BUCKLING BEHAVIOUR AND INSTABILITY OF TAPERED COLUMN MADE OF ALUMINIUM ALLOY

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SUPERVISOR DECLARATION

"I hereby declare that I have read this thesis and in my opinion this report is sufficient in term of scope and quality for the award of the degree of Bachelor Mechanical Engineering (Structure and Materials)"

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DECLARATION

"I hereby declare that the work in this report is sufficient in term of scope and quality for the award of the degree of

Bachelor of Mechanical Engineering (Structure and Materials)"

Signature: ……………………………

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Date: …………………………….

Dedicated specially for

My beloved family

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ABSTRACT

Compressive members are typically found in most structural members. It is important to know the limits of material used since it can failed in two ways. In this study, the mode of buckling failure being investigated is limited to the elastic mode. Buckling only happens in long slender structural member well before experiencing plastic deformation. Before the plastic deformation, elastic failures such as yielding or crushing can also occur. The purpose of this study is to determine the critical buckling load of tapered column with different aspect ratios and how the end support conditions is influencing the buckling load and to compare with the analytical result. In this study, the material used for the specimen is Aluminium Alloy 6061 bar with square and round cross-sections. In preparing the specimens or columns, specified machining process need to be done to fulfill the required dimension of the specimen. The specimen tapered ratios used are 0.84 and 0.66 with length of 0.16m, 0.19m and 0.22m respectively. The buckling test is conducted by using INSTRON 5585 floor mounted material testing machine. The graph of buckling test obtained had been plotted in Load (kN) against Extension (mm). The loading rate used for the test is constant at 0.75/mm/min or equivalent to 0.0125/mm/sec. From the overall result, the critical buckling load for pinned-ended support is lower than pined-fixed support. The increase of buckling load also affected as the tapering ratio and effective length increases. Besides, different cross-sectional area give different reading of buckling load which is, square column have higher buckling load compared to circular column. However, there are significant differences between the experimental and theoretical results which is mainly affected by the surface condition of the column.

ABSTRAK

Ahli mampatan adalah ahli yang sering dijumpai dalam bidang penstrukturan. Had bahan yang digunakan haruslah diketahui kerana ia boleh gagal melalui dua kaedah. Dalam kajian ini, cara kegagalan lenkokan yang diujikaji adalah lengkokan secara elastik. Lengkokan hanya berlaku bagi ahli struktur yang langsing sebelum melalui perubahan plastik. Sebelum itu, kebarangkalian untuk kehancuran dan penghasilan juga boleh berlaku. Tujuan kajian ini adalah untuk menentukan beban kritikal lengkokan bagi struktur yang berbeza nisbah tirus dan bagaimana ia akan terjejas dengan menggunakan sokongan yg berbeza dan dibandingkan dengan keputusan analisis. Pancalogam Aluminium 6061 dengan keratan rentas segi empat sama dan bulat adalah jenis bahan yang digunakan dalam kajian ini. Proses pemesinan tertentu adalah diperlukan dalam menyediakan spesimen bagi memenuhi keperluan dimensi yang sepatutnya. Nisbah tirus yang digunakan dalam ujikaji ini adalah 0.84 dan 0.66 dengan masing-masing mempunyai panjang bernilai 0.16m, 0.19m dan 0.22m. Ujian lengkokan dijalankan dengan menggunakan mesin "INSTRON 5585 floor mounted material testing system". Kadar kelajuan yang dihunakan semas berlakunya ujikaji adalah dimalarkan bagi semua specimen iaitu pada kadar 0.75/mm/min ataupun bersamaan dengan 0.0125/mm/sec. Berdasarkan hasil keseluruhan keputusan eksperimen dan teori, beban kritikal lengkokan bagi keadaan yang menggunakan sokongan pin kedua-duanya adalah lebih rendah daripada pin-tetap. Peningkatan beban lengkokan juga adalah disebabkan nisbah tirus dan panjang specimen. Selain itu, keratin rentas juga memberi bacaan beban lengkokan kritikan yang berbeza, yang mana,beban lengkokan lajur segi empat adalah lebih tinggi berbanding lajur bulat. Walaupun, terdapat perbezaan dari segi bacaan teori dan eksperimen yang mana kemungkinan dipengaruhi oleh faktor keadaan permukaan.

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LISTS OF ABBREVIATION

FE	Finite Element
ASTM	American Society for Testing and Materials
AA	Aluminium Alloy
m	Metre
kN	Kilo Newton

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CHAPTER 1

INTRODUCTION

1.1 Background

There are various types of mechanical failures. Their importance varies from a minor nuisance to a major disaster. Sometimes, such failure can cause injury, lost of human life or property damage.

Failure is defined as the inability of an engineering component to carry out its specific function. According to the International Electrotechnical Commission (IEC), failures mean the termination of the ability of an item to perform a required function. There are various type of mechanical failures and buckling is one of them. Buckling is a sudden failure of a member subjected to compressive stress (or load) where at point of failures, the actual compressive stress is less than the ultimate compressive stress (σ_{ult}) of the material.

Column in a building is an architectural invention which allowed for the support of ceiling without the use of solid walls, thereby increasing the space which could be spanned by a ceiling, allowing the entrance of light and offering an alternative aesthetics to building exteriors, particularly in the peristyles of temples and on colonnades along stoats (Cartwright, 2012). Column can be differentiated by its different cross-sectional area. The two category of column is uniform and non-uniform cross sectional area.

For column that have uniform cross sectional-area, it's usually called as straight column. Meanwhile, for non-uniform cross-sectional column, they falls into three types which is stepped column, tapered column and double tapered column. Non-uniform column also can be known as non-prismatic column. Figure 1.1 shows the different type of column visually.

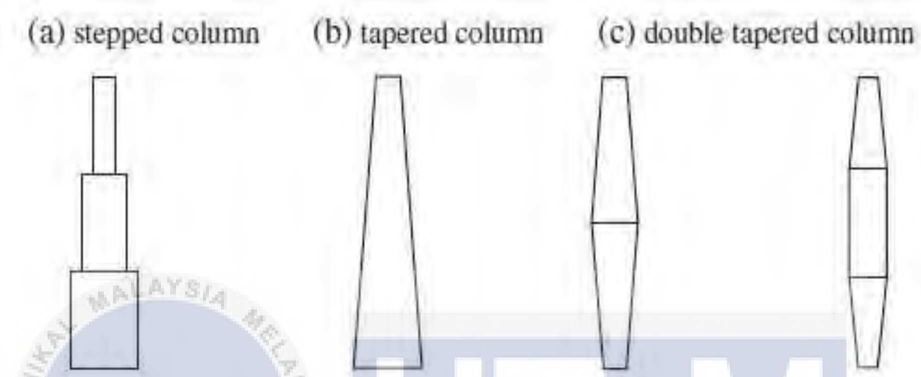


Figure 1.1: Steel column with non-uniform cross-section

(Source: Zhang, Guo & Dou, 2013)

Column with different cross-section give their own advantages and disadvantages. Straight column are easier to make and manufactured. In this research, we only covered about the tapered column to be defined its buckling behaviour. Tapered column or also known as tapered members are important in structural engineering because of their reduced weight compared with uniform or straight column for the same axial load carrying performance (buckling load) (Iremonger, 1980). This is due to the rational sectional distribution of stiffness to reduce weight or to satisfy architectural and functional requirements (Saetiew & Chucheepsakul, 2012).

The first approach and study regarding to buckling problem of column with different cross sectional is done by Dinnik in 1929 and 1932. In 1982, tapered box column under biaxial loading were analyzed by using moment curvature-thrust relationships and Horne's stability criteria (Theodore, Ioannis & George, 2012).

Laboratory test are essential in order to determine the critical load for column to buckle. Since buckling is due to compressive stress, a compression test had been conducted by using the INSTRON 5585 floor mounted universal testing machine. Compression tests were used in order to determine on how the material will react when compressed and determine the specimen behavior under a compressive load. For the compression experiment, the maximum load is limited to 200 kN which is equivalent to the maximum capacity of the Instron machine.. Figure 1.2 illustrates on how the column will be compressed by axial load to study the buckling behavior of the test columns.

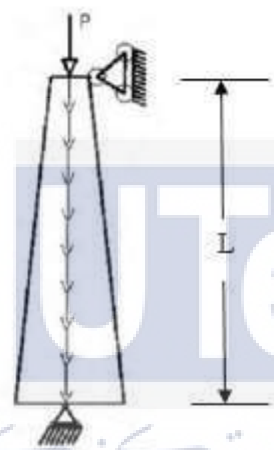


Figure 1.2: Illustration of compressive force applied to the tapered column or strut.

Tapered members are widely used in industry of automotive, aircraft component or aerospace structures, architecture and medical equipment. They usually used as slender structural member of high-rise building, long-span bridge, marine and offshores structures, aerospace, biomedical instruments and other machine parts.

1.2 Problem Statement

In this recent year, buckling had become a problem in structural engineering. Nowadays, most people doesn't know about buckling that actually happen around their surroundings. When said about buckling, it usually related to column structure. Column can be defined as the slender member that is relatively long and subjected to compressive axial load. Buckling instability can occur even by increasing in a small amount of load and it can lead to failure. As we can see, the column application had been used widely in structural of high-rise building, bridges, aircraft and aerospace structural members. From the two engineering application for example, it related to human safety. This study is important because it involve a large human safety factor. Therefore, to avoid the buckling instability the critical buckling load of the column need to be determined. The value of compressive load (P) supported by column must be less than the value of critical load (P_{cr}), in order to avoid buckling or instability.

$$\text{i.e} \quad P < P_{cr}$$

Besides that, this study is conducted due to limited number of literatures available that involve buckling of tapered column made from aluminum alloy especially. This is because, most of the research that had been conducted was about straight or prismatic column and mostly used steel as their material and as the test specimen.

1.3 Objectives

The objectives of this study is to determine the critical buckling load of tapered columns with different length, tapered ratio, cross-sectional area and how the buckling load is affected by the end support conditions and to be compared with the analytical result.

1.4 Scopes of Project

In order to conduct in-depth research of buckling problems, the study had been narrowed down to be more specific. The following scope had been suggested.

1. To design the fixtures to hold the test specimen or tapered column.
2. Fabricate square and round tapered column with solid cross section and used aluminium alloy as the material for the test column.
3. Tapered column will be designed with a three different length and two aspect ratios.
4. To conduct the compression or buckling test on the designed tapered column.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

There are variety of ways that lead to failure in load-carrying structures. It depends on the structure's type, condition of support, loads supported and the material used. For example, an axle of vehicles that may fracture due to repeated cycles of load or beam that maybe excessively deflected that intend to make the structure unable to perform (Gere and Goodno, 2012). The maximum and minimum displacements are remained within the accepted limit during designing the structures to avoid the failure. In designing any structure or parts, the strength and stiffness are the most important factors.

2.1.1 Buckling

One of the structural failures is known as buckling. If the compression member is relatively slender, it may deflect laterally and resulting to bending. According to Gere and Goodno (2012), the column can be said buckled if lateral bending occurred. Phenomenon of buckling could be occurred in many types of structures and forms. The buckling occurrence does not limited to column only. For column that being compressed by axial force, column's shortening is the only deformation that occur to the column. Thus, it leads to buckling of column. Besides that, if the column was deflected by perpendicular force, the column will bend from its straight position.

The first researcher that had begun the investigation concerning to axially loaded compressed straight column is Euler in 1744. By using Euler's theory, the column structures does not fail because of bending if the load applied is less than the critical buckling load. Euler also stated that the buckling phenomenon is highly related to the slenderness, cross-section and radius of gyration of column (Rasmussen and Hancock, 2012). Besides that, the strength of the column also affected by the end support conditions either free, pinned or fixed.

The research on stability of steel column that have non-uniform cross-section had been conducted by Theodore, Ioannis and George (2012). This paper studied on a simple and effective strategy for the investigation of non-uniform steel members with or without initial flaws or imperfections by axially loaded forces concentrically or eccentrically apply. The type of initial imperfection used is by varying the cross section of the column members. To predict the buckling deformation, a plastic criterion had been applied.

2.1 Theoretical Approach for Determination Column Strength

Most researchers used analytical and numerical solution as their theoretical approach. Analytical solution can give the exact solution while for numerical solution, it gives about the approximate value. Numerical solution is a study of algorithm that used approximate value to solve the problem that involved mathematical analysis.

2.1.1 Analytical Solution for Tapered Column

Gere and Carter (1962) had published a paper in the ASCE Journal of the Structural Division had provided the equation and design curves in order to calculate the critical buckling load of column with different cross section and four conditions of the end support which is pinned-pinned, fixed-pinned, fixed-free and fixed-fixed. The method of solution of differential equation and successive approximation of the deflection curve that had been developed by Timoshenko and Newmark had been used by Gere and Carter in order to provide a relative concise set of equations to calculate the critical buckling load. For column with a linear tapered, circular cross section and pinned-pinned, fixed-pinned end conditions, the equation is the product of the square and circular ratio of end diameters and the critical buckling load [P_{cr}] of a prismatic column. Table 2.1 shows the expression that is used to determine the critical buckling load with different end condition. In the equation used, d_a shows the dimension for the small end while d_b shows the dimension for larger end of the column. Figure 2.1 shows the notation used in tapered column geometry.

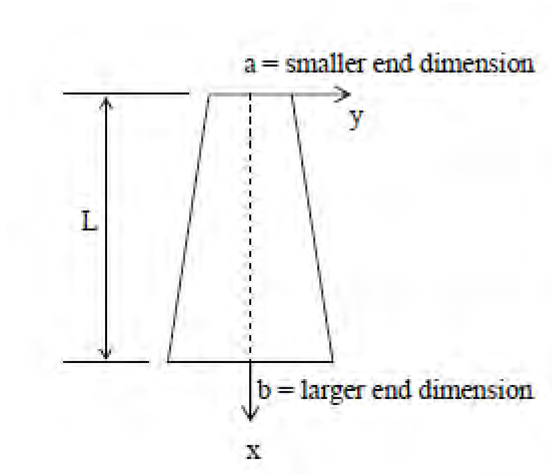
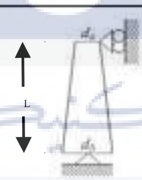
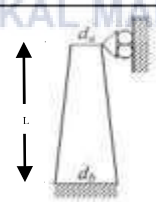
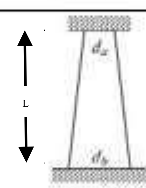


Figure 2.1: Notation used for tapered column
(Source: Gere and Carter, 1962)

Table 2.1. Buckling load for tapered column with solid cross-section of squared and circular

End Condition	Schematic	Buckling Load
Pinned-pinned		$P_{cr} = \left(\frac{\pi^2 EI_a}{L^2}\right)\left(\frac{d_b}{d_a}\right)^2$
Fixed-pinned		$P_{cr} = \left(\frac{\pi^2 EI_a}{(0.6997L)^2}\right)\left(\frac{d_b}{d_a}\right)^2$
Fixed-fixed		$P_{cr} = \left(\frac{4\pi^2 EI_a}{L^2}\right)\left(\frac{d_b}{d_a}\right)^2$

(Source: Gere and Carter, 1962)

Gere and Carter (1962) had expressed general Equation (2.1) to determine the moment inertia (I) of the linearly tapered column since it have variable cross- sectional dimension along the length of the member.

$$I(x) = I_a\left[1 + \left(\frac{d_a}{d_b} - 1\right)\frac{x}{L}\right]^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad Equation\ (2.1)$$

The value of n in Equation (2.2) is a shape factor which can be determined by using equation below:

$$n = \frac{\log \frac{I_b}{I_a}}{log \frac{d_b}{d_a}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad Equation\ (2.2)$$

Lind (1962) also had done a discussion on tapered columns critical buckling load proposed by Gere and Carter. It was found that a narrow range diameter of tapered ratio and shape factors are usually used in design. For half-point and third-point rules from the small end give a critical buckling load up to 15% to 20% error. From the analysis, the effective cross-section should be placed at 4/10 and 6/10 point for pin end and fixed-free condition respectively to get percentage error below 7%.

Another analytical solution for buckling of tapered column was provided by Smith (1988) which allows variation of cross section along the length of member. First demonstration used fixed-free end condition with moment of inertia vary by the power of 4 along the length member. Then, the result is being compared with Dinnik (1929) and it shows that small error in his calculation for small tapered ratio. However, by increasing the tapered ratio, the trigonometric assumption on deflected shape become more approximate. As the conclusion, he had recommended to use the analysis software in handling cases other than linearly tapered square and round section as the analytical expression had become complicated.

From the paper of "Design of Columns of Varying Cross-Sections" by Dinnik (1929), the tapered analysis used Bessel function to solve the buckling load of linearly tapered column that symmetric about the half-length. After a few years, which is in 1932, he had produced more example of problem with their solution that related to his previous research.

2.1.1 Numerical Solution

When it comes to numerical solution, usually it used the computer based program which needs a software to solve the mathematical analysis problem. The previous researchers had used finite element modelling to find numerical solution of the buckling problem.

From the research paper of Najla'a H. Al-Shareef (2014), her study is about non-linear buckling analysis of non-prismatic steel column subjected to axial compression loads. The paper investigated on how the cross-sectional area and tapered ratio will influence the stability of tapered column. The study is also focused on the square and round cross-section that vary with length. The finite element method had been used in the research in order to get the numerical solution According to the result as shown in Figure 2.2, it can be concluded that the critical buckling load is higher when the tapered ratio of column increases. For the support condition, the column that have fixed-end condition is having a higher critical buckling load compared to pinned-fixed and pinned end condition.

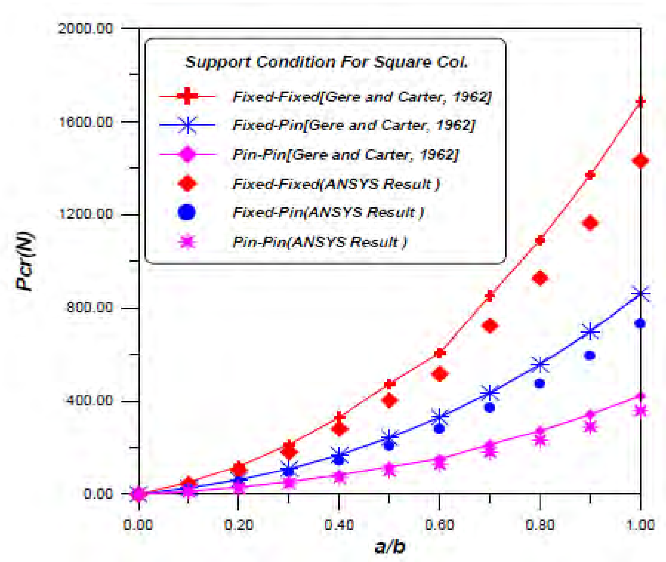


Figure 2.2: Graph of critical load against tapered ratio with different end condition.
(Source: Najla'a, 2014)

A short treatment of finite-difference method was provided by Rivello (1969) and can be applied to determine the non-prismatic column buckling problem. A set of homogenous linear equation will be produced by using Rayleigh-Ritz and finite element method that need to be solved later. From the paper, it said that Newmark's method is the suitable method to study on the buckling of tapered column. Besides that, Rivello (1969) also had provided analysis of tapered column by using Rayleigh- Ritz method. From the research of Galambos (1998), a general prologue to the used of finite element had been introduced to conduct a stability analyses.

2.2 General Column Behavior

Columns are members that compressed by axially loaded force. Beams and columns was used to make a building frame. According to Pytel and Kiusalaas (2011), for a slender column, it may fail before the compressive stress reach the yield strength of the material. Columns are divided into a few types depends on their way to fail. A short column will fail by crushing and even if the load is eccentrically applied, it will undergoes a negligible lateral deflection. Buckling typically occurs in long and slender columns. The columns will deflect and collapse if the axial load is reached the critical value since it becomes unstable. Besides that, buckling phenomenon also can occur when the stress are smaller than the yield stress or proportional limit of material. The intermediate column will fail by combination of buckling and crushing. The intermediate are designed using empirical formula that derived from experiments due to difficulty on analyzing the problem (Pytel and Kiusalaas, 2011).

Initial imperfection such as initial lack of straightness of the axis of column also will affect the column behavior (Rasmussen and Hancock, 2012). In the research, the pin- ended column had been replaced with initial crookedness column. Long column fails at their elastic buckling limit which is named as Euler buckling stress. For short column, the column will not undergoes buckling but it will straightly undergoes crushing at the ultimate compressive stress or their compressive strength limit. There are intermediate columns that lies between the range of short column and long column. This column will undergoes inelastic buckling failure mode. They failed when the stress average reach the inelastic buckling limit.

Inelastic buckling is used to determine the inelastic buckling limit of an ideal column. Buckling not occur if the failure of columns falls between the range of intermediate columns. To predict the value of stress by which a column will buckle elastically, there are two principals of theories had been used. The simplest theory of tangent-modulus is developed by F.Engesse in 1889. A plot of the equation for intermediate and short columns is defined by the stress-strain diagram in Figure 2.3. It was obtained by replacing the Young's Modulus in Euler's buckling load with the slope of compressive stress-strain curve as shown in Figure 2.3 which is called as tangent modulus (Rasmussen and Hancock, 2012).

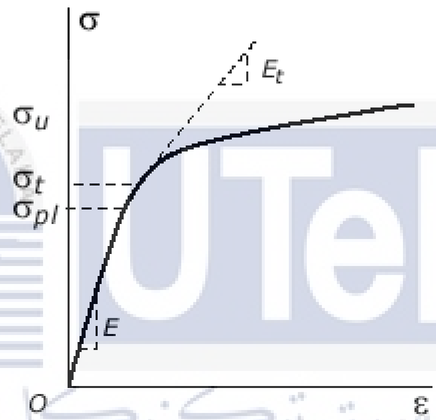


Figure 2.3: Tangent Modulus

2.3 End Support

There are four types of support end condition normally used in column's buckling theory. They are fixed- fixed, pinned-pinned, fixed-pinned and fixed-free condition. However, most of the previous researchers such as Ren et al. (2017) had used pinned-end condition which is knife hinge for the column test. Besides that, for Lee (2004) and Feng et al. (2003) they had used thicker steel plate in one of the end load.

There are also some researchers that used fixed end for column buckling test such as Ranawaka (2006), Danalakshmi and Shanmungam (2001). For Ranawaka (2006), in order to make the specimen fixed end for the distortional buckling, it was achieved by fixing in the groove that had been made on a thicker steel plate and fixing using Pyrocrete 165 coil grout. Danalakshmi and Shanmungam (2001) had welded the column to steel plate in order to make it fixed support. However, as the result, the ultimate buckling does not affected by the end condition in case of local buckling. Figures 2.4 and 2.5 show the fixed end condition that achieved by Ranawaka (2006) and Danalakshmi and Shanmungam (2001) respectively.

a) Column fixing in groove　　　　b) Groove in thicker steel plate

Figure 2.4: Fixed end condition using Pyrocrete 165 coil grout achieved by Ranawaka (2006)

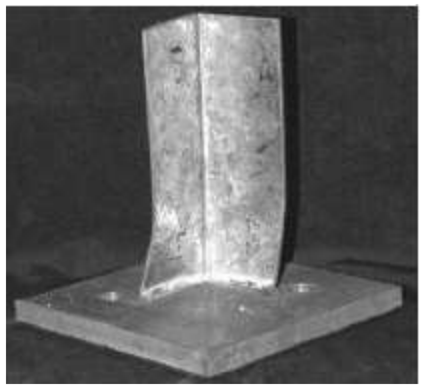


Figure 2.5: Fixed end by welded column onto steel plate used by Danalakshmi and Shamungam (2001)

CHAPTER 3

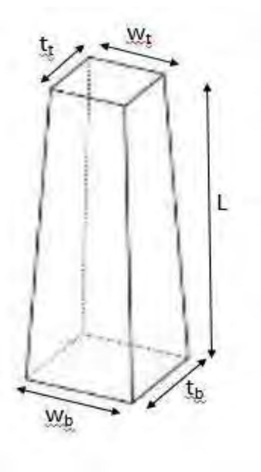
METHODOLOGY

3.1 Design and Specification

3.1.1 Test Specimen

In this research, the test specimens were designed for pinned-end and pinned-fixed conditions to investigate the buckling load of tapered column with different aspect ratio. The test specimen dimensions and design for the column should meet certain general criteria outline in the ASTM E9. The test specimens were modified based on the test specimen that were used in the laboratory of UTeM-Mechanical Engineering Faculty and according to the ASTM standard.

The compression test specimen are designed based on the ASTM E9 standard. However, there's no specific dimension for specimen that is tapered in this standard. The test specimen has been designed to be tapered which is large cross sectional area at the bottom and small cross section area at the top section. Figure 3.1 shows the notation of specimen. In this project, there are two types of cross section used which are square and circular. The details dimension of the tapered specimen is shown in Appendix D.



L: Total / Overall Length
t_t: Top thickness
w_t: Top width
t_b: Bottom thickness
w_b: Bottom width

Figure 3.1: Notation of tapered specimen / column

3.1.2 Fixture

The test specimen fixture is designed to be compatible with the testing machine used for the experiment. The fixture is placed between the compression platen of the testing machine. Figure 3.2 shows the illustration on the assembly drawing of the designed fixtures with test specimen or column. Table 3.1 shows the annotation based on the illustration drawing in Figure 3.2. The fixture is adjustable which means it can be used for pinned-ended or fixed-pinned end conditions. For the fixed ended fixture, it is placed in the pinned-ended fixtures to meet the end condition requirement for pinned-fixed column. The dimensions of the designed fixture is as shown in Appendix E.

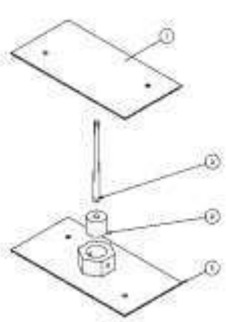


Table 3.1. Annotation

No	Part
1	Pinned-ended fixtures
2	Fixed-ended fixtures
3	Tapered specimen

Figure 3.2: Assembly Drawing of Fixtures with Specimen

3.2 Material

3.2.1 Aluminium Alloy

It is proposed that aluminium based material is used as tapered column in this study. Aluminium comes in different types of shapes and grades. The aluminium grade that being chosen is depends on how the metal intend to be used. Then, the rank of each grade can be classified from the most important to least important, so it will help in narrow down the list of suitable grades.

The test specimen material used in this research is aluminium alloy grade 6061 obtained from the store of Faculty of Mechanical Engineering UTeM. Alloy 6061 is the most widely used alloys in 6000 series. This type of aluminium alloy usually used in structural application. Alloy 6061 have an excellent corrosion resistance toward the atmospheric conditions and seawater. This standard structural alloy also have good formability or workability, weld ability and machinability. Weld ability means the metal is easily welded and can be joined by various commercial methods. Besides that, it also can be heat treated and have a good toughness characteristics. Table 3.2 shows the chemical composition in aluminium alloy 6061.

Table 3.2. Chemical composition of Aluminium alloy 6061

Component	**Wt. %**
Al	95.8-98.6
Cr	0.04-0.35
Cu	0.15-0.4
Fe	Max 0.7
Mg	0.8-1.2
Mn	Max 0.15
Si	0.4-0.8
Ti	Max 0.15
Zn	Max 0.25
Other, each	Max 0.05
Other, total	Max 0.15

3.2.2 Mild Steel

In this study, not only Aluminium based material was used. This is because, the aluminum only used for the test specimen and not for the fixture. To make the fixture, the material used must have a higher strength compare to material for the test specimen. It was to make sure that the fixture can support the test specimen while the buckling or compression test is conducted. Therefore, mild steel has been chosen as material to make the fixture. Mild steel containing a small percentage of carbon, strong and tough but not readily tempered. Mild steel is suitable for machining and usually used to make a lightly stressed component such as bolts, gear and shaft. It also have a good weld ability. In order to improve the wear resistance, it can be case-hardened. Table 3.3 shows the chemical analysis for majority grades of mild steel.

Table 3.3. Chemical Composition Majority Grades of Mild Steel

Component	Wt.%
Carbon	0.16 – 0.18
Silicone	Max 0.40
Manganese	0.70 – 0.90
Sulphur	Max 0.04
Phosphorus	Max 0.04

3.3 Preparation for Specimen and Fixture

The tapered specimens and fixtures were prepared according to the machine capability. Figure 3.3 shows the flow diagram for the preparation of the test specimen or column and fixture to hold the column during the compression test.

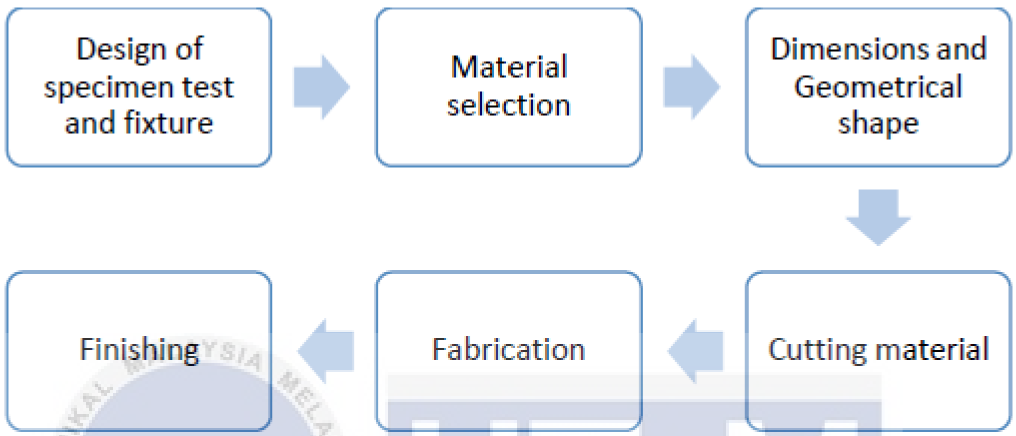


Figure 3.3: Flowchart for Specimen and Fixture Preparation

Based on Figure 3.3, the first step is to design the test specimen according to study of this project. The test specimen is designed to be tapered as shown in Figure 3.1 with two different cross-sectional area which is square and circular. The next step is material selection. The material chosen for the test specimen is Aluminium Alloy while for the fixture, the material used is mild steel. After deciding the material used for the project, we need to decide the dimension and geometrical shape for the specimen and fixture as discussed in design and specification section.

The material is cut according to specific size that had been decided at its design stage. There are two machines used for the process which is band saw machine and shearing machine as shown in Figure 3.4 and Figure 3.5 respectively. The shearing machine was used to cut material that in the form of big plate initially while band saw machine was used to cut material that in the bar form. After cutting the material, the fabrication process was carried out. Machining and drilling were involved in the fabrication process of this project.

Figure 3.4: Band Saw Machine

Figure 3.5: Shearing Machine

In machining process, one of the machine involved is conventional lathe machine. Lathe machine is one of the oldest and most important machine tools. Machine for shaping a piece of material such as wood or metal by rotating it rapidly along its axis while pressing a fixed cutting or abrading tools against it. It performs various operation such as cutting, sanding, knurling, drilling, or deformation, facing and turning. The purpose of using lathe is to rotate a part against a tool whose positions its control. In this project, the machine was used to make a hole for the inner fixture for the circular specimen.

For the inner fixture of square specimen, the machine used is CNC milling machine. It is a manufacturing machine by using the computer program. The various function of this machine tools controlled by letters, numbers and symbols. The purpose of CNC program is to write the sequence events to be done.

To make a hole, a drilling machine as shown in Figure 3.6 was used. It was used to make a hole for the fixture as in Appendix E. A drill size of 12mm and 10mm were used.

Figure 3.6: Drilling Machine

3.4 Experimental Apparatus

The machine used in this project is INSTRON 5585 floor mounted material testing machine and is operated by electrical closed-loop system. There are few type of tests that can be conducted by using this machine such as static, dynamic, bending, compression, and flexural tests. However, for this project, the test that was conducted by using this machine is compression test. Figure 3.7 shows INSTRON 5585 floor mounted material testing machine as used in conducting the compression or buckling test.

Figure 3.7: INSTRON 5585 floor mounted material testing machine

3.5 Buckling Test

Type of test that was used to determine the critical buckling load is compression test. Compression test is a test used to determine the behavior of material under axially loaded. The specimen is compressed and deformation at various load is recorded. The elastic limit, proportional limit, yield point, yield strength and material compressive strength can be obtained from this test. This test is useful for measurement of elastic and compressive fracture properties of brittle materials or low ductility material. The specimen for compression test is compressed between two parallel plates with uniform velocity as shown in Figure 3.8.

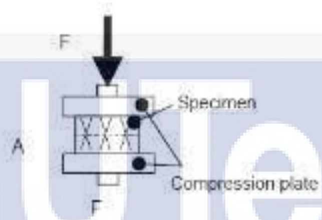


Figure 3.8: Specimen compressed between two parallel plates

Standard published by the ASTM are used to define the compression test procedures and parameter. Among all of the ASTM standards related to compression test, the most common method for compression testing of metallic material is ASTM E9. The testing procedure according to the standard is as follow:

1. Prepare the test specimen as described in standard and measure the thickness or diameter of the specimen. Calculate the average cross-sectional area for the specimen gauge section.
2. Place the specimen at the middle of the test area as shown in Figure 3.9.

Figure 3.9: Placement of Specimen

3. The load applied is constant at speed rate of 0.005 in/in/min or equivalent to 0.005 in/in/min strain-rate in the elastic portion
4. The test is continue until stress is slightly greater than the yield strength or yield point of the ductile materials.
5. Record the stress versus strain diagram or load versus extension where applicable.

CHAPTER 4

DATA AND RESULTS

4.1 Overview

This section is about the results from the experiment. The results are then being compared with the theoretical results that had been calculated based on the equation described in Chapter 2. The results are tabulated in a table form and graphs are plotted in order to ease the analysis of the results. The result of buckling load for the respective tapered column is differentiated in terms of length, cross-sectional area, tapered ratio and end support condition or its boundary condition at both ends.

4.2 Theoretical and Experimental Result for Buckling Load

Tables 4.1 and 4.2 show the result of buckling load for column with different tapered ratio, length and end-support condition for square and circular cross-section respectively. For the theoretical results, it can be referred to Appendix H for the sample of calculation.

Table 4.1. Buckling Load for Column with square cross section

Tapered Ratio	Length (m)	Pinned-ended (kN)			Fixed-pinned (kN)		
		Theoretical	Experimental	% Difference	Theoretical	Experimental	% Difference
0.84	0.16	52.43	17.62	+ 66.39	107.01	23.22	+78.30
	0.19	37.18	17.44	+ 53.09	75.88	18.72	+75.33
	0.22	27.73	17.36	+ 37.40	56.60	18.26	+67.74
0.66	0.16	11.61	16.13	- 38.93	23.69	15.08	+36.34
	0.19	8.23	12.69	- 54.19	16.80	14.39	+14.35
	0.22	6.14	11.02	- 79.48	12.53	13.20	-5.35

Table 4.2. Buckling Load for Column with circular cross section

Tapered Ratio	Length (m)	Pinned-ended (kN)			Fixed-pinned (kN)		
		Theoretical	Experimental	% Difference	Theoretical	Experimental	% Difference
0.84	0.16	30.89	27.11	+12.24	63.04	28.00	+55.58
	0.19	21.90	26.25	-19.86	44.77	27.73	+38.06
	0.22	16.34	26.15	-60.04	33.34	26.90	+19.32
0.66	0.16	6.84	17.26	-152.34	13.96	17.76	- 27.22
	0.19	4.85	13.74	-183.30	9.90	17.30	- 74.75
	0.22	3.62	13.59	-275.41	7.38	16.43	- 122.63

4.3 Result of Buckling Load against Length

4.3.1 Square Section

Figure 4.1 represented graph of theoretical and experimental result buckling load against length for tapered ratio of 0.84 while Figure 4.2 is for tapered ratio of 0.66.

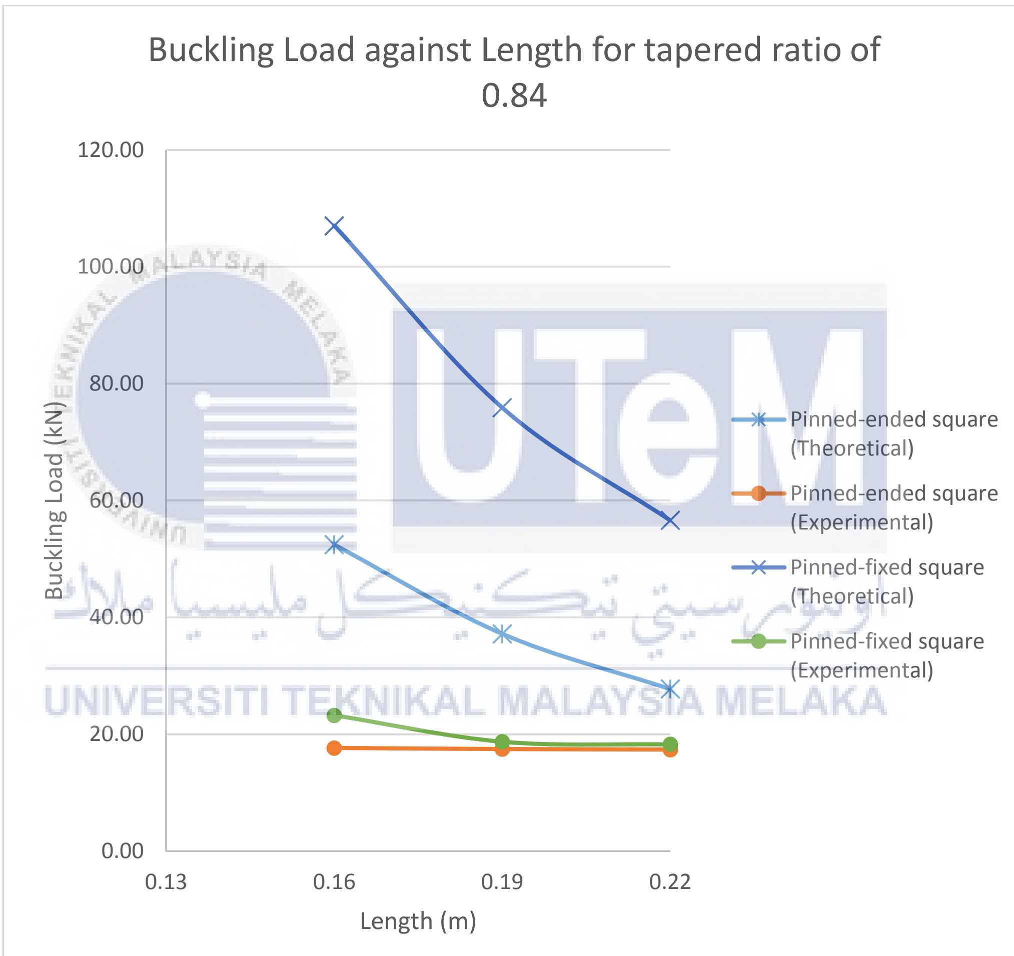


Figure 4.1: Graph of Buckling Load against Length for Tapered Ratio of 0.84 (Square)

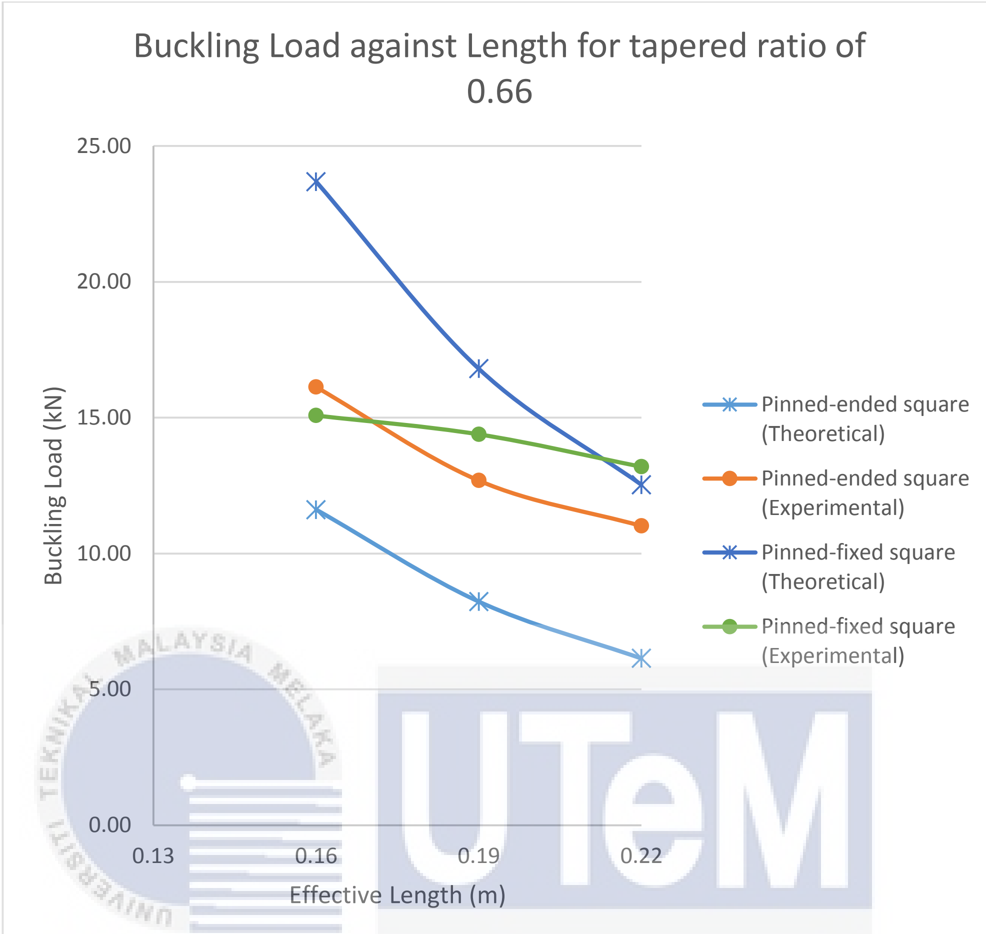


Figure 4.2: Graph of Buckling Load against Length for Tapered Ratio of 0.66 (Square)

4.3.2 Circular Section

Figure 4.3 shows graph of theoretical and experimental result buckling load against length for tapered ratio of 0.84 while Figure 4.4 is for tapered ratio of 0.66.

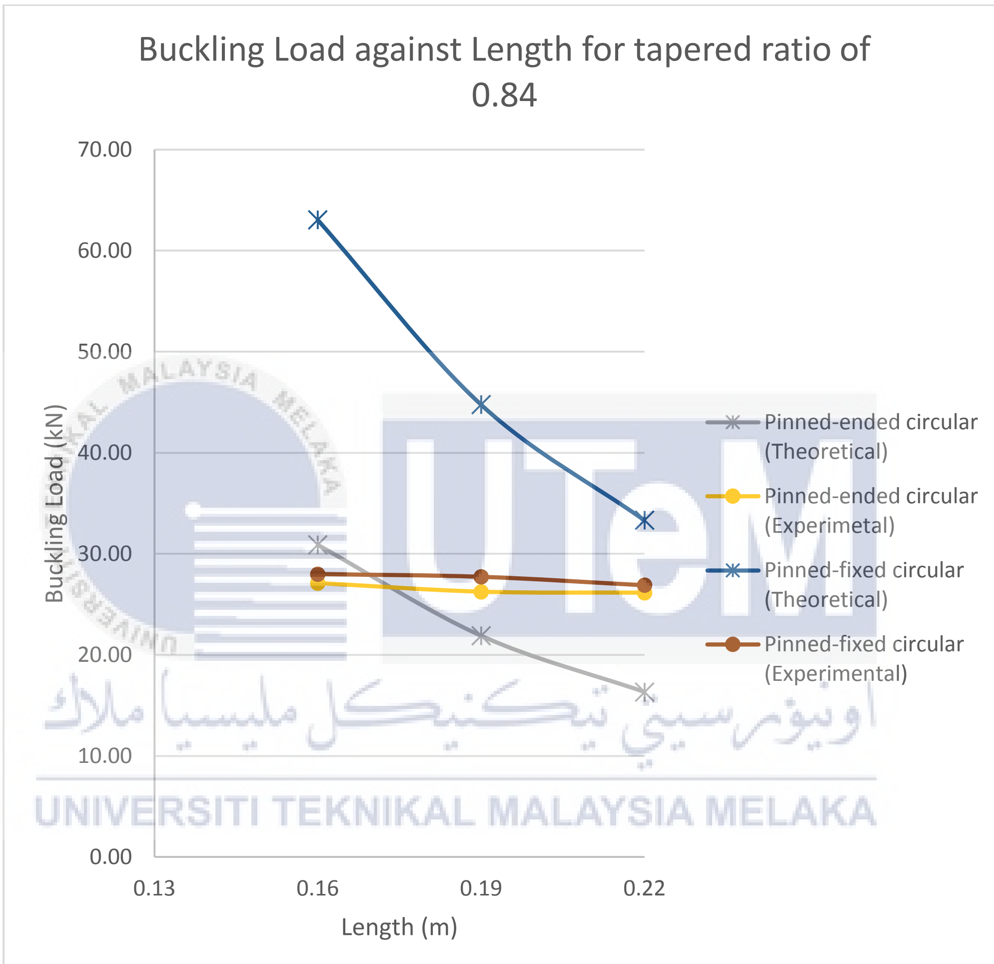


Figure 4.3: Graph of Buckling Load against Length for Tapered Ratio of 0.6 (Circular)

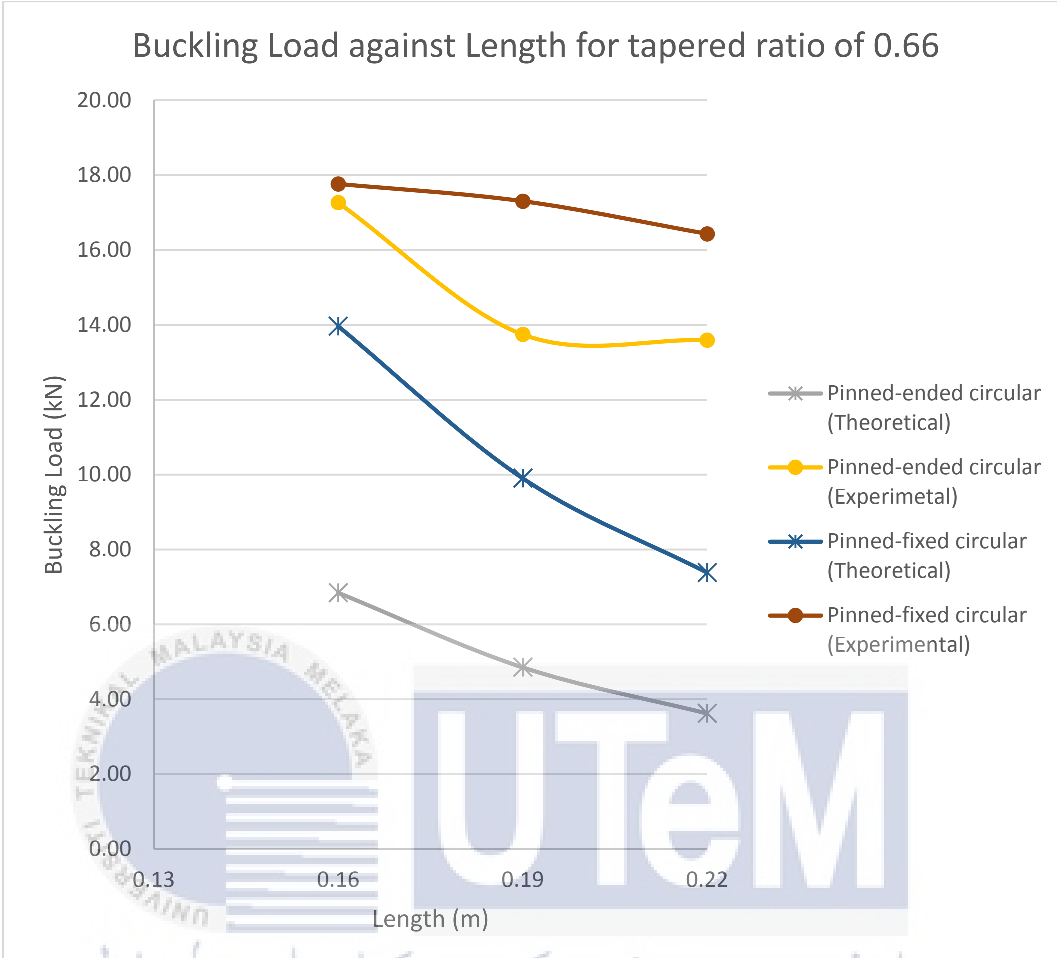


Figure 4.4: Graph of Buckling Load against Length for Tapered Ratio of 0.66 (Circular)

4.4 Result of Buckling Load against Tapered Ratio

For this section, the graph plotted is for buckling load against tapered ratio for different support condition between theoretical and experimental.

4.4.1 Pinned-ended Support Condition

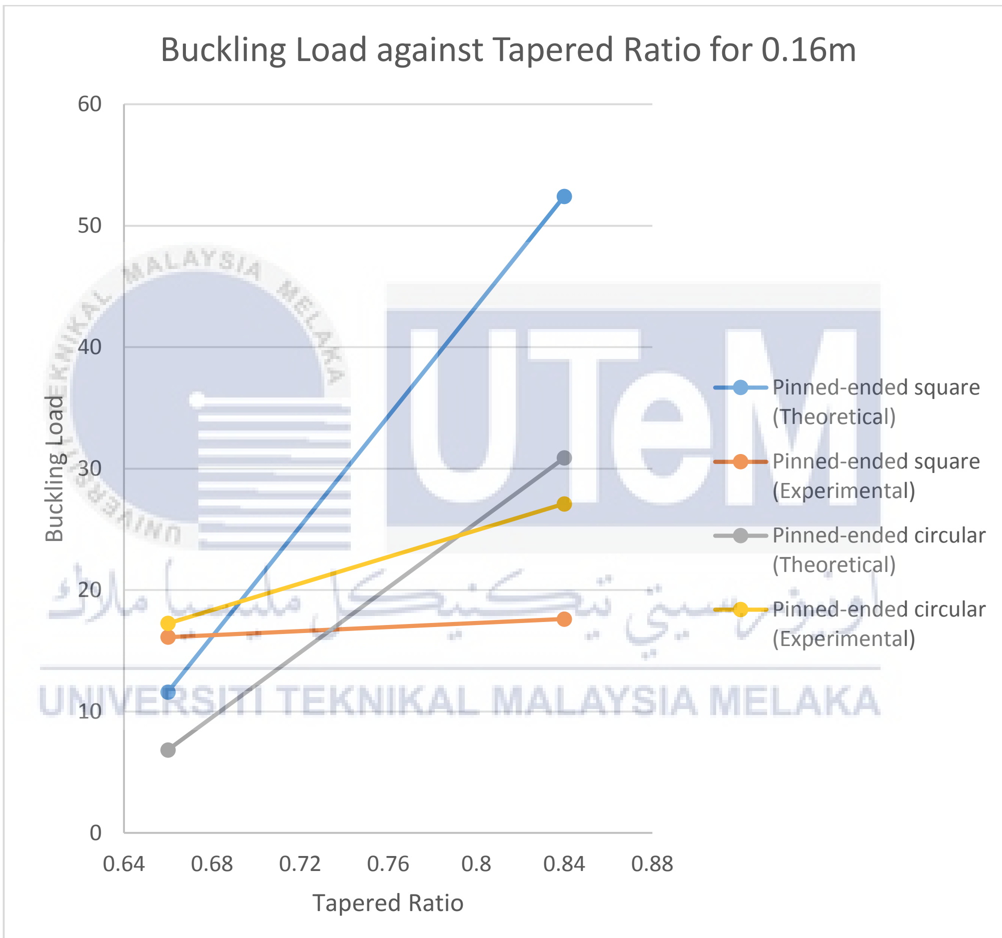


Figure 4.5: Graph of Buckling Load against Tapered ratio for length of 0.16m (Pinned-ended)

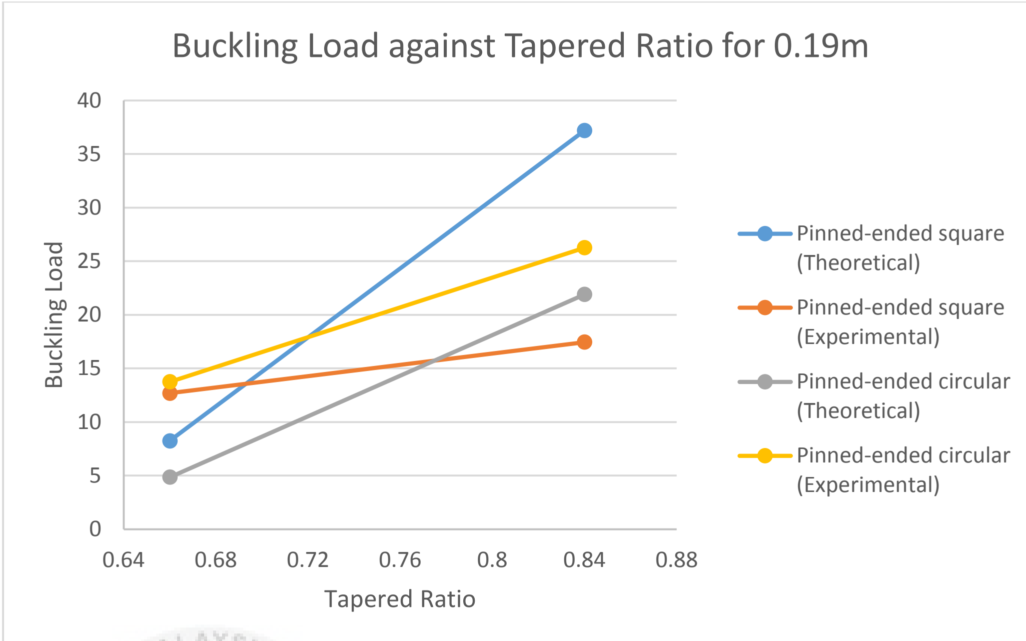


Figure 4.6: Graph of Buckling Load against Tapered ratio for length of 0.19m (Pinned-ended)

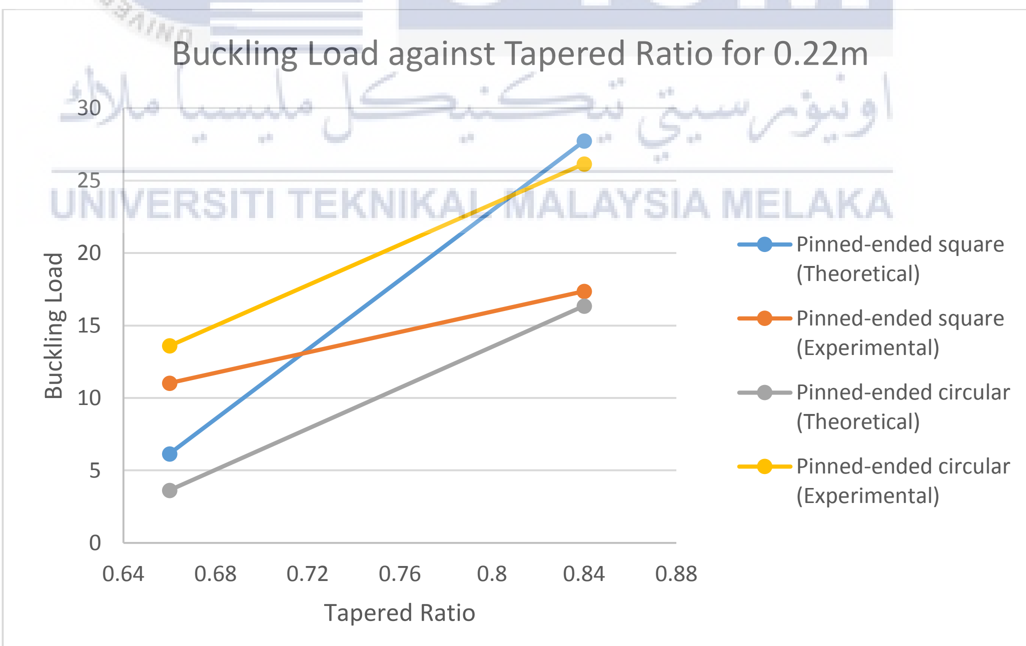


Figure 4.7: Graph of Buckling Load against Tapered ratio for length of 0.22m (Pinned-ended)

4.4.2 Pinned-fixed Support Condition

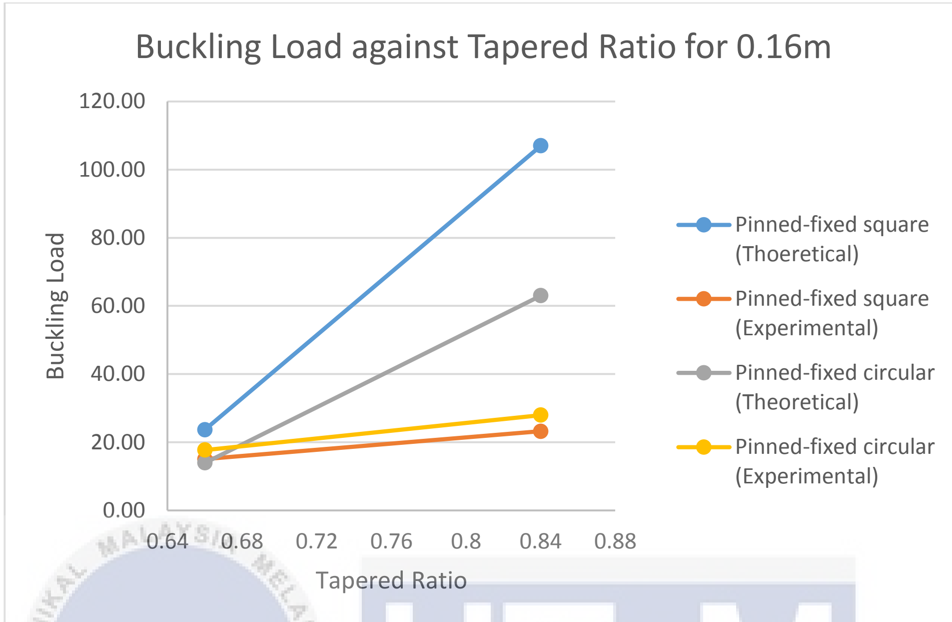


Figure 4.8: Graph of Buckling Load against Tapered ratio for length of 0.16m (Pinned-fixed)

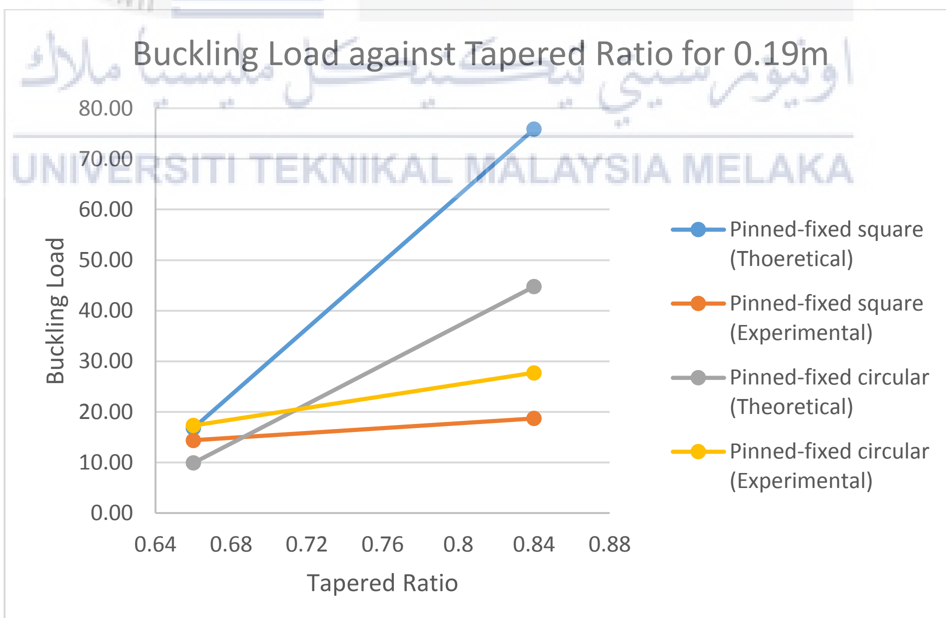


Figure 4.9: Graph of Buckling Load against Tapered ratio for length of 0.19m (Pinned-fixed)

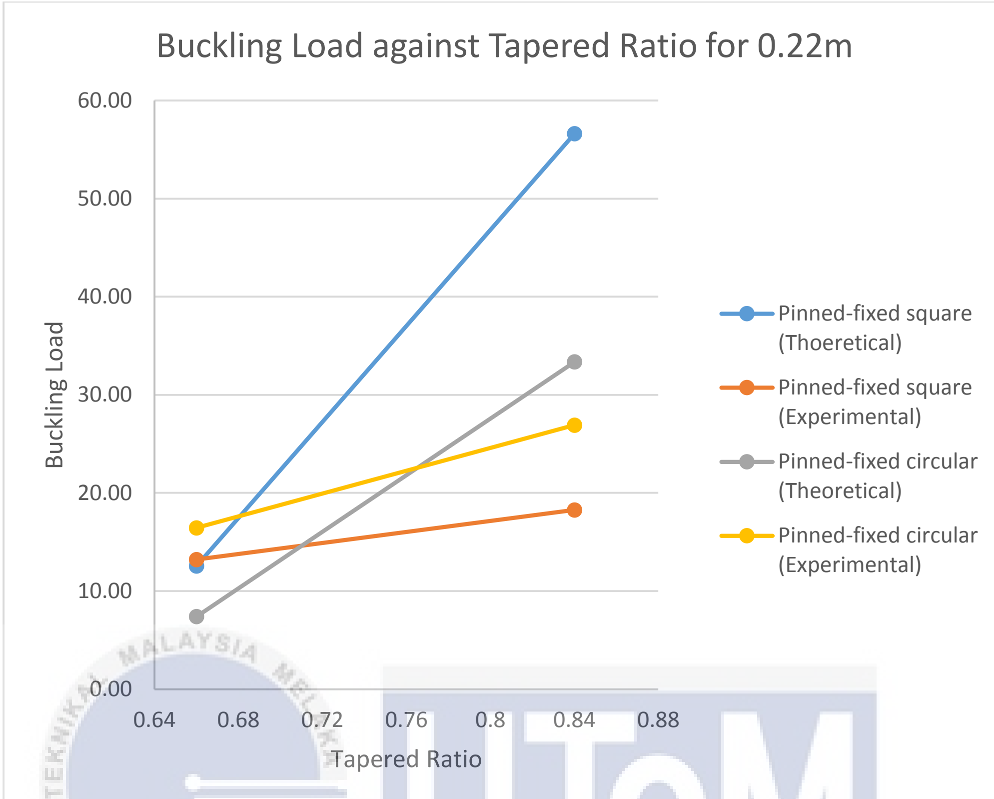


Figure 4.10: Graph of Buckling Load against Tapered ratio for length of 0.22m (Pinned-fixed)

CHAPTER 5

DISCUSSION AND ANALYSIS

5.1 Overview

The main purpose of this part is to discuss and analyze on the results that had been presented in Chapter 4. There are many factors that could influence the critical buckling load of tapered column such as length, cross-sectional area, tapered ratio and also a support end condition. Each factor has different effect to buckling load.

5.2 Analysis of Buckling Load Based On The Experimental Result

After the buckling test was conducted, a graph had been generated by the computer software. From the result, a graph of load (kN) against the extension (mm) as shown in Figure 5.1 had been plotted. Figure 5.1 shows the example result for column that is square cross- section with tapered ratio of 0.84 and length of 0.16m. However, the critical buckling load need to be determined since it didn't show directly or automatically in this experimental graph. Therefore, to determine the critical buckling load of the tested column in this study, a transition point between the elastic and plastic deformation regions as shown in Figure 5.1 is chosen as a point to represent the critical buckling load of the respective column. By using the raw data and test graph from each experiment at certain extension, the critical buckling load can be determined by using this approach.

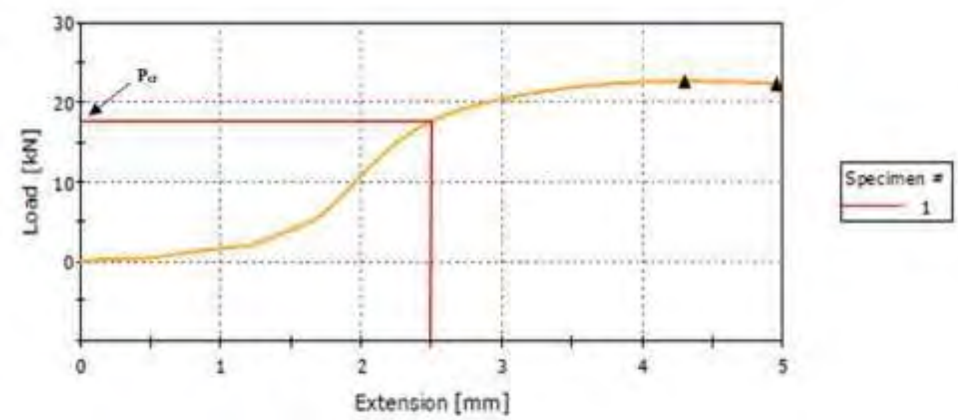


Figure 5.1: Graph of Compression Load against Extension and Method to define Pcr.

5.3 Analysis of Buckling Load with Length of Column.

A column's stability to carry load is greatly influenced by a slenderness and length of a column. For short column, it fails by crushing at a very high stress levels that are above the elastic limit or yield point while for long and slender column it fails by buckling at a stress level below the elastic limit (or yield point/stress) of the column material. An extremely large loads is needed to cause the short column to buckle.

The length used for the experimental and theoretical results is called effective length. It can be defined as the equivalent length for pinned-ended column that having the same load-carrying capacity as member under certain consideration. From Figures 4.1, 4.2, 4.3 and 4.4, it shows the graph of buckling load against length of the column for the theoretical and experimental results. From the result, the column that have the length of 0.16m have higher buckling load compared to column with length of 0.19 and 0.22m. Column that have length of 0.22m have lower buckling load. Therefore, column with smaller effective length have lower risk towards the lateral buckling and a higher compression load can be supported.

5.4 Analysis of Buckling Load with Tapered Ratio of Column

The column used in this project doesn't have a straight shape. It happen to have changing cross-sectional, and that's what we said as tapering. There are only two tapered ratio used in this study which is 0.84 and 0.66.

Figures 4.5, 4.6 and 4.7 show the graph of buckling load against tapered ratio for pinned-ended while Figures 4.8, 4.9 and 5.0 show the graph of buckling load against tapered ratio for pinned-fixed. The load consists of a concentrated load P applied axially on the smaller end of the tested column. They showed the same behavior and results for experimental and theoretical which means, the critical buckling load is decreasing as the tapering ratio decreased.

5.5 Analysis of Buckling Load with End Support Condition

From the results of experimental and theoretical that had been tabulated, it can be seen clearly that different end support conditions give a big influence to the buckling load. Two type of end support conditions used in this study. There are pinned-ended and fixed- pinned ended. According to the theoretical result, the buckling load for fixed-pinned ended should be twice (i.e 100% higher) the value for pinned-ended. But, for experimental result, the result only show a small difference between the two support conditions. For example, the critical buckling load for column with square cross-section and tapered ratio of 0.84 for pinned-ended is 17.62kN while for pinned-fixed ended is 23.2kN, which is about 32% higher than the pinned-ended column.

The result also can be seen by using plotted graph in Figures 4.1, 4.2, 4.3 and 4.4. From the graph, the column with fixed-pinned support have a higher critical buckling load compared to pinned-ended support. This is because, for pinned ended, the column specimen were free to rotate but not translate in any direction at their ends. By allowing rotation at the end of the column generally reduced the load-carrying capacity. For Fixed-pinned support, one end were freely rotate while the other end of the column being restrained. Thus, it increases the load carrying capacity of the column.

5.6 Analysis of Buckling Load with Cross-sectional area of Column

For theoretical result, by using the plotted for buckling load against the tapered ratio, in section 4.4, the columns with square cross-sectional area have shown higher value of critical buckling load compared to column with circular cross section. This might be related to the radius of gyration. Radius of gyration provides the distribution of strength of column cross section about its centroid and axis under consideration. Table 5.1 shows the radius of gyration (r) for the column that used in this study.

Table 5.1. Radius of Gyration for different tapered ratio and cross-sectional area

Tapered ratio	Radius gyration of Square (mm)	Radius gyration of Circular (mm)	% Difference
0.84	3.9	3.37	13.6
0.66	3.03	2.63	13.2

Based on results in Table 5.1, it clearly shows that radius of gyration for square with tapered ratio of 0.84 and 0.66 are 13.6% and 13.2% higher than for circular cross-section. So, it can be concluded that the shape with higher radius of gyration can increase the compressive load capacity of the tapered column member.

For the experimental result, it shows that the buckling load for circular cross section column is higher than column with square cross sectional area. From the tabulated result in Tables 4.1 and 4.2, it shows the percentage difference between the experimental and theoretical results. The highest percentage of error is 275.41% for circular cross-section and the lowest percentage of difference is for square cross-section which is 5.35%. There might be a few things that contribute such errors. First error might be due to the imperfectness of the end-condition support. The end condition is not really fixed when the experiment is conducted. Maybe there are some movement occurred during the experiment that affect the experimental result. The next error is due to the non-uniform cross-sectional area of the tested column largely due to poor surface finishing that will directly affect the value of tapered ratio. Finally, the percentage difference is may also be affected because of the theoretical result due to the non-uniformity of the material properties as assumed in the theory.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Buckling is sudden sideways failures of structural member due to high compressive load. The failure is not related to the strength of material. Column will become unstable as the applied load increase on the structural member and is said to have buckle. For column buckling analysis, it consist of determining the maximum load for column to support before it collapse.

Buckling of column is affected by it aspect ratio, cross-sectional area and end boundary conditions. In this study, the length used for the research is 0.16m, 0.19m and 0.22m. The length used actually is the same as effective length. From the theoretical and experimental results, it showed that column with length of 0.22m have a lower buckling load compared to 0.19 and 0.16m. Column with 0.16m have the highest buckling load.

In term of tapered ratio, the tapered ratio is directly proportional with the buckling load. The column with lower tapered ratio have lower buckling load. It can be concluded that as the tapered ratio increased, the maximum load of the column to support before collapse also increasing.

There are two cross-sectional areas are used in this study. There are square and the other one is circular. This is related to the distribution of an object at the axis which is radius of gyration. From the calculated result, the radius of gyration for square is higher than circular even though the tapered ratio is different. Therefore, it can be said that higher radius of gyration give a higher value of buckling load.

Only pinned-ended and pinned-fixed end support conditions were investigated in this research. The buckling load for pinned-fixed is higher than pinned-ended. This because, the pinned-ended allows rotation for both ends while for pinned-fixed, it allows rotation on one end only and the other one is fixed and being restrained. However, this two conditions doesn't allow any translation.

6.2 Recommendation for Future Research

Current study has been concentrated on determining the buckling load of column by using two types of end support condition which is pinned-ended and pinned-fixed. The effective length of column might be not long enough. For future studies, it should cover on the other two types of end support condition which is fixed-ended and free-ended. Then the buckling behavior under these type of end conditions can be compared and analyzed.

Besides that, in this study, it only cover on two types of cross-sectional area and tapered ratio. However, for future studies, it is recommended to use other cross-sectional area such as ellipse, triangle and rectangular or even with hollow tapered column. To get clearer effects on the tapered ratio, the other values of tapered ratio also suggested.

In this study, the type of material used is aluminium alloy. The material used might not supplied by the same supplier. Thus, the manufacturing and production process could be a little different from the others. This has resulted in scattering of the experimental results. In order to get smoother result, this constraint need to be avoided. So, this will minimize the effect of material in future research and could give more accurate result on the experimental result. In addition to that, material such as steel also suggested to be used for future study to be compared with other materials.

Furthermore, a good surface finishing process is also necessary in this study. Different machining process give different product of surface finish that also could be the major factor affecting the buckling behavior of column. Thus, to avoid this from occurring, a better fabrication process need to be given during the specimen's surface preparation.

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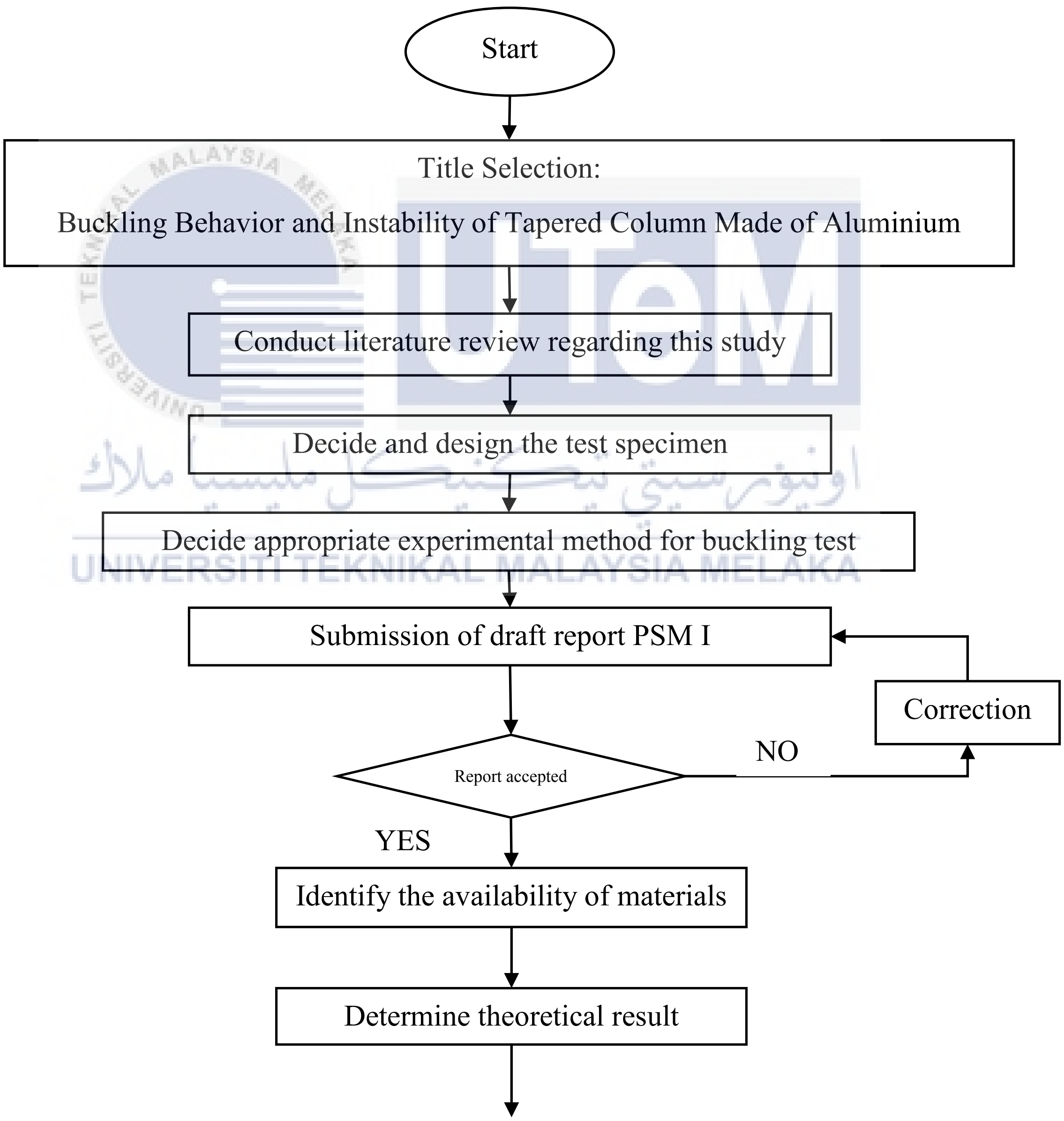
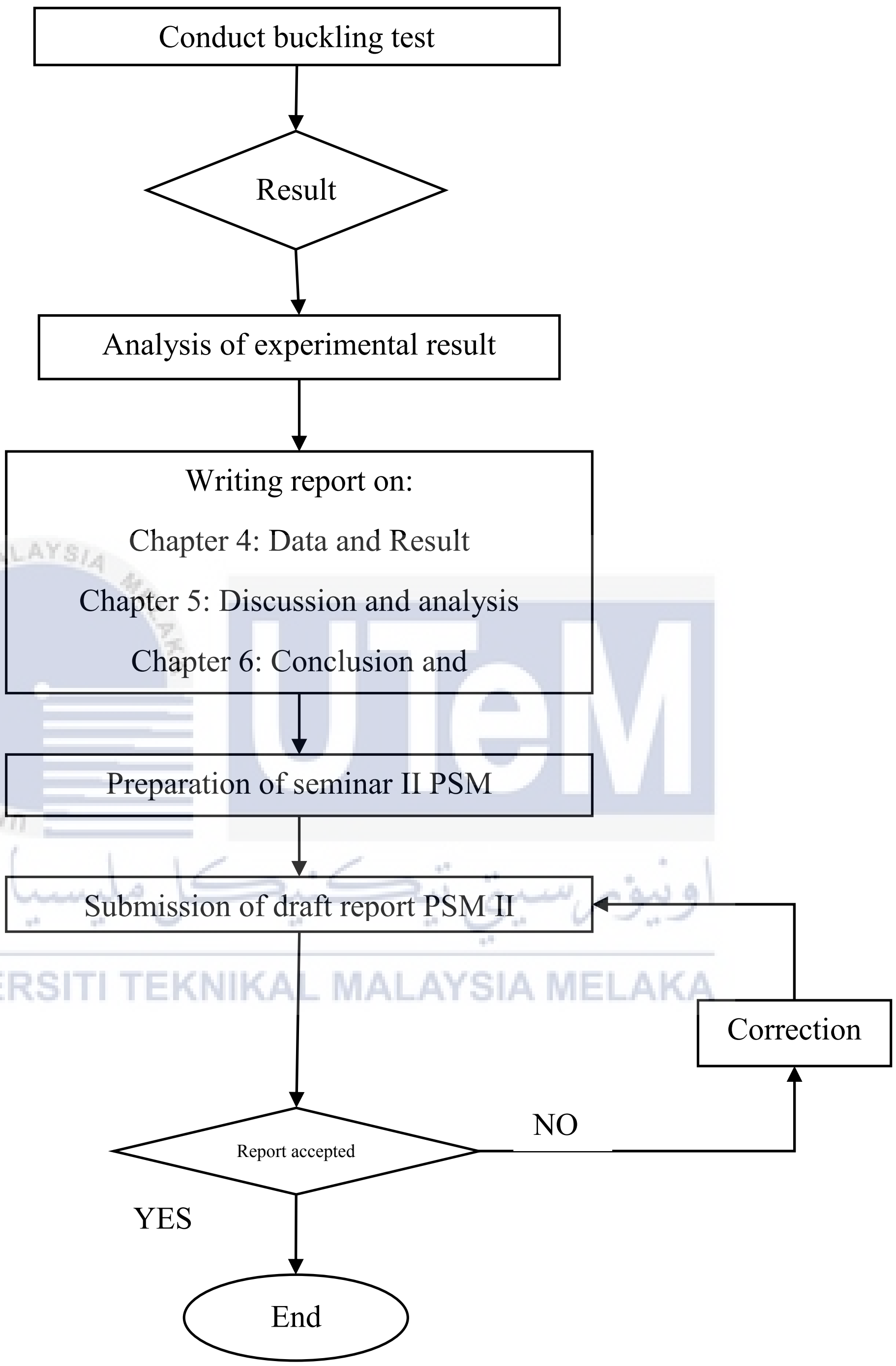
APPENDICES

Appendix A: Flowchart of Final Year Project




Conduct buckling test
Result
Analysis of experimental result
Writing report on:
Chapter 4: Data and Result
Chapter 5: Discussion and analysis
Chapter 6: Conclusion and
Preparation of seminar II PSM
Submission of draft report PSM II
Correction
NO
Report accepted
YES
End

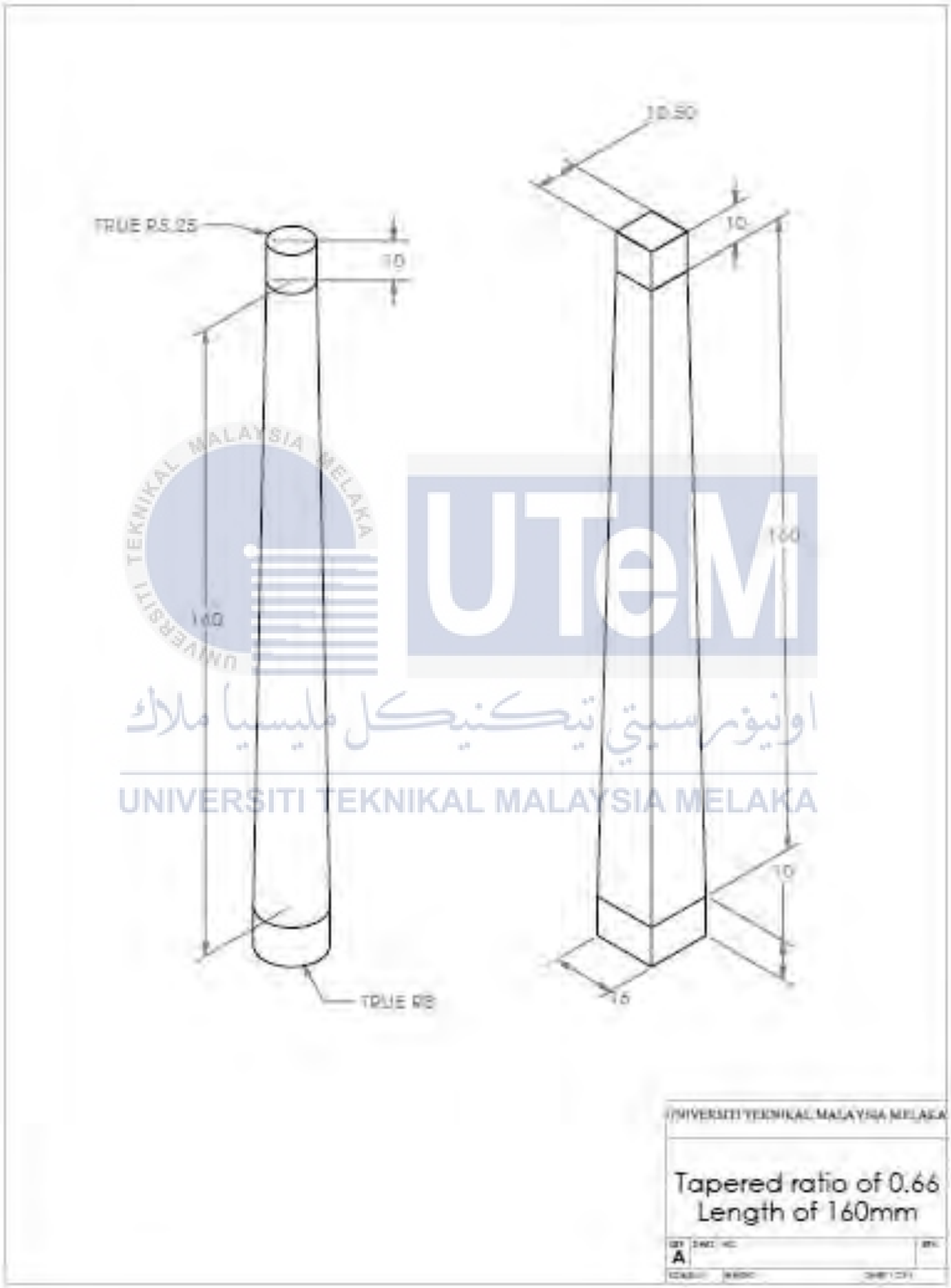
Appendix B: Gantt Chart of Final Year Project I

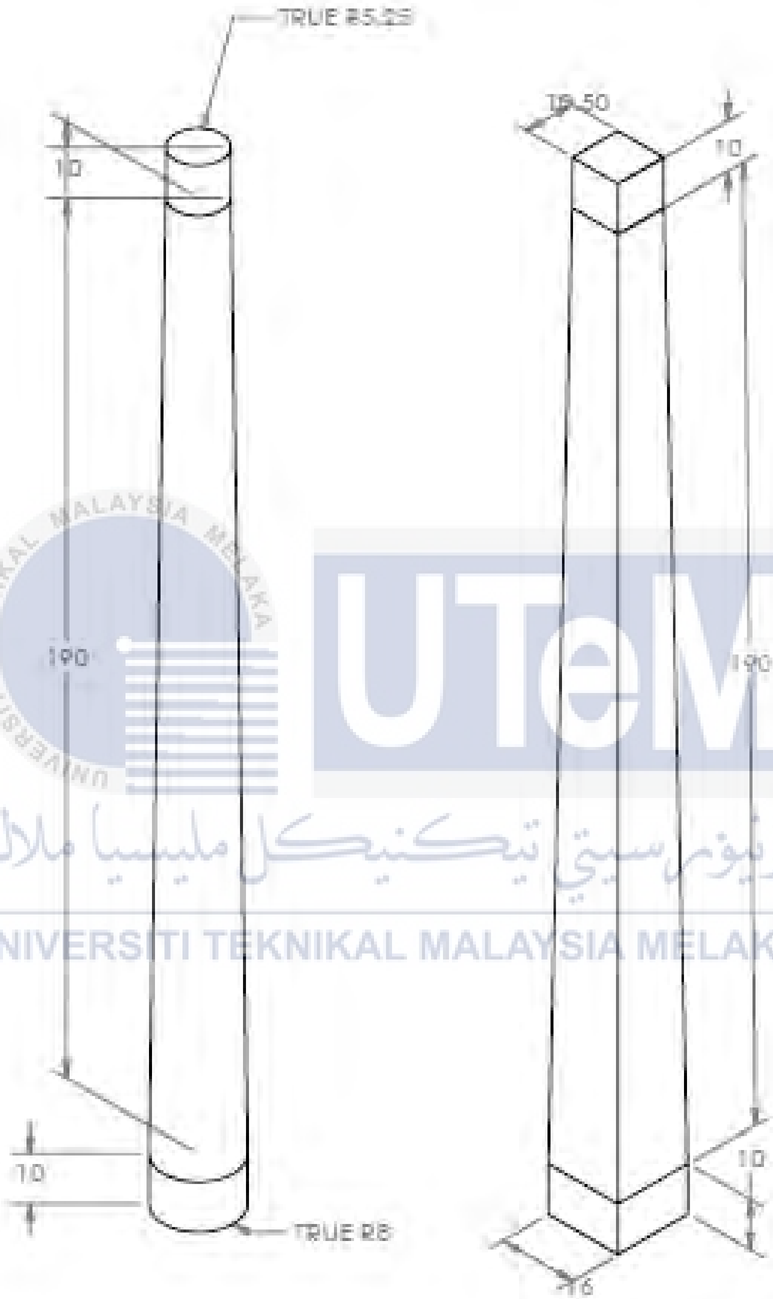
No	Task	Week																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	Selection of Final Year Project Title								SEMESTER BREAK									
2	Confirmation of Title																	
3	Literature study																	
4	Chapter 1: Introduction																	
5	Submission Progress Report PSM 1																	
6	Chapter 2: Literature Review																	
7	Design test specimen and fixture																	
8	Chapter 3: Methodology																	
9	Chapter 4: Summary																	
10	Submission of draft final report to faculty																	
11	Preparation for presentation																	
12	Seminar/ Presentation																	
13	Evaluation of PSM 1 report																	
14	Modification/ Correction report																	

Appendix C: Gantt Chart of Final Year Project II

No	Task	Week																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	Identify the availability of material								SEMESTER BREAK									
2	Determine prediction result																	
3	Fabricate specimen/ column																	
4	Fabricate fixture to hold specimen																	
5	Submission of progress report PSM II																	
6	Conduct buckling test																	
7	Chapter 4: Data and Result																	
8	Determine experimental result																	
9	Chapter 5: Discussion and Analysis																	
10	Chapter 6: Conclusion and recommendation																	
11	Preparation of PSM II draft report																	
12	Submission of draft report to faculty																	
13	Presentation/ Seminar																	
14	Evaluation of PSM 1 report																	

Appendix D: Detailed Drawing of Specimen

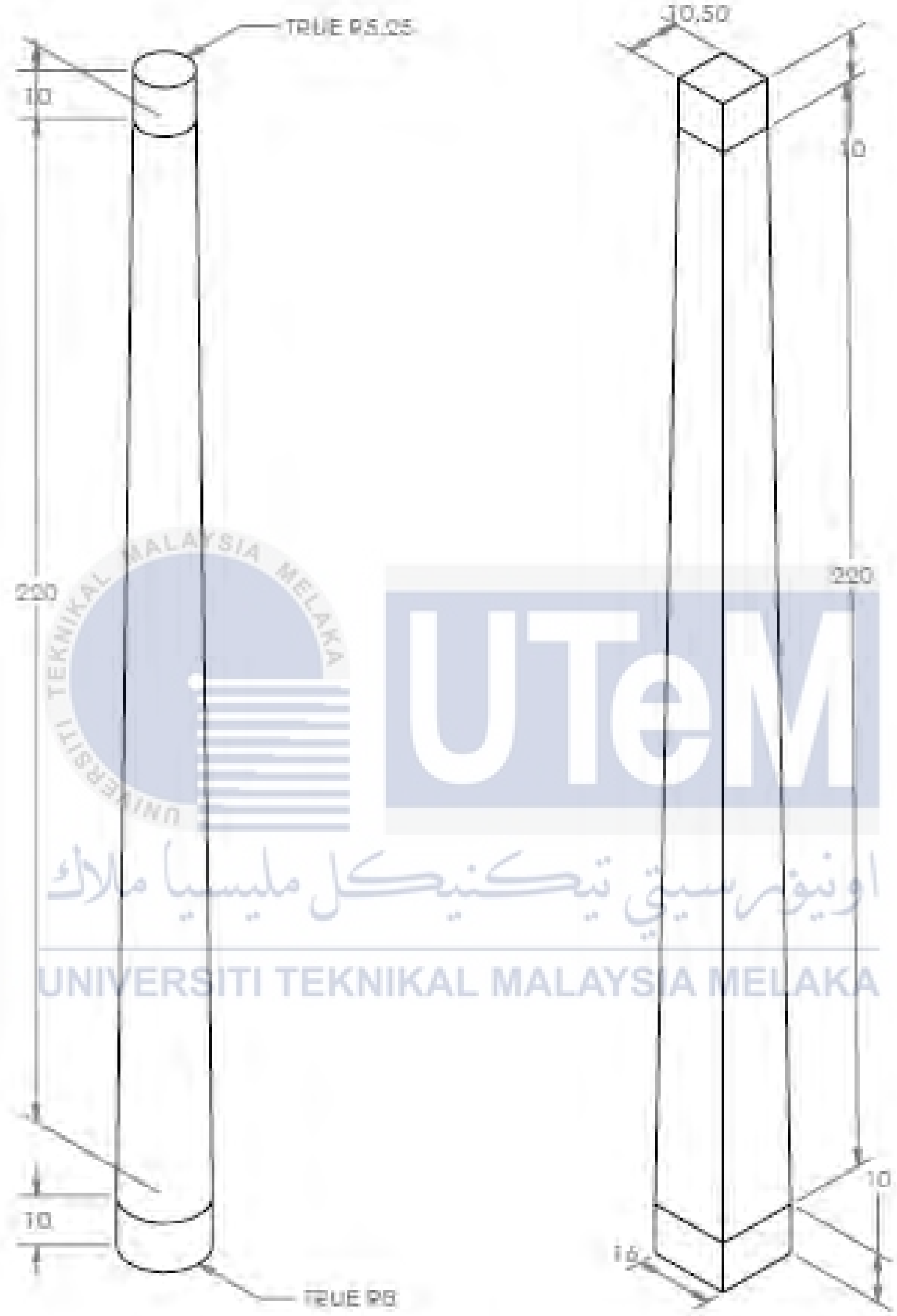




UNIVERSITI TEKNIKAL MALAYSIA MELAKA

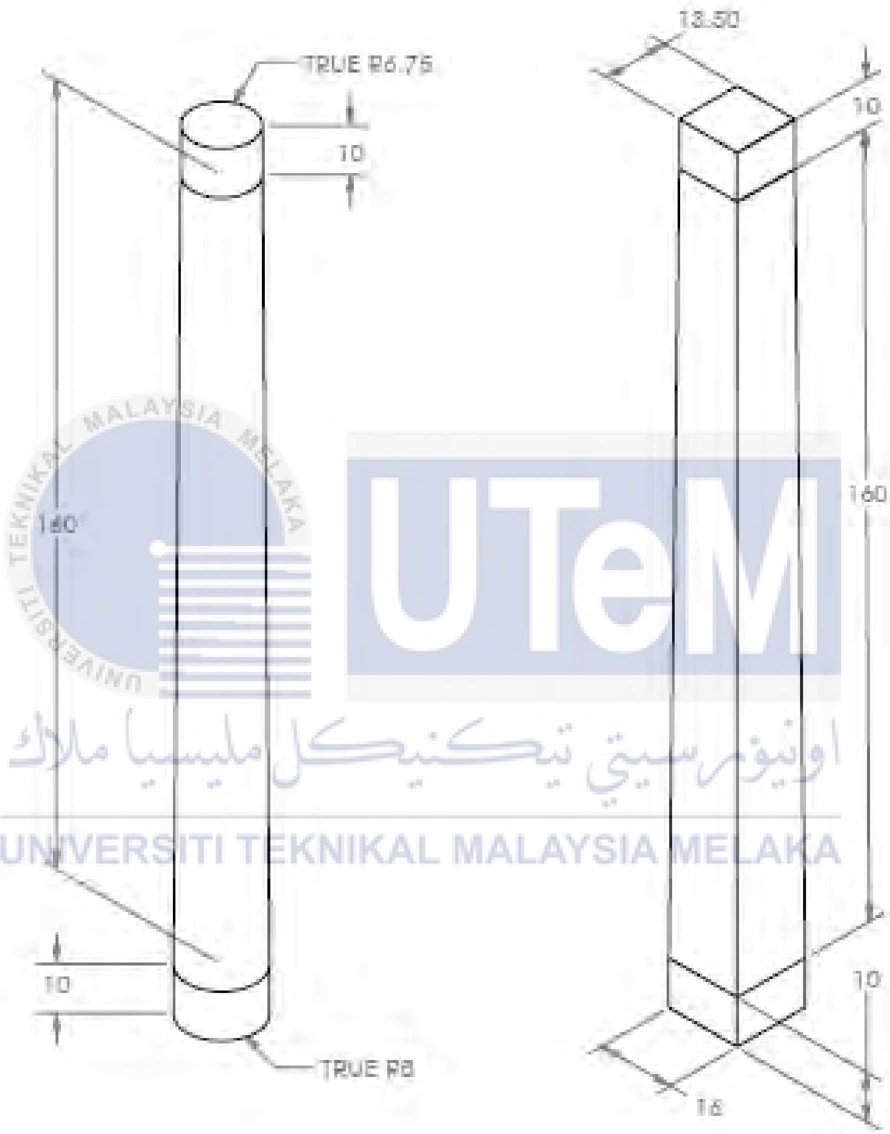
Tapered ratio of 0.66
Length of 190mm

SIZE	DWG. NO.	REV
A		



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

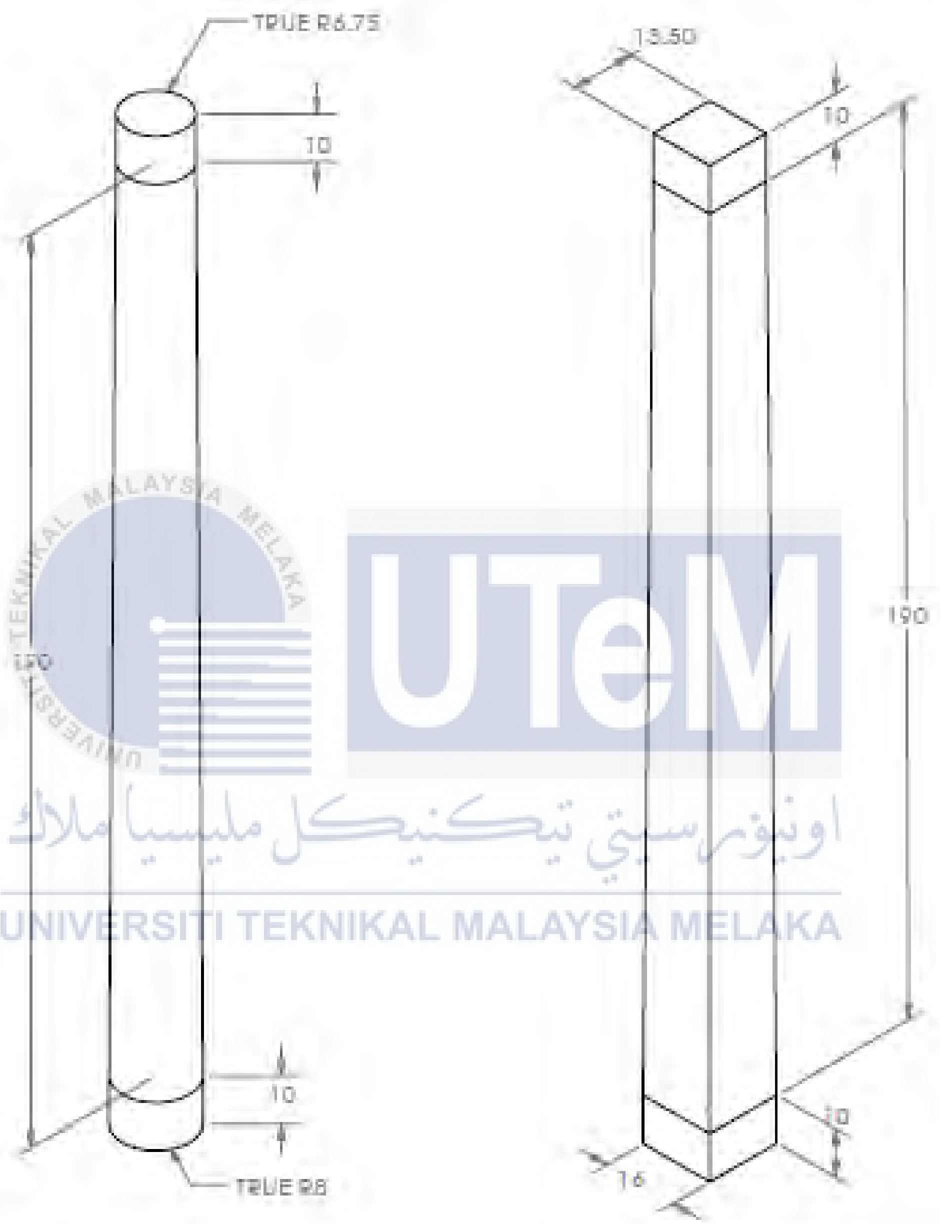
Tapered ratio of 0.66
Length of 220mm



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Tapered ratio of 0.84
Length of 160mm

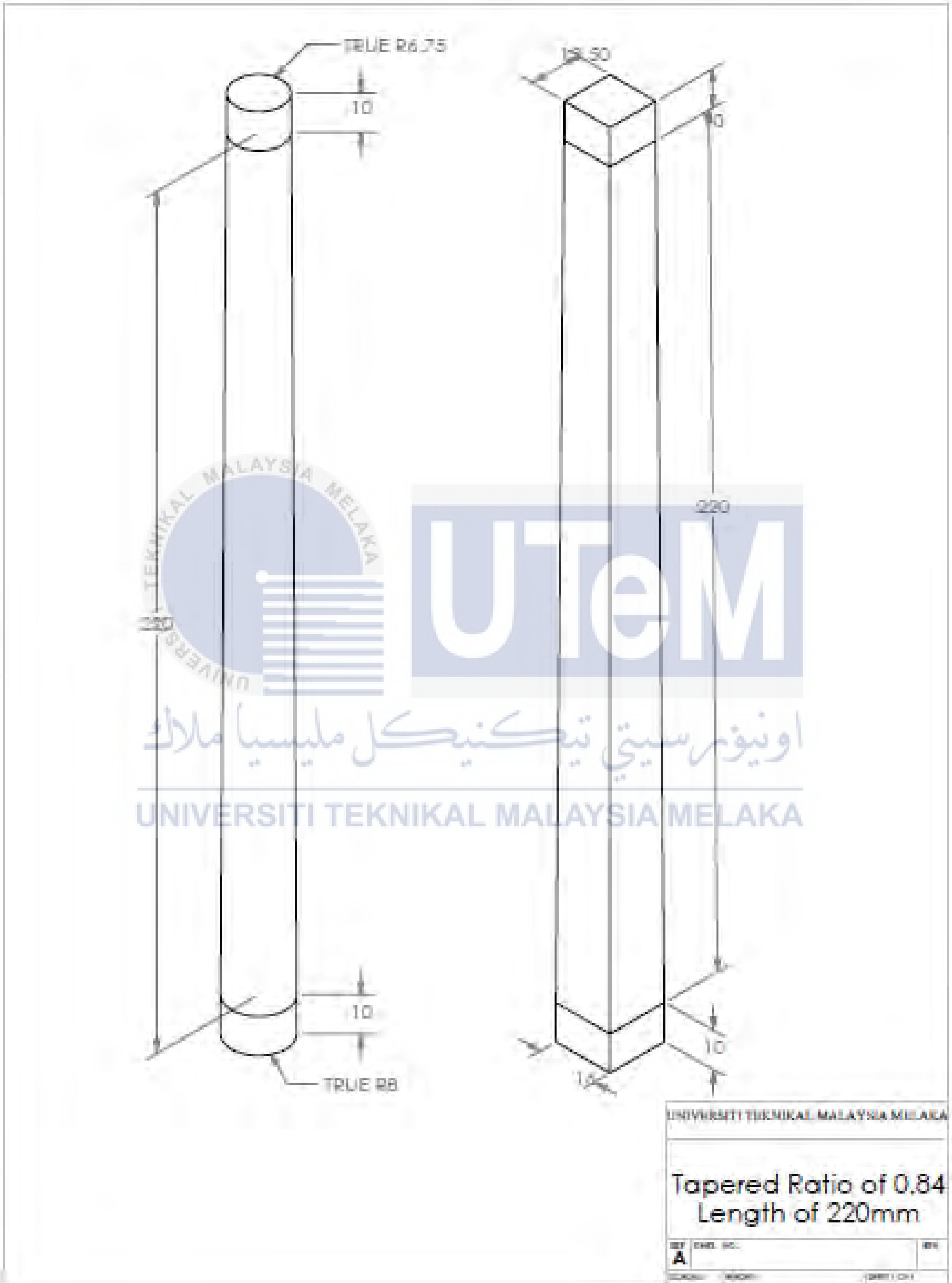
SIZE A DWG. NO. REV.



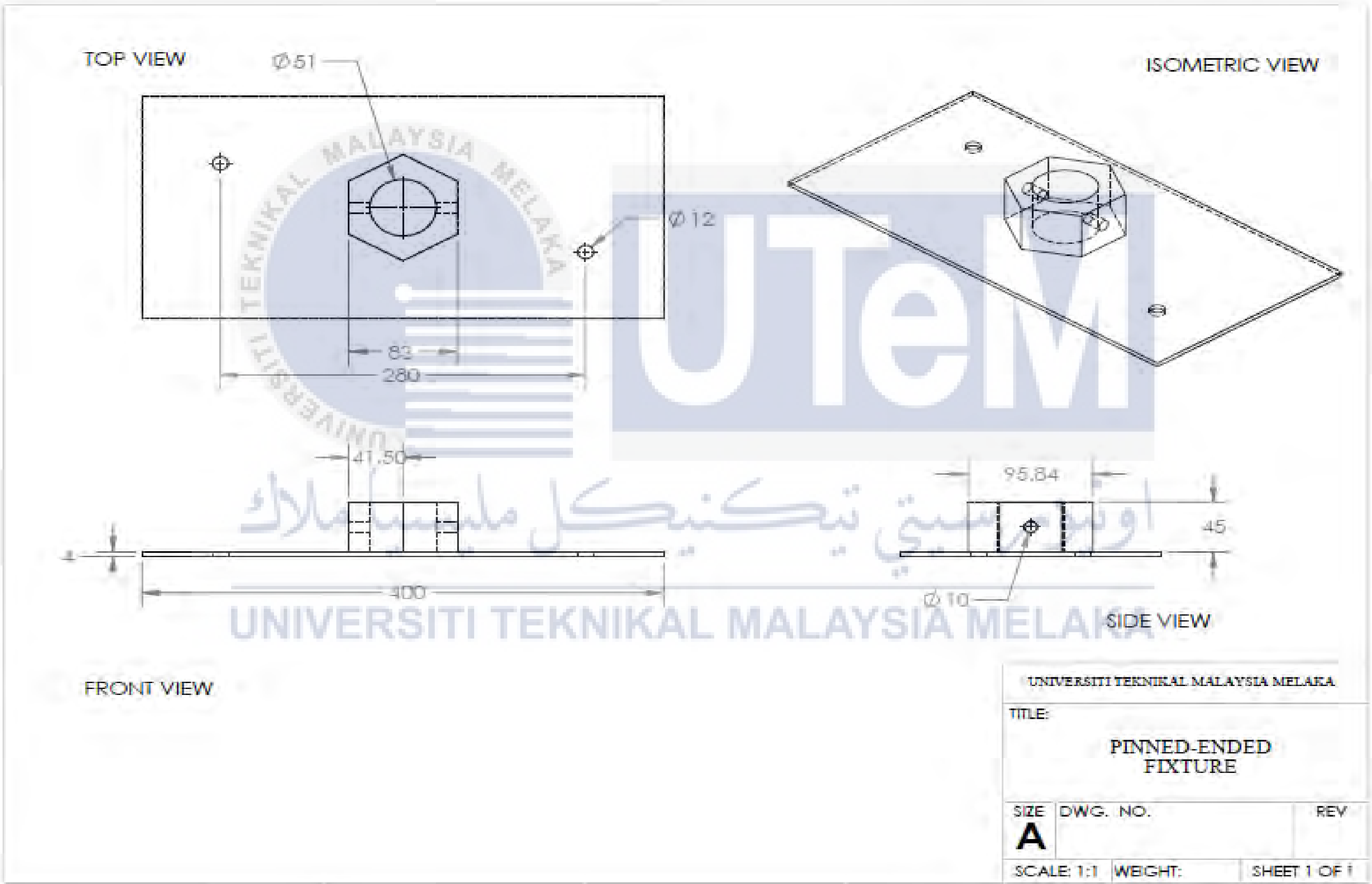
UNIVERSITI TEKNIKAL MLAYSOA MELAKA

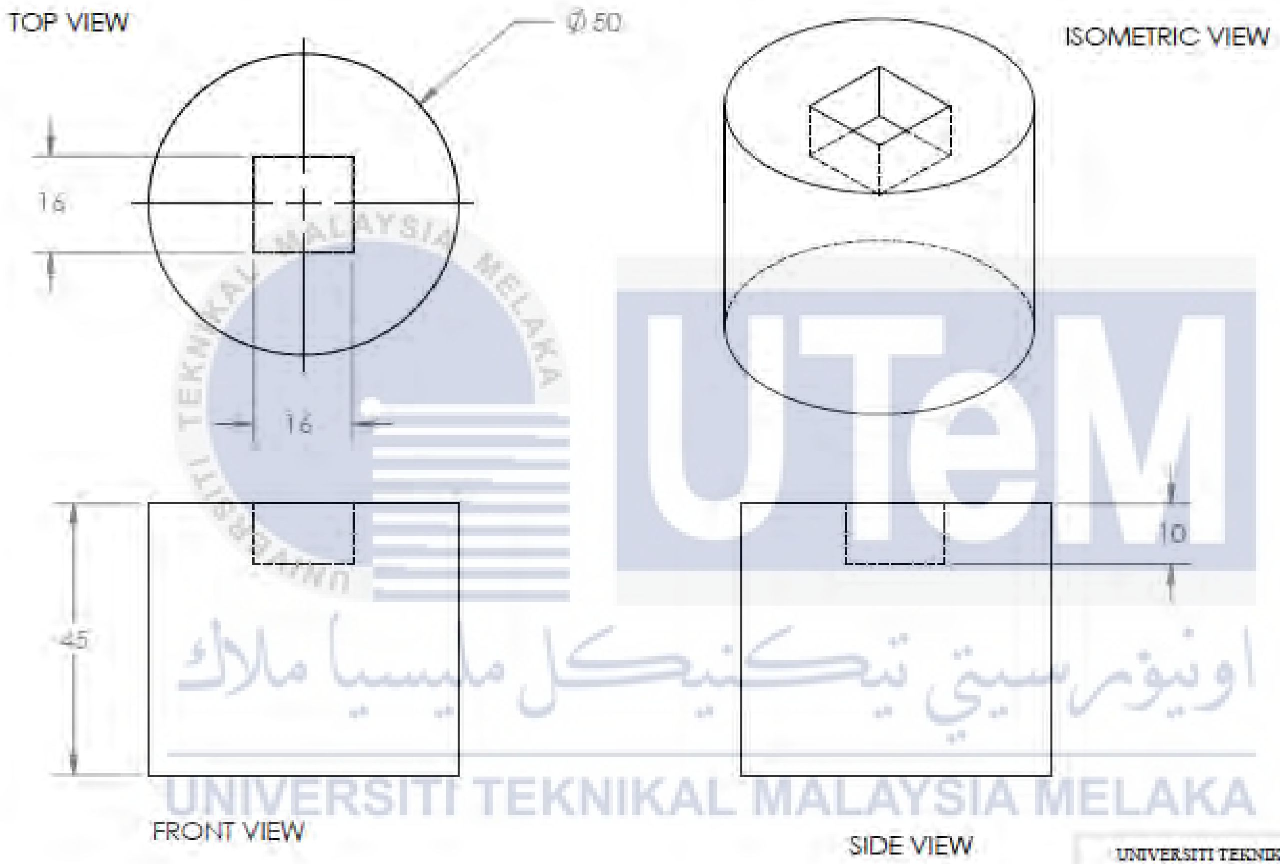
Tapered ratio of 0.84
Length of 190mm

A


TRUE R6.75
10
220
10
TRUE R8
13.50
10
220
10
16
UNIVERSITI TEKNIKAL MALAYSIA MELAKA
Tapered Ratio of 0.84
Length of 220mm
A

Appendix E: Detailed Drawing of Fixture





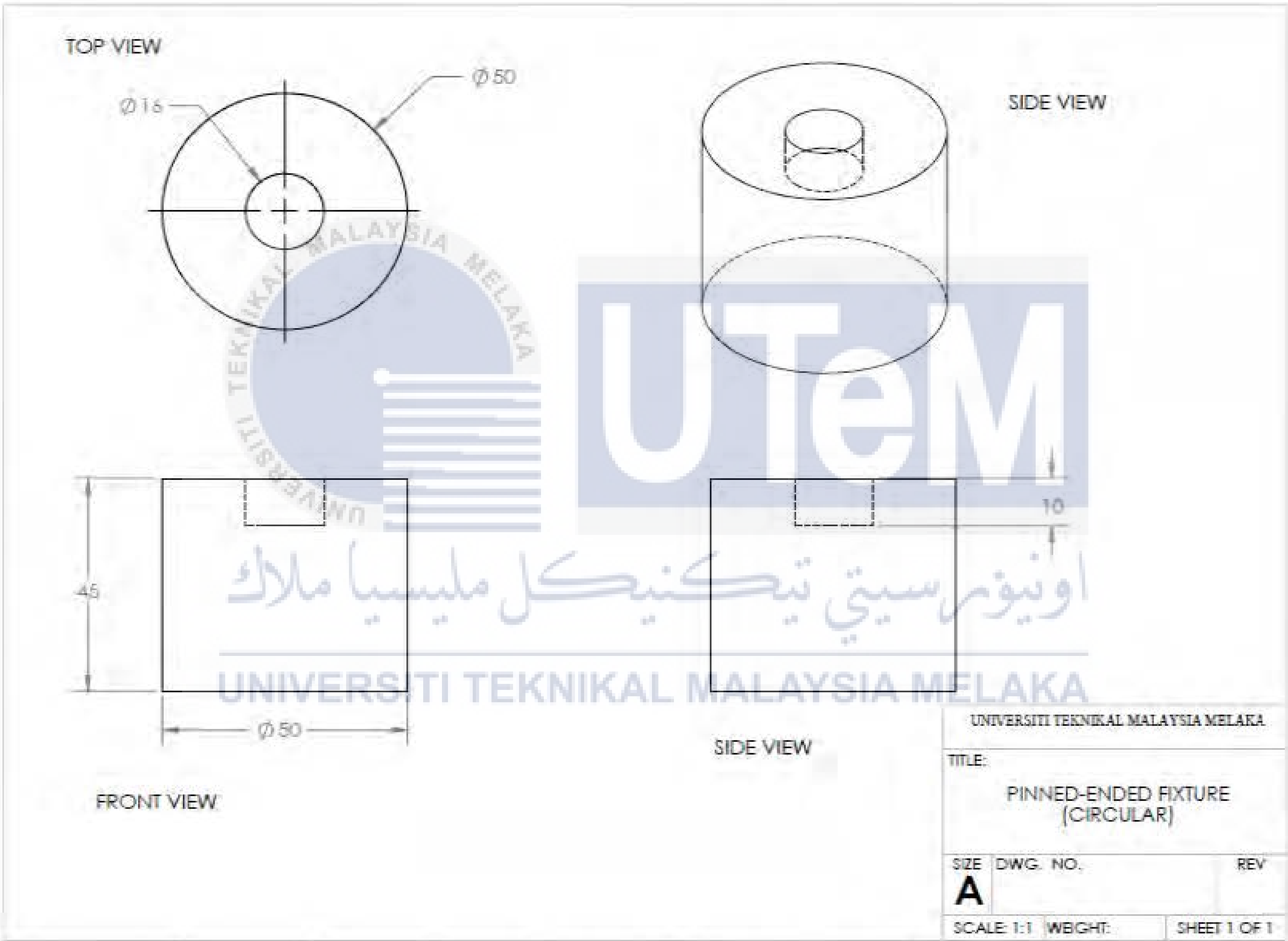
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

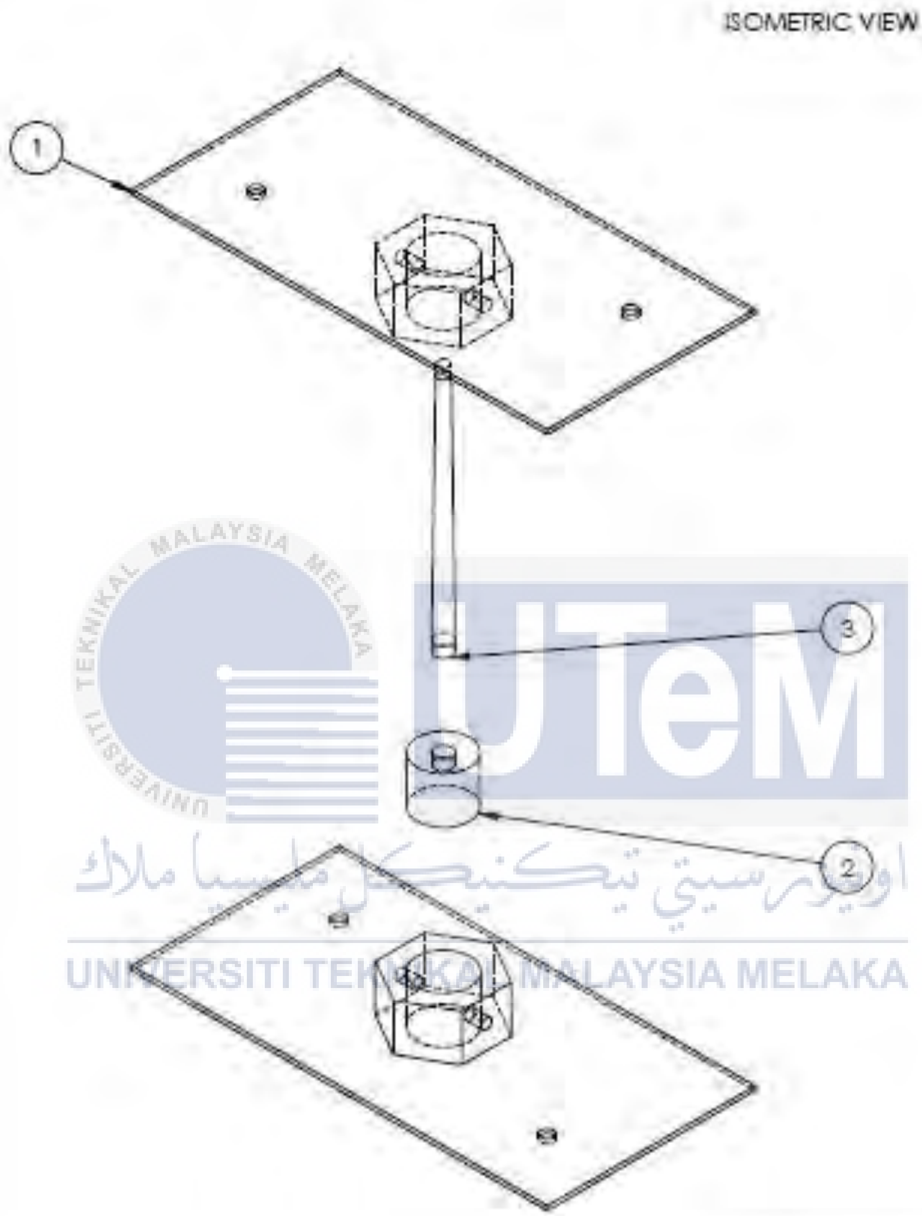
TITLE:

FIXED-ENDED FIXTURE
(SQUARE)

SIZE	DWG. NO.	REV
A		

SCALE: 1:1	WEIGHT:	SHEET 1 OF 1


TOP VIEW
Ø 50
Ø 16
SIDE VIEW
10
45
Ø 50
SIDE VIEW
FRONT VIEW
UNIVERSITI TEKNIKAL MALAYSIA MELAKA
TITLE:
PINNED-ENDED FIXTURE (CIRCULAR)
SIZE A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1



ITEM NO.	PART NUMBER	QTY.
1	Pinned-ended fixture	2
2	Fixed-ended fixture	1
3	Column	1

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

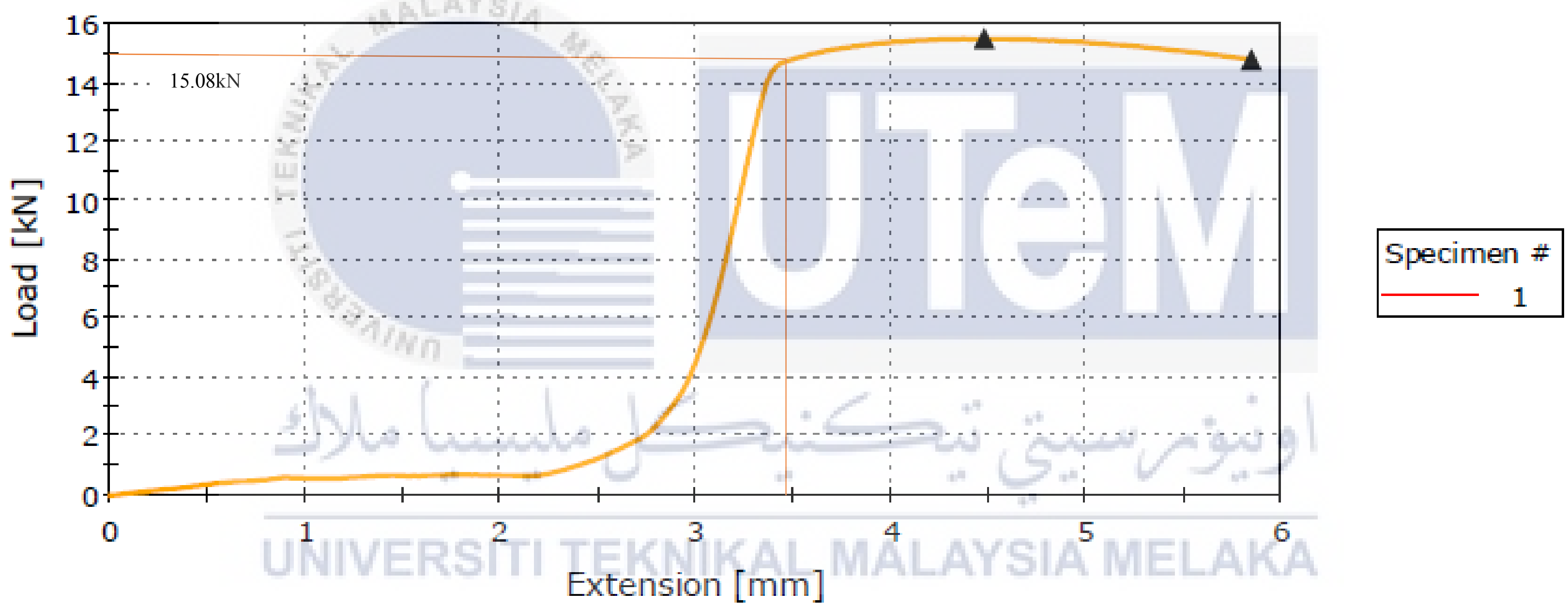
EXPLODED VIEW
BETWEEN FIXTURE AND SPECIMEN

A

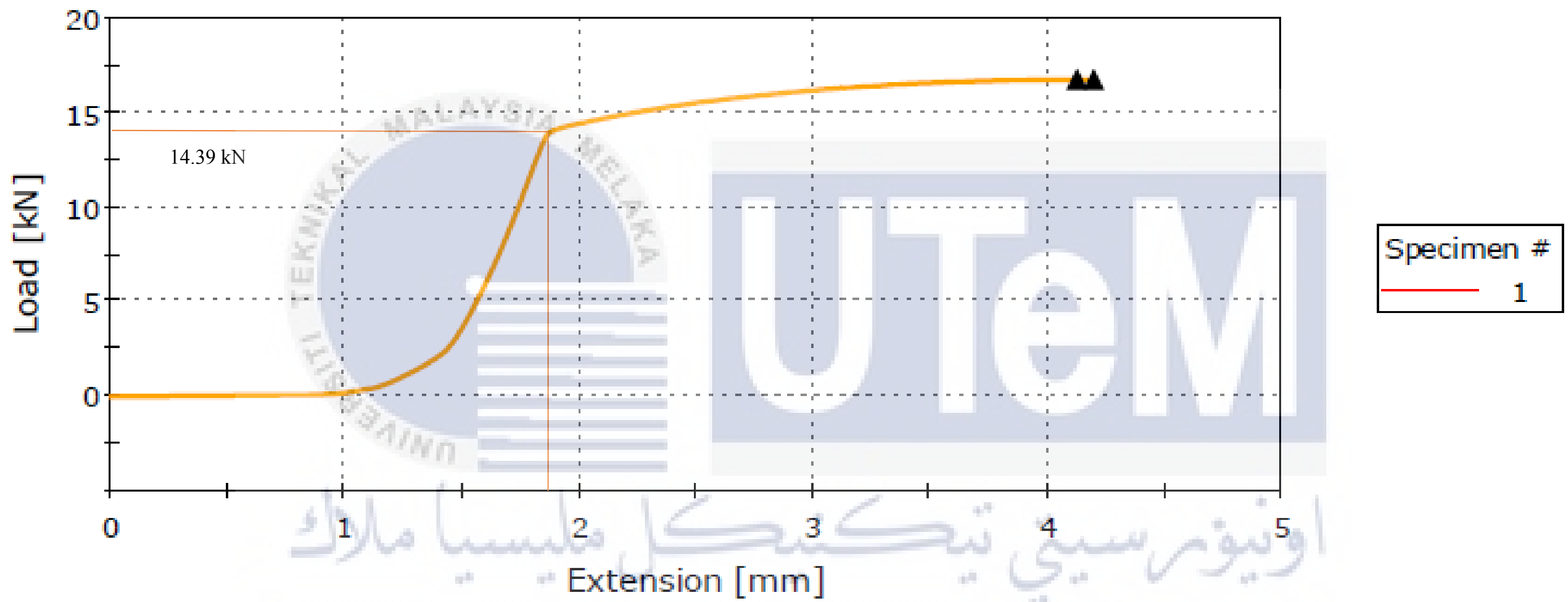
Exploded

Appendix F: Result of Buckling Test for Square Column

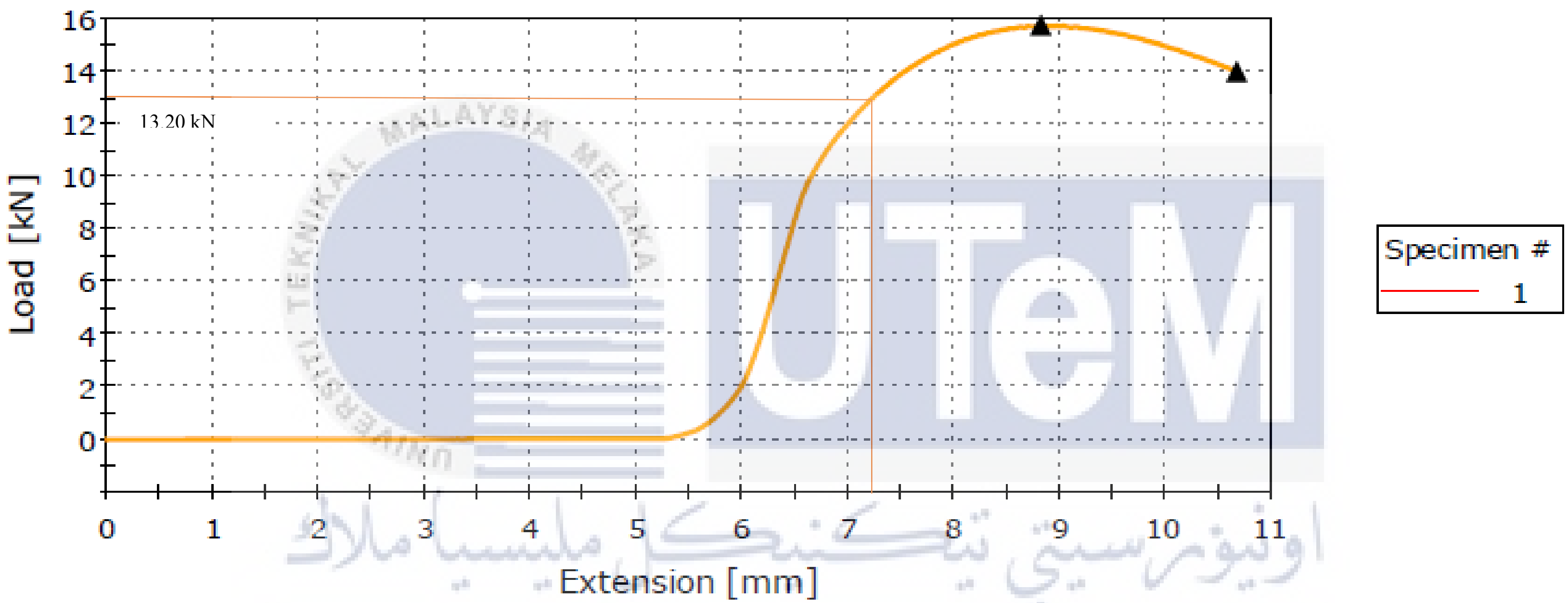
Pinned-fixed, 0.66, 0.16m



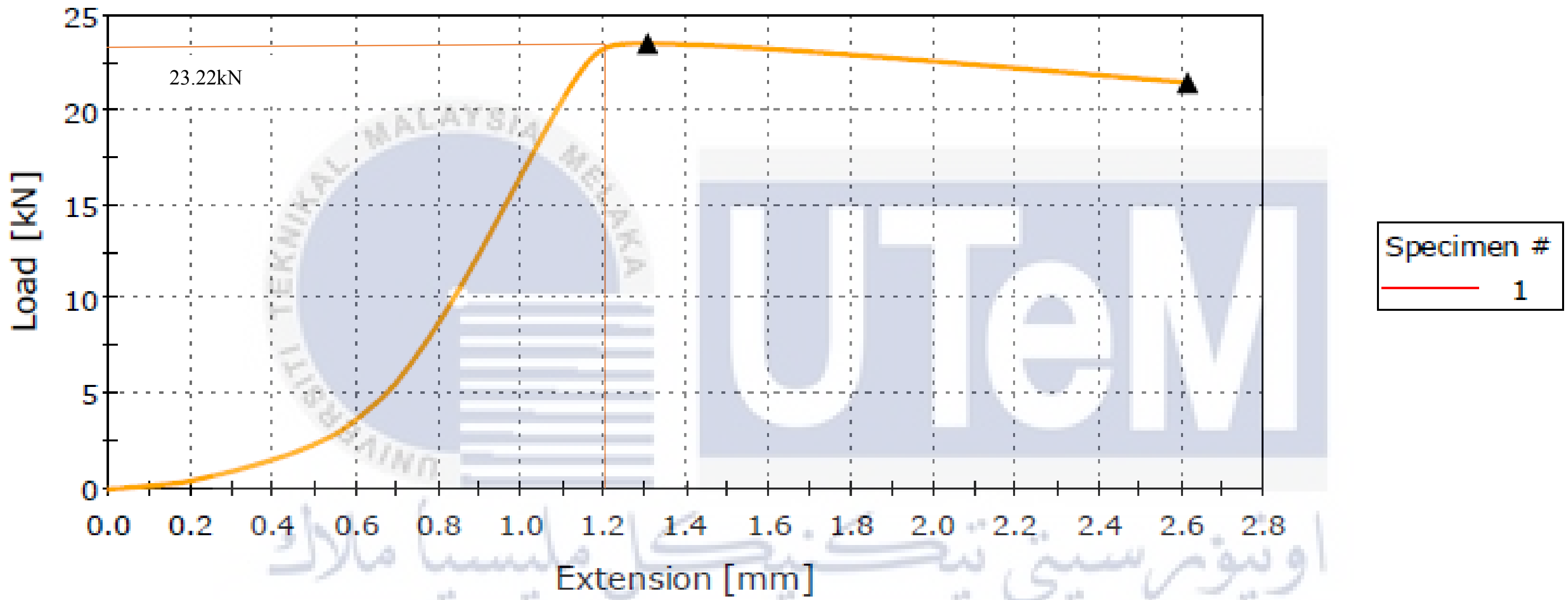
Pinned-fixed, 0.66, 0.19m



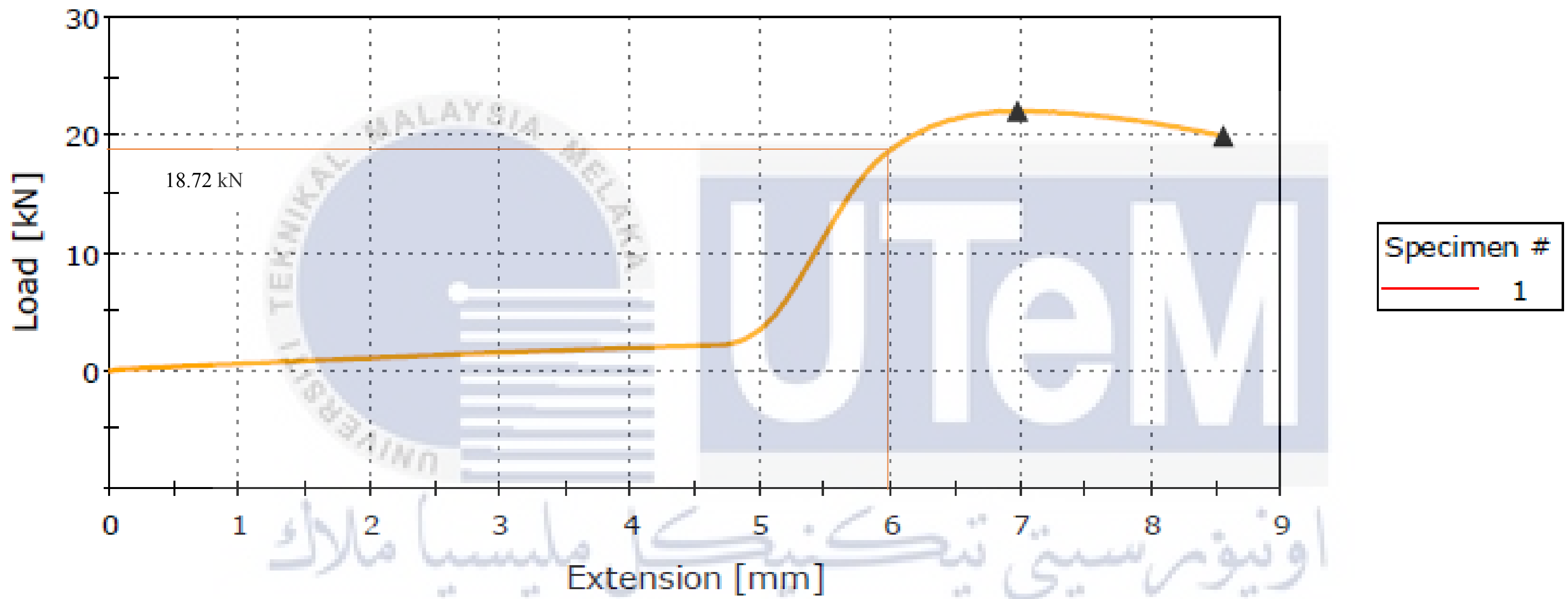
Pinned-fixed, 0.66, 0.22m



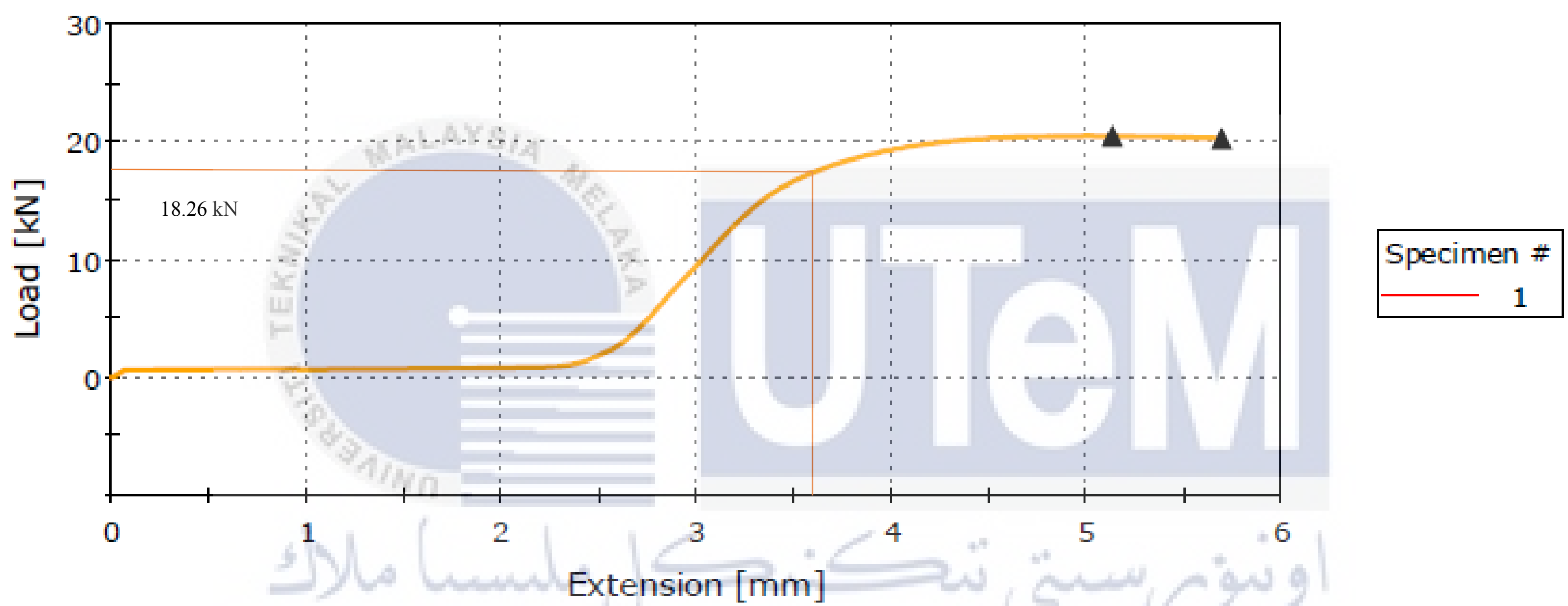
Pinned-fixed, 0.84, 0.16m



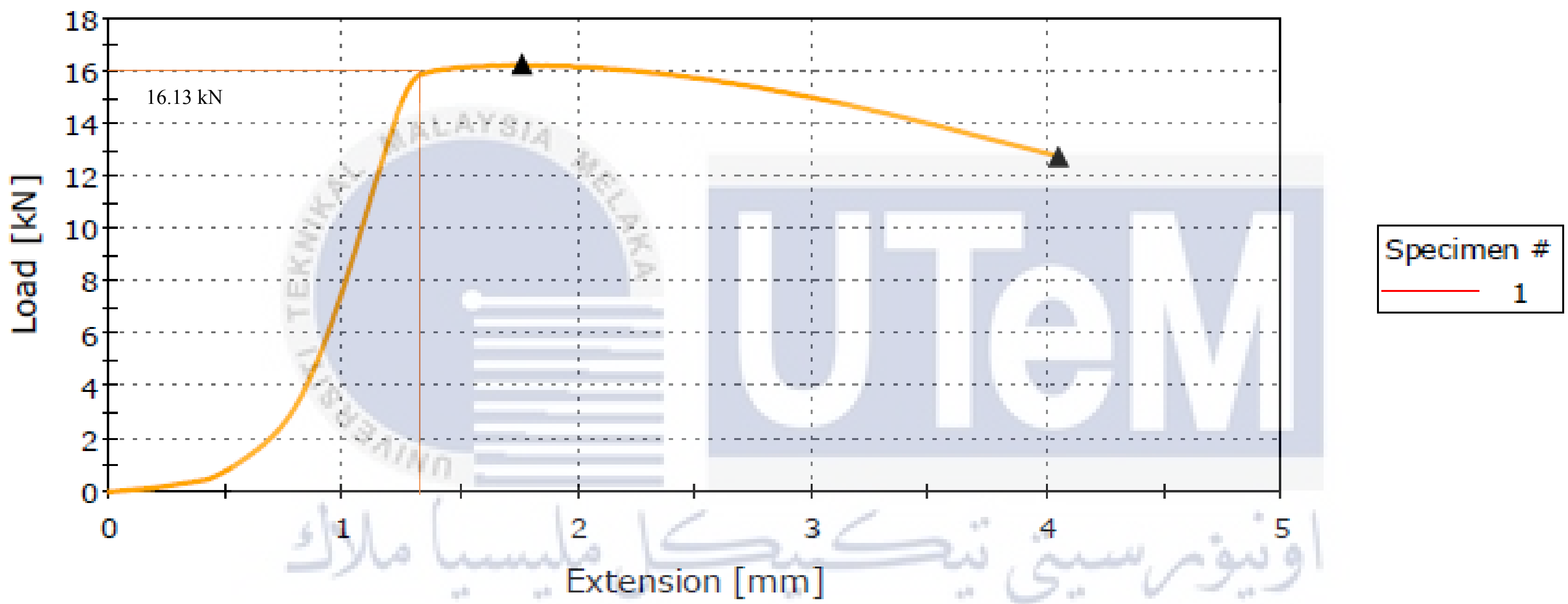
Pinned-fixed, 0.84, 0.19m



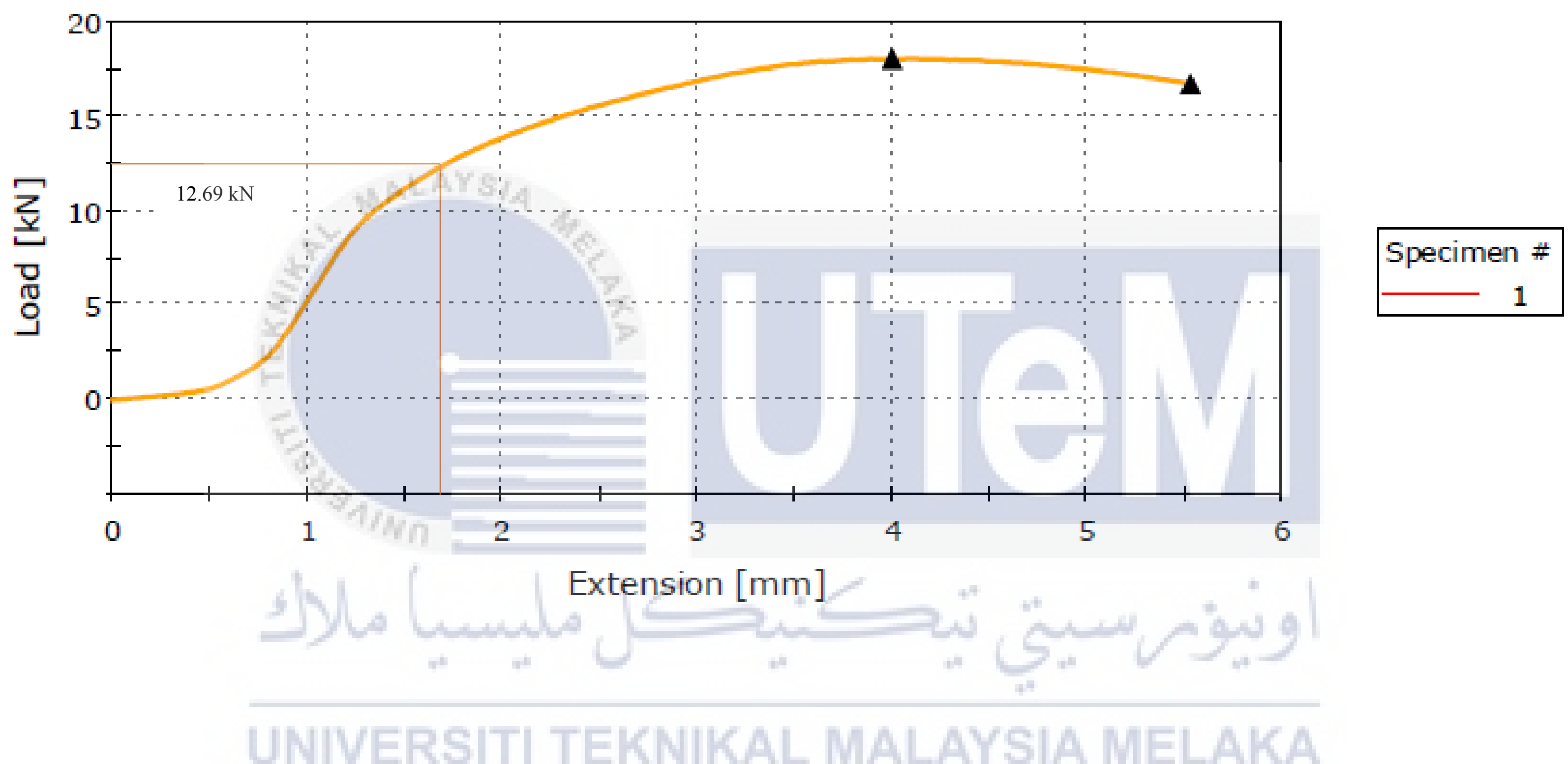
Pinned-fixed, 0.84, 0.22m



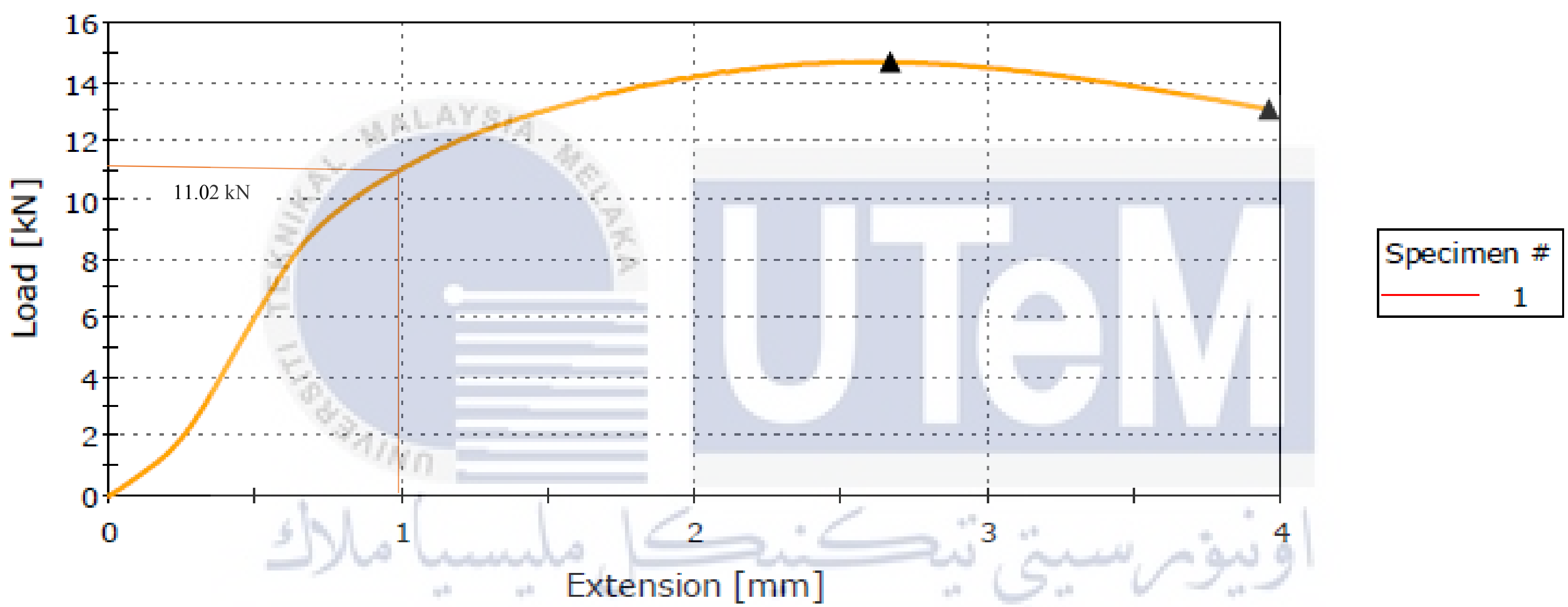
Pinned-ended, 0.66, 0.16m



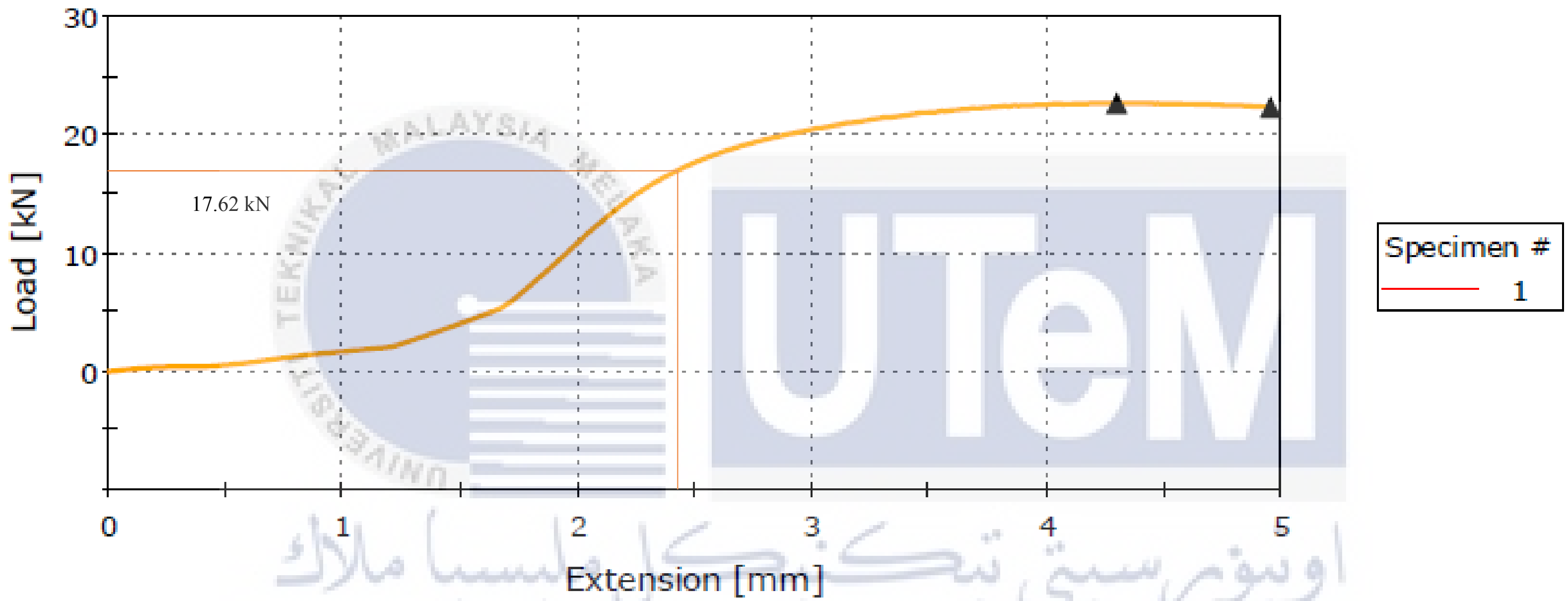
Pinned-ended, 0.66, 0.19m



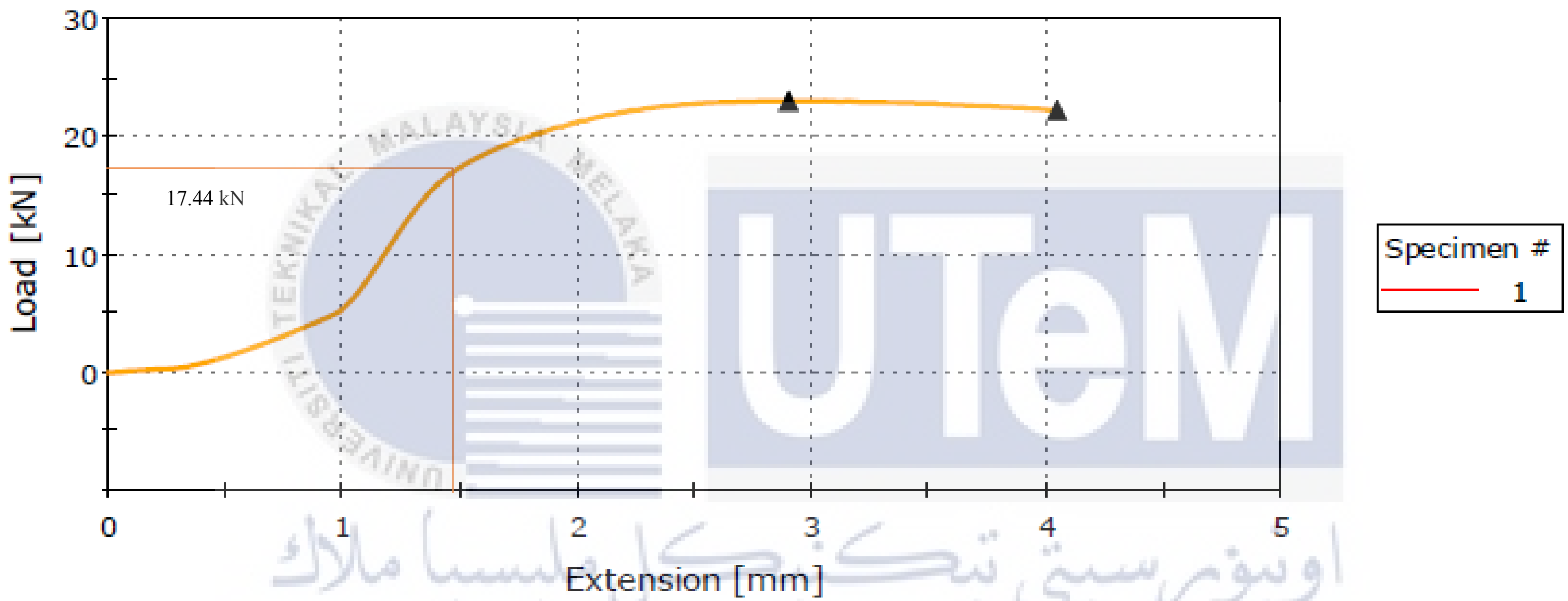
Pinned-ended, 0.66, 0.22m



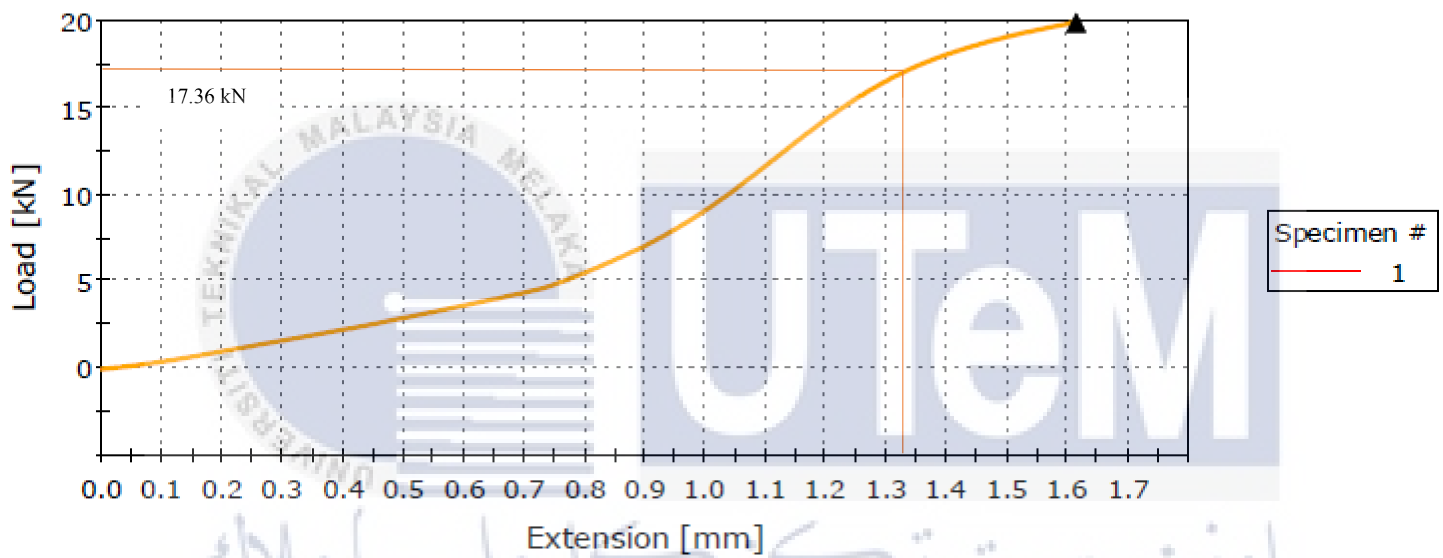
Pinned-ended, 0.84, 0.16m



Pinned-ended, 0.84, 0.19m

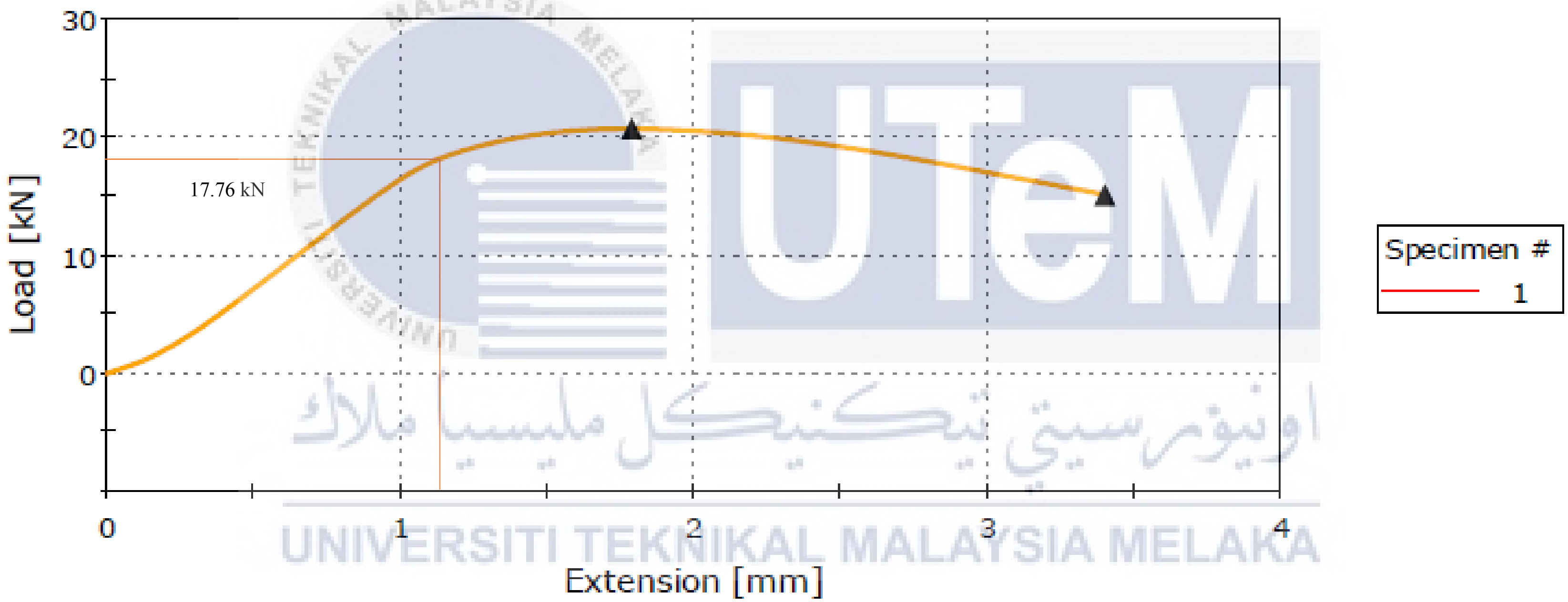


Pinned-ended, 0.84, 0.22m

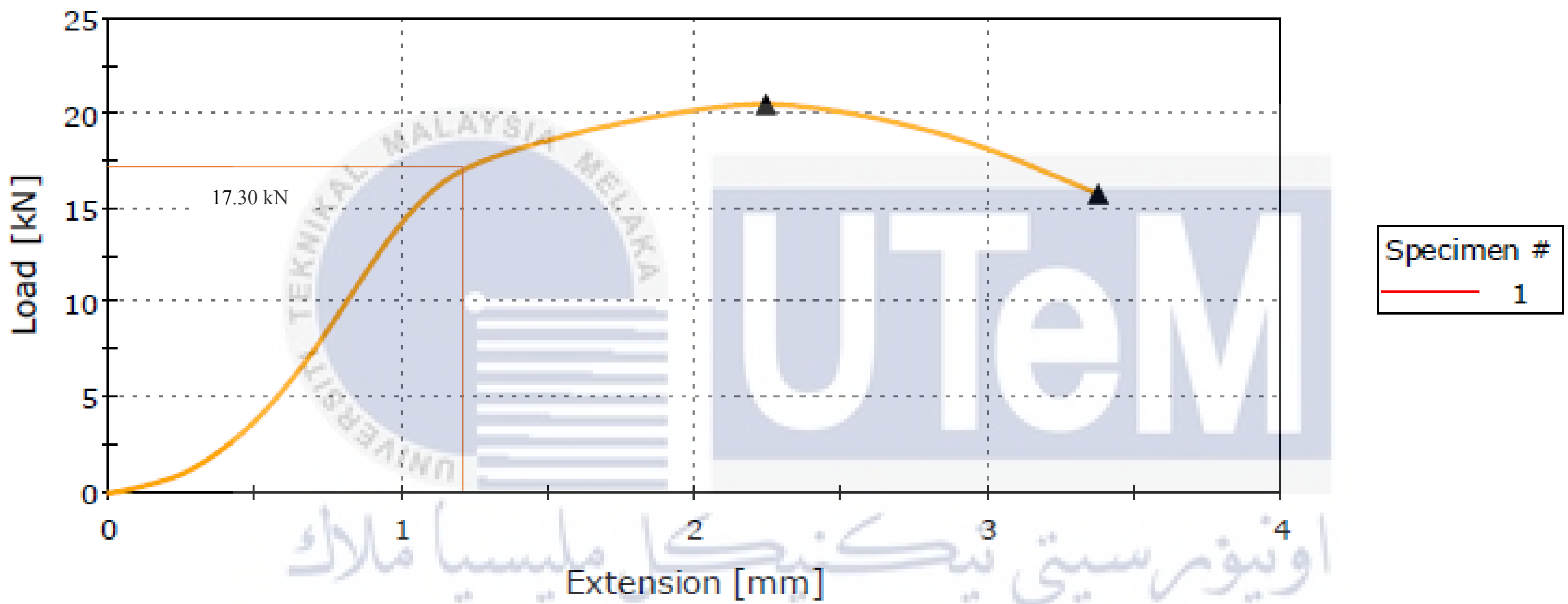


Appendix G: Result of Buckling Test for Circular Column

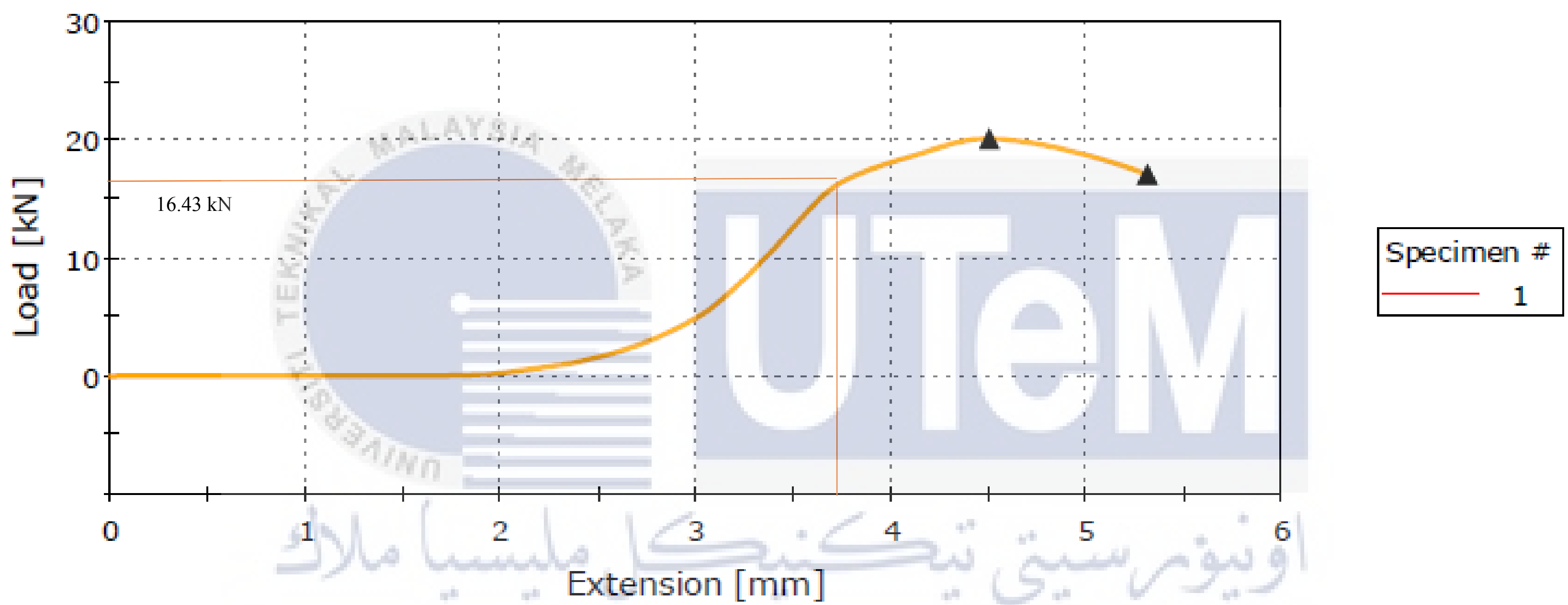
Pinned-fixed, 0.66, 0.16m



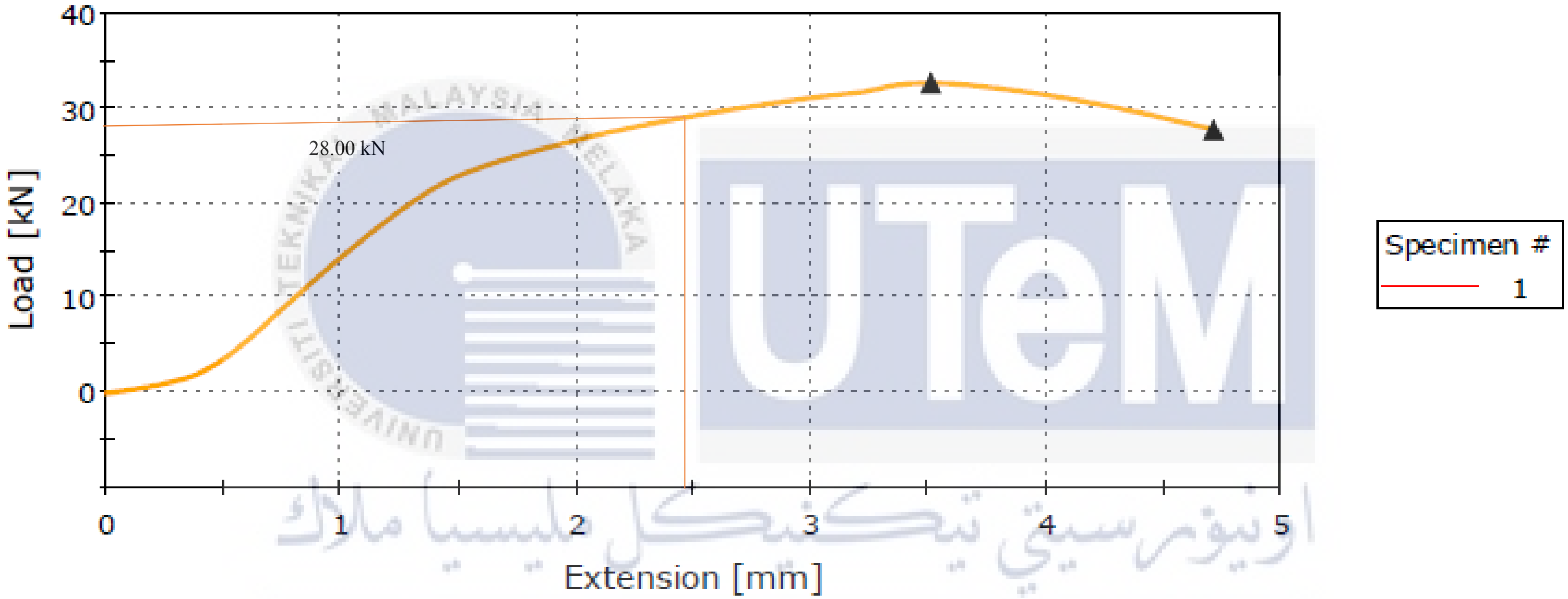
Pinned-fixed, 0.66, 0.19m



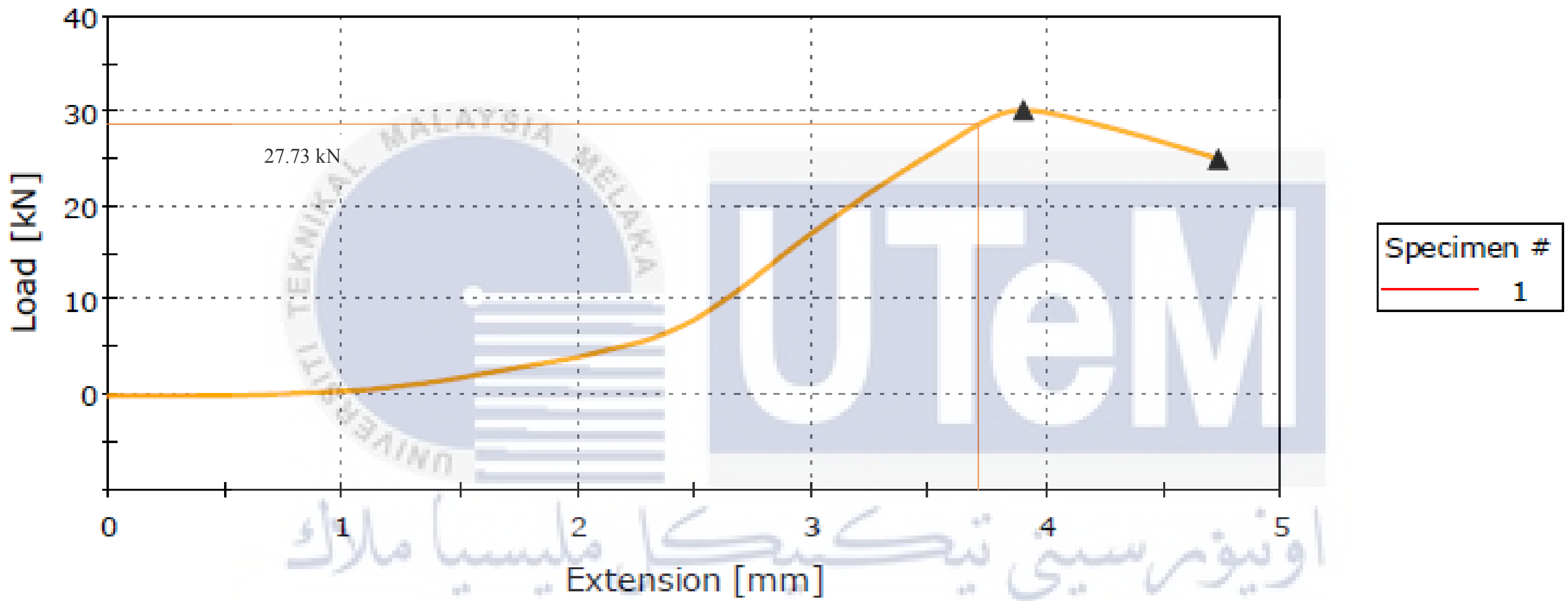
Pinned-fixed, 0.66, 0.22m



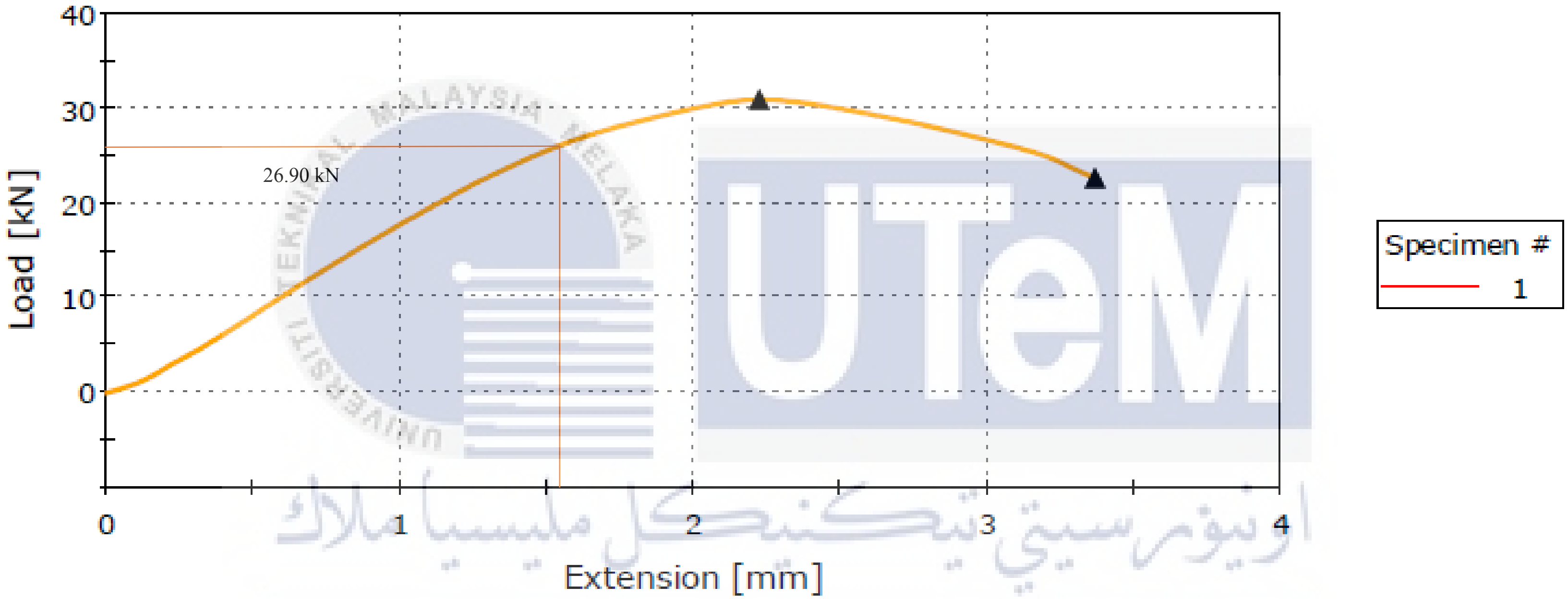
Pinned-fixed, 0.84, 0.16m



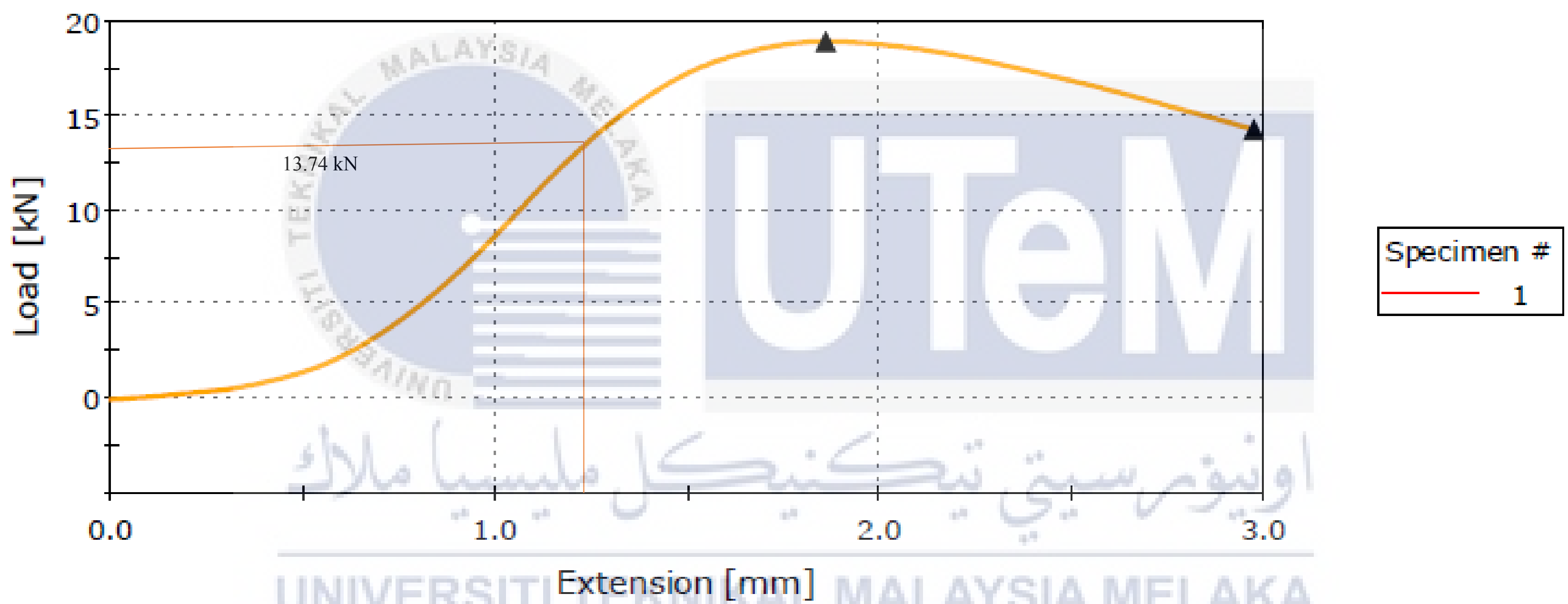
Pinned-fixed, 0.84, 0.19m



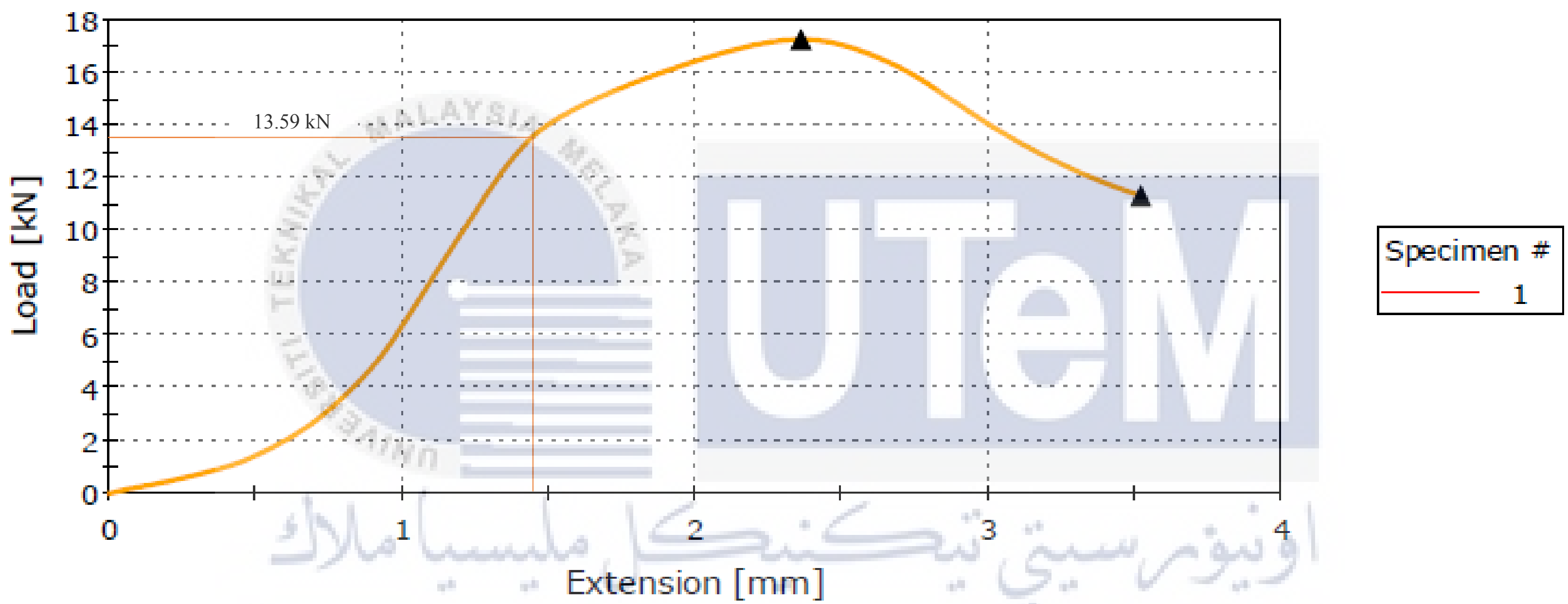
Pinned-fixed, 0.84, 0.22m



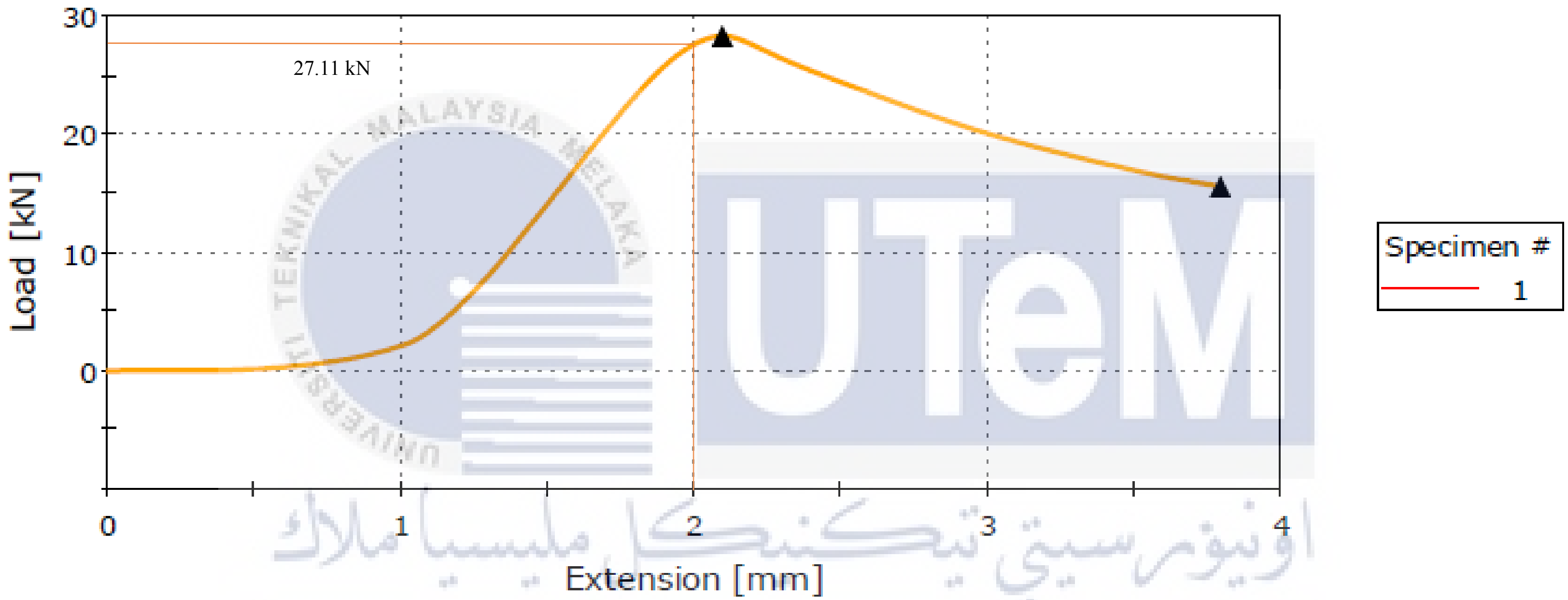
Pinned- ended, 0.66, 0.19m



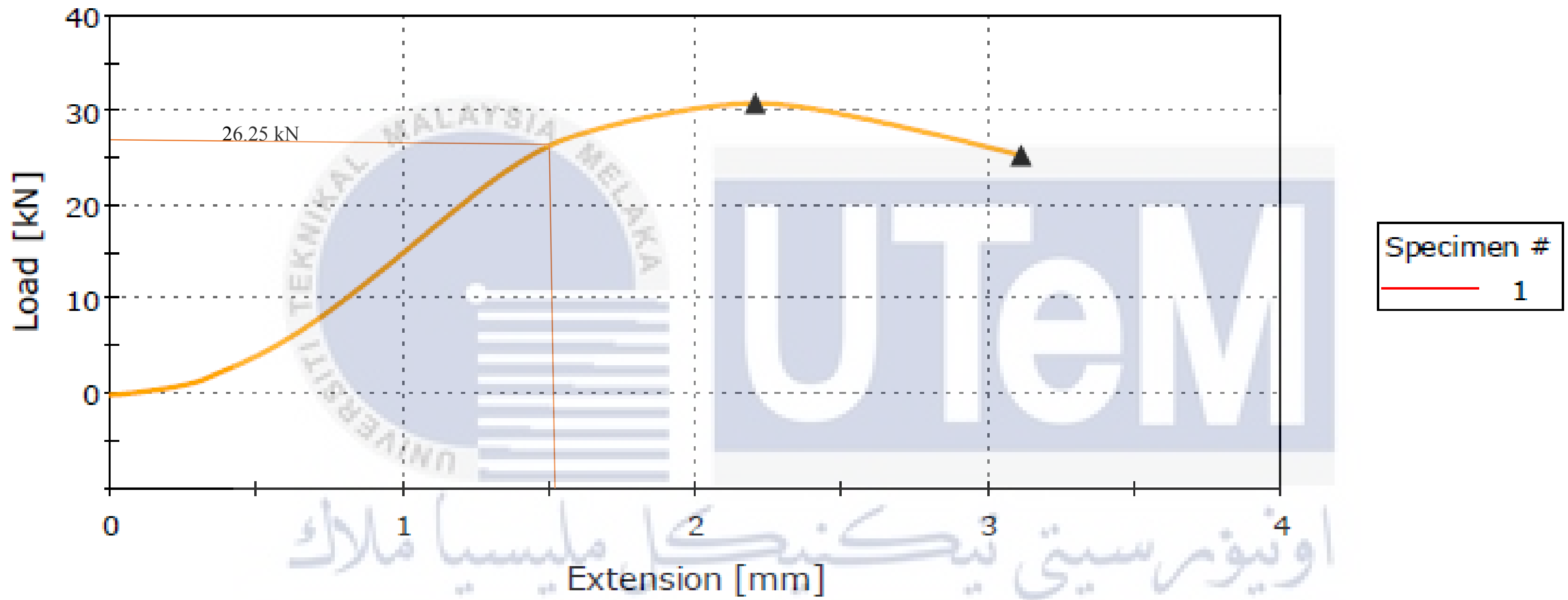
Pinned- ended, 0.66, 0.22m



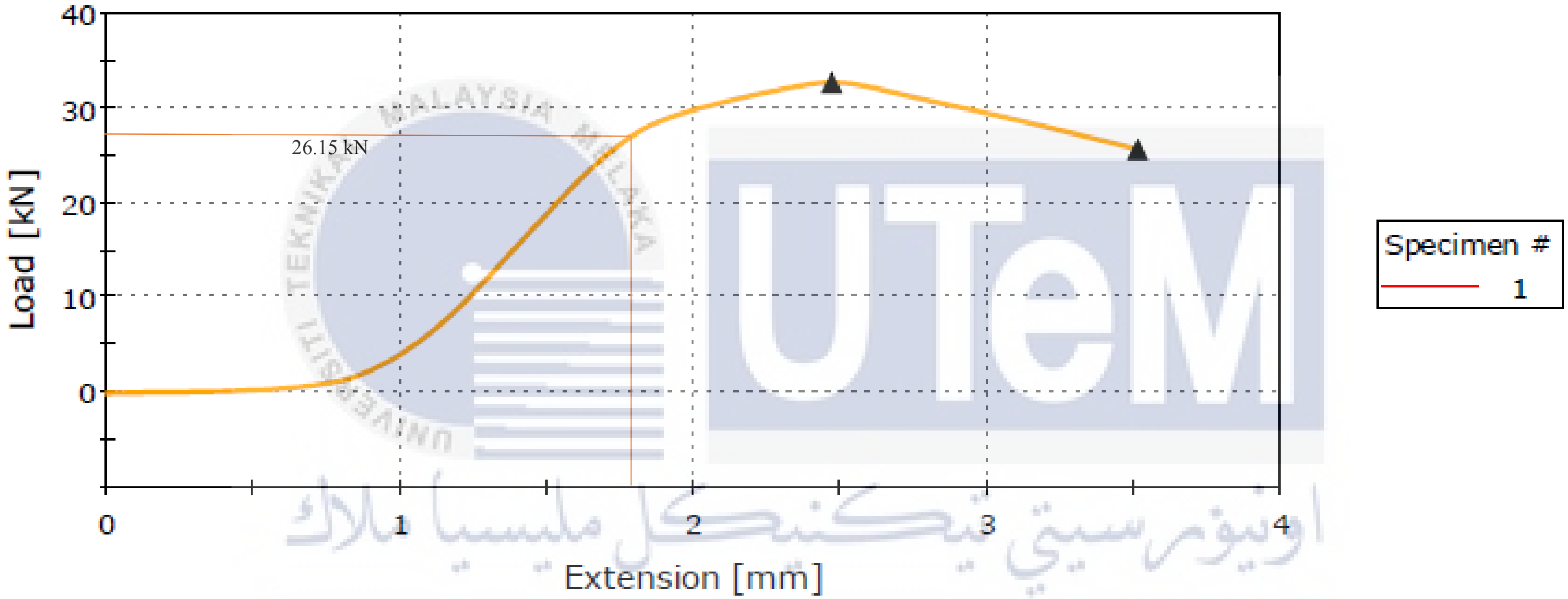
Pinned- ended, 0.84, 0.16m



Pinned- ended, 0.84, 0.19m



Pinned- ended, 0.84, 0.22m



Appendix H: Sample Calculation

For column with square cross-section and pinned-ended support

Young Modulus, E: 69 GPa

$$Length, L: 0.16m$$

$$Tapered\ Ratio = \frac{d_b}{d_a} = \frac{0.0135}{0.016} = 0.84$$

$$\text{Moment inertia at small end}, I_a: \frac{a^4}{12}$$

$$= \frac{0.0135^4}{12} = 2.7679x10^{-9}m^4$$

$$Critical\ buckling\ load, P_{cr} = \left(\frac{\pi^2 E I_a}{L^2}\right)\left(\frac{d_b}{d_a}\right)^2$$

$$= \left(\frac{\pi^2(69x10^9)(2.7679x10^{-9})}{0.16^2}\right)(0.84)^2$$

$$= 52.43\ kN$$

For column with square cross-section and pinned-fixed support

Young Modulus, E: 69 GPa

$$Length, L: 0.16m$$

$$Tapered\ Ratio = \frac{d_b}{d_a} = \frac{0.0135}{0.016} = 0.84$$

$$\text{Moment inertia at small end, } I_a : \frac{a^4}{12}$$

$$= \frac{0.0135^4}{12} = 2.7679x10^{-9}m^4$$

$$Critical\ buckling\ load, P_{cr} = \left(\frac{\pi^2 E I_a}{(0.7L)^2}\right)\left(\frac{d_b}{d_a}\right)^2$$

$$= \left(\frac{\pi^2(69x10^9)(2.7679x10^{-9})}{(0.7x0.16)^2}\right)(0.84)^2$$

$$= 107.10\ kN$$

For column with circular cross-section and pinned-ended support

Young Modulus, E: 69 GPa

$$Length, L: 0.16m$$

$$Tapered\ Ratio = \frac{d_b}{d_a} = \frac{0.0135}{0.016} = 0.84$$

$$\text{Moment inertia at small end}, I_a: \frac{\pi d^4}{64}$$

$$= \frac{\pi x 0.0135^4}{64} = 1.6304x10^{-9}m^4$$

$$Critical\ buckling\ load, P_{cr} = \left(\frac{\pi^2 E I_a}{L^2}\right)\left(\frac{d_b}{d_a}\right)^2$$

$$= \left(\frac{\pi^2(69x10^9)(1.6304x10^{-9})}{0.16^2}\right)(0.84)^2$$

$$= 30.89\ kN$$

For column with circular cross-section and pinned-fixed support

Young Modulus, E: 69 GPa

$$Length, L: 0.16m$$

$$Tapered\ Ratio = \frac{d_b}{d_a} = \frac{0.0135}{0.016} = 0.84$$

$$\text{Moment inertia at small end}, I_a : \frac{\pi d^4}{64}$$

$$= \frac{\pi x 0.0135^4}{64} = 1.6304x10^{-9}m^4$$

$$Critical\ buckling\ load, P_{cr} = \left(\frac{\pi^2 E I_a}{(0.7L)^2}\right)\left(\frac{d_b}{d_a}\right)^2$$

$$= \left(\frac{\pi^2(69x10^9)(1.6304x10^{-9})}{(0.7x0.16)^2}\right)(0.84)^2$$

$$= 63.04\ kN$$