Numerical study for new metallic and composite bone-plates model: Improving the fixation technique performance

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Abstract

Fracture-fixation by plates is proposed to hold the fractured bone and provide healing by formation of callus texture. In this work, a numerical study of new developed bone-plates with a gap value in terms of stress distribution is evaluated. 3-D finite element models for a fractured tibia with metallic (stainless steel and titanium alloy) and composite (carbon hydroxyapatite and carbon epoxy) bone-plates are analyzed using ANSYS workbench. Plates with a gap 0.7 mm and a contact plate with no gap are examined. von Mises stresses along the fractured site, along the tibia bone and on the bone-plate are also studied under the same loading and boundary conditions. The results of stresses have been compared and presented in graphs. Bone-plates model with a gap value 0.7 mm provide higher compressive stress along the fractured site and along the bone. This bone-plates model also decrease the transformed stresses to the bone-plate. Composite bone-plates materials achieve better results than metallic bone-plates materials. Along the fractured site, using composite (carbon hydroxyapatite, carbon epoxy) bone-plates materials with 0.7 mm gap increasing the stresses by average 48% at the first healing stage, 12% at the second healing stage, 10% at the final stage compared to the contact bone-plate of the same material. Along the bone, the average increasing in stress at the final healing stage is 17% for carbon hydroxyapatite and 18% for carbon epoxy bone-plates materials with 0.7 mm gap compared to the contact one of the same material. The average increasing in stress along the fractured site at the final healing stage is 18% for carbon.

Keywords: Carbon Hydroxyapatite, Carbon Epoxy, Metallic bone-plate, Tibia fracture; Stress shielding

1. Introduction

A fracture of tibia shaft is one of the most common fractured in a human. A diaphyseal fracture of the tibia is treated in many cases with a bone-plate and screws technique. Successful fracture fixation using this technique is dependent on many factors such as the health of the patient, and the fixation methods employed.

In general, traditional bone-plates are made of relative high-stiffness materials such as Stainless Steel (SS) and Titanium (Ti). So, they transfer almost of the load from the fractured bone to the rigid plate. This cause the stress shielding phenomena. Wolff's law "USE IT OR LOSS IT" is the law that controlled the living tissues. So, the bone density affects by the applied stress to it. In the case of reducing the applied stress to the bone, the density of the bone decreases (increases stress shielding), osteoporosis and screws lag occurs after the healing. Another problem that face this fixation technique is that blood supply become insufficient for the fractured bone under the bone-plate due to the direct contact pressure between the bone and rigid bone-plate. This contact leads to necrosis of the bone under the plate as a long-term effect. Using ANSYS finite element analysis software in this study as an attempt to reduce the stress shielding and permit sufficient blood supply to occur. Several parameters are studied also and include changes in bone-plate materials and design.

Pravat Kumar Satapathy et al. investigated a studying of FEA to the fractured bone using bone-plate fixation method. They investigated the using of FG bone-plate material instead of the commercially available Ti bone-plates. Loading conditions used in this paper are compressive and torsional loads. The stresses found finally are increased when using FG bone-plate material. **A. Zargar Kharazi** et al. tried to overcome the stress shielding by replacing the metallic plates by composite bone-plates with suitable mechanical properties. They examined new composite bone-plate material using 3D-finite element in micro and macro mechanical stages. **VK Ganesh** et al. tried to overcome the stress shielding phenomena by using stiffness-graded bone-plates. The stiffness of used materials were graded in two directions, the longitudinal and transverse directions. **Yubo Fan** et al. tried to reduce stress shielding and overcome the less of blood flow under bone-plate problem by inserting a soft bio-degradable material between the bone-plate and corresponding surface of the fractured bone. They investigated a series of in vitro and performed FEA to evaluate the performance of the new internal fixation system.

2. Materials and method

In this paper, 3D four bone-plates models and its screws were drawn using CATIA VSR18 software, as shown in figure 1. The cortical (outer bone) is modeled as a cylinder with an outer diameter 25 mm and 300 mm length, and the trabecular (inner bone) as a circular rod with 10 mm diameter and has the same length of the cortical. A fractured gap of 1 mm thickness divided the bone in two symmetrical parts. This gap is filled with callus which has a varied properties in each healing stages.
The dimension of bone-plate is taken as 103 mm length, 15 mm width, a curved cross-section with 13.7 mm radius, and six screw holes. The bone-plate thickness is 3.8 mm. Gap between the tibia bone and the bone-plate (X) is taken as 0.7 mm. However, there is no gap (equal zero) in case of contact bone-plate model.

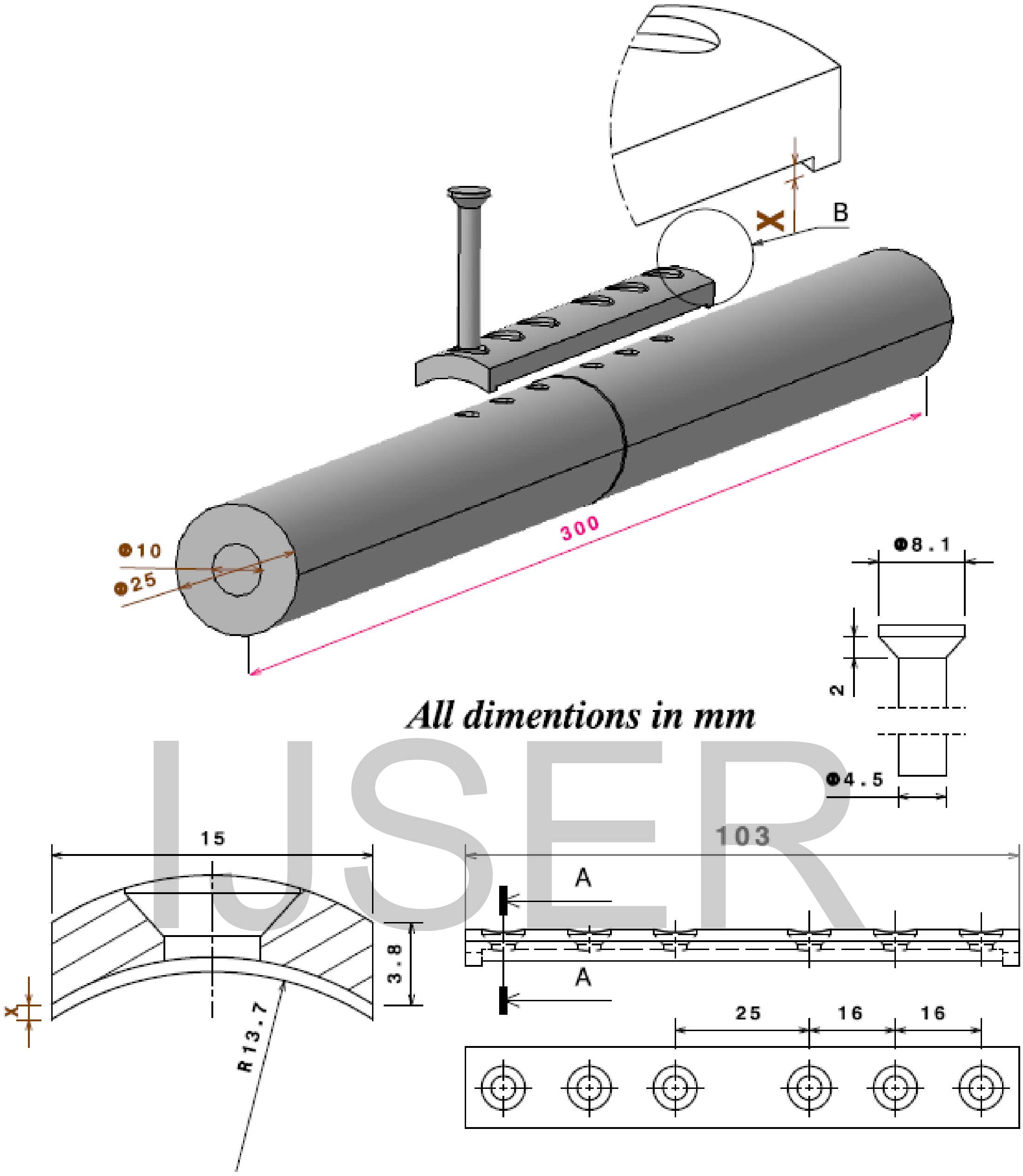


Fig. 1. Geometry details of the assembly parts (simplified fractured tibia, bone-plate and screws).

2.1. Material properties

Material properties were defined for each part in the assembly bone, callus, bone-plate and screws as shown in table 1. In this study, four metallic and composite bone-plates are modeled. SS and Ti are considered as metallic bone-plate materials. Carbon/epoxy (WSN3K) and Carbon Hydroxyapatite (C/HA) are considered as composite bone-plate materials.

C/HA and WSN3K bone-plate materials and the cortical bone are considered as anisotropic materials. SS and Ti bone-plate materials, the trabecular bone, screws are considered as isotropic materials. The material of callus is assumed to be homogenous and isotropic with different modulus of elasticity according to the healing stage. The selected material for screws is SS.

Table 1. Material properties of bone-plates, bones, and calluses.

	Young's modulus (GPa)	Poisson's ratio
Stainless steel (SS)	193	0.31
Titanium (Ti)	110	0.3
Carbon Hydroxyapatite (C/HA) 20% C and 80% HA	E_X=47.9 E_Y=78 E_Z=47.9	ν_{xy}=0.27 ν_{yz}=0.27 ν_{xz}=0.27
Carbon/epoxy (WSN3K)	E_X=70 E_Y=70 E_Z=10	ν_{xy}=0.13 ν_{yz}=0.09 ν_{xz}=0.09
Cortical bone	E_X=7 E_Y=18.4 E_Z=8.5	ν_{xy}=0.099 ν_{yz}=0.065 ν_{xz}=0.141
Trabecular bone	1.0161	0.225
Fractured bone (1%healing)	0.02	0.3
Fractured bone (50%healing)	10	0.3
Fractured bone (75%healing)	15	0.3

2.2. *Condition for analysis*

The modeling, loading condition and solution for the fractured tibia, screws and bone-plates are constructed by ANSYS Workbench 14.5. After importing the geometry models from CATIA software, the mesh is generated to the assembly. A 3D 10-node tetrahedral structural solid (Solid 187) and 3D 8-node surface-to-surface contact (CONTA 174) are selected for modelling the bone-plate, screws and bone segments. The total numbers of nodes used in the model is 108337 and number of elements is 65884. The average skewness is 0.232 which indicates that the mesh has an excellent quality. The contact interfaces between screws surfaces and surrounding surfaces of cortical, trabecular and plate are represented in Finite Element Analysis (FEA) as frictional contact with friction coefficient 0.4 [26], as shown in figure 2. The static structure analysis carried out in two steps.

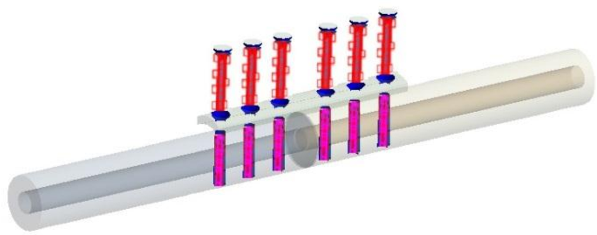


Fig. 2. Contact surfaces between: (screws) & (cortical, trabecular and plate)

The first one is the screw fastening process for a fractured bone and bone-plate using six screws, as shown in figure 3. Screw tightening force (2000 N) is applied to each screw.

The second step is the loading and fixation process. One of the fractured tibia end is fixed and the other end is loaded by axial compression force. The weight of the patient is taken as 80 Kg and the pressure due to this weight is calculated.

Ten percent of the body weight is applied at the initial healing stage (1% healing). This stage is one week after surgery, the patient moves under no load condition in the fractured leg, only the muscle forces are transmitted to this leg. Three weeks later (50% healing) the transmitted loads increased to one hundred percent of body weight. At the final stage of healing (75% healing, six week later), two hundred percent of body weight is imposed on the end of the tibia.

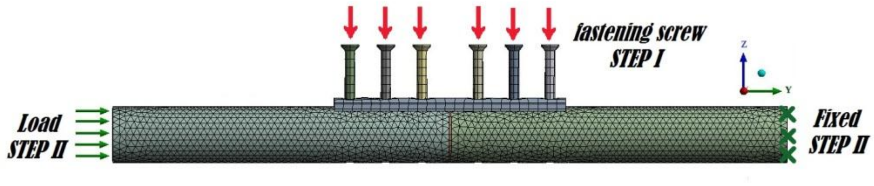


Fig. 3. Mesh generation of the assembly, analysis steps, loads and boundary condition

3. Result and discussion

Maximum von Mises compressive stress is studied along the path ***(a-b)*** along the fractured site, as shown in figure 4. It is preferred to study this path because it is located in the most dangerous surface in the callus.

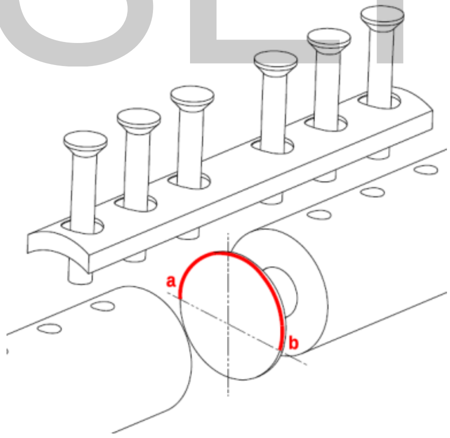


Fig. 4. Stress values along the fractured site (path a-b) are determined by selecting the nodes attached to this path

For all materials at each healing stage, it is found that although the values of stresses were different in each case, but the paths have the same trend such as shown in figure 5.

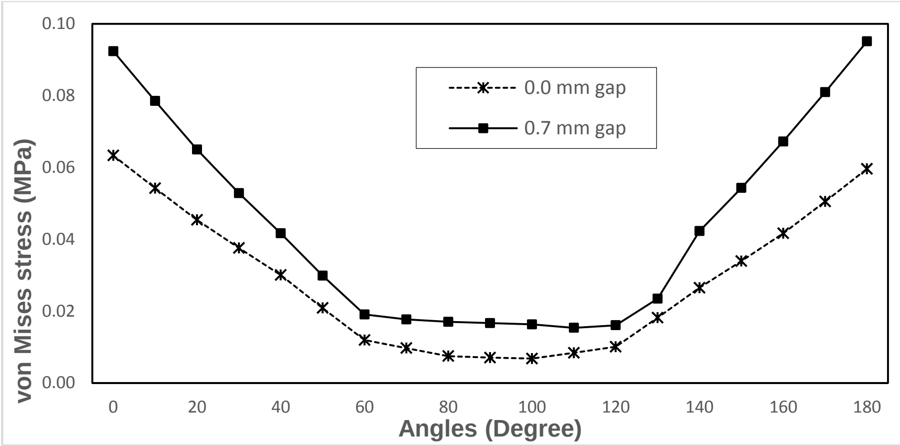


Fig. 5. von Mises compressive stress distributions through nodes from point a to b along the fractured site at 1% healing using SS bone-plates material

So, in each path the average of maximum von Mises compressive stress at each node are calculated and presented in graphs.

Initially (First healing stage), there is no hard tissues through the fractured gap. So, the stresses at the fractured site is relatively low and stress shielding is at maximum level. Bone-plates with 0.7 mm gap provides more compressive stresses along the fractured site compared to the contact bone-plate model, as shown in figure 6.

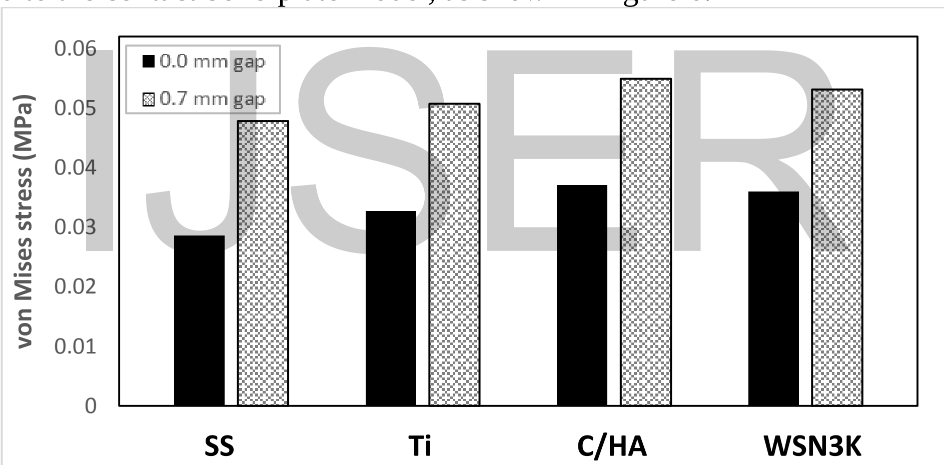


Fig. 6. Average of max. von Mises compressive stress distributions through nodes along the fractured site at 1% healing using SS, Ti, C/HA and WSN3K bone-plate materials

The average increasing in maximum von Mises stresses when using SS, Ti, C/HA and WSN3K bone-plates materials with 0.7 mm gap are 67% for SS bone-plate, 55% for Ti bone-plate and 48% for C/HA and WSN3K bone-plates compared to the contact bone-plates of the same materials in the first healing stage.

After three weeks of inserting the bone-plate (50% healing), curing tissues turned to soft callus and began to fill the fractured gap. More loads can be carried. So, stress at fractured site increase when compared to the first stage, as shown in figure 7.

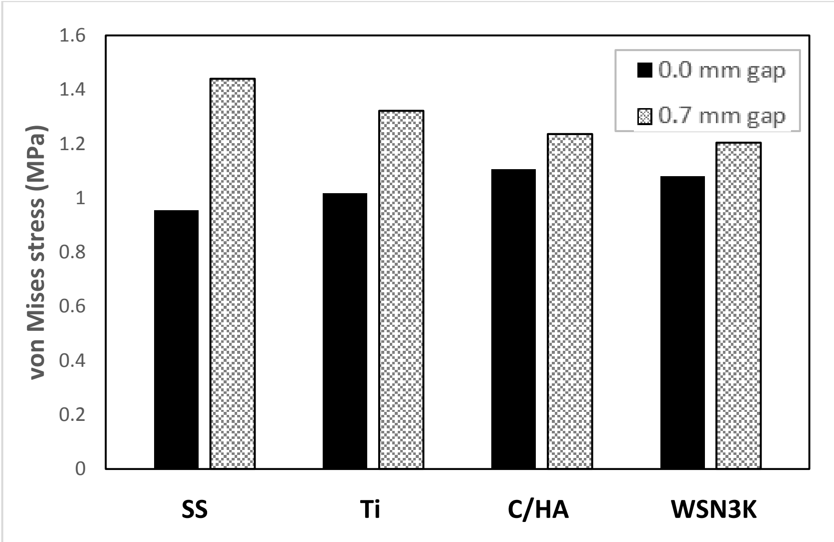


Fig. 7. Average of max. von Mises compressive stress distributions through nodes along the fractured site at 50% healing using SS, Ti, C/HA and WSN3K bone-plate materials

The average increasing in maximum von Mises stresses when using SS, Ti, C/HA and WSN3K bone-plates materials with 0.7 mm gap are 51% for SS bone-plate, 30% for Ti bone-plate and 12% for C/HA and WSN3K bone-plates compared to the contact bone-plates of the same materials in the second healing stage.

After six weeks of inserting the bone-plate (75% healing), more callus are generated and the callus became hard enough to resist more external forces. Such as the previous two steps, bone-plates with 0.7 mm gap provides more compressive stresses along the fractured site compared to the contact bone-plate, as shown in figure 8.

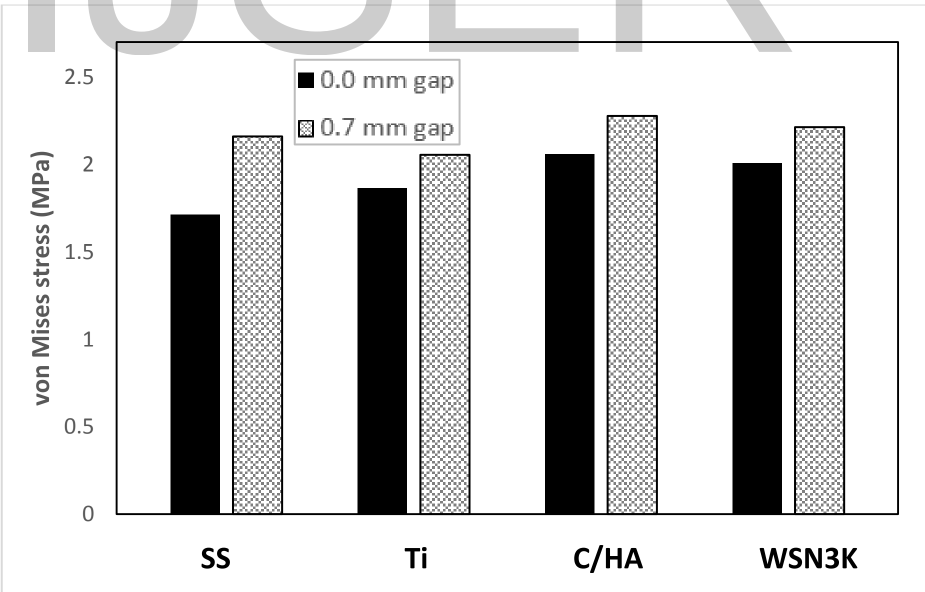
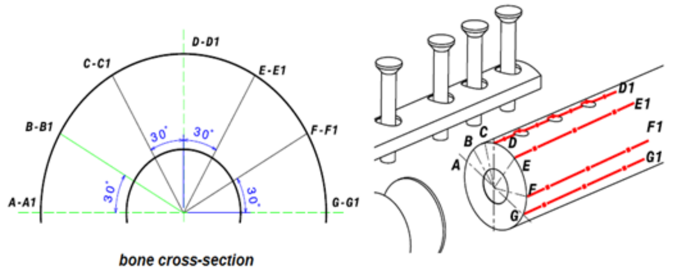


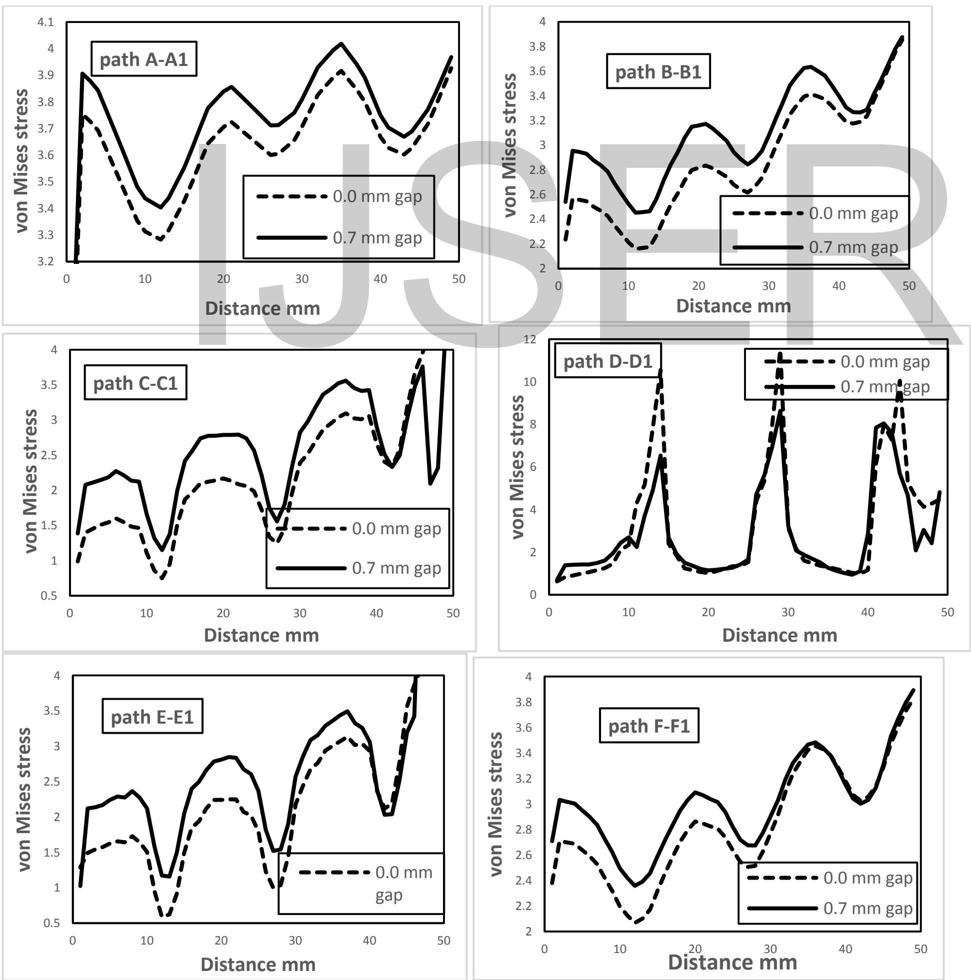
Fig. 8. Average of max. von Mises compressive stress distributions through nodes along the fractured site at 75% healing using SS, Ti, C/HA and WSN3K bone-plate materials

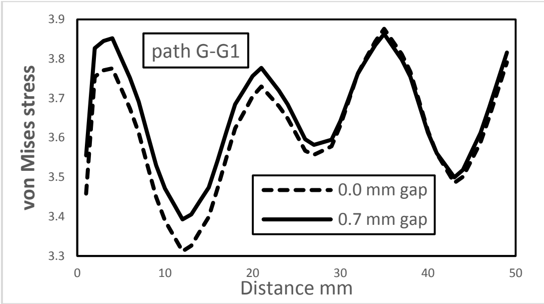
The average increasing in maximum von Mises stresses when using SS, Ti, C/HA and WSN3K bone-plates materials with 0.7 mm gap are 26% for SS bone-plate and 10% for Ti, C/HA and WSN3K bone-plates compared to the contact bone-plates of the same materials in the final healing stage. The composite bone-plates achieves more stresses along the fractured site compared to the metallic bone-plates.

The stress along the bone increases with time due to fracture healing because of increasing the loads through each healing stage. Maximum von Mises compressive stresses in the bone are studied in details along different paths, volume and surfaces of the cortical bone. It is found that, although the values of stresses were different in each case study, the ratio derived from the comparison of the stresses in each case is almost the same. Figure 9 presents a set of studied paths along the cortical and von Mises stresses along this paths using Ti bone-plates with 0.7 mm gaps and contact bone-plates at the final healing stage.



(i)





(ii)

Fig. 9. Stress values along the bone are determined by selecting the nodes attached to determined paths **i)** paths *A-A1, B-B1, C-C1, D-D1, E-E1, F-F1* and *G-G1* **ii)** stress distributions through these paths at 75% healing using Ti bone-plates material

So, the clearest path, the path which containing the least overlap, is selected to use in all following comparisons. Path ***E-E1*** is very clear and near to the upper path which affected by the smallest compressive stresses on the bone. This path will selected to present stresses in the bone.

The stresses in the bone in the first and second healing stages are not important such as the final healing stage. Because this two stages is just transition stages, but the final one is the permanent with the patient after healing the fracture. So, stresses of the final healing stage (75%) will be presented only. Such as done along the fractured site, the average of maximum von Mises stresses at each node are calculated and presented in figure 10.

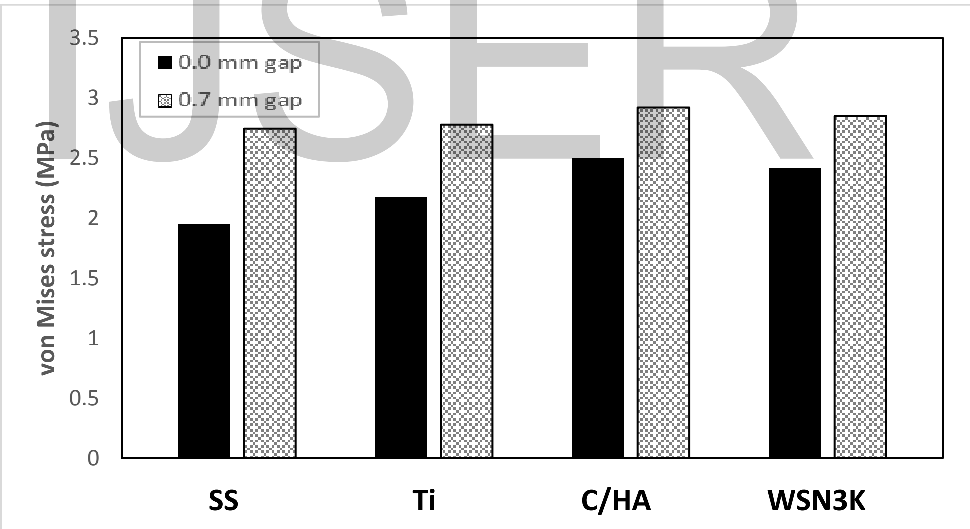


Fig. 10. Average of max. von Mises compressive stress distributions through nodes along the cortical bone at 75% healing using SS, Ti, C/HA and WSN3K bone-plate materials

The average increasing in maximum von Mises stresses along the bone when using SS, Ti, C/HA and WSN3K bone-plates materials with 0.7 mm gap are 41% for SS, 28% for Ti, 17% for C/HA and 18% for WSN3K bone-plates materials compared to the contact bone-plates of the same materials in the final healing stage. The composite bone-plates achieves more stresses along the bone compared to the metallic bone-plates.

The patient weight transformed into internal stresses on the bone, bone-plate and other parts in the assembly. It is required to increase the transformed ratio of stress in the bone. That occurs when reducing the transformed stresses in the other parts. So, the stresses on the bone-plate are also studied. So, figure 11 compares the maximum von Mises stresses on the no gap and 0.7 mm gap bone-plates models at 75% healing stage.

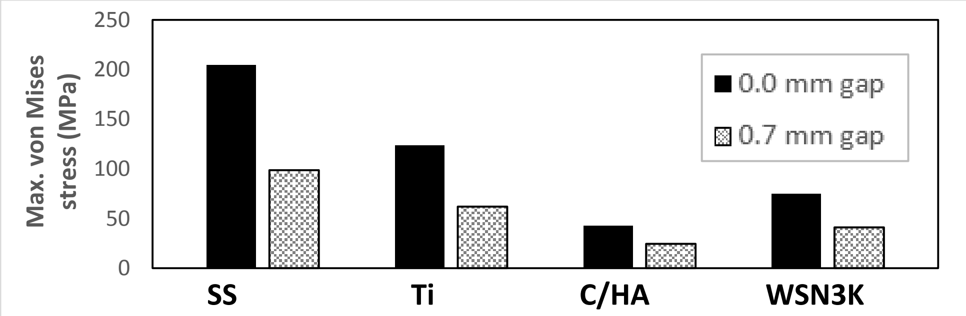


Fig. 11. maximum von Mises stress in the no gap and 0.7mm gap bone-plate models at 75% healing using SS, Ti, C/HA and WSN3K bone-plates materials

The decreasing of maximum von Mises stresses on the bone-plates when using SS, Ti, C/HA and WSN3K bone-plates materials with 0.7 mm gap are 52% for SS, 50% for Ti, 42% for C/HA and 45% for WSN3K bone-plates materials compared to the contact bone-plates of the same materials.

4. Conclusion

Based on the finite element results, it can be summarize that the bone-plates model with 0.7 mm gap for metallic and composite bone-plate materials reduced the stress shielding along the fractured site and the bone for all healing stages. The bone-plate that made of composite material achieve more stresses than the metallic one. So Along the fractured site, using composite (carbon hydroxyapatite, carbon epoxy) bone-plates materials with 0.7 mm gap increasing the stresses by average 48% at the first healing stage, 12% at the second healing stage, 10% at the final stage compared to the contact bone-plate of the same material.

Along the bone, the average increasing in stress at the final healing stage is 17% for carbon hydroxyapatite and 18% for carbon epoxy bone-plates materials with 0.7 mm gap compared to the contact one of the same material.

Therefore, using composite bone-plate model with 0.7 mm gap will accelerate the healing and offered less stress shielding to the bone.