



## ■ BIOMECHANICS

# Screw head plugs increase the fatigue strength of stainless steel, but not of titanium, locking plates

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### Objectives

Screw plugs have been reported to increase the fatigue strength of stainless steel locking plates. The objective of this study was to examine and compare this effect between stainless steel and titanium locking plates.

### Methods

Custom-designed locking plates with identical structures were fabricated from stainless steel and a titanium alloy. Three types of plates were compared: type I unplugged plates; type II plugged plates with a 4 Nm torque; and type III plugged plates with a 12 Nm torque. The stiffness, yield strength, and fatigue strength of the plates were investigated through a four-point bending test. Failure analyses were performed subsequently.

### Results

For stainless steel, type II and type III plates had significantly higher fatigue strength than type I plates. For titanium, there were no significant differences between the fatigue strengths of the three types of plates. Failure analyses showed local plastic deformations at the threads of screw plugs in type II and type III stainless steel plates but not in titanium plates.

### Conclusion

The screw plugs could increase the fatigue strength of stainless steel plates but not of titanium plates. Therefore, leaving screw holes open around fracture sites is recommended in titanium plates.

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### Article focus

- This study evaluated the effect of screw plugs on the fatigue strength of stainless steel and titanium locking plates through a cyclic loading test, failure analysis, and finite element analyses.
- The mechanical performance of plugged locking plates was hypothesized to be affected by fabrication materials.

### Key messages

- Screw plugs could increase the fatigue strength of stainless steel plates but not of titanium plates.
- A novel local deformation theory was proposed to explain the effect.
- Screw holes around fracture sites in titanium plates should be left empty.

### Strengths and limitations

- This is the first biomechanical study to investigate the plugging effect on titanium plates.
- Torsional loading was not considered.

### Introduction

Locking plates can provide high fixation stability for fracture healing and good functional recovery in fracture treatment,<sup>1-3</sup> particularly when they are applied using minimally invasive surgical techniques.<sup>4</sup> The advantage of using locking plates is firm screw locking, which can prevent loosening of screws, loss of fracture reduction, and disturbance of bone circulation.<sup>5-10</sup> However, plate failure may still occur, particularly in highly unstable fractures. Fatigue breakage is

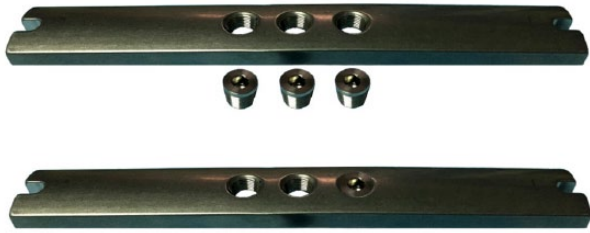


Fig. 1

Structures of the tested plates and plugs.

the most common failure mode, which mostly occurs through the screw holes around a fracture site that are frequently left open because of a fracture gap or comminution.<sup>6,7,9-12</sup> It has been reported that the insertion of screw head plugs, which are threaded screw heads without shafts, into open screw holes, could significantly increase the fatigue strength of stainless steel locking plates.<sup>13-17</sup> However, in two studies, no increase in strength was found after plugging.<sup>18,19</sup> In addition, the effect of the insertion torque of plugs on the fatigue strength is still a matter of debate.<sup>13,14</sup> The increase in the fatigue strength has been attributed to the decrease in stress concentration or the local deformation caused by the over-tightening of plugs.<sup>14,17</sup> However, these theories have not been established conclusively. More importantly, to the best of our knowledge, there have been no investigations into the plugging effects in titanium locking plates, which have been used more and more in recent years. The plugging effects in titanium plates may differ substantially from those in stainless steel plates because of the difference in their mechanical properties, particularly notch sensitivity.<sup>20,21</sup>

In the present study, locking plates similar to those used in femoral fractures were manufactured from stainless steel and titanium with identical geometries and dimensions. In addition, the corresponding screw head plugs were manufactured and inserted into screw holes with different torques. Biomechanical tests and finite element analyses (FEAs) were performed to compare the mechanical performance of the plates. We hypothesized that the screw plugs could effectively increase the mechanical strength of the plates and the increase would be greater as insertion torque increased. Additionally, the differences between the stainless steel and titanium plates and the mechanisms of the increase in strength were investigated.

## Materials and Methods

**Structures of plate and plug.** The locking plates were specially manufactured from stainless steel (AISI 316L, F138) and a titanium alloy (Ti6Al4V, F136-13) (both Carpenter Technology Corp., Reading, Pennsylvania). The screw plugs were manufactured from the same materials as the locking plate into which they were inserted (Fig. 1). Yield

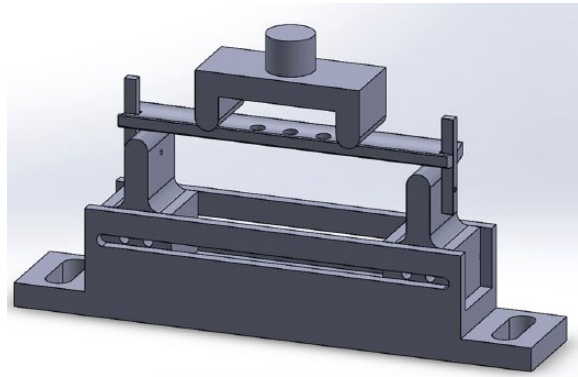


Fig. 2

Setup for biomechanical tests.

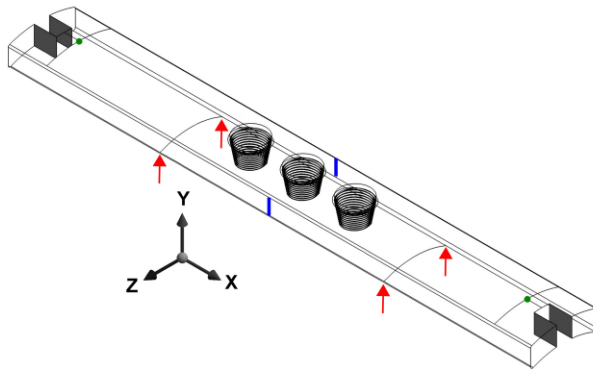
strength and percentage of elongation over two inches were 583 MPa and 59% for stainless steel, and 1005 MPa and 19% for titanium. The screw hole position, thread geometry, dimension, and thickness of the plates were modelled on the plate shaft part of a commercially available femoral plate (Periarticular Distal Femoral Locking Plate; Zimmer Biomet, Warsaw, Indiana). The length, width, and thickness of each plate were 140 mm, 18 mm, and 5.05 mm, respectively, with three locking holes at the centre and a distance of 14 mm between each hole. The outer diameter of the screw holes and the screw plugs was 8 mm. The height was 5.05 mm. The thread dimensions were 0.36 mm for the thread depth, 0.05 mm for the thread radii, 60° for the thread angles, and 0.5 mm for the pitch. The following three types of plates with or without plugs and with different insertion torques were tested: type I unplugged plates; type II plugged plates with an insertion torque of 4 Nm; and type III plugged plates with an insertion torque of 12 Nm.

**Biomechanical test and failure analysis.** Only the plate was tested to eliminate the potential variations caused by surrogate bones and to simulate worst-case scenarios with large bone defects. To evaluate the mechanical performance of the locking plates, four-point bending tests complying with ASTM F382-14 standards were performed using a servo-hydraulic material testing machine (model 8872; Instron Industrial Products Group, Grove City, Pennsylvania) (Fig. 2).<sup>22</sup> Initially, stiffness and yield strength were measured through single loading tests, and then fatigue strength was measured through cyclic loading tests. Both ends of the plates were supported by two metal rollers with spans of 120 mm, and loading was applied to the concave surface at the centre of the plates using two metal rollers with a span of 60 mm. During the loading, plate movement was prevented by the bars inserted in the slots at both ends of the plates. Yield tests were performed on six samples of each plate type using a ramp-up load in the displacement control mode at a rate of 1 mm/min. The tests were terminated when displacement reached 6 mm and the plates were

**Table I.** Results of mechanical tests and finite element analyses

Plate type	Bending stiffness (N/mm)	Yield strength (N)	Fatigue life 2100 N ( $10^3$ cycles)	von Mises stress side hole (MPa)	von Mises stress central hole (MPa)
<b>Stainless steel</b>					
I	1402 (1388 to 1419)	1720 (1700 to 1870)	273.0 (230.3 to 360.4)	1037.2	957.5
II	1415 (1396 to 1429)	1786 (1698 to 1881)	495.7 (393.8 to 771.2)*	1056.6	957.5
III	1422 (1401 to 1436)	1802 (1746 to 1893)	518.1 (306.2 to 836.8)*	1056.6	957.5
<b>Titanium</b>					
I	1234 (1203 to 1265)	5590 (5550 to 5625)	130.5 (94.1 to 288.4)	1037.2	957.5
II	1249 (1247 to 1251)	5570 (5553 to 5580)	120.9 (83.1 to 205.9)	1056.6	957.5
III	1255 (1250 to 1259)	5547 (5525 to 5565)	111.3 (88.3 to 132.6)	1056.6	957.5

\*The fatigue lives of types II and III stainless steel plates were significantly longer than that of type I plates

**Fig. 3**

Loading and boundary conditions of finite element model. The blue lines, green points, and grey planes indicate the constraints in the Y, X, and Z directions, respectively. The red arrows indicate loading.

permanently deformed. Subsequently, using the same testing constructs, dynamic cyclic fatigue tests were carried out with a sinusoidal load between 210 N and 2100 N at a frequency of 10 Hz on six new samples, and data were captured at a frequency of 100 Hz. The maximum load (2100 N) was 120% of the yield strength of the stainless steel plates obtained in the yield tests. This ensured the failure of all the plates and fatigue lives could be compared fairly. The tests were terminated when the plates cracked and the displacement of the actuator reached 6 mm.

Failure analyses including fractographic, metallographic, and micro-Vickers hardness examinations were performed on the broken plates. Fracture surfaces were examined using a scanning electron microscope (SEM, 10x to 4000x, model JCM-5000; JEOL Ltd, Tokyo, Japan). The fracture surfaces were then polished and corroded for metallographic examinations using an optical microscope (100x). Micro-Vickers hardness tests were performed using a load of 100 g on metal surfaces.<sup>23</sup> Ten values of hardness were obtained randomly in the threaded and unthreaded parts of the same plate for both types of materials. The averages were obtained and compared.

**Finite element analyses.** Analyses were performed using the static structural mode of Ansys commercial software (Workbench 15.0; Ansys, Inc., Canonsburg, Pennsylvania). Three-dimensional plate models with the same structures as those used in the biomechanical tests were produced

using CAD software (SolidWorks 2014; SolidWorks Corp., Concord, Massachusetts). The models were then saved as a Parasolid file and imported into the Ansys Workbench programme for analysis. The Young's moduli for stainless steel and titanium were 200 GPa and 114 GPa, respectively, and Poisson's ratio was 0.3 for both materials. The plates were free meshed with tetrahedral elements, with an overall element size of 3 mm. The boundary and loading conditions were the same as those in the biomechanical tests. Point loads of 525 N (2100 N in total) were applied to the four points at the plate centres, and free rigid body motion of the plate was prevented in order to facilitate computations (Fig. 3). Face-to-face contact conditions were defined between the plugs and screw holes with a friction coefficient of 0.3. The mesh was refined in peak stress areas by increasing mesh density, and numerical convergence was confirmed when the difference in sequential analysis results was less than 5%. After processing in the linear elastic model, von Mises stresses were recorded and correlated with the mechanical test results.

**Statistical analysis.** As part of the biomechanical tests, two-way analysis of variance (ANOVA) tests (SPSS v22.0; SPSS Inc., Chicago, Illinois) were performed to compare the fatigue strength of the three plate types manufactured from the two different materials. One-way ANOVA tests were performed in order to compare the stiffness and yield strength of the two metals, and the Vickers hardness of the threaded and unthreaded regions in each type of plate. Least significant difference tests were used for *post hoc* pairwise comparison. The significance level was defined as  $p < 0.05$ .

## Results

**Biomechanical test and failure analysis.** The results of the mechanical tests and FEAs are listed in Table I. In the yield tests, all plates exhibited the maximum deformation at the central hole. There was no significant difference between the mean bending stiffness and yield strength of the plugged and unplugged plates for stainless steel and titanium (plugged plates vs unplugged plates, bending stiffness:  $p = 0.41$  for stainless steel, and  $p = 0.38$  for titanium; yield strength:  $p = 0.36$  for stainless steel, and  $p = 0.27$  for titanium). In the fatigue tests, two-way ANOVA revealed significant interactions between the

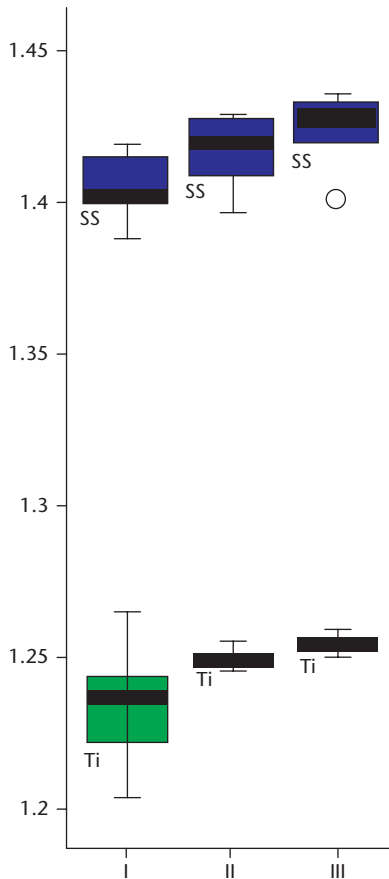


Fig. 4a

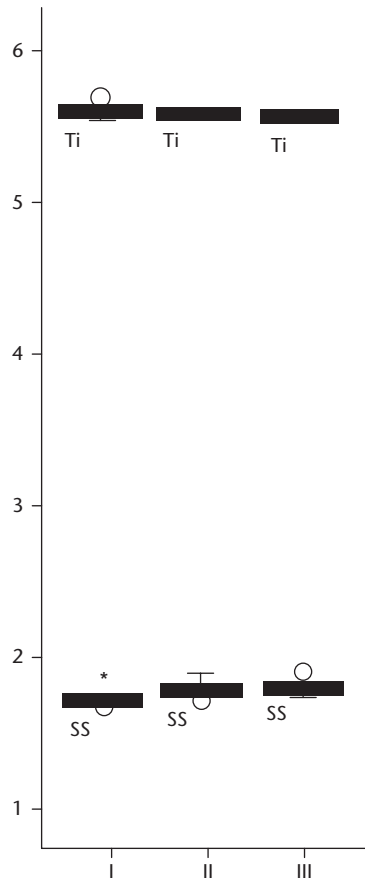


Fig. 4b

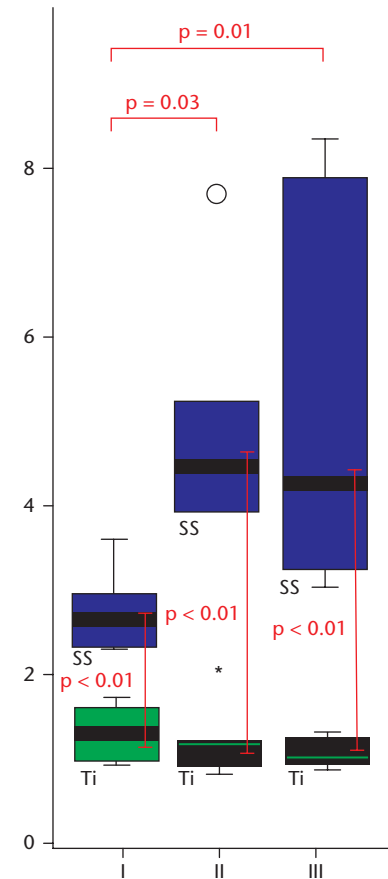


Fig. 4c

Box and whisker plot demonstrating the comparison of the (a) bending stiffness  $10^3$  N/mm, (b) yield strength  $10^3$  N, and (c) fatigue lives  $10^5$  cycles of three types of plates. The circles and stars designate the outliers. Only significant p-values are presented. SS, stainless steel; Ti, titanium.

effects of the material and type on fatigue lives ( $p = 0.01$ ). Accordingly, the simple main effects were subsequently analyzed. The results showed that stainless steel had a significantly longer fatigue life than titanium in all three types of plates ( $p < 0.01$  for all). For the stainless steel plates, the fatigue lives of type II and III plates were significantly longer than those of type I plates (type I vs type II:  $p = 0.03$ ; type I vs type III:  $p = 0.01$ ), while there was no significant difference between type II and III plates ( $p = 0.75$ ). For the titanium plates, no differences were found among the three types (type I vs type II:  $p = 0.68$ ; type I vs type III:  $0.58$ ; type II vs type III:  $0.89$ ) (Fig. 4). At the end of the fatigue tests, 33 out of 36 plates cracked at the lateral edges of the side holes, while three titanium plates cracked at the central holes. All titanium plates cracked completely, whereas the stainless steel plates cracked partially. Fractographic analysis showed crack initiation at the tip of the first thread on the tension side of the plate screw holes (Fig. 5), and high-power magnification revealed typical fatigue striations. Failure analyses demonstrated coarse abrasive marks on the lateral edges of the screw hole threads and on the corresponding surfaces

of the plug threads in the plugged stainless steel plates (Figs 6a and 6b). Magnification of these marks revealed irregular thread deformations (Fig. 6c), and metallographic examination of these regions showed evident slip lines (Fig. 6d). Micro-Vickers hardness tests demonstrated significantly higher hardness at the threaded regions as compared with unthreaded regions (stainless type II:  $p < 0.01$ ; stainless type III:  $p < 0.01$ ). All local work hardening effects were found only in the stainless steel plates. No signs of thread deformation were observed in the titanium plates, and the micro-hardness tests did not show significant differences (titanium type II:  $p = 0.26$ ; titanium type III:  $p = 0.17$ ) (Table II).

**Finite element analyses.** The stress distribution was the same in the stainless steel and titanium plates, with the deformation being higher for the latter. The maximum von Mises stress was located at the first threads of the side hole (Table I) (Fig. 7), corresponding to the crack initiation site observed in fractographic analysis. The plugged plates had smaller deformation, however, their maximum von Mises stress was 2% higher than that of the unplugged plates. The stress at the central hole was

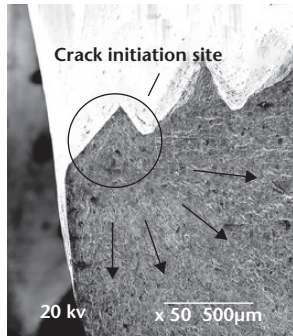


Fig. 5

Fractographic analysis. The circle indicates the region of the cracks initiating at the tip of the first thread of the screw hole. The arrows represent the crack propagation direction.

slightly lower (7.7% to 9.4%) than that at the side holes; this result is consistent with the finding that most of the plates cracked at the side holes.

### Discussion

The present study demonstrated that plugging empty holes significantly increases the fatigue lives of the stainless steel locking plates by up to two-fold. Different theories have been proposed.<sup>14,17</sup> The current study proposed a novel local deformation theory. First, the failure analysis of stainless steel plugged plates demonstrated abrasion marks on the lateral sides of the plug thread and the corresponding plate screw hole thread surfaces. Second, marked deformations were microscopically observed on these screw threads. Third, metallographic examination revealed a large number of slip lines over the thread deformation area. Fourth, the micro-Vickers hardness tests further confirmed the association between the thread deformation and local hardening of the metal. Fifth, local deformation was caused by the high compressive force incurred while loading, rather than over-tightening. Finally, increase in local deformation or micro-hardness was not found in the titanium plates, in which the fatigue life did not increase after plugging.

Based on the local deformation theory, the local work hardening effect created by plugging the screw holes strengthened only the locking part of the plate. This could explain the contradictory results of the studies that investigate the plugging effect using stainless steel locking compression plates (LCPs) with the weakest link located at the compression part of combi holes (Synthes, West Chester, Pennsylvania).<sup>24</sup> Using eccentrically loaded plate-bone constructs, Firoozabadi et al<sup>19</sup> found that plugging did not increase the fatigue strength. Even though the compression part was plugged in that study, the bonding was not as strong as that in the locking part and could not generate local work hardening effects. When the LCP was eccentrically loaded like the femur, the moment arm and stress were evenly distributed along the combi holes. Plugging could not change the strength

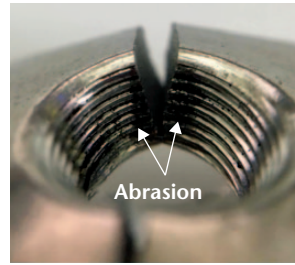


Fig. 6a

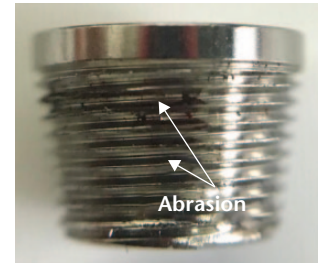


Fig. 6b

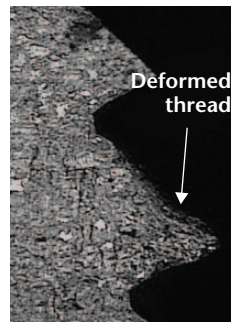


Fig. 6c

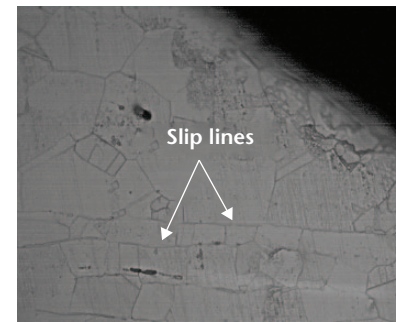


Fig. 6d

Local work hardening caused by mechanical loading. (a) Coarse abrasive marks on screw holes. (b) Coarse abrasive marks on plug. (c) Local thread deformation. (d) Metallography showing slip lines at the abrasion regions.

of the plate as the weakest part of the plate was not strengthened. Conversely, by performing three-point loading tests, Meyers et al<sup>14</sup> found that plugging increased the strength of the LCP. Because the two central combi holes of the plate pointed in opposite directions, the locking parts of these two holes were at the midpoint of the LCP and sustained the highest moment in three-point loading tests. Therefore, plugging these locking parts could effectively increase the strength of the plates.

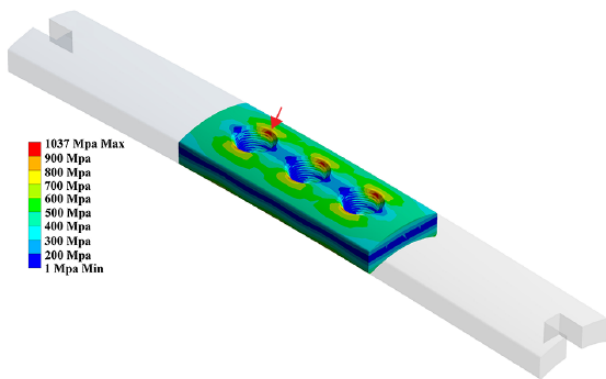
In contrast to our hypothesis, the fatigue life was not significantly increased when the insertion torque increased from 4 Nm to 12 Nm. This indicated that local thread deformation was not caused by the over-tightening of the plugs. Instead, it was primarily caused by the relatively higher compressive force compared with the yield load of stainless steel exerted by the plugs during cyclic loading, which resulted in local thread deformation and increased fatigue strength. To confirm this, plates were tested that were plugged for 24 hours and then unplugged. We observed that there were no abrasion marks on the screw threads and the fatigue lives were not increased (data not presented in this report).

Unlike the stainless steel plates, plugging did not increase the fatigue lives of the titanium plates. This can be attributed to the lower elastic modulus and higher yield strength of titanium. The compressive loads exerted by the plugs on the screw threads might not be sufficiently strong to cause local deformation and increase local hardness. Furthermore, a higher insertion torque

**Table II.** Comparison of micro-hardness between unthreaded and threaded parts in each plate type

Plate type	Micro-hardness		p-value
	Unthreaded region	Threaded region	
<b>Stainless steel</b>			
I	237.5 (211.8 to 266.4)	240.4 (215.5 to 277.6)	0.75
II	249.3 (212.3 to 265.8)	312.2 (263.1 to 366.7)	< 0.01*
III	235.7 (206.9 to 260.1)	295.5 (277.5 to 317.6)	< 0.01*
<b>Titanium</b>			
I	342.5 (310.2 to 383.2)	356.2 (316.1 to 386.2)	0.29
II	339.8 (330.8 to 364.7)	323.9 (307.9 to 362.5)	0.26
III	343.6 (321.4 to 365.6)	361.1 (326.9 to 389.4)	0.17

\*Significant difference between micro-hardness in threaded and unthreaded regions of plugged stainless steel plates

**Fig. 7**

The von Mises stress distribution on the plate. The plugs are not shown because they are minimally stressed. The red arrow indicates the location with the maximum stress.

could even produce cracks on the plates and decrease fatigue strength because the percentage of elongation of titanium is lower than that of stainless steel.<sup>25</sup> Consequently, to decrease the risk of plate failure clinically, we recommend that the empty holes at the fracture level should not be plugged in titanium plates. In addition, leaving the holes empty around the fracture site could increase the working length, thereby reducing fixation stiffness and promoting fracture healing by bone callus.<sup>5,26</sup> Regardless of plugging, the titanium plates had consistently lower fatigue lives than their stainless steel counterparts because of the former's special mechanical property of notch sensitivity, which is a measure of the fatigue strength reduction of a material caused by the presence of a surface inhomogeneity such as a notch, sudden structural change, crack, or scratch.<sup>20,21</sup> The screw threads might act like notches and considerably reduce the fatigue strength of the plates. Reduction of the notch effects is a critical concern in the design of titanium implants, and more biomechanical and clinical studies are required in this regard.

It was reported that screw holes might cause high stress because of stress concentration, and plugging empty holes might reduce this effect.<sup>17,19</sup> One study carried out FEA to demonstrate the reduction in stress after

empty holes were plugged.<sup>17</sup> However, this study did not address boundary and interface conditions adequately. In the mathematical models considered in the present study, even though the plugged plate had higher stiffness, its maximum von Mises stress conversely increased because of the compression force exerted on the plate by the plugs under the bending load. The increase in stress could explain the result of the mechanical tests that the fatigue lives of titanium plates were reduced further after plugging.

The present study had limitations. First, plates with only three locking holes were simulated. The stress distribution in these plates might be different from that in plates with a different number or distribution of holes. However, the trend of the plugging effects on the biomechanical strength of the plates would not be affected. Second, the result of fatigue testing may be different under different loading condition. It has been reported that the fatigue strength of titanium implants was frequency-dependent and tended to be lower under a high loading rate.<sup>25</sup> The high load used in this study was to simulate the worst-case scenarios. Lastly, torsional loading was not considered in the present study, which might also produce local work hardening effects similar to a bending load. However, the effects from torsional load might be relatively small compared with those produced by a bending load in femurs.

In conclusion, screw plugging could produce local work hardening effects and increase the fatigue strength of stainless steel plates, but not of titanium plates. All of these aspects must be considered as important concerns in the clinical application of locking plates for fracture fixation.

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#### Author Contributions

- L-W. Hung: Prepared the manuscript draft, Performed the experiments, Collected data, Revised the manuscript, Read and approved the final manuscript.
- C-K. Chao: Performed the experiments, Collected data, Revised the manuscript, Read and approved the final manuscript.
- J-R. Huang: Performed the experiments, Collected data, Revised the manuscript, Read and approved the final manuscript.
- J. Lin: Designed the study, Prepared the manuscript draft, Performed the experiments, Collected data, Revised the manuscript, Read and approved the final manuscript.

#### Conflict of Interest Statement

- None declared

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