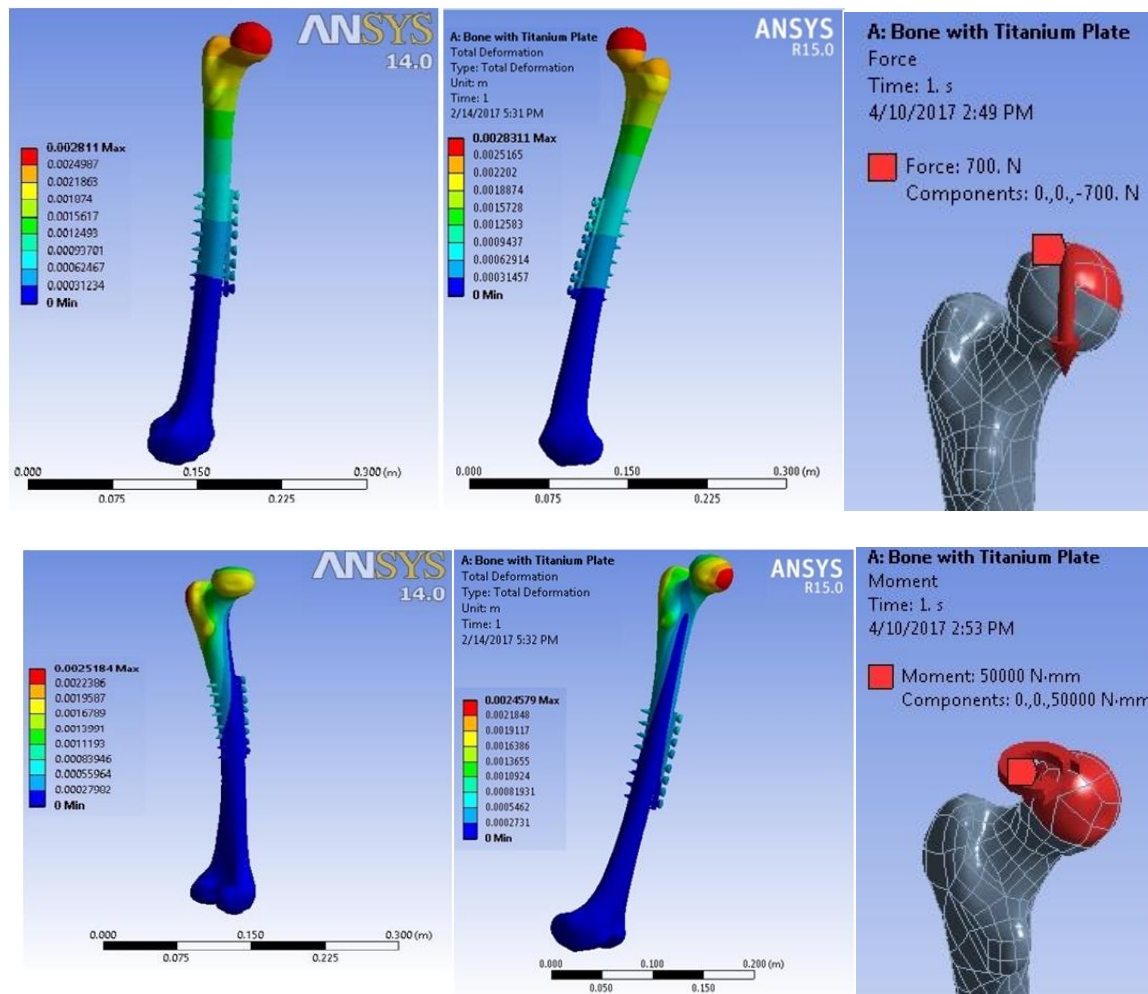
Both compressive load of 700 N and torsional load of 50 N.m are applied at the femoral head. The loading condition is based on the assumption of the weight of 70 kg person. A fixed boundary condition is assigned at the lower surface (lateral condyle, medial condyle and patellar surface) of the femur bone. Bonded contact is considered at the bone to bone interface. As the contact stress are generated at the interface between the bone plate and bone surface, frictional contact elements are used with a frictional coefficient of ($\mu=0.2$) [2].

Table 1. Material Properties represented in the FE model [2, 3].

Materials	Young's modulus (GPa)	Poisson's ratio	Density (kg/m ³)
Cortical Bone	16.7	0.3	1750
Titanium	120	0.3	4500
FG Material	40		3161
▪ Hydroxyapatite (Ha)	120	0.3	4500
▪ Titanium			

2.2 Validation of Model

First the model, analyzed in the ANSYS environment is validated using the results available in literature. For this, static structural analysis is adopted and maximum deflections and stresses are obtained by considering a compressive load of 700 N and torsional load of 50 N.m applied at the femoral head. Under compressive loading the present model shows maximum deflection as 0.0028311m whereas under torsional loading the maximum deflection is 0.024579m. These values are very close to the corresponding deflections in model available in [2]. This comparison is explained in figure 1 which indicate that the results obtained in both the cases are almost indistinguishable thus validating the present method of modeling in the ANSYS environment. The minor variation in the result is due to the inhomogeneous structure of the bone and the mesh quality.

**Figure 1.** Validation of bone plate system.

2.3 Development of Functionally Graded Bone Plate

First, the effective elastic properties of the FG bone plate are evaluated using the following methodology. For evaluating the effective elastic properties of the FG bone plate, homogeneous material properties of the Titanium and Hydroxyapatite are considered. The material properties for the Titanium and Hydroxyapatite are described in Table 1. The variation of material properties is obtained according to a power law as explained in Eq. 1 [9]. The material properties (Young's modulus) vary continuously across the thickness direction of the bone plate.

$$E_L = (E_{Ti} - E_{Ha}) \times \left(\frac{z/h + \frac{1}{2}}{\frac{1}{2}} \right)^k + E_{Ha} \quad (1)$$

E_L = Young's modulus of the layer

E_{Ti} = Young's modulus of Titanium

E_{Ha} = Young's modulus of Hydroxyapatite

k = Power law exponent

The variation of material properties along the thickness direction is continuous and for different values of power-law exponent ($k=0.2$ to 3) are plotted and shown in figure 2.

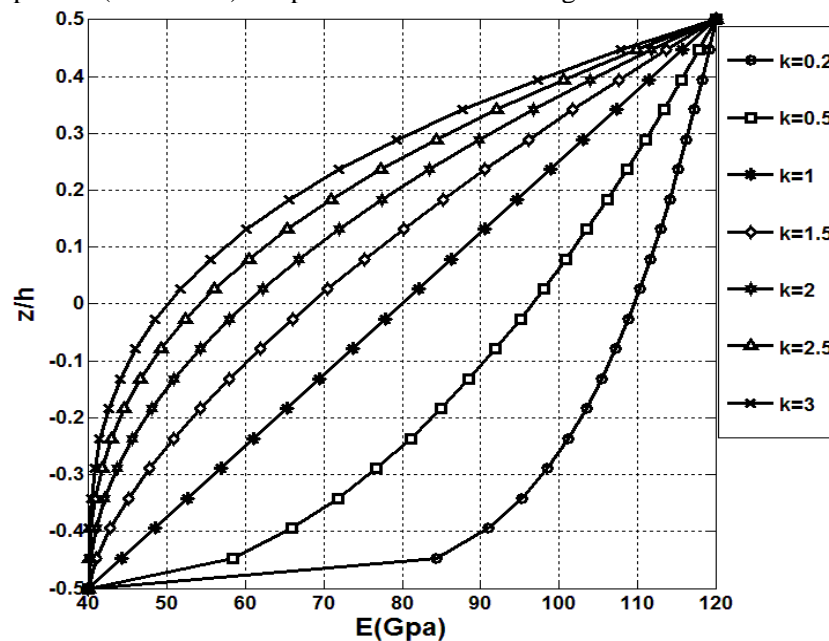


Figure 2. Variation of Elastic modulus through the thickness of bone plate.

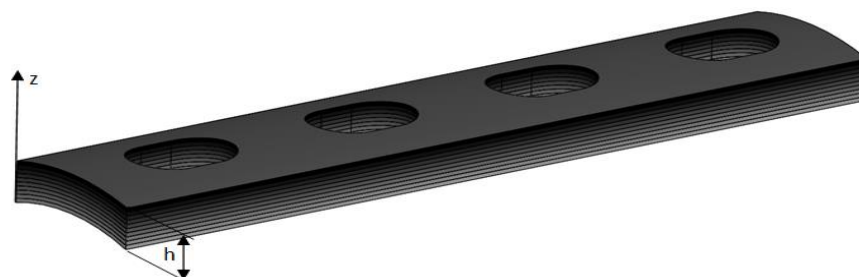


Figure 3. Geometrical 3-D model of FG bone plate.

The FG bone plate considered here is modeled in commercially available Solid works software. Ten layers are considered for the model to obtain the material properties. Ideally, the layered structure does not illustrate the gradual change in material properties. But practically, when the number of layers is sufficiently high, it can reasonably approximate the material gradation with minor negligible error. Isotropic materials properties are considered for these layers. Figure 3 explains the 3-D model of FG bone plate in the Solid works platform for the present analysis.

3. Results and Discussion

In this present investigation results are presented for the bone plate system considering static compressive and torsional loading conditions. The deformation and stress of bone-plate is shown in figure 4.

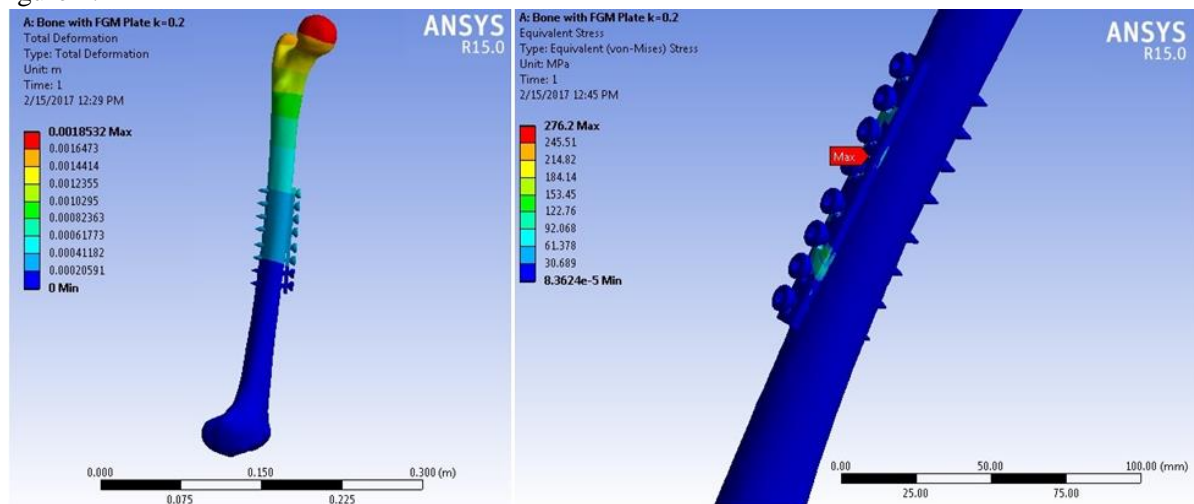


Figure 4. Deformation and stress of FG bone plate system.

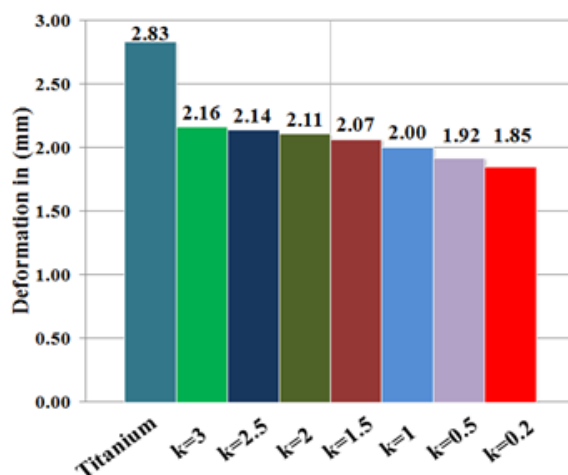


Figure 5(a). Deformation at compressive load.

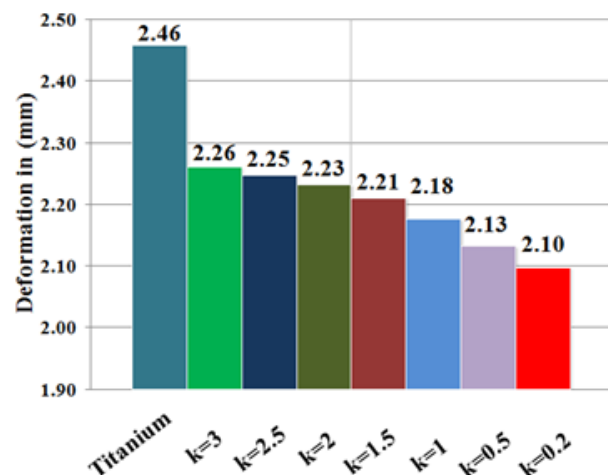


Figure 5(b). Deformation at torsional load.

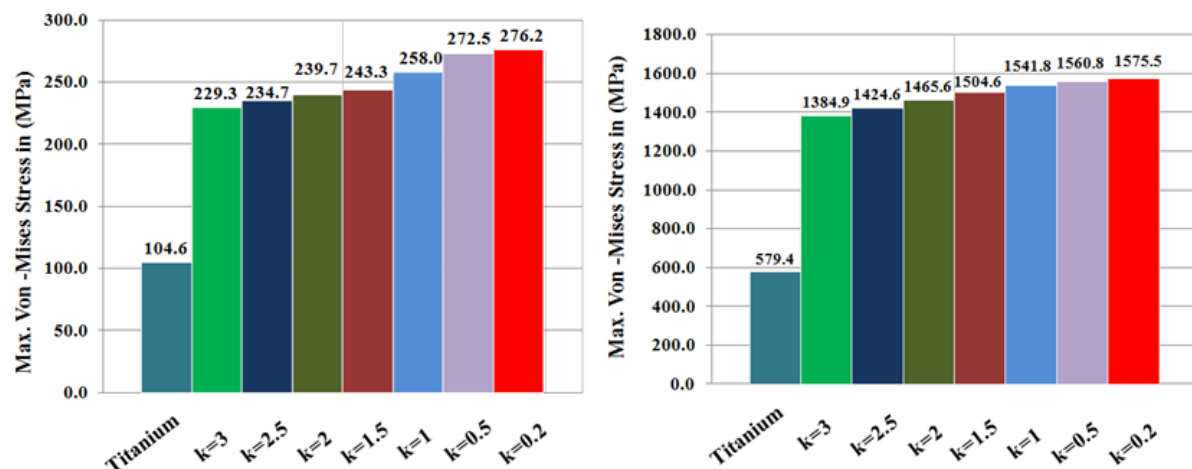


Figure 6(a). Von-Mises stress at compressive load. **Figure 6(b).** Von-Mises stress at torsional load.

The variation of maximum deformation of the bone plate system with a compressive load of 700 N and torsional load of 50 N.m is plotted in figure 5. It is observed that the deformation of the bone plate system decreases significantly while using FG material as bone plate. Again the least deformation is obtained when the power law exponent ($k=0.2$) is used as FG material. One important aspect of the present study is to investigate the stress distribution at the fracture site. The applied load for deformation of the bone plate system are considered to calculate the maximum Von-Mises stresses across the fracture site and the effect of bone plate material on the Von-Mises stresses are explained in figure 6. It may be observed that the Von-Mises stresses increases when using FG bone plate, in comparison with titanium bone plate and again it is maximum at $k=0.2$. Additionally, it could be established here that the stress at fracture site increases when torsional loading condition is taken into consideration.

4. Conclusion

The present investigation is devoted to the Finite element study of the horizontal fractured femur bone along with the bone plate system. Analysis has been carried out on the modeling of a functionally graded (FG) bone plate and compared with that commercially available titanium plate. Results (total deformation, Von-Mises stress) are presented by considering static loading condition for the bone plate system. Analysis reveals that, for FG bone plate the stress at the fracture site increases by 63 percentage and the deformation decreases by 15 percentage, especially when torsional load is considered. Hence it may be concluded that, by introduction of the FG bone plate the strength and stabilization of the bone plate system increases and stress shielding decreases at the fracture site. Consequently, callus zone promotes better bone healing environment.

References

- [1] Lenz M, Stoffel K, Kielstein H, Mayo K, Hofmann G O and Gueorguiev B 2016 Plate fixation in periprosthetic femur fractures vancouver type B1-trochanteric hook plate or subtrochanteral bicortical locking *Injury Int. J. Care Injured* **47** 2800–2804
- [2] Das S and Sarangi S K 2014 Finite element analysis of femur fracture fixation plates *Int. J. of Basic and Appl. Biology* ISSN: 2349-5839 Volume **1** No. 1
- [3] Mehboob H and Chang S H 2014 Application of composites to orthopedic prostheses for effective bone healing: A review *Composite Structures* **118** 328–341
- [4] Kim S H, Chang S H and Jung H J 2010 The finite element analysis of a fractured tibia applied by composite bone plates considering contact conditions and time-varying properties of curing tissues *Composite Structures* **92** 2109–2118

- [5] Mehboob H, Kim J, Mehboob A and Chang S H 2017 How post-operative rehabilitation exercises influence the healing process of radial bone shaft fractures fixed by a composite bone plate *Composite Structures* **159** 307–315
- [6] Miramini S, Zhang L, Richardson M, Mendis P and Ebeling P R 2016 Influence of fracture geometry on bone healing under locking plate fixations: A comparison between oblique and transverse tibial fractures *Medical Eng. and Physics* **38** 1100–1108
- [7] Fouad H 2011 Assessment of function-graded materials as fracture fixation bone-plates under combined loading conditions using finite element modelling *Medical Eng. & Physics* **33** 456–463
- [8] Enab T A 2012 A comparative study of the performance of metallic and FGM tibia tray components in total knee replacement joints *Computational Mat. Sci.* **53** 94–100
- [9] Tripathy A, Panda R K, Das S and Sarangi S K Static analysis of smart functionally graded beams *Spvryan's Int. Journal of Eng. Sciences & Technology (SEST)* ISSN : 2394- 0905 Issue 4 Volume 2