MECHANICAL EVALUATION OF LOCKING COMPRESSION PLATE

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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LIST OF ABBREVIATION

DIC	Digital Image Correlation
FEA	Finite Element Analysis

ABSTRAK

Plat penguncian mampatan telah banyak digunakan dalam pemulihan patah tulang femoral. Terdapat banyak kes menunjukkan bahawa kerosakan boleh berlaku sebelum pemulihan patah tulang femoral. Contohnya, kepatahan plat penguncian mampatan, kebengkokan plat penguncian mampatan, kerosakan tulang dan penarikan skru daripada tulang.

Kajian ini fokus pada pengkajian pencatatan dalam arah y, maksimum ketegangan utama, minimum ketegangan utama dan ketegangan dalam arah y plat penguncian mampatan dengan menggunakan kaedah korelasi imej digital dan analysis unsur terhingga. Keputusan bagi kedua-dua cara ini akan diperbandingkan untuk menentukan ketepatan keputusan korelasi imej digital. Selain itu, analysis unsur terhingga juga digunakan untuk menganalisa pengagihan tekanan bagi tulang.

Kadar perbezaan antara keputusan kaedah korelasi imej digital dan analisis unsur terhingga adalah kurang daripada 15%. Oleh itu, kaedah korelasi imej digital boleh digunakan untuk menentukan pencacatan dan pengagihan ketegangan plat penguncian mampatan. Selain itu, analisis unsur terhingga menunjukkan bahawa pengagihan tekanan adalah tinggi di antara muka skru dan tulang. Tekanan di anatara muka skru pertama dengan tulang ialah 43.1 MPa dan tekanan di antara muka skru kedua dengan tulang ialah 77.5 MPa. Tekanan yang rendah iaitu 2.9 MPa dijumpai di bahagian lain tulang.

ABSTRACT

Locking Compression Plate, LCP has been widely used in the femoral shaft fracture fixation. The clinical cases show that the failure of locking compression plate is possible before the adequate healing of the fracture. The types of failures occur are plate bending, plate breakage, bone failure at the screw and screw pulling out.

This research is focus on determining the deformation in y-direction, maximum principal strain, minimum principal strain and strain in y-direction of locking compression plate surface using Digital Image Correlation and Finite Element Analysis. The results of two methods is compared to determine the accuracy of Digital Image Correlation method. Relative error will be calculated to determine the accuracy of Digital Image Correlation results. Besides, Finite Element Analysis is used to analyse the stress distribution of transverse fracture femoral shaft to determine the stress distribution at bone screw interface.

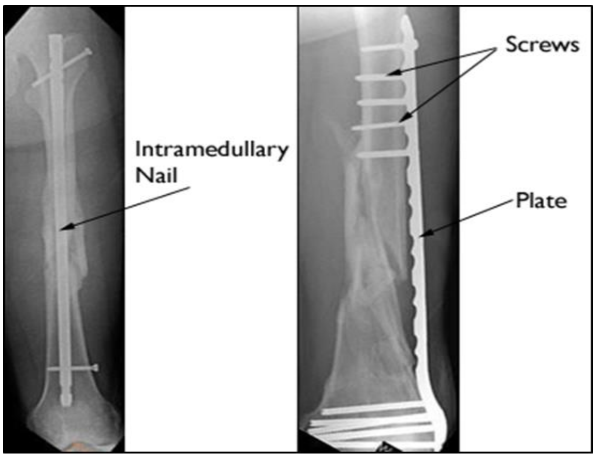
The relative errors between Digital Image Correlation and Finite Element Analysis results are less than 15%, meaning that Digital Image Correlation is applicable to determining deformation and strain distribution of locking compression plate surface. Besides, the Finite Element Analysis shows that the stress distribution at first screw and second screw bone interfaces are 43.1 MPa and 77.5 MPa while the stress at other region of the bone is 2.9 MPa.

CHAPTER ONE: INTRODUCTION

1.1 Research Background

Cases of femoral fractures constituted 39% of the total patients admitted in Orthopaedic Department of Benazir Bhutto Hospital during the study period, followed by humerus (15%), tibia and fibula (11%) [1]. In the case of femoral fractures, fractures of shaft of femur comprised around 45% of total femoral fractures, pertrochanteric fractures 35% and neck of femur 20%. Majority (34.6%) were in the age group of 11 to 40 years and 31.1% patients were over 60 years of age, showing bimodal trend in both male and female patients [2].

Femoral shaft fracture can be fixed by placing metal pins and screws into the bone above and below the fracture site. The metal pins and screws are used to hold the fracture bone in fix position so that the bone fracture can be healed. Currently, there are two types of fixation method for femoral shaft fracture that are intramedullary nailing and locking compression plate as shown in Figure 1.1. Intramedullary nailing is the insertion of metal rod into the marrow canal of the femur. The rod passes across the fracture to keep it in position [4]. For the operation using locking compression plate, the bone fragments are first repositioned into their normal alignment. They are held together with special screws and metal plates attached to the outer surface of the bone [4]. Locking compression plate is a type of screw plate system which utilizes standard screws and locking head screws to achieve fixed-angle stability.



(a) (b)

Figure 1.1: (a) Intramedullary nailing and (b) Locking compression plate [3]

The patients treated with locking compression plate exhibited the best results with respect to consolidation and joint mobility. In other words, disphyseal femur fractures or femoral shaft fractures with complex features can be managed well by using locking compression plate as it is easier to control rotational and angular deformities and initial shortening of the fracture.

1.2 Problem Statement

Locking compression plate, LCP has been widely used in the treatment of femoral shaft fracture due its proven advantages. But, there is still some cases where the failure of LCP occurs before the healing of fracture. The most common types of failures occur are implant loosening, screws pulling out, bending of locking compression plate and breakage of locking compression plate. Research has been done to study the breakage and bending of locking compression plate by determining the strain distribution of locking compression plate. Strain rosettes has been used to study the strain distribution on the locking compression plate, but it only can be used to study the strain of a point at a time. Therefore, the use of strain rosettes in studying the strain distribution of locking compression plate is inefficient. Besides, the pulling out of screw from the bone or implant loosening is deduced that it is caused by high stress concentration at the bone screw interface.

1.3 Objectives

In this study, the objectives are:

1) To compare strain and deformation of locking compression plate determined using Digital Image Correlation (DIC) and Finite Element Analysis (FEA).
2) To determine the stress distribution at bone screw interface using Finite Element Analysis (FEA).

1.4 Thesis Outline

In this project, five chapters are included. In chapter one, the research background is first discussed, followed by problem statements and objectives of this project.

Chapter two discuss the femoral shaft fracture as well as how it is treated and implant failures. Then, the Finite Element Analysis and Digital Image Correlation are discussed in the aspect of previous works that have been done by others researchers. Next, the principle of plane strain is discussed.

Chapter three discuss about the preparation of sample which include preparation of transverse fracture femoral shaft, locking compression plate, self-tapping screws, speckles pattern and fabrication of fixture. Then, procedure of mechanical testing is discussed which involves setting up of apparatus followed by image analysis which include scaling, volume extraction and processing of images. Next, Finite Element Analysis is discussed in the aspect of model, material, contact modelling, mesh and boundary conditions.

Chapter four discuss the mesh convergence study to determine the appropriate element size. Then, the comparison of DIC and FEA is discussed to determine the accuracy of the DIC method. Next, stress distribution of bone is discussed to determine the stress distribution at screw bone interface.

In chapter five, the conclusion is made based on the findings to determine whether the objectives of this project is achieved or not. Then, suggestions are given to improve the future works so that better results can be obtained.

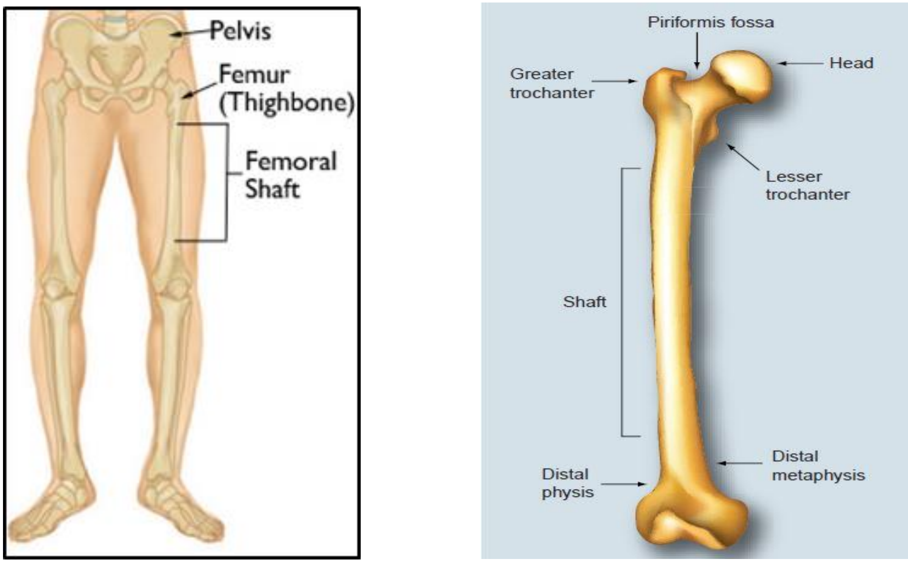
CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter is about the femoral shaft fractures and how it is treated with locking compression plate. Some of the clinical cases showing the failure of femoral shaft fracture treated with locking compression plate are also discussed. Besides, the research that have been done by other people to study the failure of locking compression plate using Digital Image Correlation and Finite Element Analysis are included in this chapter.

2.2 Femoral Shaft Fracture

The femur is the longest, strongest, and heaviest tubular bone in the human body and one of the principal load bearing bones in the lower extremity [4]. The long and straight part of the femur is known as the femoral shaft. When there is a break on the femoral shaft, it is known as femoral shaft fracture. Fractures of the femoral shaft often result from high energy forces such as motor vehicle collisions [4]. Bone structure of human lower body and anatomy of bone femur are illustrated in Figure 2.1. Femoral shaft fracture can be categorized into many types that are transverse, linear, non-displaced, displaced compound, spiral, greenstick and comminuted as shown in Figure 2.2.



(a) (b)

Figure 2.1: (a) Bone structure of human lower body (b) Anatomy of human bone femur [3]

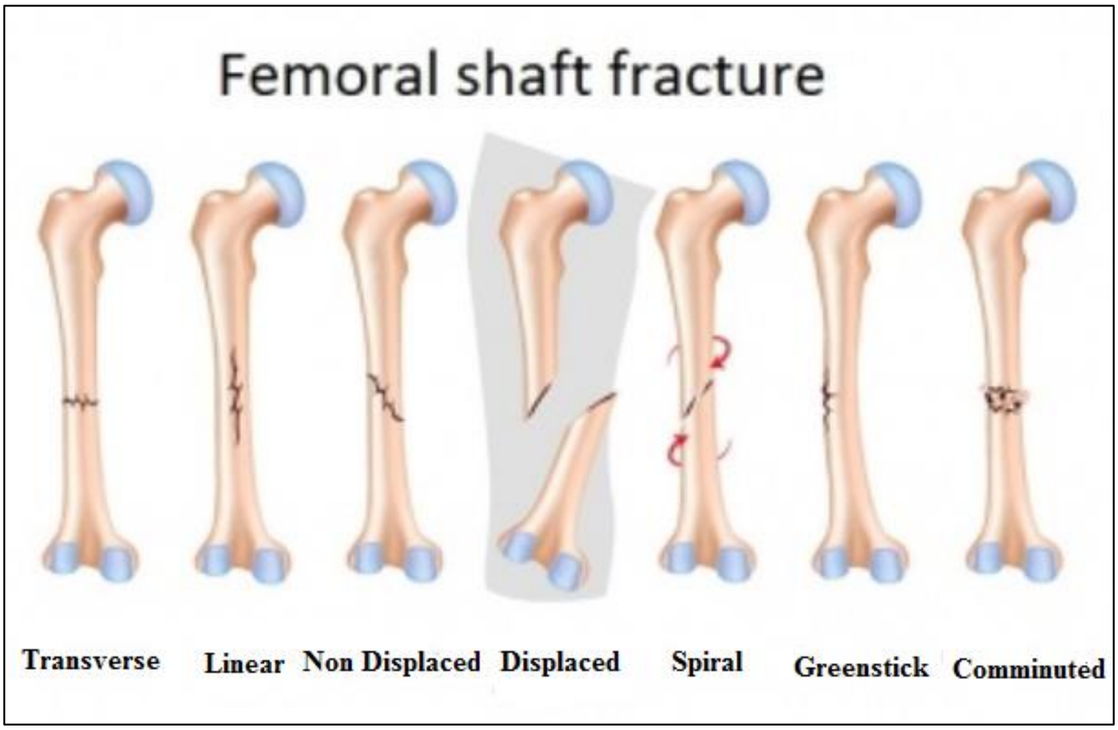


Figure 2.2: Types of femoral shaft fracture [5]

2.2.1 Internal Fixation

During a bone fracture, the bone needs support to withstand the load and movement of the body while passing through the healing process. To provide support to the body throughout the healing process, internal fixation has been used to hold the fracture bones in place. Currently, one of the most common types of internal fixation method for femoral shaft fracture is the use of locking compression plate as shown in Figure 2.3 and Figure 2.4.

Locking compression plate is a type of fixation plate used for internal fixation. Locking compression plate offers the possibility of inserting conventional and locking head screws into the specially designed combination holes, improving the fracture fixation. It can house both locking and non-locking screws depending upon the fracture type and bone rigidity. The threaded hole section for locking screws and non-threaded hole section for non-locking screws. The non-locking screw also can be known as conventional screws. Conventional screws create friction at the interface of plate and screws by pressing the plate to the bone while locking screws does not press the body towards the bone [6]. By using conventional screws and locking screw, fixed-angle stability can be achieved. Figure 2.5 shows how a femoral shaft fracture is treated with locking compression plate.

Figure 2.3: Locking compression plate [7]

Figure 2.4: Locking screw hole and non-locking screw hole [7]

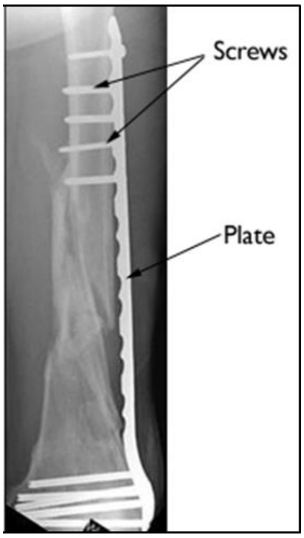
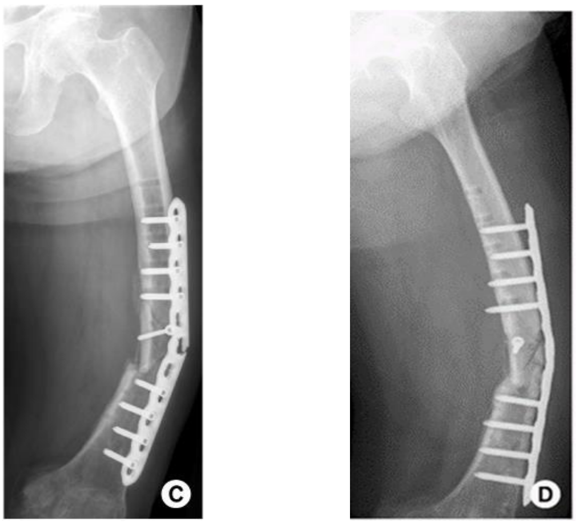


Figure 2.5: Femoral shaft fracture treated with locking compression plate [3]

2.2.2 Implant Failures

As the treatment of femoral shaft fractures using locking compression plate increases, more clinical studies have been reported [8]. And, the effectiveness of locking compression plate in treating femoral shaft fractures have been confirmed. But, there are still cases regarding the failure of locking compression plate such as breakage of locking compression plate [9], bending of locking compression plate [9] and screws pulling out [10] as shown in Figure 2.6 and Figure 2.7.



(a) (b)

Figure 2.6: (a) Breakage of locking compression plate (b) Bending of locking compression plate [9]

Figure 2.7: Screws pulling out from bone [10]

2.3 Finite Element Analysis

Finite element model has been used to study the stress distribution on the locking compression plate. By understanding the stress distribution on locking compression plate, the factors that cause the failure of locking compression plate can be determined.

Finite element analysis has been used to determine the effect of working length on breakage of locking compression plate. Working length is the number of unoccupied screw holes over the fracture side [11]. In this research, two cases are studied that are one unoccupied screw holes over the fracture site and six unoccupied screw holes over the fracture site as shown in Figure 2.8 and Figure 2.9. In the case of one unoccupied screw hole over the fracture site, high stress is observed on the outer edges of the unoccupied screw hole because of the short working length which hinder the callus formation through micro motion. When the stress at the outer edges of the unoccupied hole is greater than the yield strength of stainless steel, the plate breaks and this is known as fatigue failure.

In the case of six unoccupied screw holes over the fracture site, low stress is observed on the outer edges of the unoccupied screw holes compared to case one because of the large working length which allows the callus formation through micro motion. Since the stress at the outer edges of the unoccupied screw holes is smaller than the yield strength of stainless steel, the plate does not break. In short, the insertion of screws over the fracture site is not an ideal position because it will lead to the breakage of locking compression plate due to fatigue failure. For fracture like transverse fracture femoral shaft which only involves small fracture site, one unoccupied screw hole is enough to prevent the breakage of locking compression plate. For oblique fracture femoral shaft which involves large fracture site, more than one unoccupied screw holes are needed to prevent the breakage of locking compression plate. The number of unoccupied screw hole should be enough to cover the entire fracture site.

.

(a) (b)

Figure 2.8: (a) Femoral shaft fracture treated with locking compression plate (b) Locking compression plate breakage [11]

(a) (b)

Figure 2.9: (a) Femoral shaft fracture treated with locking compression plate (b) Condition of locking compression plate after 6 months of treatment [11]

Besides, finite element model as shown in Figure 2.10 has been built to study the effect of position of locking screws on the ability to withstand bending and torsion motion. Four point bending and five degree of torsion are applied on the bone model separately for different position combination of locking screws as shown in Figure 2.11. The results shows that the control treatment with locking screws at every position of the locking compression plate except for the hole over the facture site has the best ability to withstand the bending and torsion motion without the happening of pulling out of screw [12]. In short, it is better to insert the screws at every position of locking compression plate except for the hole over the fracture site.

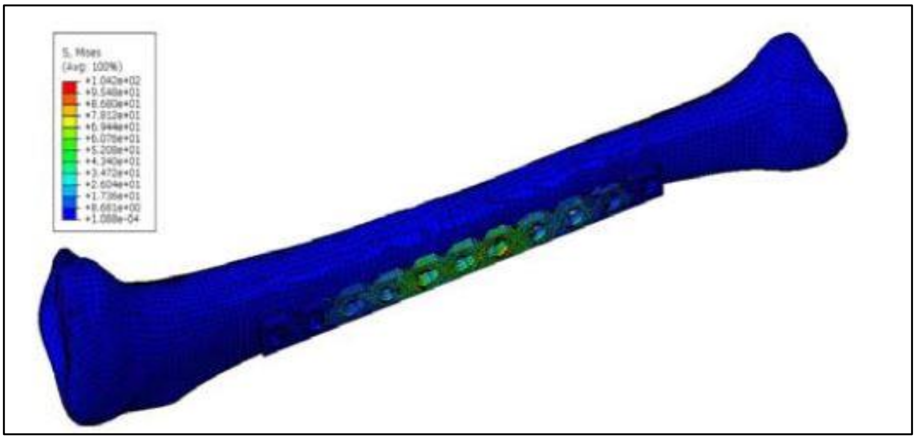


Figure 2.10: Finite element model of femoral shaft fracture treated with locking compression plate [12]

Treatment	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
Control	L[a]	L	L	L	L	_	L	L	L	L	L
1	L	L		L		_		L		L	L
2	L		L		L	_	L		L		L
3			L	L	L	_	L	L	L		
4	L	L	L			_			L	L	L
5	L			L	L	_	L	L			L
6		L		L	L	_	L	L		L	
7	L	L			L	_	L			L	L
8		L	L	L		_		L	L	L	

a. "L" Shows a LCP hole which house a locking screw.

Figure 2.11: Different combination of locking screws position on locking compression plate [12]

2.4 Digital Image Correlation (DIC)

Digital image correlation is a non-invasive technique to measure the deformation of a sample by just studying image taken from it [13]. This technique can only be applied to 2D deformation calculation of a sample. To determine 3D deformation of a sample, Digital Volume Correlation is needed.

In DIC, a camera is needed to image the speckle pattern on the sample surface. The image taken will be processed by software named Davis and discretises the image into smaller subcells or facets as shown in Figure 2.12. When load is applied on the sample, its surface will begin to displace and deform. The displacement of the pattern can be observed in the facet. When there is a best match of the pattern, displacement can be observed within that facet as shown in Figure 2.13. In other words, DIC tracking and comparing the position of the same physical points shown in a reference image and a deformed image [14].

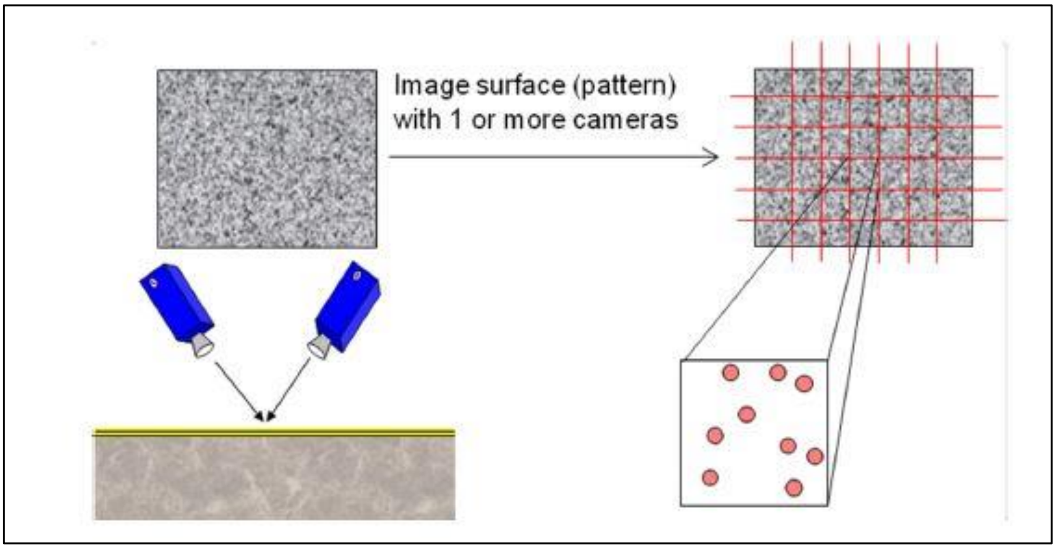


Figure 2.12: Discretizing of image into subcell or facet [13]

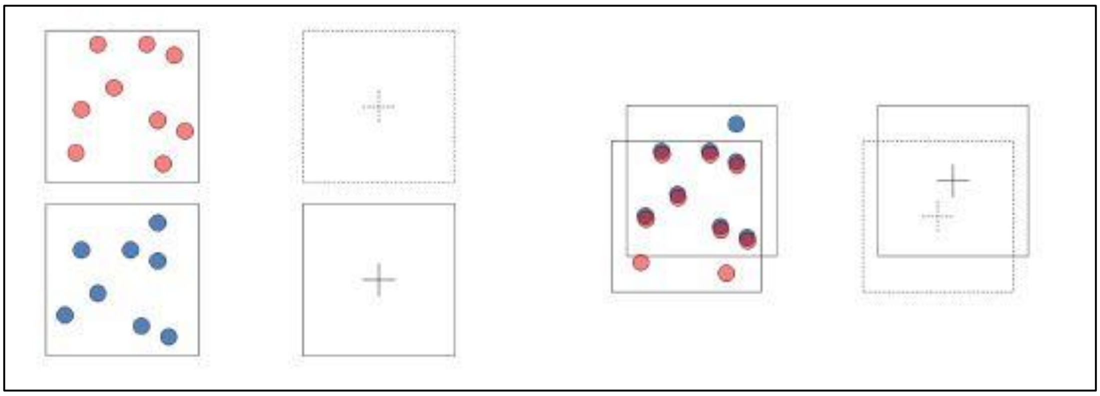


Figure 2.13: Comparison of reference image and deformed image [13]

Digital Image Correlation, DIC has been applied by researchers to study the strain distribution or deformation on the surface of the locking compression plate when it is under loading [15]. By performing this analysis, the region where the failure of locking compression plate occur can be known and also factors that cause failure of locking compression plate through applying different loading conditions. The experiment is set up as shown in Figure 2.14. Since the sample is too large for the camera to image the entire surface of locking compression plate, so the camera only used to image the upper part of the locking compression plate. Digital Image Correlation is used to study the lateral deformation of region between screw 1 and screw 2. And, also the lateral deformation of region between screw 2 and screw 3. The results obtained from Digital Image Correlation is compared with the results of Finite Element Analysis.

The results from both DIC and FEA shows that maximum deformation is observed at the edge of the holes. And, the difference of results obtained using DIC and FEA is relatively small which is 5% to 8% [15]. In other words, DIC can be used to determine the deformation on the surface of a locking compression plate with high accuracy. Figure 2.15 shows another experiment that has been conducted to determine the deformation of locking compression plate. The deformation of locking compression plate is obtained using DIC and FEA. The results obtained using both technique are compared. The results shows that the maximum deformation happened at the edge of the hole [16]. And, the difference between results obtained using DIC and FEA is relatively small which is around 5% to 10%.

Figure 2.14: Strain and deformation analysis of locking compression plate using digital image correlation [15]

Figure 2.15: Experiment set up for digital image correlation [16]

2.5 Plane Strain

The general state of strain at a point in a body is represented by a combination of three components of normal strain, ε_x, ε_y, ε_z and three components shear strain γ_{xy}, γ_{xz}, γ_{yz} as shown in Figure 2.16 [17]. Three components of normal strain, ε_x, ε_y, ε_z can be calculated using the equation 2.1, 2.2, and 2.3 shown below. The changes of these six components at each point of the material tend to deform the entire body. In plane strain, the effect of components ε_z, γ_{xz} and γ_{yz} are neglected. In other words, plane strain is subjected to two normal strain ε_x, ε_y and one shear strain γ_{xy}as shown in Figure 2.17.

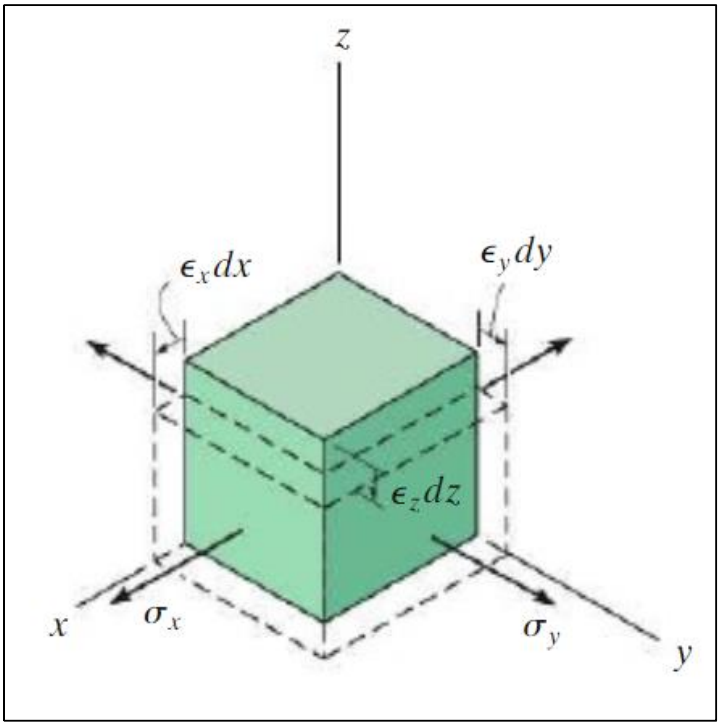


Figure 2.16: State of strain at a point in a body [17]

$$\varepsilon_x = \frac{1}{E}\,[\sigma_x - v\,(\sigma_y + \sigma_z)] \qquad (2.1)$$

$$\varepsilon_y = \frac{1}{E}\,[\sigma_y - v\,(\sigma_x + \sigma_z)] \qquad (2.2)$$

$$\varepsilon_x = \frac{1}{E}\,[\sigma_z - v\,(\sigma_x + \sigma_y)] \qquad (2.3)$$

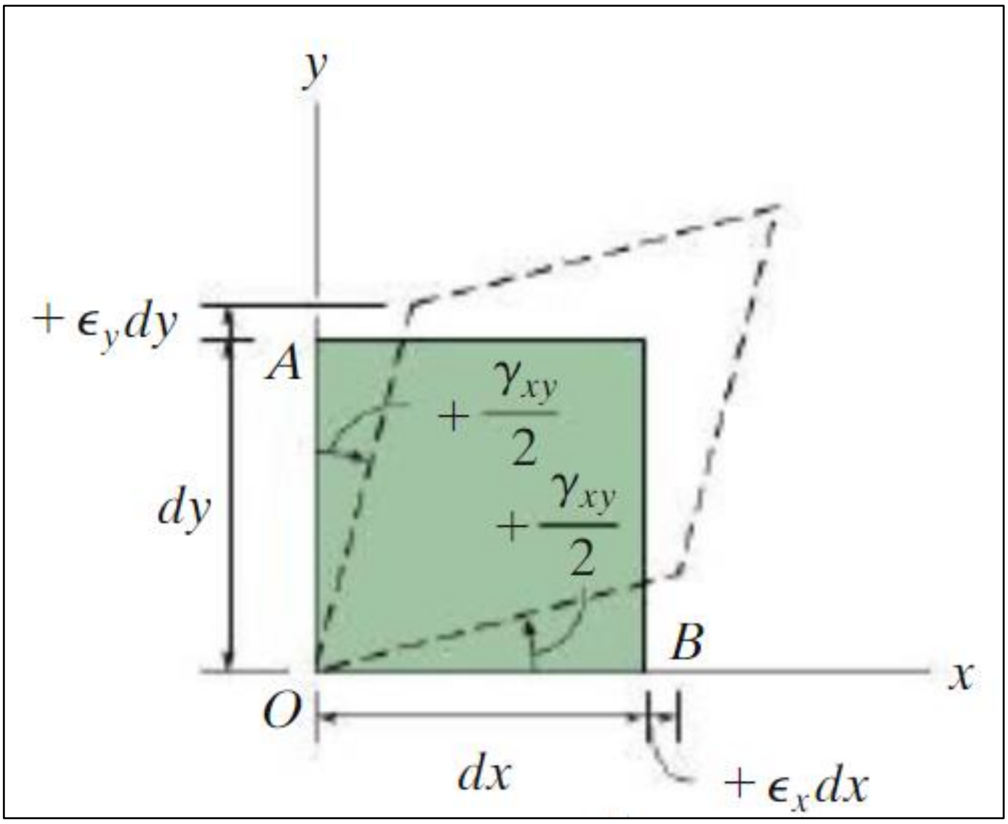


Figure 2.17: Plane strain [17]

The two normal strain ε_x, ε_y and one shear strain γ_{xy} can be calculated using euqation 2.4, 2.5 and 2.6 when the element is oriented to certain angle. The state of the strain can also be represented in principal strain as illustrated in Figure 2.18. Principal strain occurs when an element is oriented so that the deformation is only caused by normal strain and shear strain is zero. Principal strain can be categorized into maximum and minimum principal strain depends on the magnitude of ε_1 and ε_2. The value of ε_1 and ε_2 can be calculated using equation 2.8 shown below. In order to know ε_1 and ε_2 acting in which direction, the angle calculated using equation 2.7 can be substituted into equation 2.4 and 2.5. If the value is same with ε_1 or ε_2 then the strain is acting on that direction

$$\varepsilon_{x'} = \frac{\varepsilon_x+\varepsilon_y}{2} + \frac{\varepsilon_x-\varepsilon_y}{2}\cos 2\theta + \frac{\gamma_{xy}}{2}\sin 2\theta \tag{2.4}$$

$$\varepsilon_{y'} = \frac{\varepsilon_x+\varepsilon_y}{2} - \frac{\varepsilon_x-\varepsilon_y}{2}\cos 2\theta - \frac{\gamma_{xy}}{2}\sin 2\theta \tag{2.5}$$

$$\frac{\gamma_{x'y'}}{2} = -(\frac{\varepsilon_x-\varepsilon_y}{2})\sin 2\theta + \frac{\gamma_{xy}}{2}\cos 2\theta \tag{2.6}$$

$$\tan 2\theta_p = \frac{\gamma_{xy}}{\varepsilon_x-\varepsilon_y} \tag{2.7}$$

$$\varepsilon_{1,2} = \frac{\epsilon_x+\epsilon_y}{2} \pm \sqrt{(\frac{\varepsilon_x-\varepsilon_y}{2})^2 + (\frac{\gamma_{xy}}{2})^2} \tag{2.8}$$

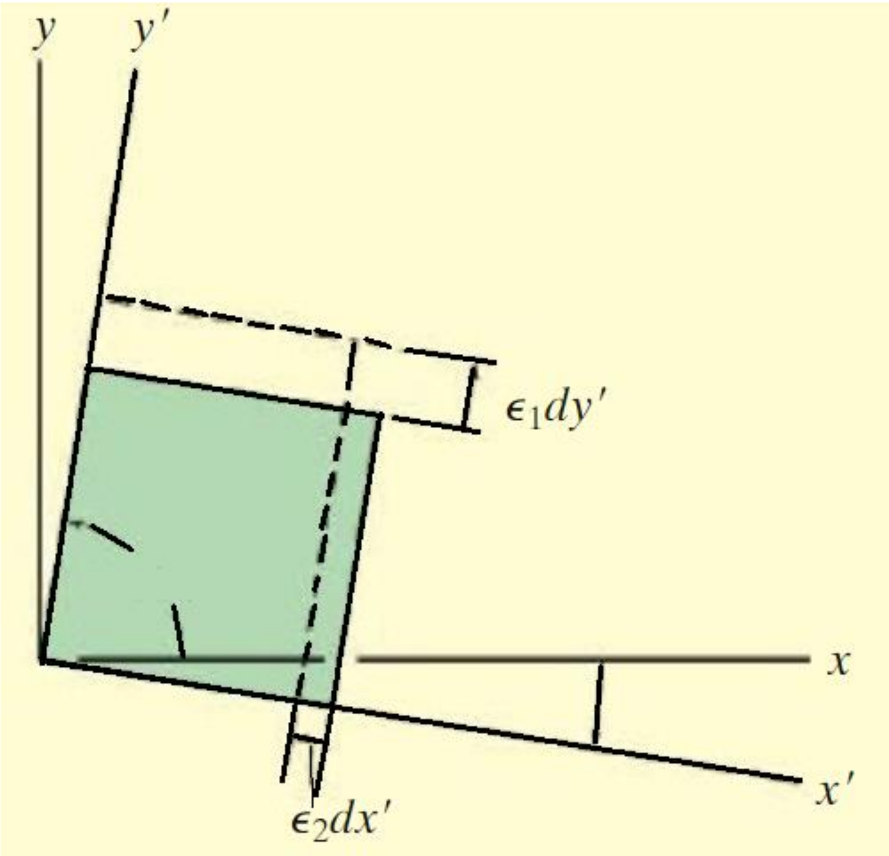


Figure 2.18: Principal strain [17]

CHAPTER THREE: RESEARCH METHODOLOGY

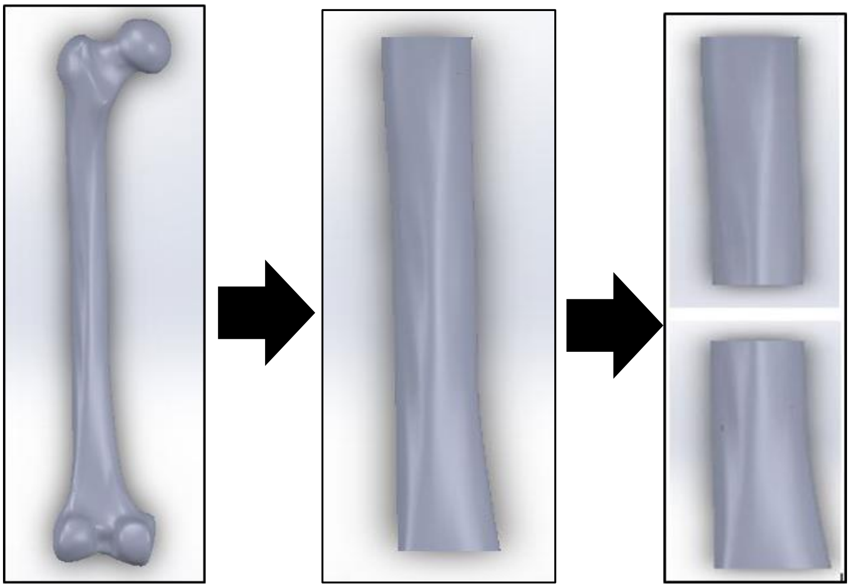
3.1 Introduction

A transverse fracture femoral shaft model with locking compression plate fixation was prepared. The transverse fracture femoral shaft model was compressed using Universal Testing Machine. At the same time, the deformation and strain distribution of locking compression plate were determined using Digital Image Correlation (DIC). A finite element model of transverse fracture femoral shaft was built to determine the deformation, strain distribution of locking compression plate and stress distribution of bone.

3.2 Sample Preparation

3.2.1 Preparation of Transverse Fracture Femoral Shaft

The human femur model in STL format was obtained from Sawbones 3rd generation. The human femur model was modified in SolidWorks to obtain the transverse fracture femoral shaft. To obtain the transverse fracture femoral shaft, the proximal femur and distal femur were removed using extrude cut in SolidWorks. Figure 3.1 shows how transverse fracture femoral shaft was obtained from human femur model.



(a) (b) (c)

Figure 3.1: (a) Human Femur Bone Structure (b) Femoral Shaft (c) Transverse Fracture Femoral Shaft

Transverse fracture femoral shaft was printed using OBJET30 Desktop 3D Printer and the software used was known as OBJET 30. The materials used for 3D printing can be categorized into model material and support material. The model material was known as VeroWhitePlus while the support material was known as FullCure705. OBJET 30 Desktop 3D printer was capable of printing model with the maximum dimension of 293mm in x-axis, 191mm in y-axis and 148mm in z-axis. Since the length of the transverse fracture femoral shaft was 285mm, so it was printed horizontally in x-direction as the z-axis limit was exceeded. The model was printed layer by layer with each layer thickness of 25.4 mm. Around 4 hours 30 minutes was needed to print the model. The modulus of elasticity of VeroWhitePlus was determined by using tensile test. To perform tensile test, dogbone shaped specimen made up of VeroWhitePlus was prepared according to the dimension shown in Appendix 1. The specimen was pulled using Instron 3367 Universal Testing Machine and the results were shown in Appendix 2. Since the modulus of elasticity of VeroWhitePlus is 1 GPa, it can be used to represent the osteoporotic bone [18]. The parameters such as layer thickness, model materials, support materials, time needed, software used and maximum dimension of printing model were shown in Table 3.1.

Table 3.1: Parameters of OBJET30 Desktop 3D Printer

Specification	Details
Name	OBJET30 Desktop 3D Printer
Layer Thickness (Z-axis)	25.4 mm
Model Materials	VeroWhitePlus
Support Material	FullCure705
Time Needed	4 hours 30 minutes
Software	OBJET30
Maximum Dimension	• x-axis – 293 mm • y-axis – 191 mm • z-axis – 148 mm

3.2.2 Preparation of Locking Compression Plate

The length of locking compression plate was depend on the plate span width. Plate span width was the ratio of plate length to fracture length. The recommended plate span width for simple fracture like transverse fracture femoral shaft was ratio 8 to 10 [19]. To achieve plate span width of 8 to 10, locking compression plate of length 100 mm with five holes was used, considering the maximum fracture length was 10 mm. The locking compression plate was cut into the required size using shear cutter and the holes were drilled using drilling machine. The dimensions of five holes locking compression plate was shown in Figure 3.2. The material used to fabricate the locking compression plate was stainless steel.

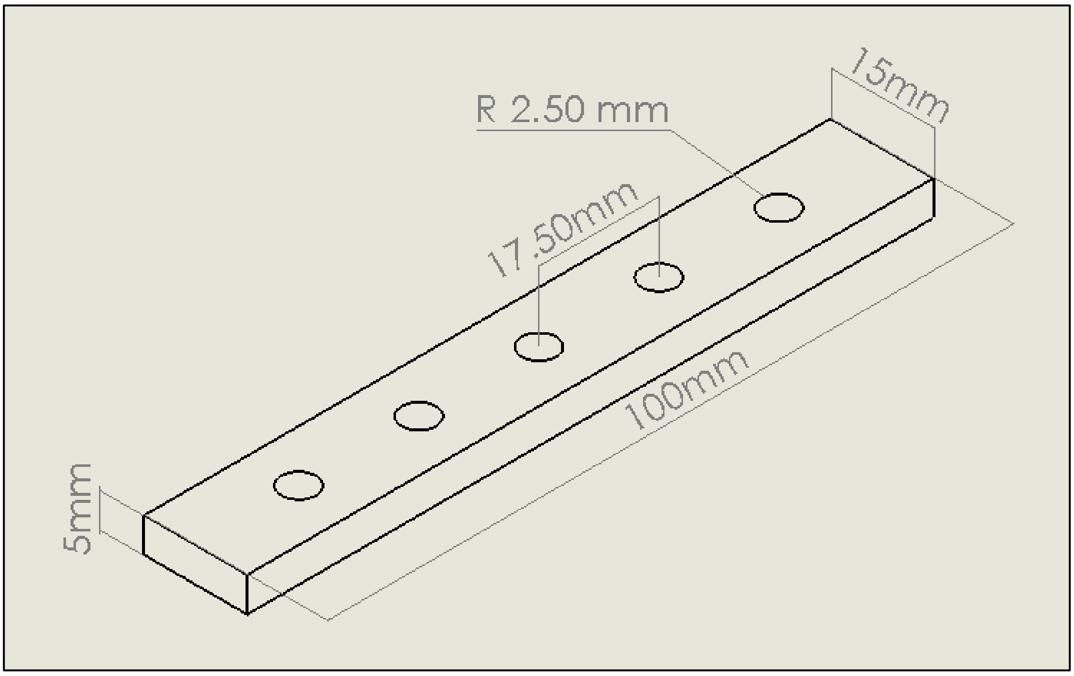


Figure 3.2: Dimension of Locking Compression Plate

3.2.3 Preparation of Speckle Pattern

Speckle pattern was prepared on the surface of locking compression plate so that the deformation of the plate could be determined. This is because deformation of locking compression plate was determined by DIC based on the displacement of the speckles. To prepare the speckles pattern, white and black colour spray of any brand could be used. The surface of locking compression plate would first be sprayed with white colour as the background colour. Next, the black colour would be sprayed at an elevation level of 300mm from the surface of locking compression plate as illustrated in Figure 3.3 to produce small black speckles on the locking compression plate. The ideal speckle size was 0.5mm to 0.80mm in diameter. By having speckle pattern with size of 0.5mm to 0.8mm in diameter, the deformation of every region on the surface of locking compression plate could be determined accurately. This is because large speckle would result in overlapping of one speckle with its neighbour, making DIC to track the displacement of speckle. By spraying white colour as the background colour, the black colour speckles can be observed easily as shown in Figure 3.4.

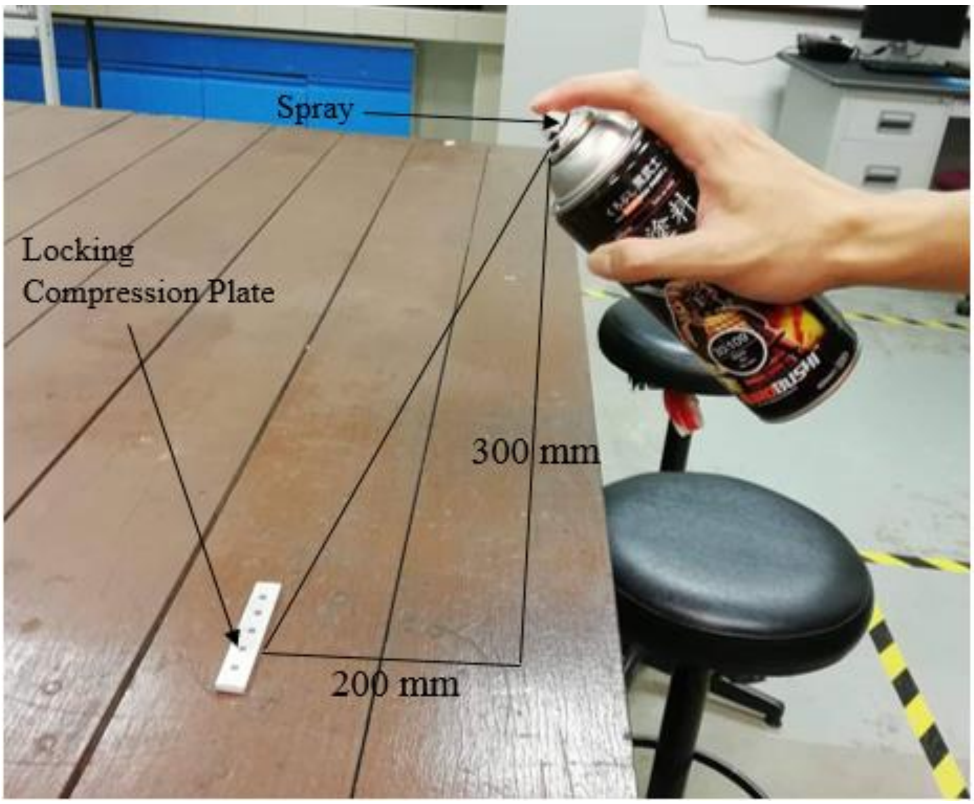


Figure 3.3: Elevation level for creating speckle pattern

Figure 3.4: Locking compression plate with speckle pattern

3.2.4 Fixation of Transverse Fracture Femoral Shaft

Locking compression plate was fixed on the lateral surface of the transverse fracture femoral shaft as shown in Figure 3.5. When load was applied on the femur as shown in Figure 3.5, bending moment occurs on the femur. By fixing the plate on the lateral surface of femoral shaft, the tension on the lateral surface of bone can be converted into compressive force on the lateral surface of bone, preventing the fracture of femoral shaft over the fracture site. Drill bit with diameter of 3.5 mm was first used to drill four holes on the transverse fracture femoral shaft before inserting self-tapping screws of 4.8 mm in diameter and 50 mm in length. The small holes function as a guideway to ease the insertion of self-tapping screws and prevent the breakage of femoral shaft. A gap of 10 mm was maintained between the transverse fracture femoral shaft. Four self-tapping screws were inserted into four holes of the locking compression plate except the hole over the fracture site. Figure 3.6 shows the complete model of transverse fracture femoral shaft fitted with locking compression plate and this mimic how transverse femoral fracture was treated in actual condition.

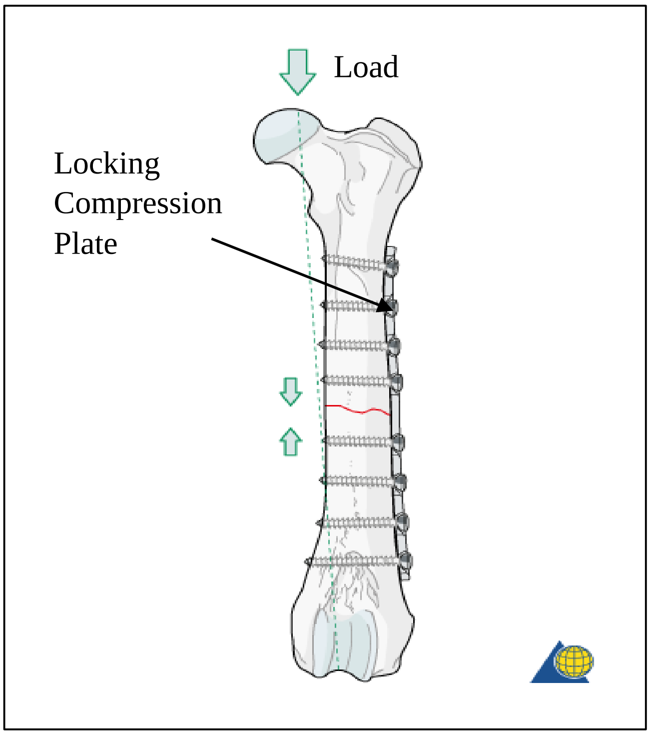


Figure 3.5: Location of locking compression plate fixation [20]

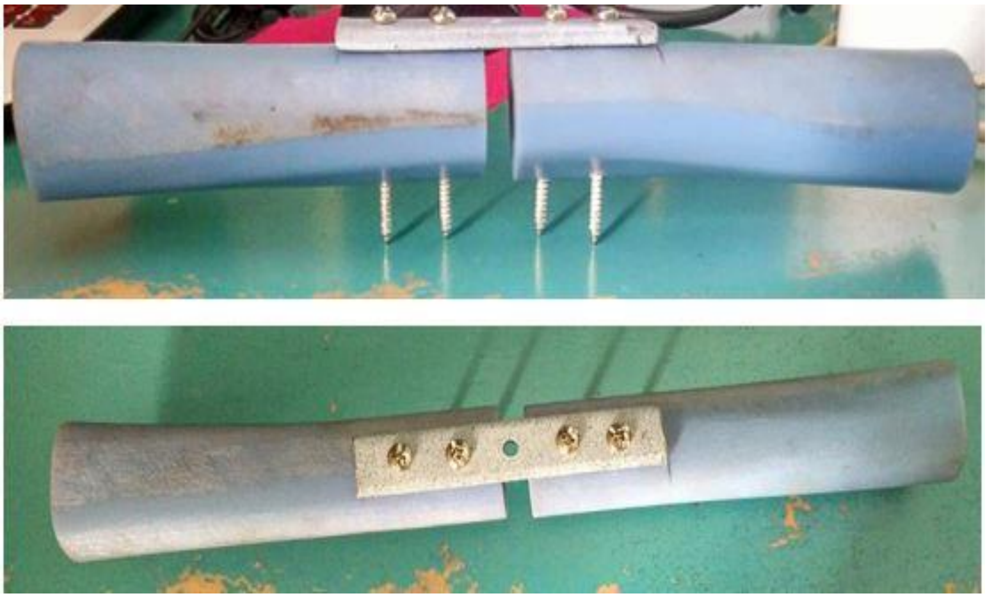


Figure 3.6: Transverse fracture femoral shaft treated with locking compression plate

3.2.5 Preparation of Fixture

The fixture was divided into two parts that are upper fixture and lower fixture. Fabrication of fixture was started with cutting of big mild steel plate into the required sizes by using shear cutter machine. Then, the plate with required sizes were joined together using welding to form a square container for holding transverse fracture femoral shaft model. Hole was drilled on each side of the upper fixture and lower fixture using drilling machine. After that, nut was welded over the hole site for each side of the upper fixture and lower fixture. Bolts were rotated into the nuts welded so that the transverse fracture femoral shaft could be fixed in position. The upper fixture was fixed to the Instron 3367 Universal Testing Machine using a clamp while the lower fixture was fixed to the Universal Testing Machine using two bolts which could be inserted into the machine. Figure 3.7 shows fixture used to hold the tansverse fracture femoral shaft model.

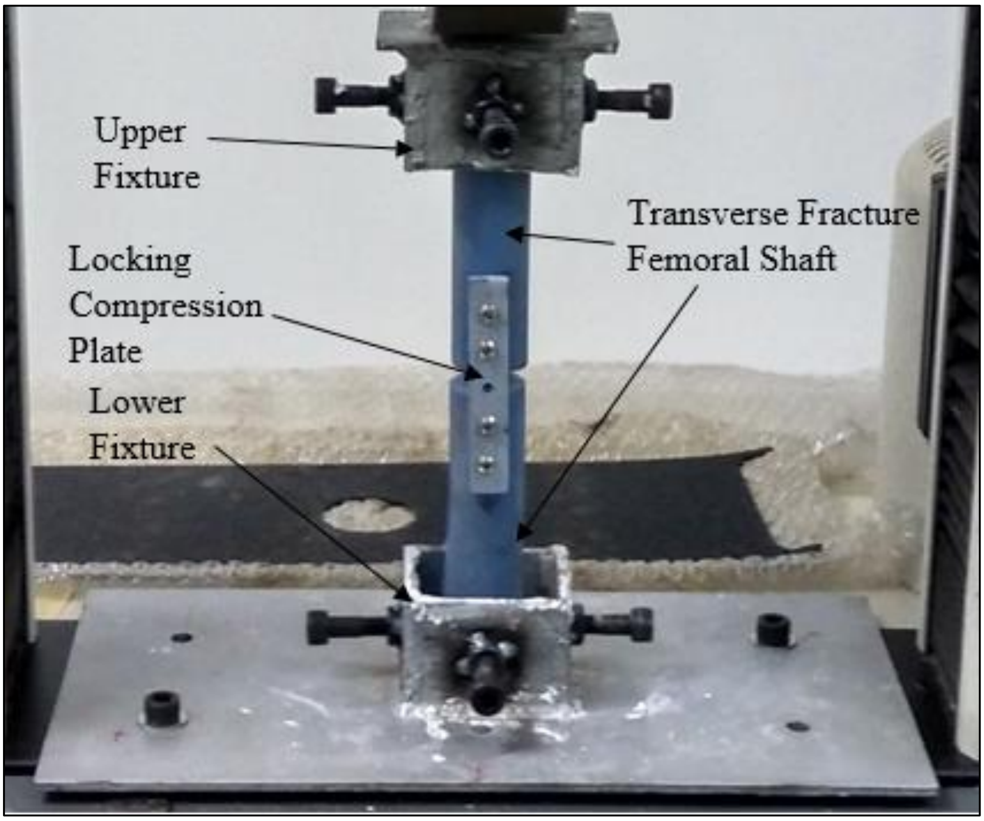
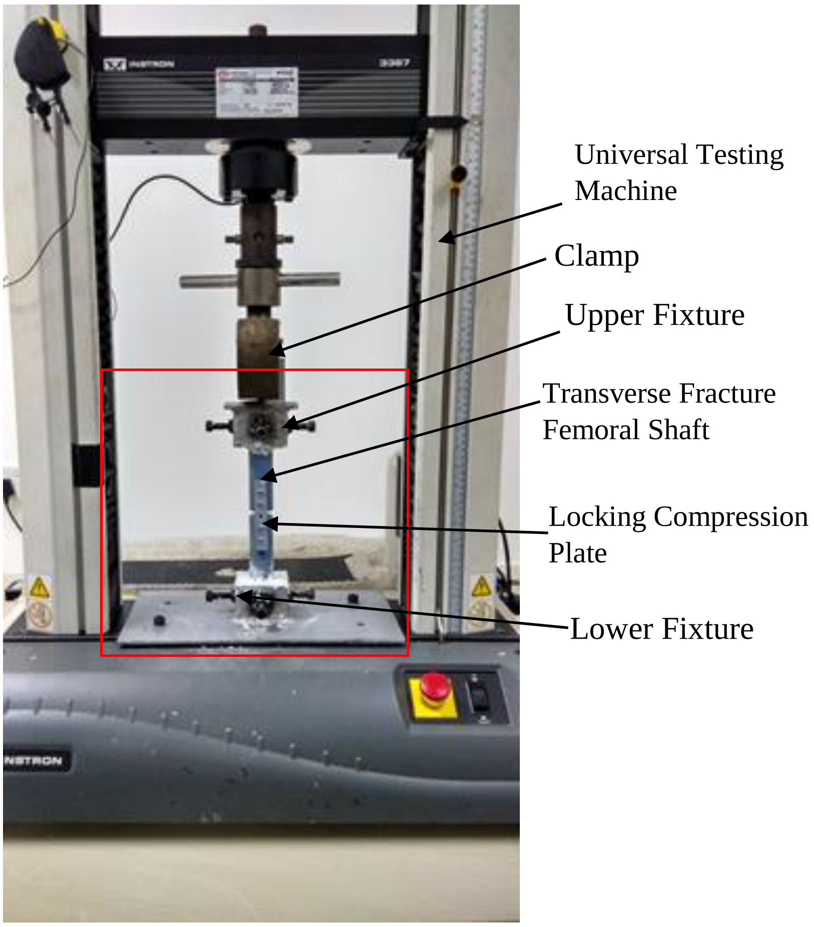


Figure 3.7: Fixture for holding bone model

3.3 Mechanical Testing

The transverse fracture femoral shaft with locking compression plate was maintained in upright position using the fixture through tightening of bolts located at the sides of the fixture. Then, the fixture was fitted to the Instron 3367 Universal Testing Machine. The bolts of the fixture was adjusted to ensure that the center of the bone model was aligned with the center of the Universal Testing Machine. Since the upper fixture and lower fixture were aligned, the any misalignment of the bone model with the center of Universal Testing Machine could be observed when tilting of bone model occurred. After the alignment is achieved, plaster of paris was poured into the fixture, ensuring that there was no slipping of the bone model during testing. Plaster of paris was prepared based on the ideal ratio of two cups of plaster of paris powder to one cup of water regardless of the types of cup. The plaster of paris was mixed continuously until a uniform and smooth mixture was obtained. The mixture was stirred gently to avoid the formation of air bubbles. Figure 3.8 shows the joining of bone model to fixture and Universal Testing Machine.



(a)