Biomechanical Analysis of The Effects of Distance Between Bone and Locking Compression Plate on Construct Stability

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ABSTRACT

Bone fractures which are treated, the Locking Compression Plate (LCP) with locked screws is commonly employed. Appropriate distance between the LCP and the bone may enhance periosteal blood supply. Aim: This study aims to determine the effect of distance between the LCP and the bone analogue on the stiffness of the locking compression plate itself using Finite Element Analysis (FEA). Method: To investigate the effect of distance between the LCP and three models bone of transversely fractured tibia, the bone fixed with locked Compression Plate (LCP) containing eight holes each is 4.5 mm using cortex screws. Results: The current study revealed that the stiffness construct will be reduced when the distance between the Locking Compression Plate and the bone analogue increased. Conclusion: To preserve the bone's peripheral blood supply, the plate should be kept at a small distance from the bone during internal fixation.

1. Introduction

Internal fixation is commonly used as a method for treating fractured long bones. Fixation using plate is an interesting option for internal fixation [1,2]. Broken long bones are very frequently repaired with locking Compression Plate (LCP). In the locking Compression Plate (LCP), locking screws are utilized. The plate and the bone are held together by the compressive force created by the applied torque at the screw head [3]. Theoretically, the contact plate compresses the bone and disrupts periosteal blood flow of the bone [4,5]. Using locking screws, the locking Compression Plate (LCP) was created to alleviate this problem [6,7]. The locking screws are utilized to create the space between the plate and the bone in the locking compression type of plates. The stiffness of the implant bone construct is influenced by the distance between the locking Compression Plate (LCP) and the bone. The purpose of this study is to examine the stiffness in the LCP at various distances.

2. Modeling and simulation of the fractured bone and the fixation plate

2.1 Internal fixator (locked Compression Plate (LCP))

A generic internal plate fixator was built using Solid Works software program to create conventional 8-holes, each is 4.5 mm. The plate measured 150×13.5×4.5 mm as shown in Figure 1.
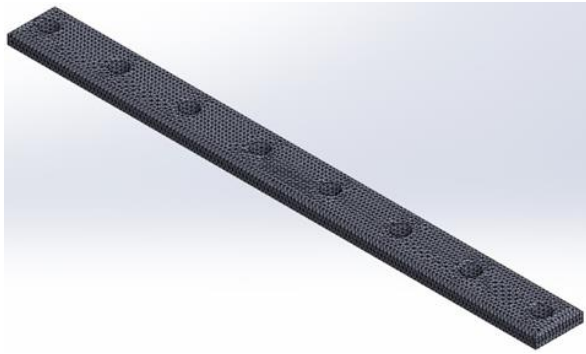
Figure 1. Locking Compression Plate (LCP)

2.2 Solid model of a hollow cylinder (bone analogue)

A bone analogue was built using Solid works software program to create a hollow cylinder (bone analogue) 236 mm long with a 20 mm outer diameter and 3 mm wall thickness. An extruded cut was performed to simulate a 3 mm osteotomy (fracture gap) as shown in Figure 2.
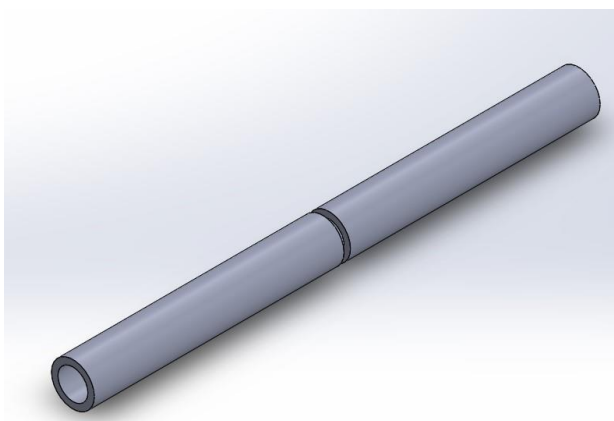

Figure 2. Solid model of a hollow cylinder (bone analogue)

2.3 Implant-Bone analogue construct

Solid works also used to assemble the implant structures. The model of the 8 holes internal fixator was fitted to the hollow cylinder (bone analogue) flush with the bone, at 1 mm offset (the distance between the LCP and the bone analogue) and at 2 mm offset from the bone analogue. Four screws were used to secure the fixator on either side of the fracture gap, as illustrated in Figure 3.
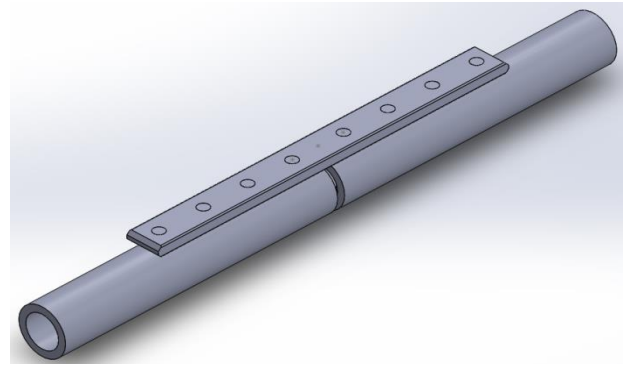

Figure 3. The locking Compression Plate attached to cylinder (bone analogue)

2.4 Creation of Finite Element (FE) model

For the implant-bone analogue construction, a 3D Finite Element model was developed by ANSYS Workbench software. Linear elastic isotropic material characteristics were used to characterize all constructions. Titanium alloy (E_{Ti} = 110 GPa, v_{Ti} = 0.33) was used to make up the implant material (plate and screws) [8]. Unlike living tissue, such as bone which is nonhomogeneous and non-isotropic, titanium alloy has homogeneous material qualities throughout, So, identifying material properties is challenging. Young's modulus is commonly assigned as a single value in the literatures. However, the sensitivity analysis for the material properties of cortical bone ranges from 16-20 GPa [9,10]. As a result, a Young's modulus of (E_{cort} = 16 GPa) and a Poisson's ratio of (v_{cort} = 0.3) were selected for the cortical bone [10]. Surface-to-surface contact components were used to simulate all structure-to-structure connections. In all degrees of freedom, the contact between the screws and the plate, as well as the screws and the bone, were characterized as bonded [11]. Ten-node tetrahedral elements were used to mesh all the constructions as shown in figure 4.

Figure 4. Mesh densities for the components of the plate-bone analogue structure

2.5 Boundary conditions

Six independent load scenarios are considered in the analysis. These six loads which are axial compression (240 N), torsion (3 N.m), bending (12 N.m) in anterior-posterior directions (AP), medial-lateral (ML) directions and shear (30 N) with bend (3.54 N.m) in both anterior-posterior (AP) and medial-lateral (ML) directions according to the boundary conditions described in mechanical testing Augat et al.,

2008 [12]. All simulated load scenarios during postoperative weight-bearing [13,14]. In this study, loads were usually applied at the Proximal end of the bone when the distal end fixed in all degree of freedom (DoFs). The top end of the proximal/upper bone fragment piece is subjected to axial compression, bending moments and shear forces. The distal/lower bone fragment was fixed firmly in all DoFs as shown in Figure 5.
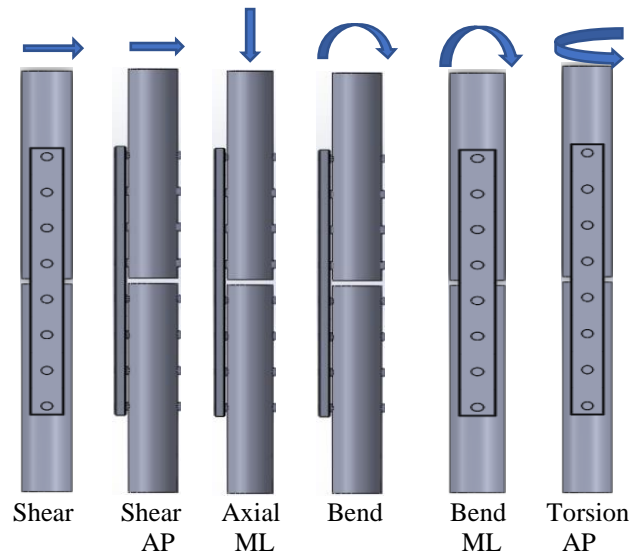

Figure 5. Boundary conditions for six load cases

In which:
AP Shear = Force in (X) direction.
ML Shear = Force in (Y) direction.
Axial Force = Force in (Z) direction.
ML Bend = Moment about (X)axis.
AP Bend = Moment about (Y)axis.
Torsion = Moment about (Z)axis.

2.6 Determining stiffness

Using a technique specific to the Finite Element method, a remote point at the center of the fracture gap was created. The movement of a remote point at the center of the fracture gap indicate the translational and rotation inter-fragmentary motions. The relationship between force and displacement is called stiffness. A complete 6 by 6 stiffness matrices (equation 1 is shown below)

$$
\begin{pmatrix} F_x\,[\mathrm{N}] \\ F_y\,[\mathrm{N}] \\ F_z\,[\mathrm{N}] \\ M_x\,[\mathrm{Nm}] \\ M_y\,[\mathrm{Nm}] \\ M_z\,[\mathrm{Nm}] \end{pmatrix}_i = \begin{pmatrix} s_{11} & s_{12} & s_{13} & s_{14} & s_{15} & s_{16} \\ s_{21} & s_{22} & s_{23} & s_{24} & s_{25} & s_{26} \\ s_{31} & s_{32} & s_{33} & s_{34} & s_{35} & s_{36} \\ s_{41} & s_{42} & s_{43} & s_{44} & s_{45} & s_{46} \\ s_{51} & s_{52} & s_{53} & s_{54} & s_{55} & s_{56} \\ s_{61} & s_{62} & s_{63} & s_{64} & s_{65} & s_{66} \end{pmatrix} \begin{pmatrix} \delta_x\,[\mathrm{mm}] \\ \delta_y\,[\mathrm{mm}] \\ \delta_z\,[\mathrm{mm}] \\ \gamma_x\,[°] \\ \gamma_y\,[°] \\ \gamma_z\,[°] \end{pmatrix}_i \quad (1)
$$

Was calculated by relating the three forces (Fx, Fy, Fz, forces in the x, y and z directions) and three moments (Mx, My, Mz, moments about the x, y and z axes). In each case, the six independent loads were applied and the resulting inter-fragmentary movements were (ux, uy, uz translations in x, y, and z and α, β, γ rotations about x, y, and z) [15]. The diagonal values of the stiffness matrix (S11, S22…, S66) correspond to the stiffness in the principal directions (i.e., S11 = anterior-posterior shear, S22 = medial lateral shear, S33 = axial compression, S44 = medial-lateral bending, S55 = anterior-posterior bending, S66 = axial torsion).

3. Results and discussion

3.1 Results of the six load cases for an Implant-bone analogue construct with offset (0 mm) (flush with the bone)

Table 1: The matrix of six load cases

Load	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
F_X (N)	30	0	0	0	0	0
F_Y (N)	0	-30	0	0	0	0
F_Z (N)	0	0	-240	0	0	0
M_X (N.m)	0	-3.54	0	12	0	0
M_Y (N.m)	-3.54	0	0	0	12	0
M_Z (N.m)	0	0	0	0	0	3

Table 2: The matrix of inter-fragmentary movements for the six load cases

Deformation	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
δ_X (mm)	0.1735	0	0	0	0.7618	0.0683
δ_Y (mm)	0	-0.1502	-0.0151	-0.6563	0	0
δ_Z (mm)	0	-0.0016	-0.0566	-0.2079	0	0
α (deg)	0	0.0924	0.2494	1.4023	0	0.0014
β (deg)	0.1094	0	0	0.0015	0.7926	0.0058
γ (deg)	0.0423	0	0.0014	0.006	-0.0586	0.5341

Table 3: The inverse matrix of inter-fragmentary movements

$$
\begin{bmatrix}
16.0161 & 0.1003 & 0.6991 & 0.1753 & -15.5328 & -1.8799 \\
-0.0589 & -22.5723 & -116.8857 & -27.8937 & 0.0626 & 0.0799 \\
-0.0523 & -13.9162 & -123.0177 & -24.7515 & 0.0555 & 0.0709 \\
0.0147 & 3.9623 & 29.5807 & 6.9532 & -0.0156 & -0.0199 \\
-2.1996 & -0.0212 & -0.1518 & -0.0371 & 3.3939 & 0.2445 \\
-1.5098 & -0.0183 & -0.0818 & -0.0312 & 1.6025 & 2.048
\end{bmatrix}
$$

Table 4: The stiffness matrix that determined from the load matrix multiply by the inverse matrix of inter-fragmentary movements

$$
\text{Stiffness} =
\begin{bmatrix}
480.48 & 3.01 & 20.97 & 5.26 & -465.98 & -56.39 \\
1.77 & 677.16 & 3506.57 & 836.81 & -1.87 & -2.39 \\
12.55 & 3339.89 & 29524.26 & 5940.37 & -13.33 & -17.03 \\
0.38 & 127.45 & 768.74 & 182.18 & -0.41 & -0.52 \\
-83.09 & -0.61 & -4.29 & -1.06 & 95.71 & 9.59 \\
-4.53 & -0.05 & -0.24 & -0.09 & 4.81 & 6.14
\end{bmatrix}
$$

Table 5: The stiffness components determined from the 3D stiffness matrix

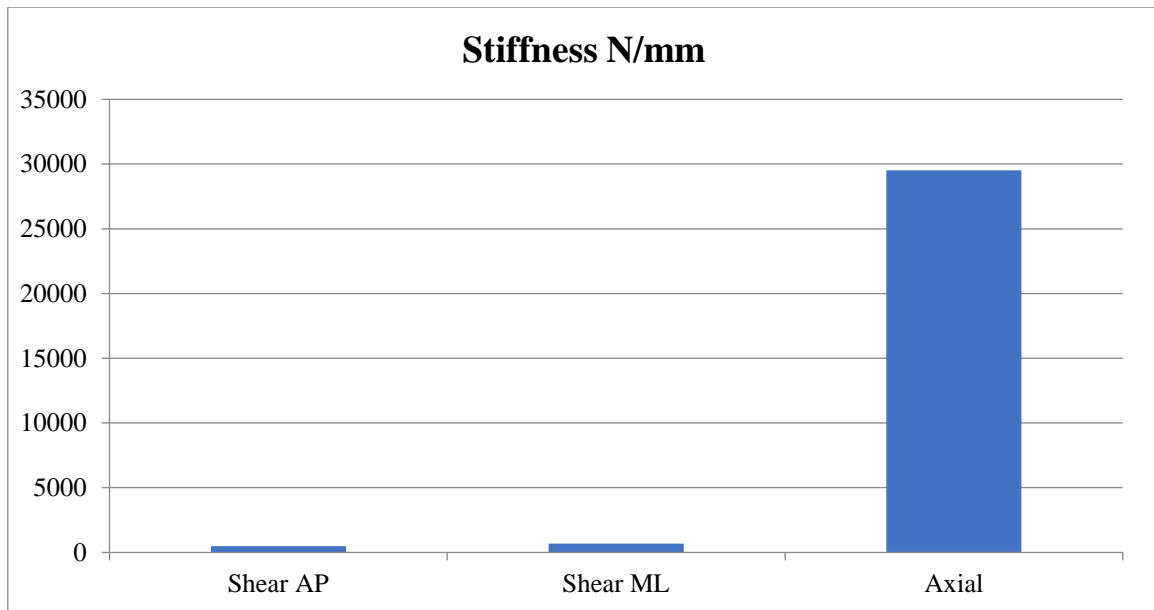|	
Stiffness of shear force in X direction (N/mm)	480.48
Stiffness of shear force in Y direction (N/mm)	677.16
Stiffness of axial force in Z direction (N/mm)	29524.26
Stiffness of moment about (X) axis (N. m / deg)	182.18
Stiffness of moment about (Y) axis (N. m / deg)	95.71
Stiffness of moment about (Z) axis (N. m / deg)	6.14

Figure 6. The stiffness components (Shear AP, Shear ML, Axial) determined for the internal fixator affixed at an offset distance of (0) mm to the bone analogue construct
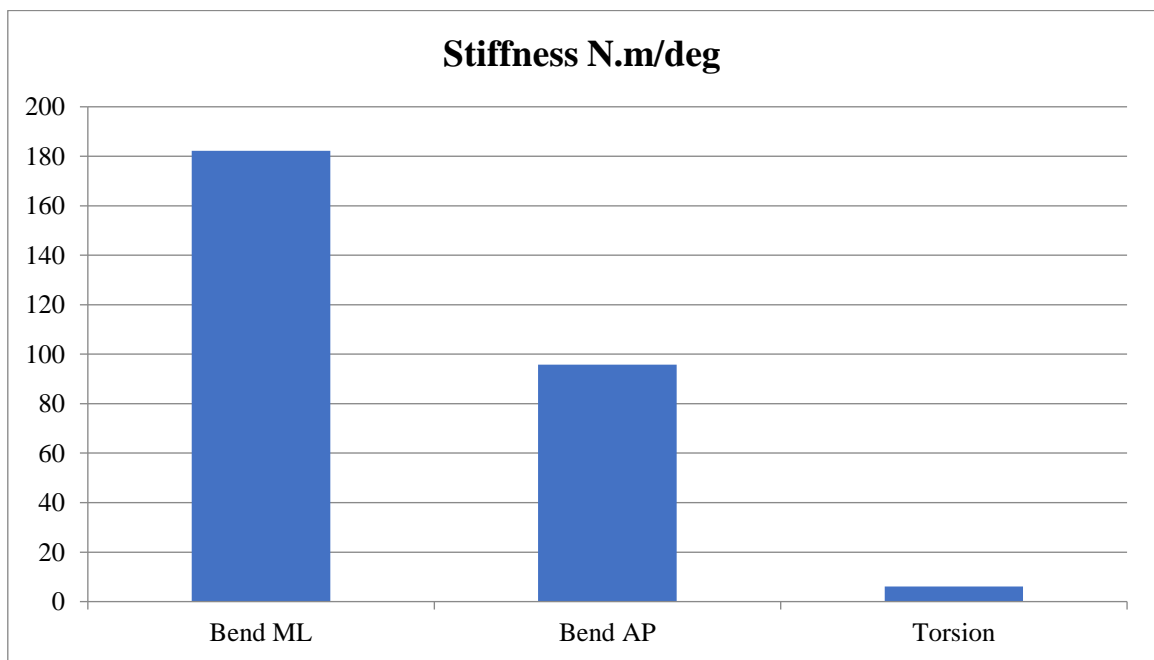

Figure 7. the stiffness components (Bend ML, Bend AP, Torsion) determined for the internal fixator affixed at an offset distance of (0) mm to the bone analogue construct

3.2 Results of six load cases for an Implant- Bone analogue construct with offset (1 mm)

Table 6: The matrix of six load cases

Load	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
F_X (N)	30	0	0	0	0	0
F_Y (N)	0	-30	0	0	0	0
F_Z (N)	0	0	-240	0	0	0
M_X (N.m)	0	-3.54	0	12	0	0
M_Y (N.m)	-3.54	0	0	0	12	0
M_Z (N.m)	0	0	0	0	0	3

Table 7: The matrix of inter-fragmentary movements for the six load cases

Deformation	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
δ_X (mm)	0.1857	0	0	0	0.7645	0.1241
δ_Y (mm)	0	-0.1621	-0.0097	-0.6721	0	0
δ_Z (mm)	0	-0.0011	-0.1202	-0.4304	0	0
α (deg)	0	0.0953	0.5046	2.3289	0	0
β (deg)	0.1104	0	0	0	0.9146	0.0055
γ (deg)	0.0783	0	0	0.0016	-0.0839	0.8714

Table 8: The inverse matrix of inter-fragmentary movements

$$\begin{bmatrix} 12.3003 & 9.1323 & 0.0677 & 0.0163 & -10.4363 & -1.6858 \\ 0 & -19.4916 & -98.3219 & -23.7958 & 0 & 0 \\ 0 & -11.9444 & -97.3628 & -21.4405 & 0 & 0 \\ 0 & 3.3856 & 25.1188 & 6.0486 & 0 & 0 \\ -1.4773 & -0.0016 & -0.0078 & -0.0018 & 2.3461 & 0.1956 \\ -1.2475 & -0.0071 & -0.0529 & -0.0127 & 1.1636 & 1.3178 \end{bmatrix}$$

Table 9: The stiffness matrix that determined from the load matrix multiply by the inverse matrix of inter-fragmentary movements

$$\text{Stiffness} = \begin{bmatrix} 369.01 & 0.27 & 2.03 & 0.49 & -313.09 & -50.57 \\ & 584.75 & 2949.66 & 713.87 & 0 & 0 \\ 0 & 2866.64 & 23367.08 & 5145.72 & 0 & 0 \\ 0 & 109.63 & 649.48 & 156.82 & 0 & 0 \\ -61.27 & -0.04 & -0.33 & -0.08 & 65.09 & 8.31 \\ -8.74 & -0.02 & -0.16 & -0.04 & 3.49 & 3.95 \end{bmatrix}$$

Table 10: The stiffness components determined from the 3D stiffness matrix

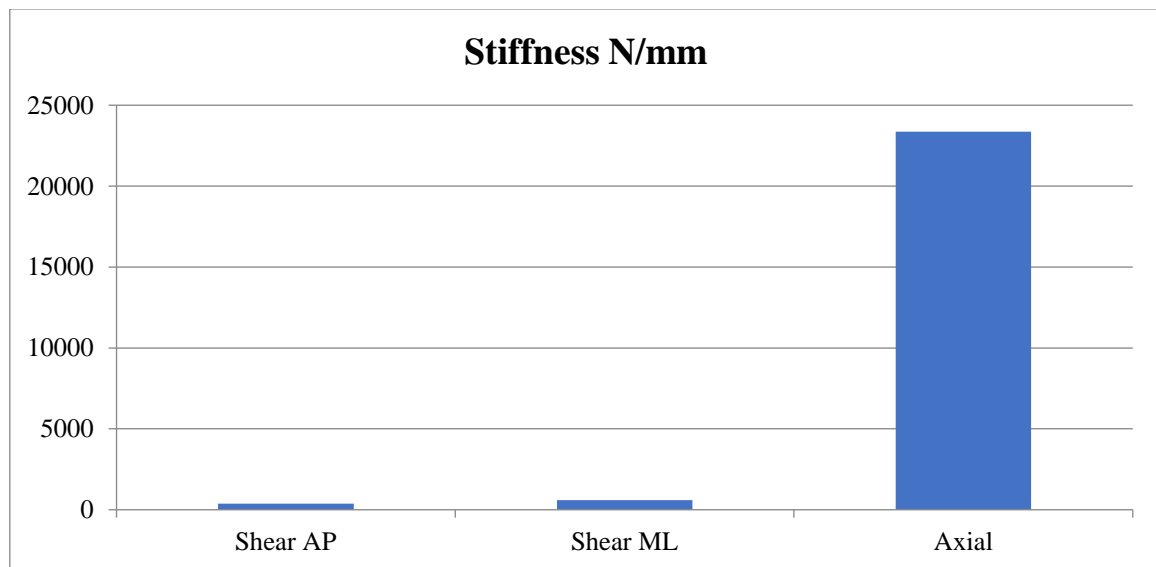|	
Stiffness of shear force in X direction (N/mm)	369.01
Stiffness of shear force in Y direction (N/mm)	584.75
Stiffness of axial force in Z direction (N/mm)	23367.08
Stiffness of moment about (X)axis (N.m / deg)	156.82
Stiffness of moment about (Y)axis (N.m / deg)	65.09
Stiffness of moment about (Z)axis (N.m / deg)	3.95

Figure 8. The stiffness components (Shear AP, Shear ML, Axial) determined for the internal fixator affixed at an offset distance of (1) mm to the bone analogue construct
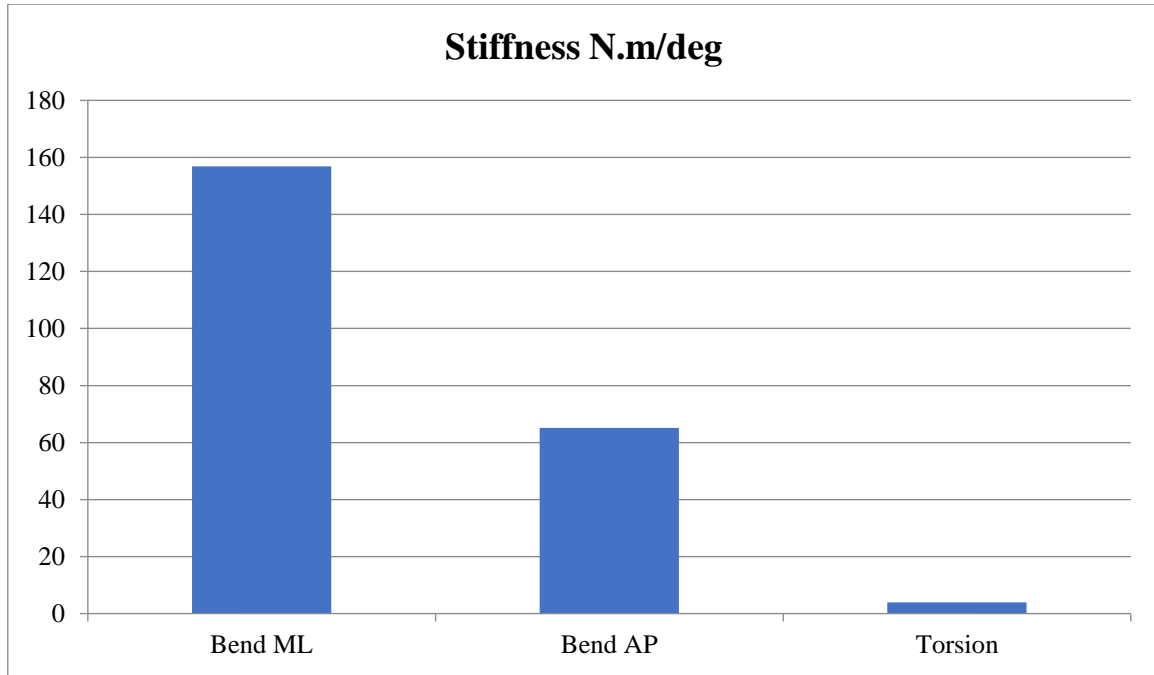
Figure 9. The stiffness components (Bend ML, Bend AP, Torsion) determined for the internal fixator affixed at an offset distance of (1) mm to the bone analogue construct

3.3 Results of six load cases for an Implant- bone analogue construct with offset (2 mm)

Table 11: The matrix of six load cases

Load	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
F_X (N)	30	0	0	0	0	0
F_Y (N)	0	-30	0	0	0	0
F_Z (N)	0	0	-240	0	0	0
M_X (N.m)	0	-3.54	0	12	0	0
M_Y (N.m)	-3.54	0	0	0	12	0
M_Z (N.m)	0	0	0	0	0	3

Table 12: The matrix of inter-fragmentary movements for the six load cases

Deformation	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
δ_X (mm)	0.1892	0	0	0	0.7649	0.1398
δ_Y (mm)	0	-0.1625	-0.0091	-0.6723	0	0
δ_Z (mm)	0	-0.0011	-0.1383	-0.4634	0	0
α (deg)	0	0.0955	0.5426	2.3326	0	0
β (deg)	0.1108	0	0	0	0.9299	0.0062
γ (deg)	0.0881	0	0	0	-0.0893	0.9205

Table 13: The inverse matrix of inter-fragmentary movements

$$\begin{bmatrix} 11.9588 & 0 & 0 & 0 & -10.0048 & -1.7488 \\ 0 & -3.4846 & 18.9032 & 4.7597 & 0 & 0 \\ 0 & -2.0415 & -21.7059 & -3.7237 & 0 & 0 \\ 0 & 0.6175 & 4.2752 & 1.1 & 0 & 0 \\ -1.4164 & 0 & 0 & 0 & 2.2596 & 0.1999 \\ -1.2819 & 0 & 0 & 0 & 1.1767 & 1.2731 \end{bmatrix}$$

Table 14: The stiffness matrix that determined from the load matrix multiply by the inverse matrix of inter-fragmentary movements

$$
\text{Stiffness} =
\begin{bmatrix}
358.76 & 0 & 0 & 0 & -300.14 & -52.46 \\
0 & 616.21 & 2975.2 & 768.66 & 0 & 0 \\
0 & 2888.15 & 21811.91 & 5165.63 & 0 & 0 \\
0 & 116.39 & 653.49 & 168.52 & 0 & 0 \\
-59.33 & 0 & 0 & 0 & 62.53 & 8.59 \\
-3.84 & 0 & 0 & 0 & 3.53 & 3.82
\end{bmatrix}
$$

Table 15: The stiffness components determined from the 3D stiffness matrix

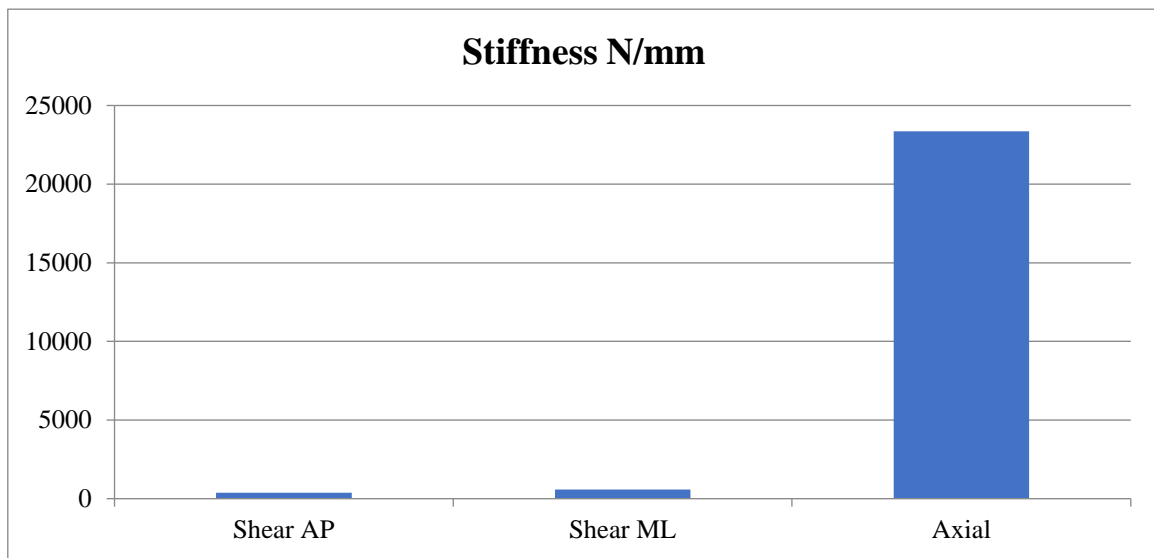|	
Stiffness of shear force in X direction (N/mm)	358.76
Stiffness of shear force in Y direction (N/mm)	616.21
Stiffness of axial force in Z direction (N/mm)	21811.91
Stiffness of moment about (X)axis (N.m / deg)	168.52
Stiffness of moment about (Y)axis (N.m / deg)	62.53
Stiffness of moment about (Z)axis (N.m / deg)	3.82

Figure 10. the stiffness components (Shear AP, Shear ML, Axial) determined for the internal fixator affixed at an offset distance of (2) mm to the bone analogue construct
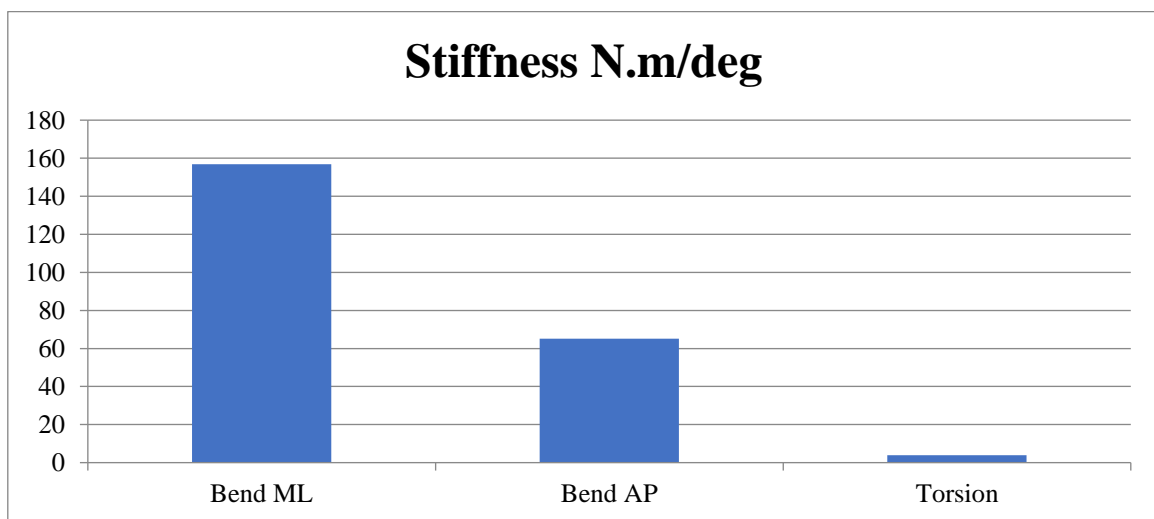

Figure 11. the stiffness components (Bend ML, Bend AP, Torsion) determined for the internal fixator affixed at an offset distance of (2) mm to the bone analogue construct

Internal fixator offset:

Table 16: The influence of implant offset to the bone analogue on the stability of internal plate fixation

	implant-Bone analogue construct flush to the bone	implant-Bone analogue construct 1 mm offset	% reduction in stiffness
Stiffness of AP shear force (N/mm)	480.48	369.01	23
Stiffness of ML shear force (N/mm)	677.16	584.75	14
Stiffness of axial force (N/mm)	29524.26	23367.08	21
Stiffness of Bend ML (N.m / deg)	182.18	156.82	14
Stiffness of Bend AP (N.m / deg)	95.71	65.09	32
Stiffness of Bend Torsion (N.m / deg)	6.14	3.95	36

The stiffness decreased by 14 to 36 % when the implant was offset 1mm to the bone analogue. The greatest reduction occurred in the torsion direction (36 %).
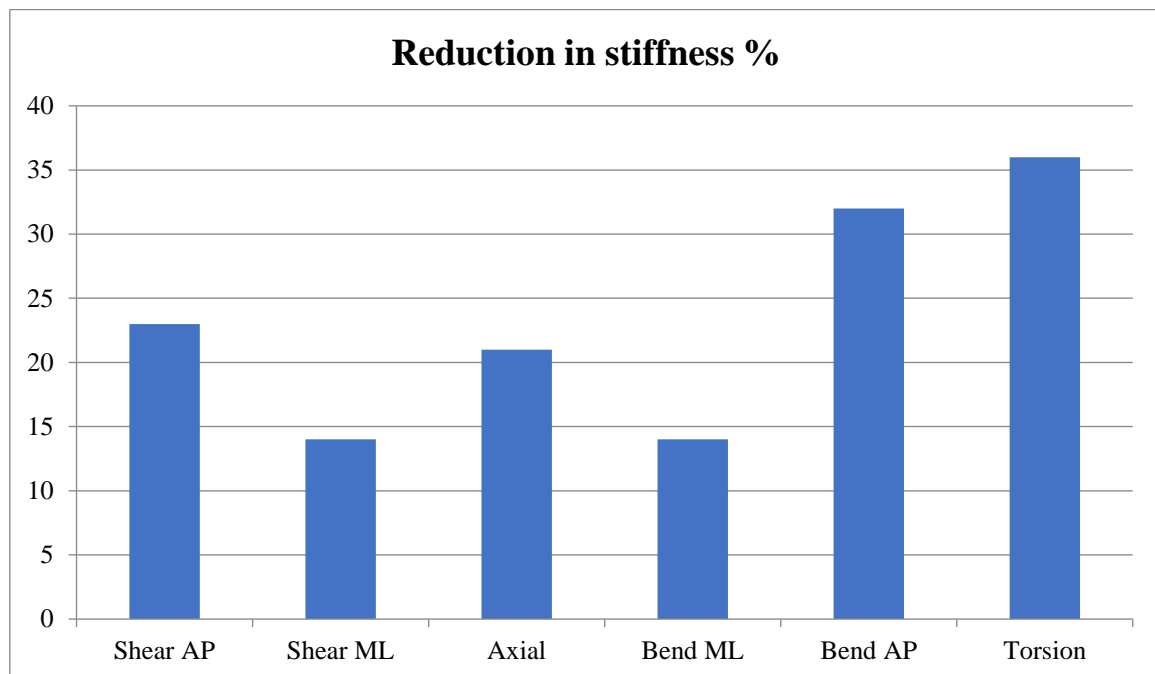

Figure 12. Reduction in stiffness when the implant was offset 1 mm to the bone analogue

Internal fixator offset:

Table 17: The influence of implant offset to the Bone analogue on the stability of internal plate fixation

	implant-Bone analogue construct flush to the bone	implant-Bone analogue construct 2 mm offset	% reduction in stiffness
Stiffness of AP shear force (N/mm)	480.48	358.76	25
Stiffness of ML shear force (N/mm)	677.44	616.21	9
Stiffness of axial force (N/mm)	29534.03	21811.91	26
Stiffness of Bend ML (N.m / deg)	181.15	168.52	7
Stiffness of Bend AP (N.m / deg)	95.09	62.53	34
Stiffness of Bend Torsion (N.m / deg)	6.14	3.82	38

The stiffness was decreased by 7 to 38 % when the implant was offset 2 mm to the Bone analogue. The greatest reduction occurred in the torsion direction (38 %).
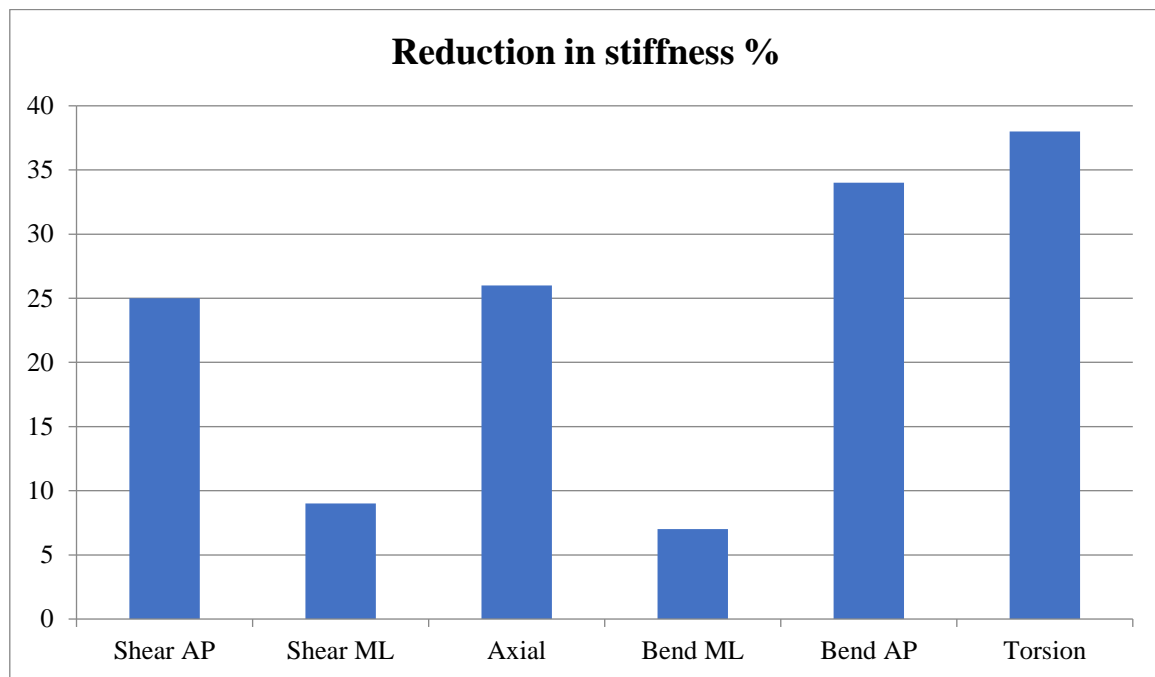

Figure 13. Reduction in stiffness when the implant was offset 2mm to the bone analogue

4. Conclusions

To preserve the bone's peripheral blood supply, the plate should be kept at a small distance from the bone during internal fixation. The effect of offset was explored in this study by: Increasing the offset between the plate and the bone analogue from flush to the bone to a 1 mm and flush to the bone to a 2 mm. The stiffness was decreased by 14 to 36 % when the implant was offset 1 mm to the Bone analogue. The greatest reduction occurred in the torsion direction (36 %), and the stiffness were decreased by 7 to 38 % when the implant was offset 2 mm to the Bone analogue. The greatest reduction occurred in the torsion direction (38 %). From the analysis of ANSIS results, the following conclusions can be obtained:

1. All stiffness components were decreased when increasing the offset between the plate and the bone analogue.

2. The greatest reduction occurred in the torsion direction when increasing the offset between the plate and the bone analogue.

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