Biomechanical Analysis of Bone Plate Fixation

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Abstract

Metal plates are commonly used in the operative treatment of bone fractures. Rigid metal plates stabilize the fracture site, maintain good contact between bone fragments and allow early weight bearing and patient mobility.
Although they cause some problems, metallic bone plates have been used widely in the healing of especially long bone fractures. As composites are less rigid, and their mechanical properties may be closer to that of bone, it seems possible to avoid these problems with their usage as alternative implant materials. The aim of this study was to compare theoretically the effects of thickness of bone plates used in the healing of fractures according to their effects on the bone and the fracture site, and their behaviors under the condition of compression, the difference of material used for the fixation of the bone/plate system are compared for metallic and composite plate cases.
A model with a standard metal fixation plate was also generated for comparison purposes. Results show that changes in compressive and tensile stresses of bone occur when increasing thickness of rectangular plate and modulus of elasticity.

Key Words: Bone, Fractures, Plate, Fixation.

Introduction:

In the plate fixation of fractured bone by means of bone-plates fastened to the bone on its tensile surface, an on-going concern has been the excessive stress-shielding of the bone by the excessively-stiff stainless-steel plate. The compressive stress-shielding at the fracture interface immediately after fracture-fixation delays callus formation and bone healing. Likewise, the tensile stress-shielding of the layer of the bone underneath the plate can cause osteoporosis and decrease in tensile strength of this layer [1].
Rigid plate fixation systems provide the initial support and stability necessary for successful healing of this nature. However, differences in stiffness between the plate and bone causes an alteration of the normal bone loading conditions. This stress shielding effect causes a reduction in the rate of bone remodeling [2].
The density of the living bone is always controlled by the stress conditions applied to the bone; thus if a higher stress is applied to the bone, the density of the region increases. So if the metal plate, with high modulus of elasticity, is attached to the bone, the stress will be transmitted by the plate to the bone directly beneath the plate leading to a high stress concentration region. Hence the possibility of re-fracture of the bone increases after loading or unloading of the bone. [3].
Bone remodelling is an adaptive process involving the resorption and deposition of bone tissue in response to mechanical, chemical, and biological stimuli. The rate of remodeling is partly dependent on the physiologic loading conditions applied to a region of bone, which is inherent to its anisotropic behaviour. A reduction in bone re-modeling can lead to implant loosening and subsequent improper fracture healing [4].
Stress analysis of cracked and fractured femur with fixing plate using finite element method studied by Sahoo et al in 2005, they investigated the nature of stress generation near the cracked zone and also fined out a better fixation plate to fix the fractured femur. They conclude that various engineering materials used initially in orthopedic applications for bone replacement, repair and fixation in a variety of surgical procedures are mostly metallic, and the polymer-ceramic composite plate have a greater prospect to be used as a fixation plate to fix the fractured human bone for better surgical procedure [5].
In 2001, Y. M. Behairy, determined the clinical, radiologic, and functional status of patients who underwent posterior fracture fixation using round hole bone plates and cancellous screws, and evaluate the construct's ability to maintain reduction of the fracture. Seventeen patients were included in this study. They concluded that the use of round hole bone plates along with 6.5 mm cancellous screws inserted into the pedicles provides an angle-stable construct that allows for better stability in the sagittal plane [6].
In 2005 Ganesh et al studied the biomechanics of bone-fracture fixation by stiffness-graded plates in comparison with stainless-steel plates. They concluded that stiffness graded plates (with in-built variable stiffness) are deemed to offer less stress shielding to the bone, providing higher compressive stress at the fractured interface (to induce accelerated healing) as well as higher

tensile stress in the intact portion of the bone (to prevent bone remodeling and osteoporosis) [1].
Development of an in vitro three dimensional loading-measurement system for long bone fixation under multiple loading conditions was made by John et al in 2007. In their conclusion, the 3D loading-measurement system designed: a) mimics unconstrained relative 3D motion between radius ends that occurs in clinical situations, b) applies uniform compression, torsion, and 4-point bending loads over the entire length of the test specimen, c) measures interfragmentary 3D relative motion between test segment ends to directly determine stiffness thus being void of potting-fixture-test machine stiffness error, and d) has the resolution to detect differences in the 3D motion and stiffness of intact as well osteotomized-instrumented and ostectomizedinstrumented equine radii. [7].
Szydek et al in 2010 used a numerical analysis of displacements of mandible bone parts using various elements for fixation of subcondylar fractures. They concluded that fixation with the use of a miniplate osteosynthesis enables one to obtain the minimal dislocation values 3 and 4 times lesser than for the other cases [8].

Unsymmetric Bending of Bone with Plate

Irregular bone cross section with a plate was idealized as systems where the bone was modeled as a concentric circular cylinder. Real bones are not perfectly straight circular cylinders, and the resulting bone-plate systems generally do not have a plane of symmetry. However, using the ideas of composite beams, it can find the bending stresses for any cross section and any plate position, as long as it can treat the bone as a straight beam. This is usually a quite acceptable assumption for diaphyseal fractures of long bones. The general approach for determining the structural stiffness and stresses for a bone-plate system where the bone has an irregular cross section is illustrated in Fig.(1) [9]. It may be assumed that the bone is rigidly fixed to the plate.

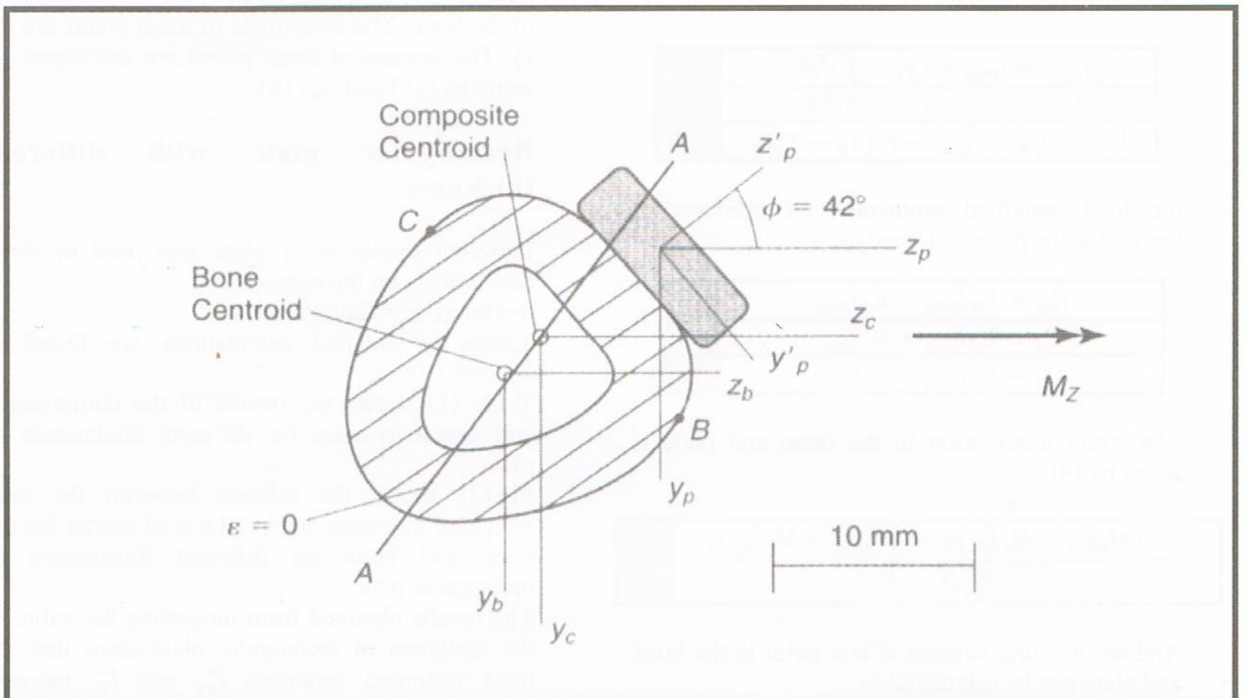

Fig.(1) A bone cross section with an attached plate. [9]

The stress and strain distribution was calculated with the use of composite beam theory. The reference point is the centroid of the bone cross section y_b, z_b.

The moments and products of inertia are:

$$I_{Py'y'} = \frac{bh^3}{12} \qquad I_{Pz'z'} = \frac{hb^3}{12} \tag{1}$$

The moment and product of inertia were transformed from these principal axes to the y and z axes by using the following equations [9]

$$I_{Pzz} = \frac{I_{Pz'z'} + I_{Py'y'}}{2} + \frac{I_{Pz'z'} - I_{Py'y'}}{2}\cos(2\phi) \tag{2}$$

$$I_{Pyy} = \frac{I_{Pz'z'} + I_{Py'y'}}{2} - \frac{I_{Pz'z'} - I_{Py'y'}}{2}cos(2\phi) \tag{3}$$

$$I_{Pyy} = \frac{I_{Pz'z'} + I_{Py'y'}}{2} - \frac{I_{Pz'z'} - I_{Py'y'}}{2} cos(2\phi) \quad (3)$$

$$I_{Pyz} = \frac{I_{Pz'z'} - I_{Py'y'}}{2} sin(2\phi) \quad (4)$$

The weighted centroid (neutral axis) of the composite section is given by [9]

$$\bar{y}_c = \frac{E_B A_B y_B + E_p A_p y_p}{E_B A_B + E_p A_p}, \quad \bar{z}_c = \frac{E_B A_B z_B + E_p A_p z_p}{E_B A_B + E_p A_p} \quad (5)$$

The moments and product of inertia of the bone about the centroid of the composite are obtained by using the parallel axis theorems [9]

$$\bar{I}_{Byy} = I_{Byy} + (\bar{y}_B - \bar{y})^2 A_B \quad (6)$$

$$\bar{I}_{Bzz} = I_{Bzz} + (\bar{z}_B - \bar{z})^2 A_B \quad (7)$$

$$\bar{I}_{Byz} = I_{Byz} + (\bar{y}_B - \bar{y})(z_B - \bar{z}) A_B \quad (8)$$

Similarly, for the plate

$$\bar{I}_{Pyy} = I_{Pyy} + (\bar{y}_P - \bar{y})^2 A_P \quad (9)$$

$$\bar{I}_{Pzz} = I_{Pzz} + (\bar{z}_P - \bar{z})^2 A_P \quad (10)$$

$$\bar{I}_{Pyz} = I_{Pyz} + (\bar{y}_P - \bar{y})(z_P - \bar{z}) A_P \quad (11)$$

the total weighted moments and products of inertia for the plate and bone are

$$\bar{I}^*_{yy} = E_B \bar{I}_{Byy} + E_P \bar{I}_{Pyy} \quad (12)$$

$$\bar{I}^*_{zz} = E_B \bar{I}_{Bzz} + E_P \bar{I}_{Pzz} \quad (13)$$

$$\bar{I}^*_{yz} = E_B \bar{I}_{Byz} + E_P \bar{I}_{Pyz} \quad (14)$$

The strain distribution in the bone and plate is given by [9]

$$\varepsilon = \frac{(M_y \bar{I}^*_{zz} + M_z \bar{I}^*_{yz}) z - (M_y \bar{I}^*_{yz} + M_z \bar{I}^*_{yy}) y}{\bar{I}^*_{yy} \bar{I}^*_{zz} - \bar{I}^{*\,2}_{yz}} \quad (15)$$

And the bending stresses at any point in the bone and plate can be calculated as

$$\sigma_B = E_B \varepsilon; \qquad \sigma_P = E_P \varepsilon \quad (16)$$

Eq.(2) was used to calculate the stress distribution across the bone and plate. To determine the location of the peak stress, it is most convenient to determine the orientation of the neutral axis of bending. This is found by setting ε in eq.(15) to zero, leading to

$$z = \frac{(M_y \bar{I}^*_{yz} + M_z \bar{I}^*_{yy})}{(M_y \bar{I}^*_{zz} + M_z \bar{I}^*_{yz})} y \quad (17)$$

Results and discussion

The analysis depicted here focused on one implant variable plate thickness and variable plate material.

According to Fig.(1), it is assumed that the bone is rigidly fixed to the plate. A bending moment of 1000 N.mm is applied about z-axis.

About the bone centroid, the area properties are given as [9]:

$A_B = 276$ mm^2; $I_{Byy} = 3990$ mm^4;
$I_{Bzz} = 4170$ mm^4; $I_{Byz} = -335$mm^4

The centroid of the rectangular plate is located at y_b, z_b, with respect to the centroid of the bone cross section, and the plate is oriented at angle ϕ with respect to the z-axis. The dimensions of the plate are $b \times h$, and the elastic modulus of the plate is E_p. The modulus of the bone is E_B=15GPa.

Eq.(17) gives the line with angle θ with y-axis, which is shown as line AA in Fig.(1). By inspection, the greatest perpendicular distance from the neutral axis is at point B on the compressive side and point C on the tensile side of the bone. The coordinate of these points are (y, z). The stresses at these points are calculated by using eq.(15) and eq.(16).

Rectangular plate with different thickness

Different thickness of plate was used to show their effects on the stresses.

b=10mm, E_p=120GPa, ϕ =42°

Tables of detailed calculations are found in appendix (A1).

Table (1) shows the results of the compressive and tensile stresses for different thicknesses of plate.

Fig.(2) shows the relation between the total weighted moments and products of inertia for the plate and bone for different thicknesses of rectangular plate.

The results obtained from increasing the value of the thickness of rectangular plate show that the total weighted moments $\bar{I}^*_{yy}$ and $\bar{I}^*_{zz}$ increase linearly while the products of inertia $\bar{I}^*_{yz}$ decrease linearly.

Fig.(3) shows the relation between the compressive and tensile stresses for different thickness of rectangular plate.

The results obtained from increasing the value of the thickness of rectangular plate show that the compressive stresses increase in a noticeable amount, but the tensile stresses have insignificant change.

Table (1) Compressive & Tensile stresses for different thicknesses

t mm	$\bar{I}^*_{yy}$ N.mm^2	$\bar{I}^*_{zz}$ N.mm^2	$\bar{I}^*_{yz}$ N.mm^2	σ_B (C) MPa	σ_B (T) MPa
2	1.21E8	1.39E8	-7.29E7	-1.4715	1.22625
3	1.49E8	1.72E8	-1.01E8	-1.36992	1.23027
4	1.72E8	2.09E8	-1.27E8	-1.30674	1.22748
5	2.05E8	2.39E8	-1.53E8	-1.25595	1.22129
6	2.36E8	2.74E8	-1.76E8	-1.22436	1.21509
7	2.68E8	3.12E8	-1.98E8	-1.208565	1.21850
8	3.04E8	3.52E8	-2.19E8	-1.20237	1.21230

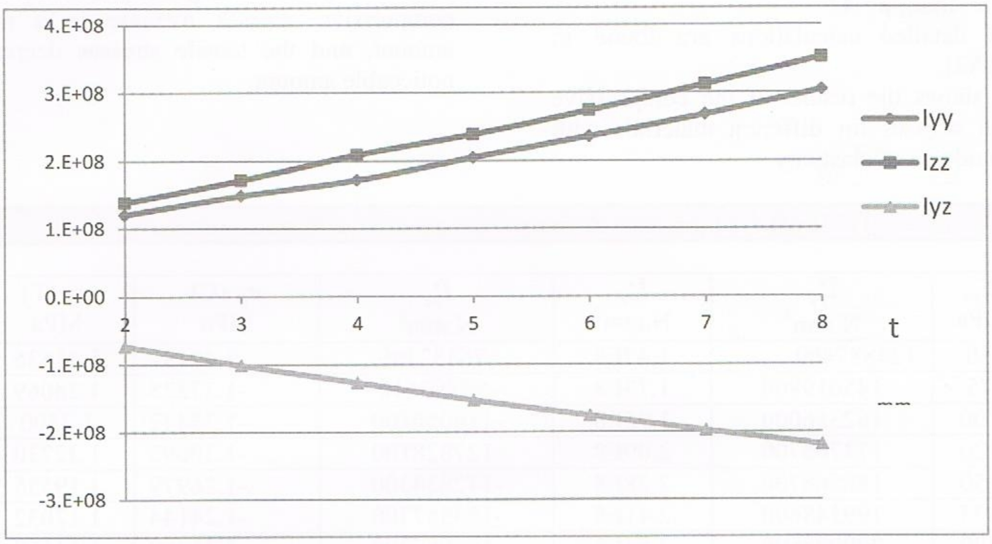

Fig (2) Total weighted moments and products of inertia for the plate and bone for different thickness of rectangular plate.

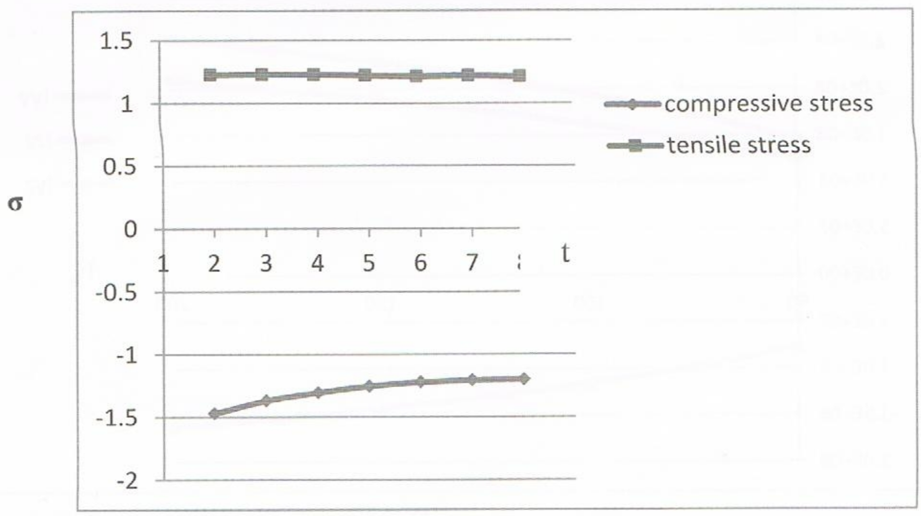

Fig (3) Compressive & Tensile stresses for different thickness of rectangular plate.

Rectangular plate with different materials

The early fixation plates were made from 306 or 316 stainless steel due to their good corrosion resistance. However, orthopedic industry has closely followed the aerospace industry in utilizing high performance metal alloys, based on Cobalt-Chromium and Titanium alloys, with an elastic modulus 10 times that of bone, for superior implant performance and might be on the road to repeating this with advanced composite materials. Different material of plate was used to show the effect of change in modulus of elasticity on the stresses

b=10mm, h=4mm, ϕ =42°

Tables of detailed calculations are found in appendix (A2).

Table (2) shows the results of the compressive and tensile stresses for different materials with different modulus of elasticity.

Fig.(4) shows the relation between the total weighted moments and products of inertia for the plate and bone for different material (different modulus of elasticity) of rectangular plate.

The results obtained from increasing the modulus of elasticity of rectangular plate show that the total weighted moments $\bar{I}^*_{yy}$ and $\bar{I}^*_{zz}$ increase while the products of inertia $\bar{I}^*_{yz}$ decrease.

Fig.(5) shows the relation between the compressive and tensile stresses for different material (different modulus of elasticity [10]) of rectangular plate.

The results obtained from increasing the modulus of elasticity of rectangular plate show that the compressive stresses increase in a noticeable amount, and the tensile stresses decrease in a noticeable amount.

Table (2) Compressive & Tensile stresses for different materials

E_p, GPa	$\bar{I}^*_{yy}$ N.mm^2	$\bar{I}^*_{zz}$ N.mm^2	$\bar{I}^*_{yz}$ N.mm^2	σ_B (C) MPa	σ_B (T) MPa
50	124887400	1.47E8	-76352190	-1.42187	1.31536
75	145619800	1.73E8	-98493610	-1.37325	1.28069
100	162356000	1.95E8	-116050100	-1.33432	1.2500
120	173768700	2.09E8	-127828100	-1.30693	1.22730
150	188568700	2.28E8	-142834300	-1.26979	1.19535
175	199348600	2.41E8	-153557300	-1.24144	1.17032
200	209088600	2.54E8	-163087200	-1.21489	1.14650

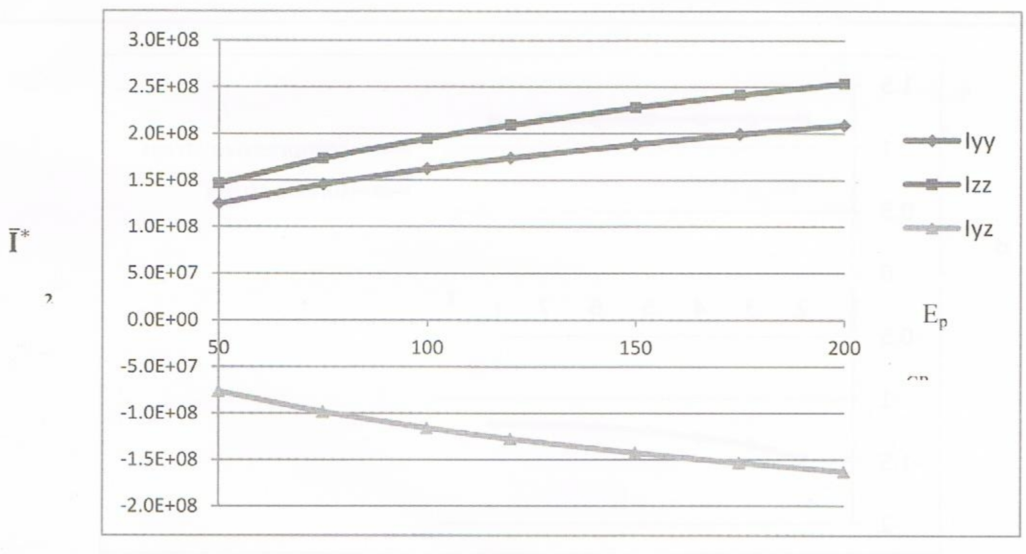

Fig (4) The total weighted moments and products of inertia for the plate and bone for different material (Modulus of elasticity) of rectangular plate

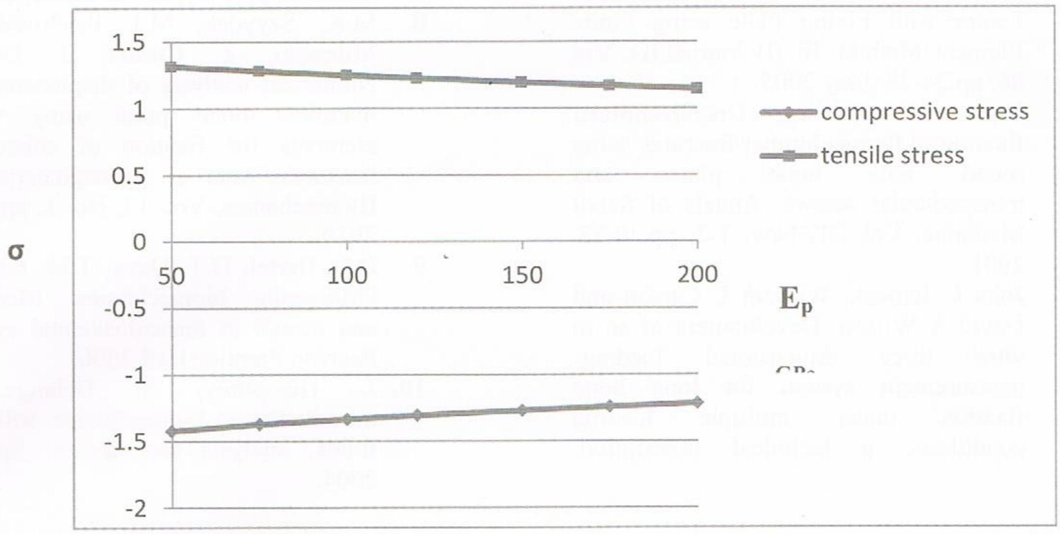

Fig (5) Compressive & Tensile stresses for different material (Modulus of elasticity) of rectangular plate

Conclusions

- Various engineering materials used initially in orthopedic applications for bone replacement, repair and fixation in a variety of surgical procedures are mostly metallic.
- Major loads being carried through metal plates due to their high modulus of elasticity rather than bone, a high elastic mismatch between the bone and its fixation devices are found that becomes a problem in clinical practice.
- Changing thicknesses of rectangular plate cause increase in bone compressive stresses and little change in bone tensile stresses.
- Using different material (different modulus of elasticity) of rectangular plate cause a change in bone stresses (both compressive and tensile).
- The calculation of torsional stresses for the composite section is considerably more complicated and is usually achieved only by using numerical models, such as the finite element method.

Nomenclature

A_P area of the plate

I_{Pzz}, I_{Pyy} moment of inertia of plate about z and y axes

I_{Pyz} product of inertia of plate

$\bar{I}_{Byy}, \bar{I}_{Bzz}$ the moments of inertia of the bone about the centroid of the composite

$\bar{I}_{Byz}$ the product of inertia of the bone about the centroid of the composite

$\bar{I}^*_{yy}, \bar{I}^*_{zz}$ the total weighted moments of inertia for the plate and bone

$\bar{I}^*_{yz}$ the total product of inertia for the plate and bone

M_y, M_z bending moment about y and z axes

$\bar{y}_c\ \bar{z}_c,$ the weighted centroid (neutral axis) of the composite section

ε the strain distribution in the bone and plate

σ_B, σ_P bending stresses in the bone and plate

E_B, E_P modulus of elasticity of the bone and plate

References

1. Ganesh, VK, Ramakrishna, K, Dhanjoo, Ghista. Biomechanics of bone-fracture fixation by stiffness-graded plates in comparison with stainless-steel plates. BioMedical Engineering OnLine 2005, 4:46
2. Taylor ME, Tanner KE, freeman MAR, Yettram AL: Stress and strain distribution within the intact femur: Compression or Bending. Med Eng Phys 1996, 18(2):122-131.
3. H. Saidpour, Finite element stress analysis of a hybrid fracture fixation plate. Advances in Computing and Technology. The School of Computing and Technology 1st Annual Conference, University of East London, pp.173-183, 2006.
4. E.J. Cheal, W.C. Hayes, A.A. White, S.M. Perren, "Stress analysis of a simplified compression plate fixation system for fractured bones", Computers & Structures, vol. 17, no. 5/6, pp. 845-855, 1983.

5. Sahoo, Ghosh, Roychowdhury, Stress Analysis of Cracked and Fractured Femur with Fixing Plate using Finite Element Method. IE (I) Journal.ID, Vol 86, pp.24-28, May 2005.
6. Yaser M. Behairy, Unconventional fixation of thoracolumbar fractures using round hole bone plates and transpedicular screws. Annals of Saudi Medicine, Vol. 21, Nov. 1-2, pp.30-33, 2001.
7. John C Janicek, William L Carson and David A Wilson, Development of an in vitro three dimensional loading-measurement system for long bone fixation under multiple loading conditions: a technical description. Journal of Orthopaedic Surgery and Research pp.1-11, 24 November 2007.
8. M.K. Szyydek, M.J. Pawlowska, G. Milewski, Z. Cieslik, J. Drugacz, Numerical analysis of displacements of mandible bone parts using various elements for fixation of subcondylar fractures. Acta of Bioengineering and Biomechanics, Vol. 12, No. 1, pp.11-18, 2010.
9. D.L. Bartel, D.T. Davy, T.M. Keaveny, Orthopedic biomechanics: Mechanics and design in musculoskeletal systems. Pearson Prentice Hall 2006.
10. J. Humphrey, S. Delange, An introduction to biomechanics; solids and fluids, analysis and design. Springer, 2004.

تحليل ميكانيكي أحيائي لتثبيت صفيحة العظم

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الخلاصة:

تستعمل الصفائح المعدنية عموماً في المعالجةِ الفعّالةِ للكسورِ العظميةِ. تقوم هذه الصفائح المعدنيةُ بتثبيت موقعُ الكسرَ وتحافظ على إتصال الأجزاءِ العظميةِ وكذلك تَسمح بحمل الوَزن وقابليةِ الحركة.

بالرغم من أن هذه الصفائح تسبب بعض المشاكلِ، لكنها تستعمل على نحو واسع في معالجة كسور العظام وخاصة الطويلة منها. تستخدم بعض المواد المركبة مع أنها أقل مقاومة، لكن خواصها الميكانيكية قَد تَكون أقرب إلى خواص العظم، مما يؤدي إلى تَفادي بعض المشاكلِ عند إستعمالها كمواد زرع بديلة. هدف هذه الدراسة هو إجراء مقارنة نظرية لاستخدام أسماك مختلفة للصفائح العظميةَ المعدنية والمركبة والتي تستخدم في معالجة الكسور وتأثيرها على العظمِ وموقع الكسر، وسلوكها تحت الانضغاط.

تم عرض نموذج رياضي لمقطع عظمي مثبت بواسطة صفيحة معدنية لغرض مقارنته بتغيير سمك الصفيحة والمادة المستخدمة. بينت النتائج حدوث تغييرات في إجهادات الشد والإنضغاط داخل العظم عند تغيير سمك صفيحة التثبيت والمادة المستخدمة.