CORRELATION BETWEEN PULL-OUT STRENGTH AND INSERTION STRAIN FIELD IN RELATION TO BONE SCREW INSERTION ANGLE

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DECLARATION

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LIST OF SYMBOLS

^{o}	Unit of angle in degree
ε_{xx}	Strain in x-direction
ε_{yy}	Strain in y-direction
θ	Angle of screw insertion
L	Load

LIST OF ABBREVIATIONS

ASTM	American Society of Testing Materials
CAD	Computer-Aided Design
CCD	Charge-coupled device
DIC	Digital Image Correlation
ORIF	Open Reduction Internal Fixation
PU	Polyurethane
UTM	Universal Testing Machine
USM	Universiti Sains Malaysia

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ABSTRAK

Dalam projek tahun akhir ini, hubungan antara kekuatan tarik dan medan terikan penyisipan berkaitan dengan sudut penyisipan skru tulang dikaji. Secara umum, skru kortikal adalah salah satu alat fiksasi dalaman yang digunakan oleh pakar bedah untuk melakukan pembedahan ortopedik namun, kajian mendapati bahawa penggunaan alat-alat ini boleh menyebabkan kelonggaran perkakasan. Banyak kajian telah dikeluarkan dengan beberapa penyelesaian yang mengubah bahan skru dan mengubah kedalaman sisipan skru. Walau bagaimanapun, kajian ini akan menjelaskan bagaimana sudut penyisipan skru mempengaruhi daya tarik skru ketika medan terikan terhasil di dalam tulang, dan mempengaruhi daya tarik keluar. Skru kortikal dan blok busa PU 0.32 g/cm^3 adalah bahan utama untuk eksperimen ini. Terdapat dua eksperimen yang dijalankan iaitu Ujian Penyisipan Skru dan Ujian Tarik Keluar Skru yang akan dilakukan mengikut piawaian ASTM. Dalam ujian penyisipan skru, regangan penyisipan skru yang dikembangkan dalam blok busa PU dianalisis menggunakan sistem Korelasi Imej Digital (DIC) dan perisian Davis 10. Semasa dalam ujian tarik keluar skru, kekuatan tarik keluar dianalisis dan dikira menggunakan perisian khusus dengan UTM Instron 8874. Hasilnya menunjukkan bahawa daya tarik skru maksimum yang direkodkan adalah 607.43 N ketika skru dimasukkan pada 30^o, anjakan terikan tertinggi dalam arah x dan y adalah masing-masing 0.0115 pada sisipan skru 15^o dan sisipan skru 0.025 pada 0^o.

ABSTRACT

In this final year project, an investigation of the correlation between pull-out strength and insertion strain field in relation to bone screw insertion angle is studied. In general, cortical screw is one of the internal fixation devices that surgeons used to perform orthopedic surgery however, studies have found that the use of these devices may cause hardware loosening. Many studies have come out with several solutions which are changing the screw material and alter the screw insertion depth. However, this study will explain on how the screw insertion angle influences the pull-out force of the screw as the strain field developed within the bone, and the affects the pull-out force. A cortical screw and 0.32 g/cm^3 rigid PU foam block are the main material for this experiment. There are two experiments conducted which are the Screw Insertion and Screw Pull-out Test that will be done according to the ASTM standards. In screw insertion test, screw insertion strain developed within the PU foam block are analyzed using Digital Image Correlation (DIC) system and Davis 10 software. While in screw pull-out test, the pull-out strength is analyzed and calculated using a specialized software with the UTM Instron 8874. The results show that the maximum recorded screw pull-out force is 607.43 N when the screw is inserted at 30º, the highest strain displacement in x and y direction is 0.0115 at 15º screw insertion and 0.025 at 0º screw insertion, respectively.

CHAPTER 1

INTRODUCTION

1.1 Overview

Bone fractures, often known as fractured bones, are a frequent problem that many individuals face nowadays. Bone fractures can develop as a result of catastrophic events such as car accidents, sports injuries, and diseases like osteoporosis [1]. Normally, these sorts of fractures usually heal on their own. However, some severe injuries or fractures, on the other hand can only be healed by surgery, and the best method is by Open Reduction Internal Fixation (ORIF) as illustrated in Figure 1.1.

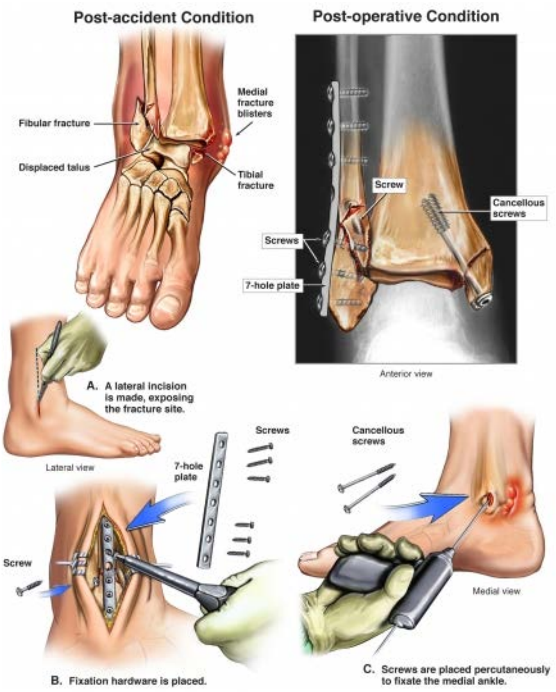


Figure 1.1 ORIF surgery of the ankle [2]

In medical field, internal fixation or commonly known as Open Reduction Internal Fixation (ORIF) surgery is basically a surgical procedure performed by orthopedic surgeons to repair and fix a severely broken bone [3]. Basically, this type of surgery only needs to be done if the bone fracture cannot be repaired and fixed using cast or splint. On the other hand, internal fixation refers to the bones that are held together using specialized devices such as metal plates, rods or screws [4]. Screws, plates, wires, and pins, as well as intramedullary rods and nails, are examples of internal fixation devices.

Apart from many internal fixation devices, screw is the device that is mostly used for internal fixation. Types of screws available including cortical screw, cancellous screw and lag screw. Each screw has its own unique properties and characteristics and can only be selected and implanted based on the severity of the fracture and how it is to be used [5]. In recent years, surgical screws have frequently been manufactured of a material with a high tensile strength, durability, and strength, such as titanium or stainless steel [6].

1.2 Project Background

This project emphasizes on how the screw insertion angle strains the bone material and thus affects the pull-out strength of the screw. A 0.32 g/cm^3 PU foam block is used to replace the bone specimen. To determine the load required to pull the cortical screw out of the PU foam block, the UTM Instron 8874 machine is used, and the ASTM F543-17 standards guidelines is followed to ensure the validity of the test. A series of preparation setup are essential to make sure that the experiment is conducted in a perfect condition.

After reading and analyzing the experiment setup done by other related articles and journals, some components such as jig and metal clamp are fabricated. Firstly, both components are drawn using CAD software which is Solidworks. The finalized CAD drawing will then be fabricated using band saw and milling machines.

After the screw insertion and pull-out tests have been performed, the strain field obtained and analyzed using the Digital Image Correlation (DIC) using software called Davis 10. From the software, the maximum strain value for each insertion angle is identified from the analyzed strain field.

1.3 Problem Statement

The use of screw internal fixation may bring up to several issues and complications. The fact that the screw may induce hardware loosening is one of the orthopedic problems. Metal implants, such as the cortical screw used to keep the bone together at the side plate, may become loose over time [7]. To address this issue, many attempts favor more on biocompatibility of the screw with the host bone, but less on the biochemical compatibility that emphasizes on the mechanical response of the host bone to the screw insertion. Although it has been shown that the insertion configuration angle significantly influences the integrity of the fixation. Hence, this research aims to further investigate the bone biomechanical response to different angles of screw insertion in terms of strain field developing in the vicinity of the insertion and how it affects the pull-out strength of the screws.

1.4 Objectives

The objectives of this final year project are:

a) To determine the screw insertion angles on screw pull-out strength.
b) To characterize the strain field in the vicinity of screw insertion with respect to the variation of insertion angles.
c) To determine the relationship between the insertion strain field and the screw pull-out strength with respect to the variation of insertion angles.

1.5 Scope of Work

This research project focuses on designing and fabricating a custom jig and custom screw clamp that can work and performed properly during the screw pull-out test. Screw pull-out test is the main purpose of this experiment to investigate the pull-out strength of the cortical screw varies across different screw insertion angles. 4 equal size of rigid PU foam block have been tested with 4 different cortical screws at 4 different insertion angles. Apart from that, the use of Digital Image Correlation also plays its role to determine the strain value of the foam block during screw insertion method. By analyzing and observing strain field from the DIC, the relation between maximum strain values across all 4 foam blocks with different screw insertion angles will be discussed later.

1.6 Thesis Outline

This thesis contains five chapters that need to be discussed. Chapter One contains the introduction to overview and background of the project, problem statement, research objectives, scopes of project and the thesis outline. Chapter Two discuss the literature reviews that are related to the thesis title. Chapter Three contains detailed explanation of the experiment. Chapter Four consists of the precise explanation on the findings and Chapter Five contains a brief conclusion of the whole project work and the short summary for the future research of the project. Lastly, all references are listed in the References section at the end of the thesis.

CHAPTER 2
LITERATURE REVIEW

In this chapter, the review on the latest and relevant research that have been performed in this medical field are presented. Most of the journals and papers discussed in this literature review is from collection of literatures from the year of 2005-2020. The reviews are sub-sectioned according to the subjects that will be individually discuss which include the properties of cortical screw, different type of internal fixation devices, the Digital Image Correlation (DIC) method and effect of screw insertion angle towards pull-out strength.

2.1 Open Reduction Internal Fixation (ORIF) Surgery and Its Significance

Internal fixation is a surgical treatment that involves the use of internal fixation devices to hold the bones together. It is a form of orthopedic surgery in which implants are surgically placed to repair a fractured bone. The goal of the operation is to provide solid fracture fixations with minimal devascularization, early mobility, and midway stacking. Furthermore, even after the bones have healed, the fixations are not removed from the patient's body [5]. Screws, rods, metal plates, and intramedullary nails are examples of implant types. The goals of implant are to give a temporary support for the bone, keep it aligned during the healing process, and allow for functional rehabilitation [8].

The surgical technique in which the physician creates a cut or incision to move the bones back to their original place is known as open reduction [9]. ORIF method frequently are utilized in cases including genuine breaks like comminuted or dislodged cracks or, in situations where the bone in any case would not recuperate effectively with projecting or bracing alone [10].

Surgical screws are commonly used to repair injuries, particularly those involving bone fractures. Most screws are composed of stainless steel or titanium, depending on the surgical situation. Cortical screws are the sort of screw that will be utilized in this project. Cortical screw is one of the orthopedic screws that are named based on the bone types that they are inserted during surgery, in which in this case is the cortical bone. The unique property of the cortical screw is what makes it a perfect, suitable choice for surgeon to use it in surgery.

2.2 Effect of Screw Insertion Angle Towards Pull-Out Strength

There are some journals that mentioned about the relationship between the screw insertion angle and the pull-out strength. V. Varghese et. al. [11] described the several factors that affect the performances and the strength of the cortical bones such as bone density, screw insertion angle and screw insertion depth. P.S.D. Patel et. al. studied the effect of bone screw insertion angle using a rigid polyurethane foam model representing a normal cancellous bone model (0.32 g/cm^3) and found that screws inserted at 0° and 10° exhibited higher pull-out force compared to screws inserted at 20°, 30° and 40°. He also mentioned that the correlation between pull-out strength and screw insertion angle resulted in an obvious pattern whereby in 0.32 g/cm^3 PU foam, the pull-out strength of the cortical screw decreased when angle of insertion screw increased (P.S.D. Patel et al.) [12].

2.3 Digital Image Correlation (DIC)

The DIC method was first used by Peters and Ranson (1982) to measure displacement fields on plane surfaces of loaded components, which was later improved by Sutton et al. (1983) who demonstrated the precision of the method in obtaining strain fields [13]. The use of DIC to measure full-field deformation near the tip of a crack for the determination of fracture characteristics of various materials was first suggested by McNeill et al. (1987) [14]. Since then, Dehnavi et. al. [15] has been utilizing DIC widely determine the singular components of the stress field in the vicinity of the crack-tip as it has made it possible to infer the local crack-tip displacement fields at sufficient accuracy.

2.3.1 Strain Measurement in DIC

The fundamental concept of DIC method is based on the relation between consecutive images of specimen surface captured at different stages of deformation. The individual image is essentially a two-dimensional array of intensities that can be discretized into small subsets. Correlation between two images is done by matching a subset in the undeformed image (or reference image) to its locations in the subsequent image after deformation, as illustrated in Figure 2.1, by a series of mathematical mapping and cross correlation functions. For an optimum correlation, the specimen surface needs to be applied with a greyscale random pattern, in which the intensity of the greyscale must be unique for it to be traced from one image to the next. The random pattern can be created by randomly scratching the specimen surface with sandpaper or spraying the surface of the specimen with white or black paints. Hence, the purpose of applying the strain measurement technique in DIC is to measure the strain field developed within the specimen when the screw is inserted at different angles.

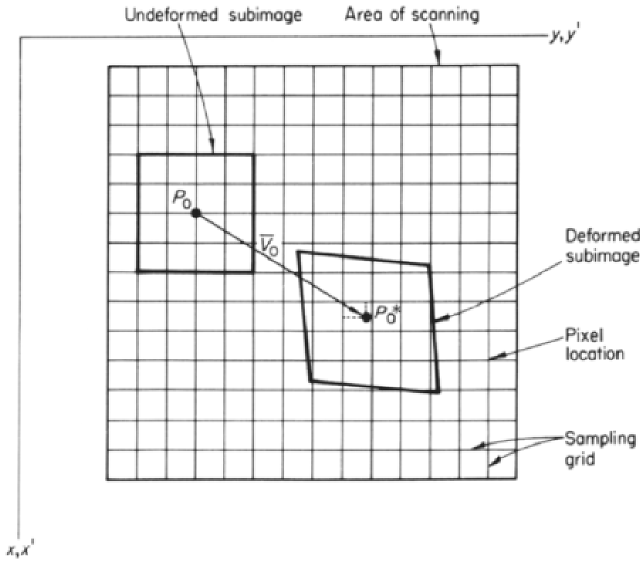


Figure 2.1 Deformation of a subimage in a sampling grid

2.4 Summary

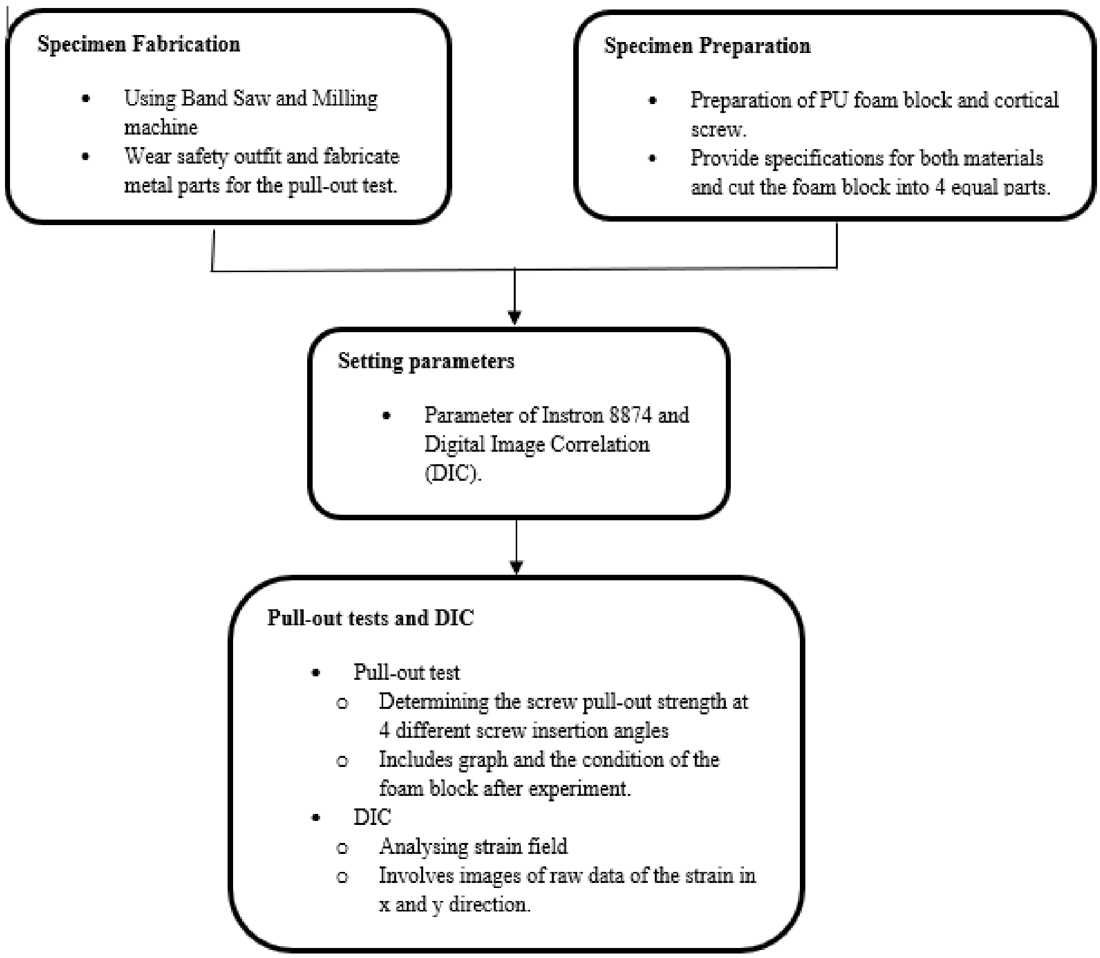
Based on the literature review, it can be concluded that the variety of different screw insertion angles may greatly affect the screw pull-out strength, θ vs L., which may be quantitatively reflected by the intensity of material deformation caused by the insertion. Therefore, the objective of this study is to examine the effect of screw insertion on the pull-out strength in relation to the resulted strain field in the vicinity of the screw insertion.

CHAPTER 3
METHODOLOGY

This chapter is presented in 2 major sections. The first section is the preparation method that describes 3 essential steps which are specimen fabrication, specimen preparation and apparatus setup of the experiment. The second section describes the experimental procedures for the screw insertion and screw pull-out tests to determine the pull-out strength of each screw at different angles as well as the strain field developed at the specimen.

3.1 Workflow of the project

The workflow of the project can be further summarized and presented as shown in the chart below.



3.2 Experiment Setup

3.2.1 Fabrication of Jig and Clamp

3.2.1(a) Custom Metal Jig

For the custom metal jig design, it started with a metal bar that was cut into two parts, each with the same length of 115 mm. Band saw machine, as illustrated in Figure 3.1(a) was used to cut the metal bar into 2 parts. Next, a milling machine, as illustrated in Figure 3.1(b) which was set at 90 mm/min for the feed rate and the rotating speed of 410 rpm was used to acquire the specific width and thickness of the metal bar.

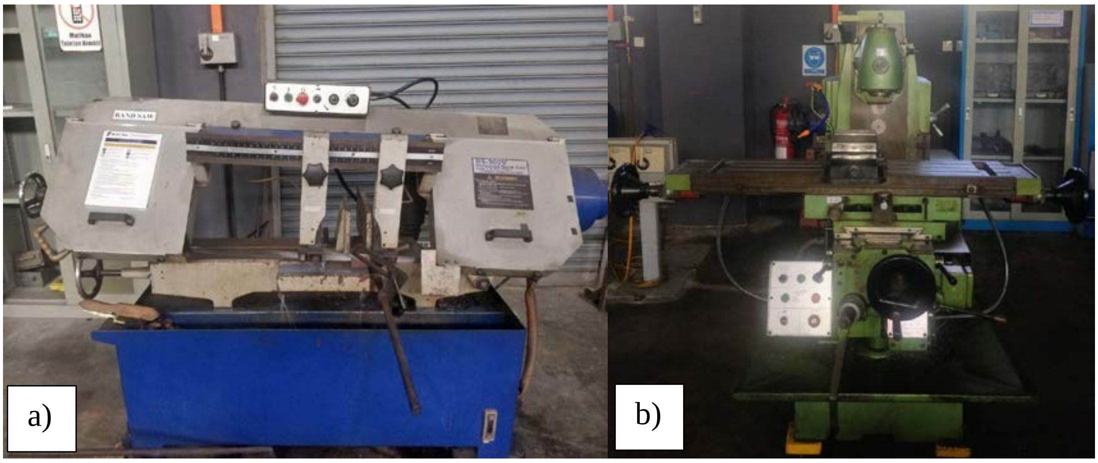


Figure 3.1 Machines used for metal fabrication a) Band Saw machine b) Milling machine.

The dimensions of the metal bar are 115 mm x 37 mm x 15 mm as shown in Figure 3.2. Then, 2 equal sizes of metal plate were fabricated with a size of 115 mm x 75 mm x 5 mm.

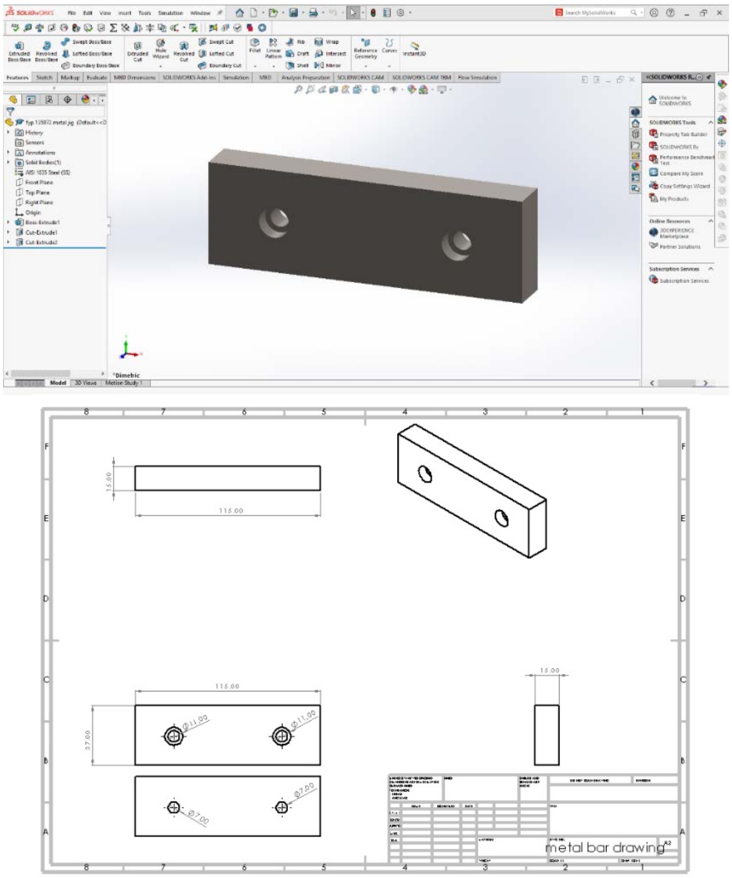


Figure 3.2 The CAD Drawing and isometric view of the metal bar (with dimension).

Figure 3.3 shows the design and dimension of the metal plate. Both the metal bars and metal plates are joined and welded together by using arc welding. The final product of the jig design is shown below, as illustrated in Figure 3.4.

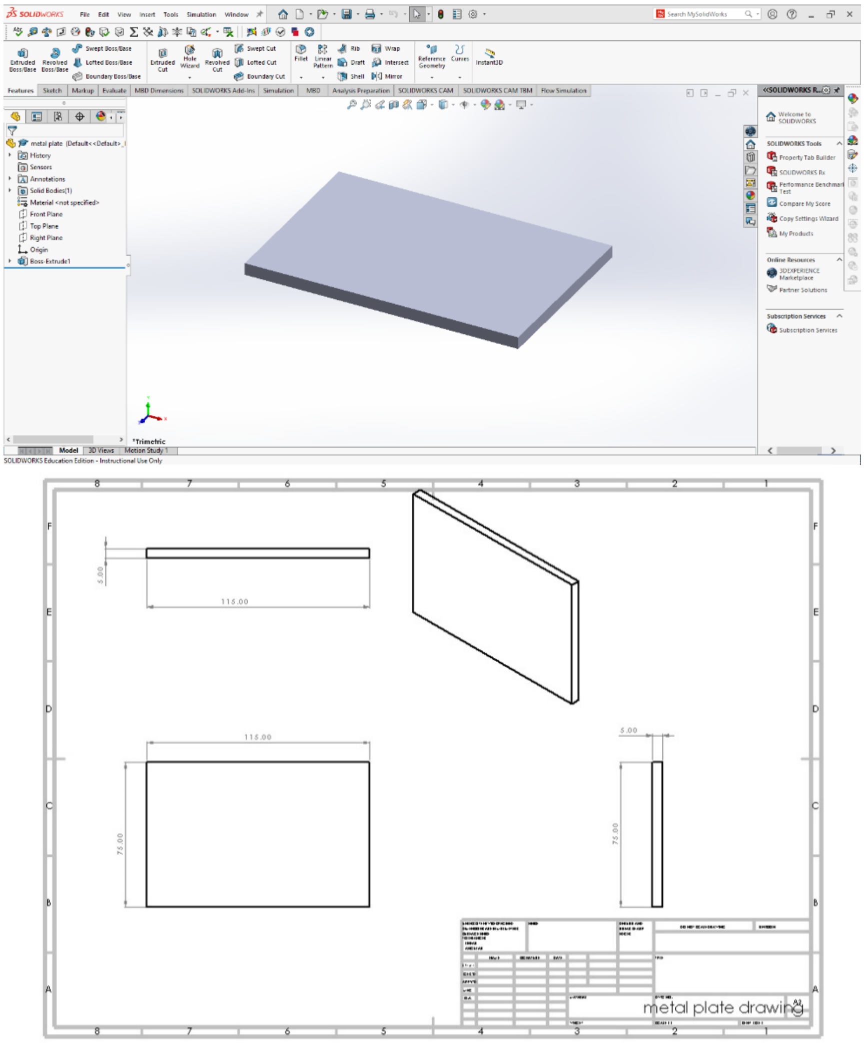


Figure 3.3 The CAD drawing and isometric view of the metal plate (with dimension).

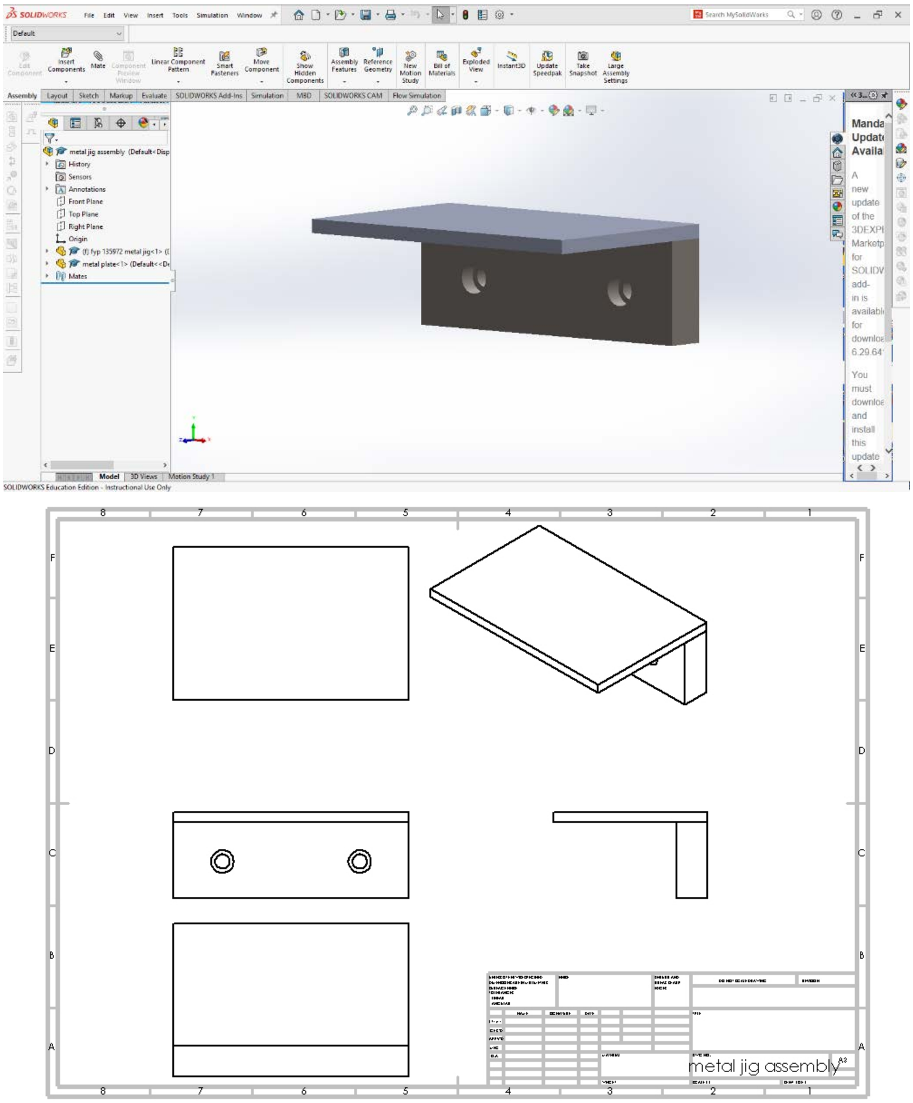


Figure 3.4 The CAD drawing and isometric view of the jig

3.2.1(b) Custom Metal Screw Clamp

For the custom metal screw clamp, 2 mm thick metal plate was used to fabricate the clamp. The metal plate was cut into 4 equal parts (8 cm x 3.7 cm). Then, one of the metal plates was drilled through and a slot with a depth of 22 mm and width of 5 mm was made as shown in Figure 3.5. The slot is used to hold the screw that is already attached to the PU foam block. This is to make sure that the screw can be pulled out by pulling the screw head. All the metal plates are welded together using MIG and the product of the custom metal screw lamp is shown below.

Figure 3.5 Custom metal screw clamp with 3-point welded area.

3.2.2 Specimen Preparation

3.2.2(a) Rigid PU foam block

Rigid polyurethane (PU) foam block as illustrated in Figure 3.6 was used and selected as the main material for this experiment because it is the suitable medium to replace the human cancellous bone. It also allocates consistent characteristics of properties in the range of human cancellous bone. For this project, the foam was supplied as block (130 mm x 180 mm x 40 mm) from Sawbones USA. 4 smaller blocks with dimensions of (65 mm x 90 mm x 40 mm) were sawn from the block to accommodate 4 different screw insertion angles, each labelled with a sticker (0º, 15º, 30º & 45º).

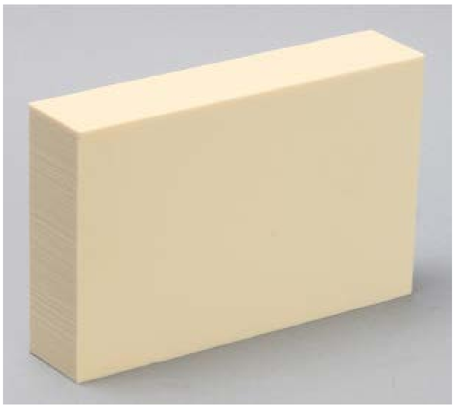


Figure 3.6 The rigid PU foam block

The density, compressive, tensile and shear values of the PU foam block follow the American Standard of Testing for Materials (ASTM D1622, ASTM D1621, ASTM D638 and ASTM C273) as shown in Table 3.1.

Table 3.1 The overall specifications of the selected PU foam block

Density			Compressive		Tensile		Shear	
(PCF)	(g/cm^3)	Volume Fraction	Strength (MPa)	Modulus (MPa)	Strength (MPa)	Modulus (MPa)	Strength (MPa)	Modulus (MPa)
ASTM D1622			ASTM D1621		ASTM D638		ASTM C273	
20	0.32	0.27	8.4	210	5.6	284	4.3	49

3.2.2(b) Cortical Screw

Cortical screw was selected for this project because it is suitable for the fixation of the small fragment implants. 4 cortical screws with dimensions of 3.5 mm diameter x 4.5 cm length were used for the 4 different angles of investigation. The screws were manufactured from Nazmed SMS Sdn Bhd and the material is stainless steel. Figure 3.7 shows the detailed specifications of the screw.

Figure 3.7 The specifications of the cortical screw [16].

From the figure, we can see that the core which is 2.4 mm in diameter can assist in giving strength for the screw itself to be inserted into the PU foam. Next, this cortical screw also is a non-self-tapping screw, which means it does need pre-drilling of a pilot hole before it is being inserted into the bone specimen [17].

For this experiment, the screw insertion depth was kept constant at 20 mm. The only manipulative variable is the screw insertion angle in which will be explained later.

3.2.3 Apparatus Setup

3.2.3(a) UTM Biaxial Instron

The machine used for the screw pull-out experiment is the UTM 8874 Biaxial Servohydraulic Fatigue Testing System or known as Instron 8874. It is a machine that can do axial, torsion and axial-torsion tests. Also, Instron 8874 is a perfect platform to test a variety of medical devices and biomaterials. The features of this machine include a force capacity of up to 25 kN, 100 mm of actuator axial strokes and has an 8 mm width of clamp [18].

3.2.3(b) Digital Image Correlation (DIC)

In this project, DIC was used to determine the strain field of the PU foam in two scenarios; the first one is when the screw was inserted into the PU foam and another one is for the screw pull-out tests. A 2D DIC setup generally requires a fixed CCD camera, a white light source, a data acquisition computer, and a planar sample, as schematically shown in Figure 3.8.

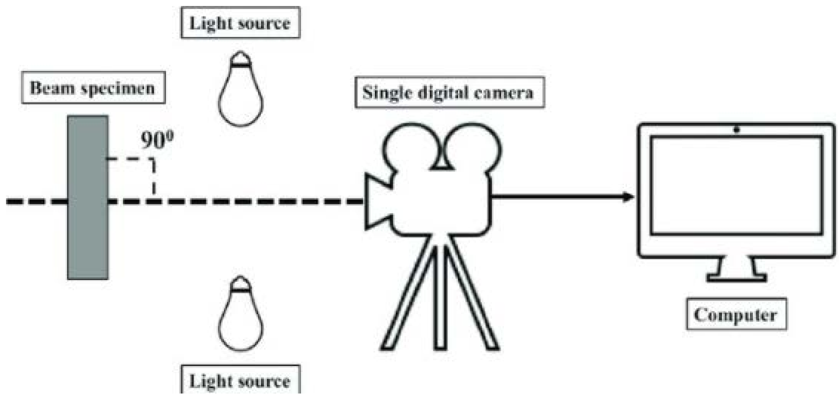


Figure 3.8 A schematic representation of a 2D DIC experimental setup.

3.3 Experimental Procedures

3.3.1 Screw Insertion Experiment

For the complete experimental procedures, it all started with the PU foam block that was cut into 4 equal sizes (65 mm x 90 mm x 40 mm). Next, all 4 blocks were sprayed with white paint on the side for two to three times, each with interval of 10 to 15 minutes. After the white paint completely dried, the blocks were sprayed with black paint using toothbrush and let it dry out as illustrated in Figure 3.9.

Figure 3.9 The PU blocks with white and black paints on the side.

Next, all four blocks were placed into a rotating, angular clamp with a pre-set angle of 0º, 15º, 30º & 45º, respectively. A 20 mm hole was made at 0.5 cm from the side of the block using hand drill and a drill bit with 3.2 mm in diameter.

Digital Image Correlation (DIC) was setup and prepared before the screws were inserted into the blocks. For the DIC setup, the parameters such as fixed frequency, illumination and number of images are determined as in Table 3.2.

Table 3.2 Parameters 2D DIC setup for screw insertion process

Fixed frequency (Hz)	Illumination (μs)	Number of images	Duration (s)
15	900	300	20

Then, the DIC recorded simultaneously with the process of the screw insertion at four different angles as shown in Figure 3.10. To ensure that the screws were inserted at exactly 20 mm, a sticker was placed to mark the 20 mm depth from the screw bit. The screws were inserted using hexagonal screw tap until it reached the 20 mm mark. Then, the data was recorded and saved at four different folders for the four angles.

Figure 3.10 The experimental setup for 2D DIC.

The inserted cortical screws at four different angles are shown in Figure 3.11

Figure 3.11 Variation of insertion cortical screw angle (from left: 0º, 15º, 30º & 45º)

3.3.2 Screw Pull-out Experiment

For the screw pull-out tests, Digital Image Correlation (DIC) was setup and prepared with the same parameters as the screw insertion process earlier. However, the values are quite different. Table 3.3 shows the exact setup for the fixed frequency, illumination, number of images and the duration for DIC, and shown in Figure 3.12. This setup is kept the same across all four different screw insertion angles.

Table 3.3 Parameters DIC setup for screw pull-out test

Fixed frequency (Hz)	Illumination (μs)	Number of images	Duration (s)
10	900	2500	250

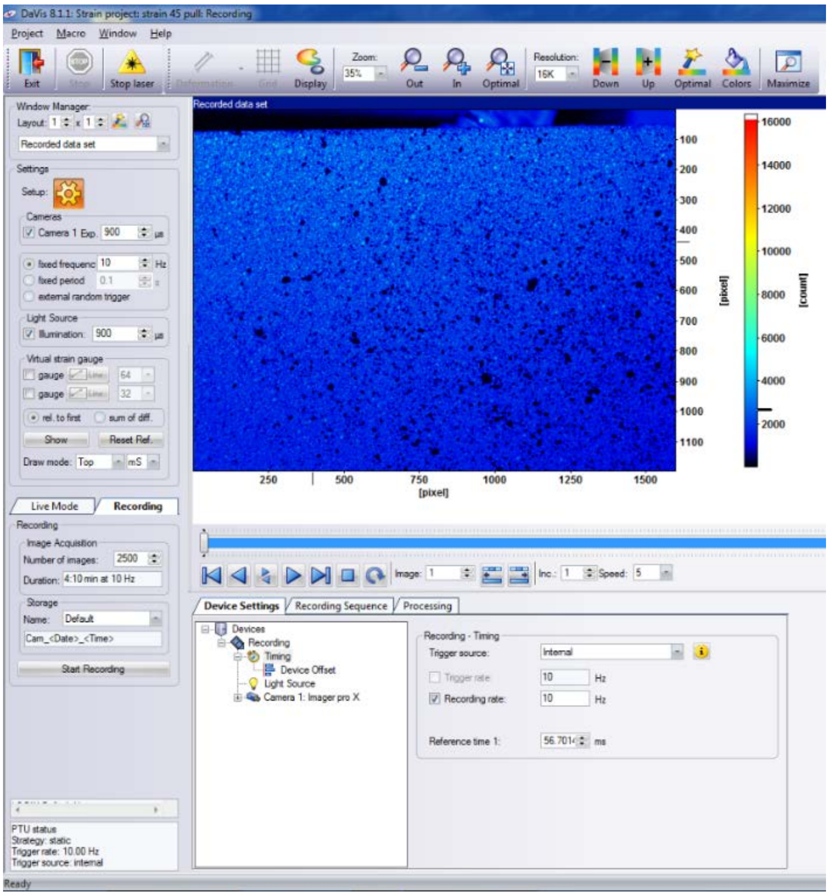


Figure 3.12 Setup DIC for screw pull-out test

First and foremost, the custom metal jig was placed and screwed into the rotating, angular clamp using 2 allen keys. The metal jig is used to hold the blocks and make sure that they are fixed onto its position as illustrated in Figure 3.13. Next, the specimen (PU foam block) with 0^{o} screw insertion angle was inserted in between the gap of the metal jig to secure its place.

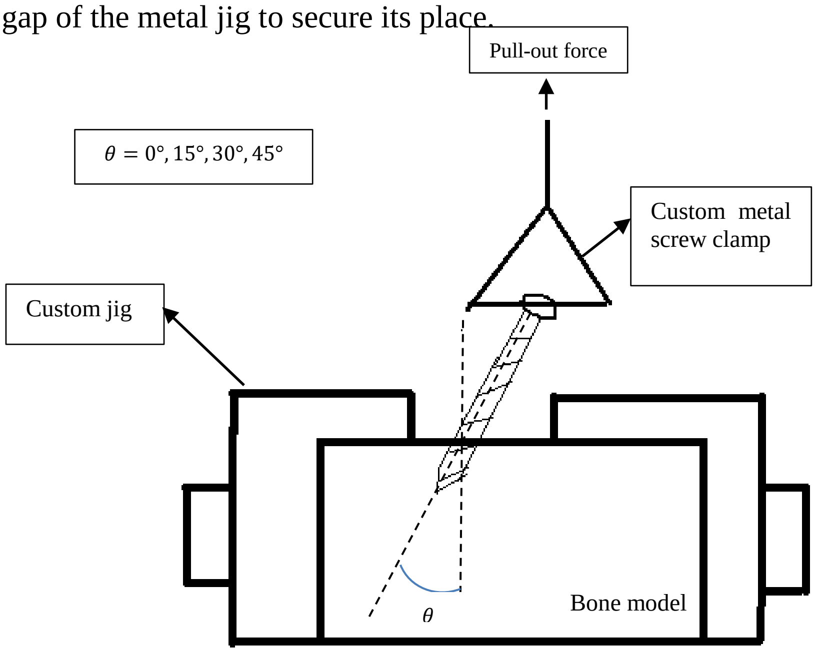


Figure 3.13 Schematic representation of the pull-out test

For this step, the side of the block that has the white and black paint is to be facing towards the camera for the DIC to record as shown in Figure 3.14. A custom metal screw clamp was used to connect the screw and the machine's clamp. A close look of the setup experiment for 0^{o} screw insertion angle can be best represented in Figure 3.15.

Figure 3.14 Overall setup including custom metal clamp & metal screw clamp with PU foam block.

Figure 3.15 Close-up look of the setup experiment for 0° screw angle

The screw pull-out tests followed the ASTM F543-17 standards whereby the pull-out rate is set at 5 mm/min. The DIC recorded simultaneously, in synchronize with the pulling the screw out from the foam block which was along the axis perpendicular to the top surface of the foam block. The Instron 8874 kept pulling the screw until the screw was completely detached from the foam block. Then, the data from the Instron 8874 and DIC were recorded and analyzed. All the steps above are repeated with 15°, 30° and 45° screw insertion angles.

The overall experiment setup involves DIC and Instron 8874 is shown in Figure 3.16. The detailed setup of the machines is included in Appendix.

Figure 3.16 Overall setup experiment involving DIC and Instron 8874