COMPRESSION TEST OF C-SECTION COLD-FORMED STEEL WITH AN OPENING

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ABSTRAK

Bahagian tunggal adalah pilihan pertama sebelum bahagian berkembar digunakan untuk menahan beban yang disebabkan oleh struktur seperti contohnya bumbung. Kewujudan lubang dalam anggota struktur boleh memberi manfaat kepada kerja-kerja mekanikal dan elektrik, selain itu, secara teorinya kekuatan muktamad struktur akan berkurang disebabkan kewujudan bukaan. Tesis ini membentangkan huraian terperinci mengenai kajian eksperimen kekuatan gelangsar lentur dengan adanya pembukaan tiang keluli terbentuk sejuk. Sebanyak 8 tiang pendek, setiap panjang 600 mm, berbeza mengikut saiz (203 mm dan 103 mm) dan ketebalan (1.3 mm dan 2.0 mm). Ujian mampatan dilakukan dengan menggunakan Mesin Ujian Universal dan kekuatan muktamad diperhatikan. Keputusan ujian 4 spesimen dengan pembukaan dibandingkan dengan yang tidak ada pembukaan. Hasilnya dibentangkan dalam tiga bahagian yang merupakan beban anjakan menegak, beban anjakan melintang dan tingkah laku.

ABSTRACT

Single sections are the first choice before built-up sections used to resist load induced in a structure for example roof trusses. An existence of perforation in the structural member can be benefit to mechanical and electrical works, aside from that, theoretically the ultimate strength of the structure will be reduce due to existence of openings. This paper presents a detailed description of an experimental study of the flexural buckling strength in the presence of a perforation of cold-formed steel column. A total of 8 short columns, each length 600 mm, vary in size (203 mm and 103 mm) and thickness (1.3 mm and 2.0 mm). Compression test were done by using Universal Testing Machine and the ultimate strength were observed. The test result of 4 specimens with an opening were compared to the ones without opening. The result is presented in three section which are load vs vertical displacement, load vs horizontal displacement and buckling behaviour.

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LIST OF SYMBOLS

LIST OF ABBREVIATIONS

BS	British Standard
CFS	Cold-Formed Steel
AISI	American Iron and Steel Institute
AISC	American Institute of Steel Construction (AISC)
FKASA	Fakulti Kejuruteraan Awam dan Sumber Alam
SC	Single C-Section
FE	Finite Element
LRFD	Load and Resistance Factor Design
NH	No Hole
H	Hole

CHAPTER 1

INTRODUCTION

1.1 Introduction

In building construction there are basically two types of structural steel: hot-rolled steel shapes and cold-formed steel shapes. The hot rolled steel shapes are formed at elevated temperatures while the cold-formed steel shapes are formed at room temperature. Cold-formed steel structural members are shapes commonly manufactured from steel plate, sheet metal or strip material. The manufacturing process involves forming the material by either press-braking or cold roll forming to achieve the desired shape(Stone and LaBoube, 2017).

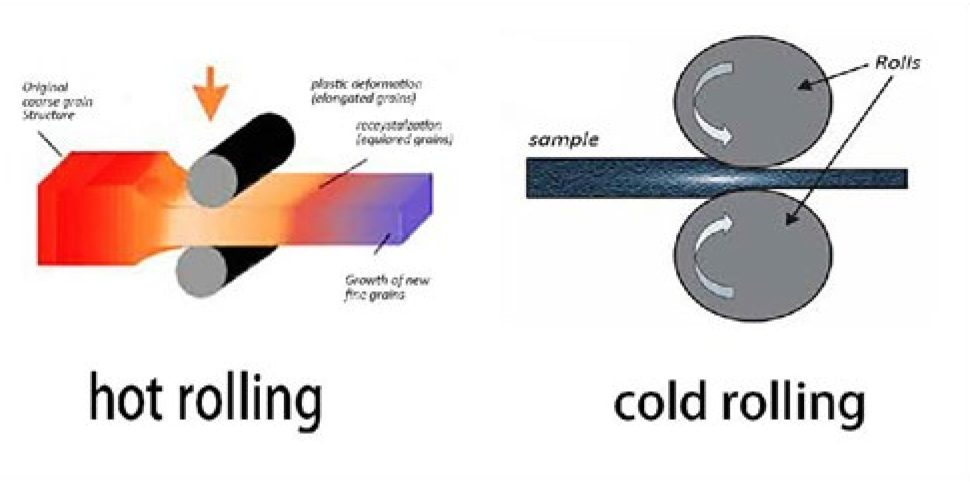

Figure 1. 1: Difference between hot rolled steel and cold formed steel
Source: (What is the Difference between Hot Rolled Steel and Cold Rolled Steel, 2019)

When steel is formed by press-braking or cold rolled forming, there is a change in the mechanical properties of the material by virtue of the cold working of the metal(Liu, Igusa and Schafer, 2010; Gilbert, Teh and Gilbert, 2012). When a steel section is cold-formed from flat sheet or strip the yield strength, and to a lesser extent the ultimate strength, are increased as a result of this cold working, particularly in the bends of the section.

Cold-formed thin-walled members are used in building industry in many fields. The probably largest area of use is in conventional – mainly industrial – steel structures as secondary and tertiary load-bearing elements – purlins, sheeting – on a steel or reinforced concrete primary structure. Cold-formed members are extensively used in North-America and Australia/New Zealand in residential housing as primary load-bearing structures; light-gauge building systems are gaining on popularity and compete with the traditional building material, wood(Fratamico *et al.*, 2018). There are several examples of multi-storey office buildings with a primary load-bearing system consisting entirely of cold-formed members as well. Another large area of use is composite slabs, where trapezoidal sheeting and cold-formed sections are used as tension and a thin concrete slab as compression parts resulting in light floor systems applicable in buildings made of cold-formed members or in refurbishment. Cold-formed members are also extensively used in warehouse racks.

Figure 1. 2: One of the usage of cold-formed steel

Source:(Dinis *et al.*, 2012)

Cold-formed steel often produced with opening specifically for fasteners like bolts, screws, rivets, etc. and such openings may be neglected as they are filled with material(de Barros Chodraui *et al.*, 2009) (Figure 1.2). However, any other openings should be taken into account. The ultimate strength and elastic stiffness of a structural member can be vary due to opening, size and shape in this case reduction of surface area(Georgieva *et al.*, 2012). Openings need to be considered in evaluation of the section properties of members in compression. The perforations can be classified into two; pre-punched and punched-on-site but mostly pre-punched are more favourable due to the problem that will rise later if the holes are not accurately made.

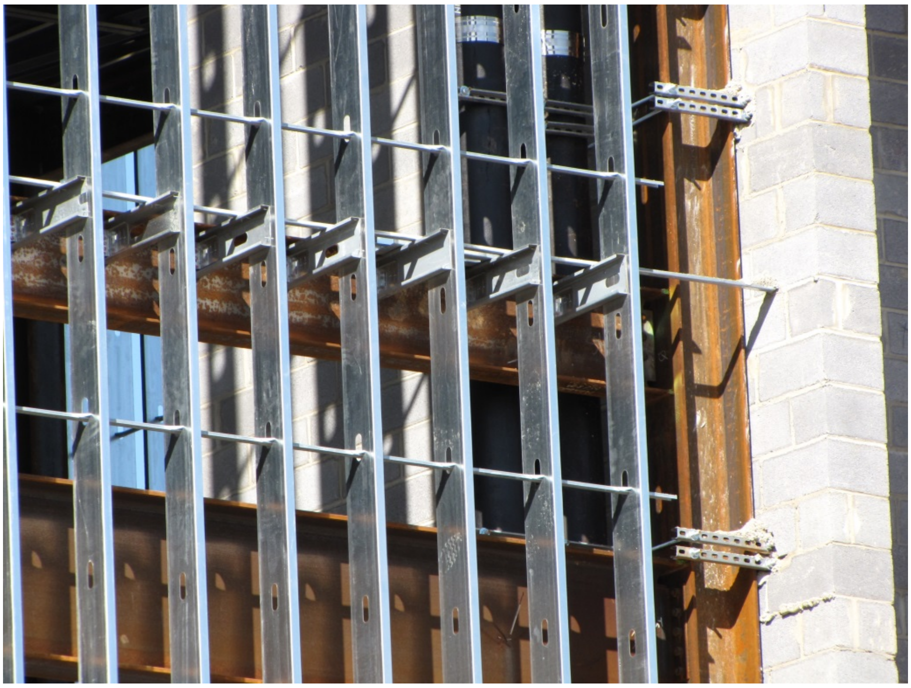

Figure 1. 3: One of the usage of cold-formed steel
Source: (Dinis *et al.*, 2012)

1.2 Problem Statement

Cold-formed steel structural member are widely produced with holes or opening such as joist, beam or column, purposely for piping, electrical-wiring, plumbing or bracing(Yap and Hancock, 2010). Basically it is manufactured with different shapes and sizes. Due to more complex and intense mechanical and electrical works in construction industry, large openings on the web is become more preferred by the contractors since it offer larger working area. Because of the variety of size and shape, a practical design need to be provide where the strength is theoretically reduced by the existence of perforations. A great deal of problems had risen caused by the existence of opening because the design process will be more complicated and complex and need extra work from experts as it could lead to building to come apart. This lead to limited usage of cold-formed steel with openings in the industry and this can be changed with more study and research by experts.

There are numerous researches and studies have been conducted on the structural response of hot rolled steel member affected local, distortional and global buckling. There are lacking of research on cold-formed member especially C-section cold-formed members with perforation and based on past research, it is proven that the occurrence of these buckling modes interactions result in a substantial strength erosion. Therefore, additional researches is a must concerning the structural behavior of single C-section of cold-formed column affected by local, distortional and global buckling interactive failure modes.

1.3 Research Objective

The primary aim of this research is to study the behavior of single C-section of cold-formed steel with and without an opening under compression test. In order to achieve this target, several objectives are identified as follows:

i- To determine the ultimate load of single C-section cold-formed steel with and without an opening

ii- To study the failure mode of C single section under compression test.

1.4 Scope of Research

For this research, 8 specimens of single C-section of cold-formed short column were prepared. Both end of the each columns will be welded with a steel plate to act as fixed support. The scope of the research covers on the compression test for axially loaded single C-section of cold-formed section. The experiment will be done at the laboratory. The scope of work are:

i- Single C-section

ii- With and without an opening

iii- Size of specimens (thickness and depth)

1.5 Research Significance

For this research, it will be conducted by applying axial load (compression test) on series of specimens of single C-section pf cold-formed steel short column member to determine the maximum load of axially load. These specimens are vary in term of size of specimens which are 103 mm and 203 mm and with and without an opening. By carrying out this experiment, its can alter the elastic stiffness and ultimate strength of structural steel member. It also improvise the understanding about buckling mode, post-load buckling and collapse behavior.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Cold-formed thin-walled are widely used in building industry in various field. The probably largest area of use is in conventional – mainly industrial – steel structures as secondary and tertiary load-bearing elements – purlins, sheeting – on a steel or reinforced concrete primary structure (Jakab, 2009). Cold-formed members are extensively used in North-America and Australia/New Zealand in residential housing as primary load-bearing structures; light-gauge building systems are gaining on popularity and compete with the traditional building material, wood.

According to (Banwait, 2009), the use of cold formed steel sections started in the middle of the 19^{th} century. However, these thin walled sections were not widely used because of a lack of knowledge about their behaviour. With the development of the aircraft industry in the early 20^{th} century, much research work was done on thin wa1led structures to help design as 1ight an aircraft as possible. The material used in aircraft structural components was aluminium, due to its better weight to strength ratio over steel, but the basic principles used in the analysis of aluminium thin walled structures are applicable for steel structures as well.

The first standard was developed by American Iron and Steel Institute (AISI) in 1946 and was based largely on researched work done under the direction of Prof George Winter at Cornell University (Seong, 2009). Since the development of building codes and specification in various countries, the application of cold formed steel is increasing rapidly for constructing of:

i- Roof and wall system – typical sections are Z-(zee) of C-(channel) section, uses as purlins and girt. Corrugated roofing sheet will be fastened with self-drilling screw to Z or C sections.

ii- Steel rack for supporting storage pallets – the uprights are usually channels with or without additional rear flanges or tubular sections. Tubular sections such as lipped channels intermittently welded toe to toe are normally bolted to the upright.

iii- Structural member for plane and space trusses – typical sections used are angle, hollow and channel as diagonal or chords members. Sections joint usually by welded joints or bolted joint. The most common section used for trusses are cold formed channel and Z.

iv- Frameless stressed-skin structure – corrugated sheets or sheeting profiles with stiffened edges are used to form small structure up to 30 ft clear span with no interior support.

v- Steel floor and roof deck – formed steel deck is laid across steel beams to provide a safe working platform and a form for concrete. It is normally designated as a wide rib, intermediate rib, or narrow rib deck.

The main reason behind the extensive use of cold-formed members is that these are easy and cheap to fabricate, need minimal maintenance due to the zinc coating, no heavy cranes nor special tools are needed for the erection of the structures, in many cases even the lack of experience with the erection of steel structures may not be a problem.

2.2 Material and Cold Work of Forming

2.2.1 Cold Formed Steel Standard

In accordance of (Kalavagunta, Naganathan and Mustapha, 2013), design clauses for cold formed steel structural members were first introduced with the preparation of the American Iron and Steel Institute Specification (AISI), using research work on cold formed members of Prof George Winter at Cornell University. The British Steel Standard was modified in 1961 to include design of cold formed members by Addendum No. 1 based on the work of Professor A.H Chilver. In Australia, the Australia Standard for the design of cold formed steel structural members was first published in 1974. It was mainly based on the 1968 Edition of the American Specification but with modifications to the beam and column design curves to keep them aligned with the Australian Steel Structure Code ASCA1.

In 1988, a significant revision of the 1974 edition of AS 1538 was produced using the 1980 and 1986 editions of the AISI specification. The Australian Standards is in permissible stress format and the AISI specification is in allowable stress format (ASD). In 1991, the AISI produced a limit state version of their 1986 specification called Load and Resistance Factor Design (LRFD). The limit states design philosophy in the AISI specification is based on load factors applied to the factored design loads should not exceed factored strengths. The 1991 LRFD specification operates in parallel with the latest ASD specification(Yan and Young, 2004).

In 1996 edition of the specification combines allowable stress design (ASD) and Load and Resistance Factor Design (LRFD) into one document. Other international standard are Australia/New Zealand Standard AS/NZS 4600 (base mainly on1996 AISI specification), British Standard BS 5950-Part 5, Canadian Standard CAN/CSA S136 and the Euro code 3 Part 1.3 (Gholipour, 2011).

2.2.2 Typical Stress-Strain Curve of Steel

Stress strain curve is a behavior of material when it is subjected to load (Afsar 2014). From the diagram 2.1, one can see the different mark points on the curve. It is because, when a ductile material like mild steel is subjected to tensile test, then it passes various stages before fracture.

Those stages are:

i- Proportional Limit

ii- Elastic Limit

iii- Yield Point

iv- Ultimate Stress Point

v- Breaking Point

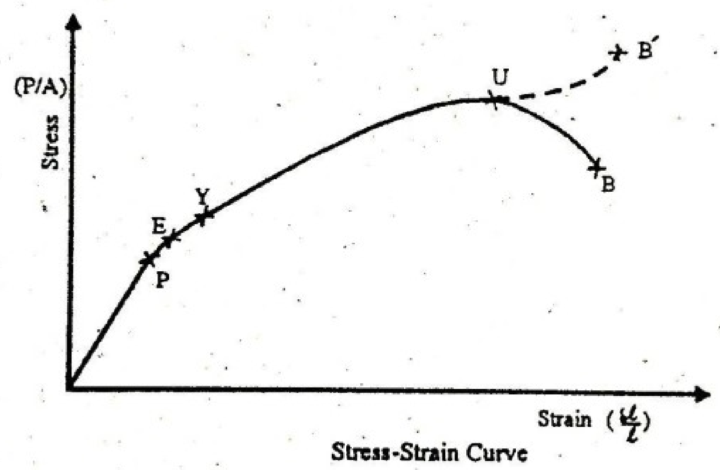

Figure 2. 1: Typical stress-strain curve
Source: (Afsar, 2014)

Proportional limit- Proportional limit is point on the curve up to which the value of stress and strain remains proportional. From the diagram point **P** is the called the proportional limit point or it can also be known as limit of proportionality. The stress up to this point can be also be known as proportional limit stress. Hook's law of proportionality from diagram can be defined between point **O** and **P**. It is so, because **OP** is a straight line which shows that Hook's law of stress strain is followed up to point **P.**

Elastic limit- Elastic limit is the limiting value of stress up to which the material is perfectly elastic. From the curve, point **E** is the elastic limit point. Material will return back to its original position, If it is unloaded before the crossing of point **E**. This is so, because material is perfectly elastic up to point **E**.

Yield stress point- Yield stress is defined as the stress after which material extension takes place more quickly with no or little increase in load. Point **Y** is the yield point on the graph and stress associated with this point is known as yield stress.

Ultimate stress point- Ultimate stress point is the maximum strength that material have to bear stress before breaking. It can also be defined as the ultimate stress corresponding to the peak point on the stress strain graph. On the graph point **U** is the ultimate stress point. After point **U**, material have very little or zero strength to face further stress.

Breaking point (Rupture point)- Breaking point or breaking stress is point where strength of material breaks. The stress associates with this point known as breaking strength or rupture strength. On the stress strain curve, point **B** is the breaking stress point.

There are two types of stress-strain curves, one is of sharp yielding type (Figure 2.2) and the others are of gradual yielding type (Figure 2.3). Steel produced by hot rolling are usually sharp yielding. For this type of steel, yield point is defined by the level at which the stress- strain curve becomes horizontal. Steel that are cold formed shows gradual yielding. For gradual yielding steel, the stress strain curve is rounded out at the 'knee' and the yield strength is determined by either offset method or strain under load method The load carrying capacity of cold formed steel flexural and compression members are usually limited by yield point of buckling stresses that are less than yield point of steel, particularly for those compression elements having relatively large flat width ratio and for compression members having relatively large slenderness ratio.

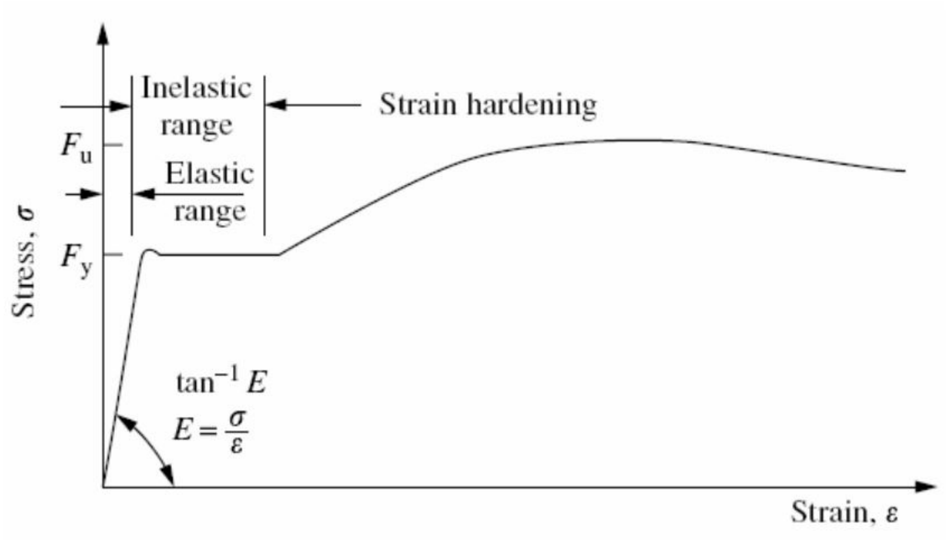

Figure 2. 2: Sharp yielding stress-strain curve type

Source: (Seong, 2009)

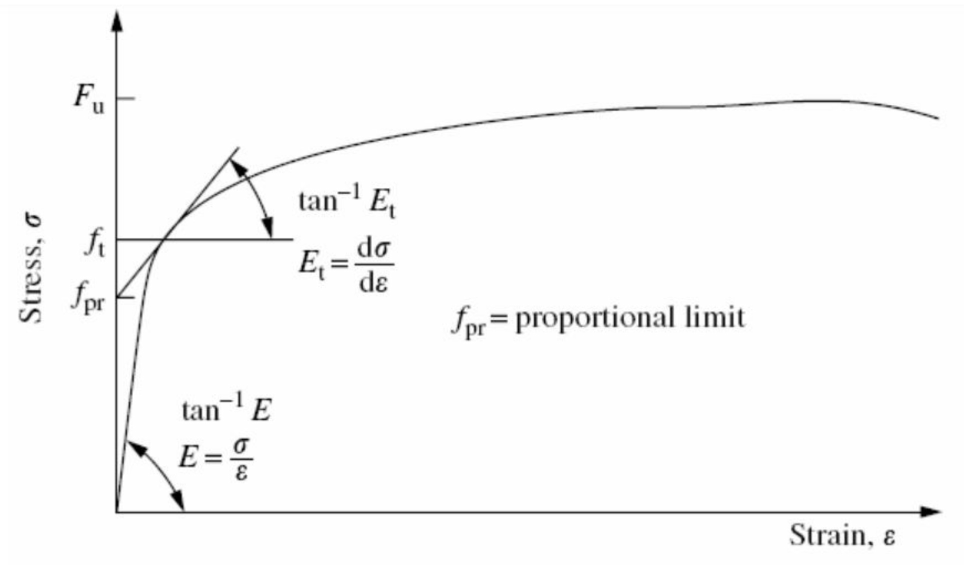

Figure 2. 3: Gradual yielding stress-strain curve type

Source: (Seong, 2009)

2.2.3 Modulus of Elasticity, Tangent Modulus and Shear Modulus

The strength of cold formed steel members that are governed by buckling depends not only on the yield strength but also on the modulus of elasticity, *E* and the tangent modulus, E_t. The usual value for *E* is 203 N/mm²(Haidarali and Nethercot, 2012), which is used in the American Institute of Steel Construction (AISC). The tangent modulus is defined by the slope of the stress-strain curve at any given stress level (refer figure 2.1). For sharp yielding, $E_t = E$ up to the yield, but with gradual yielding steels, $E_t = E$ only up to the proportional limit f_{pr} (refer figure 2.3).

Once the stress exceeds the proportional limit, the tangent modulus become progressively smaller than the initial modulus of elasticity(Jakab and Dunai, 2009). For cold formed steel design, the shear modulus is taken as G = 77.9 GPa according to the AISI specification.

2.2.4 Effect of Cold Work on Column Buckling

A paper by Chajes,Britves and Winter describes a detailed study on the effects on cold straining on the stress-strain characteristic of various mild carbon structure sheet steels. The study included tension and compression test of cold formed stretched material both in the direction of prior stretching and transverse it. The material studied includes:

i- cold reduced annealed temper rolled killed sheet coil
ii- cold reduced annealed temper rolled rimmed sheet coil
iii- hot rolled semi killed sheet coil
iv- hot rolled rimmed sheet coil

The terms rimmed, killed and semi killed describes the method of elimination or reduction of oxygen from molten steel(Yu and Laboube, 2010). In rimmed steels, oxygen combines with the carbon during solidification and the resultant gas rises through the liquid steel so that the resultant ingot has a rimmed zone which is relatively purer than the center of the ingot. Killed steels are deoxidized by addition of silicon or aluminium so that no gas is involved and they have more uniform material properties. Most of the cold formed steel material are continuously cast and are aluminium or silicon killed. A series of significant conclusion are:

i- Cold work has a pronounced effect on the mechanical properties of the material both in the direction of stretching and also in the direction normal to it.

ii- Increases in the yield strength and ultimate tensile strength as well as decreases in the ductility were to be directly dependent upon the amount of cold worked.

iii- A comparison of the yield strength in tension and compression for a specimen were taken both transversely and longitudinally demonstrates the Bauschinger effect. The longitudinal specimen demonstrates higher yield in tension than compression whereas transverse specimen of the same steel with the same degree of cold work demonstrate a higher yield in the compression than in tension.

iv- The higher the ratio of the ultimate tensile strength to the yield strength, then the larger is the effect of strain hardening during cold work.

v- Ageing of steel occurs if it is held at ambient temperature for several weeks or for a much shorter period at a higher temperature. The effect of ageing on a cold worked steel is to:

  a- increases the yield strength and the ultimate tensile strength
  b- decreases the ductility of the steel
  c- restore or partially restore the sharp yielding characteristic

2.3 Local Buckling of Plate Element

When a thin plate is loaded in compression, the possibility of local buckling arises. Elastic local buckling of in a member is characterized by a number of ripples or buckles (Velayutham and Sukumar, 2015). In cold formed steel design, individual members are usually thin and the width to thickness ratio is large. Thin element may buckle locally at stress lower than the yield point of steel when are subject to compression in flexural bending, axial compression, shear or bearing.

2.3.1 Local Buckling Analysis

In accordance to AISI, considered a plate supported on all four edges and compressed uniformly on its longitudinal edges to produce a displacement u. Due to the loading, out of plane deflections w occurs as shown. The strain energy due to bending U_b can be written in terms of the deflection as:

$$U_B = \frac{D}{2}\iint_{area}\left\{\left(\frac{\delta^2 w}{\delta x^2}+\frac{\delta^2 w}{\delta y^2}\right)-2(1-\nu)\left[\frac{\delta^2 w}{\delta x^2}\frac{\delta^2 w}{\delta y^2}-\left(\frac{\delta^2 w}{\delta x \delta y}\right)^2\right]\right\}dxdy \qquad 2.1$$

The strain energy in plate due to the membrane action is given by:

$$U_D = \frac{1}{2}\int_{vol} p_x \varepsilon_x d(vol) = \frac{Eta}{2}\int\left(\bar{\varepsilon}-\frac{1}{2a}\left(\frac{\partial w}{\partial x}\right)^2\right)^2 dy \qquad 2.2$$

The total strain energy stored in the plate is given by the sum of the bending and membrane energies. Since the displacement of the plate ends is prescribed, the principle of minimum potential energies requires that the strain energy is minimum. In case where plate is supported four sides and the deflection w at buckling are given by the expression:

$$w = w_c \sin\left(\frac{n\pi x}{a}\right)\sin\frac{\pi y}{b} \qquad 2.3$$

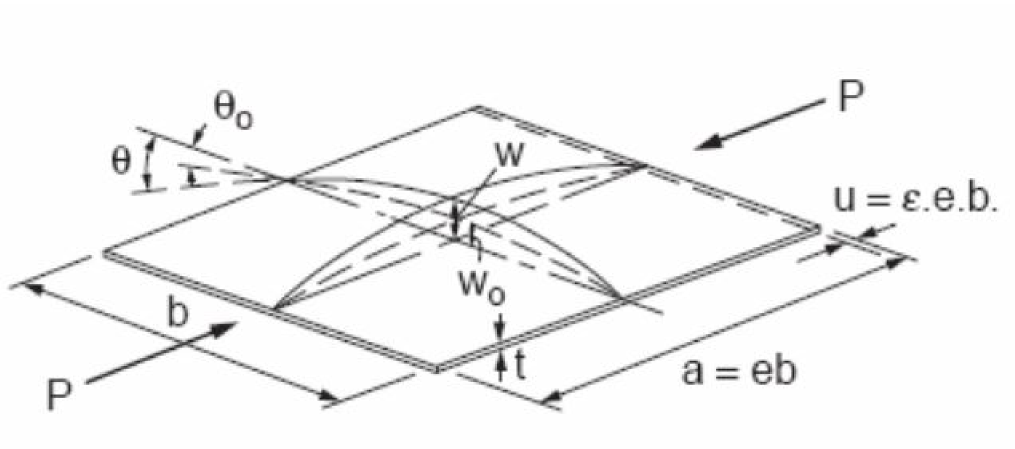

Figure 2. 4: Uniform Compressed Plate

Using the principle of minimum potential energy it can be shown that the critical stress (p_{cr}) to cause local buckling is given as:

$$p_{cr} = E\bar{\varepsilon}_{cr} = \frac{\pi^2 D}{b^2 t}\left[\frac{nb}{a} + \frac{a}{nb}\right]^2 = \frac{K\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{b}\right)^2 \qquad 2.4$$

The coefficient K is called the buckling coefficient and is given by:

$$K = \left[\frac{nb}{a} + \frac{a}{nb}\right]^2 \qquad 2.5$$

The variation of K with the variation in the plate length to width ratio a/b is shown in Figure 2.4 for various number of buckles, n.

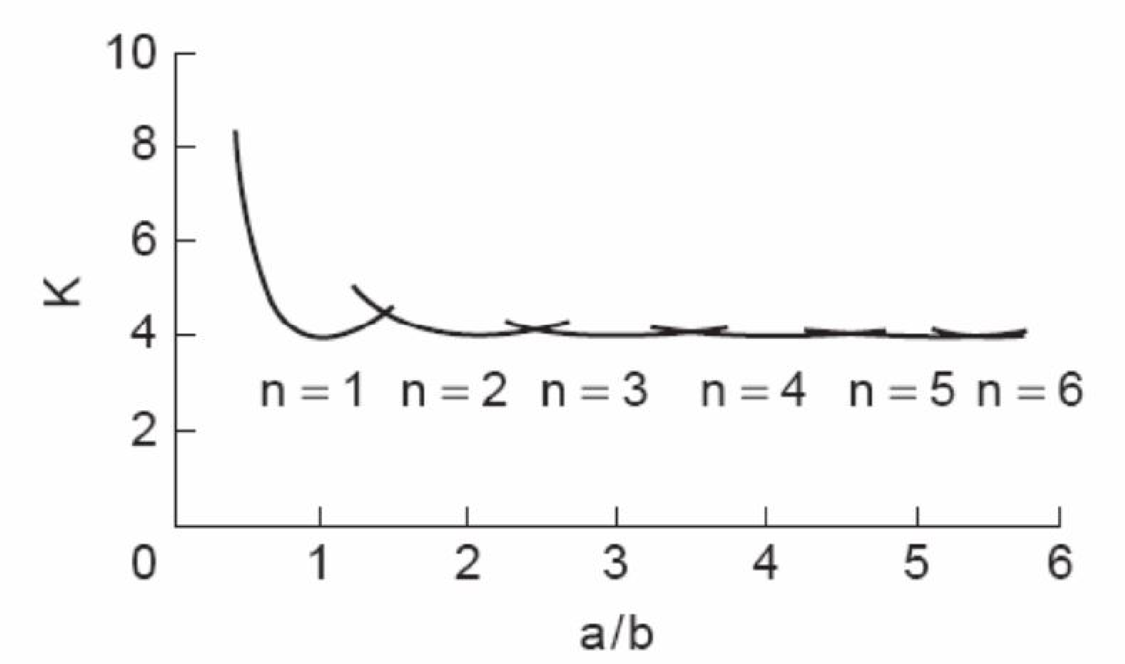

Figure 2. 5: Variation of buckling coefficient with length for a simply supported plate

2.3.2 Post Buckling Analysis

If the plate has buckled, the magnitude of the local buckles is related to the compression magnitude. Local buckling does not normally results in failure of the section as does flexural buckling in a column. The variation of stresses with the variation in strains after buckles can be shown to be:

$$p_x = E\left[\bar{\varepsilon} - \frac{4}{3}\left(\bar{\varepsilon} - \bar{\varepsilon}_{cr}\right) \sin^2 \frac{\pi y}{b}\right] \quad 2.6$$

The average stresses vary across the plate as indicated in Figure 2.5. Strips of plate near the supports are relatively unaffected by local buckling and carry increased loading as further compression is applied, while strips of plate near the center shed offer very little resistance to further compression.

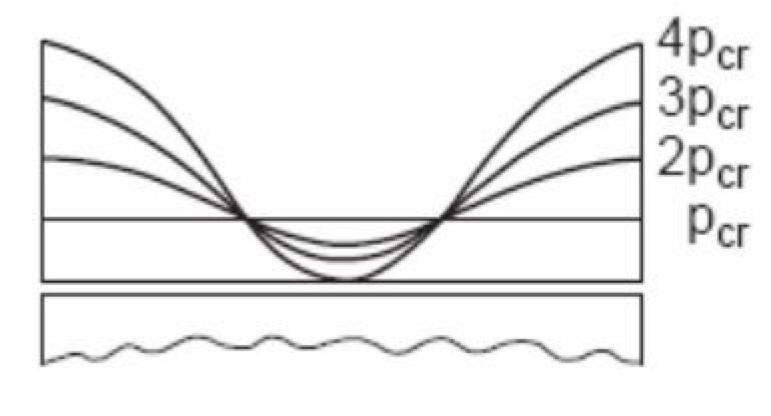

Figure 2. 6: Variation of stress across a plate after local buckling

The plate is assume to consist a series of slender columns linked together, with those near the edges largely prevented from buckling and those near the center buckling relatively freely. The plate does not behave completely like a column and lose all its compression resistance after local buckling, but its resistance after local buckling is confined to portions of the plate near the supported edges. This will occur irrespective of whether the plate is stiffened or unstiffened element. The plate element will continue to carry load although with a stiffness reduced to 40.8% of the initial linear elastic value for a square stiffened element and to 44.4% for a square unstiffened element. The line of action of the compressive force in an unstiffened element will move towards the stiffened edge in the post buckling range.

The load on plate at any end compression is obtained by summing the stresses across the plate. The plate load grows after buckling with increasing compression, but the rate of growth is substantially reduced relative to that before buckling.

$$p = t\int p_x\,dy = Etb\left[\bar{\varepsilon} - \frac{2}{3}\left(\bar{\varepsilon} - \bar{\varepsilon}_{cr}\right)\right] = \frac{Etb}{3}\left[\bar{\varepsilon} + 2\bar{\varepsilon}_{cr}\right] \qquad 2.7$$

Analysis shows that after buckling the plate stiffness reduces, the edge stresses increase more quickly with the load than before buckling, and the plate center becomes inefficient at resisting the load. The plating could only be considered effective in resisting compression over a short width adjacent to the supports.

2.4 Behaviours under Axial Compression

Meiyalagan (2010) indicates that non symmetric open web cross sections (whose centroid does not coincide with shear centre) will undergo flexural torsional buckling. Single symmetric sections will likely to fail flexural buckling or flexural torsional buckling depending on their actual sizes (Figure 2.7). Double symmetrical members, may be susceptible to lateral torsional buckling (flexural buckling) due to the presence of the imperfections. Pure torsional buckling modes are likely to occur for point symmetric sections in which the shear centre and centroid coincides. Lateral torsional buckling (or flexural 10rsional buckling) FT is a combination of flexural buckling (F) and torsional buckling (T). Long columns fail in flexural - torsional buckling and short colurins in distortional buckling.

According to Crisan, et al.(2012), limited to stub columns and upright specimens, do not characterize the distortional buckling mode. In fact, the upright specimens considered for the so called ‘’distortional" tests in the code are, in almost all the cases, prone either to an interaction between distortional and overall buckling (F/FT) or to an elastic--plastic overall failure mode.

Distinct behaviours were found between different cross-sections along the member length. This was reflected by the alternating patterns of the stress distributions obtained at the crests of “inward’’ and “outward’’ buckles, and at the nodal lines of local buckles (Yao, et al., 2012) In particular, an “inward” buckle produced higher membrane stresses within the flanges, while an “outward”' buckle tended to have stresses concentrated near the web-flange comers and the tips of the lip. In contrast, nodal lines produced a significant stress decrease in the central part of the web but fairly uniform stresses between the lips and the web-flange corners.

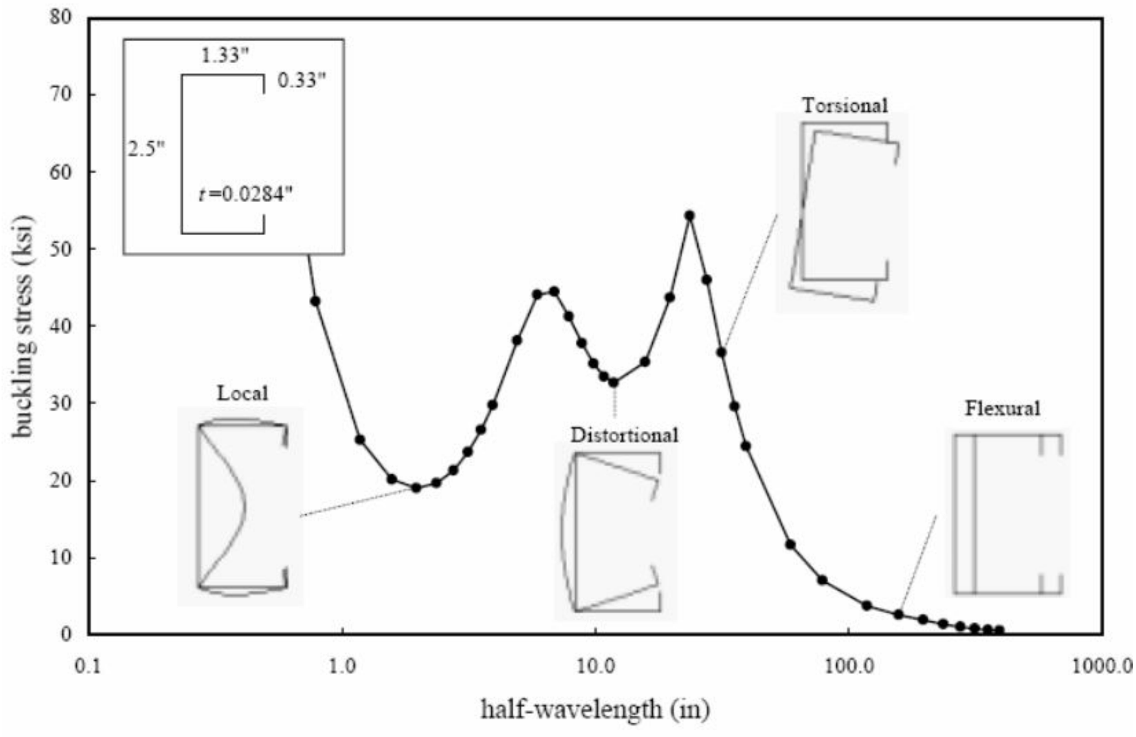

Figure 2. 7: Mode of failure for cold formed steel

2.4.1 Local Buckling

The base plate elements of CFS sections are normally thin higher plate slenderness ratio and hence they buckle locally before yield stress is reached, Local buckling mode of a given thin walled member depends, on its cross section geometry (shape & dimensions), and support conditions. The elastic local buckling of thin elements does not immediately lead to failure. The elements can carry additional load in the post buckling strength before failure occurs. The post buckling strength of elements having relatively large flat width to thickness ratio may be several times the load that causes local buckling. Consequently all the cold-formed steel design specifications take into account the post buckling strength.

2.4.2 Distortional Buckling

Distortional buckling, also known as “stiffener buckling” or “1ocal torsional buckling” is mode characterized by a rotation of the flange at the flange/web junction in numbers with edge stiffened elements. In members with intermediate stiffened elements distortional buckling is characterized by displacement of the intermediate stiffener normal to the plane of the element.

2.4.3 Torsional-Flexural Buckling

When an open section column buckles in the torsional flexural mode, bending and twisting of the section occur simultaneously. The section translate in the x and y direction and rotates an angle about the shear centre. The critical buckling load is the smallest value of the three roots of P_{cr}.

2.5 Method of Cold-Forming

There are three methods generally used in the manufacture of cold-formed steel sections which are cold-rolling, press brake operation and folding. According to Banwait (1987), cold-forming is a term used to describe the manufacture of products by forming material from a strip or sheet of uniform thickness.

2.5.1 Cold-Rolling

This is the most widely used method for mass production of cold formed steel sections (TATA STEEL, 2017). With this method, a section is formed continuously by gradually feeding the steel sheet through successive pairs of rolls, which act as male and female dies. Each pair of rolls progressively forms the section from the sheet. Depending upon the geometry of the section, 5 to 16 pairs of rolls may be used. The usual speed of forming a section may vary between 10 to 25 m/min. But it can be as high as 100 m/min. The cross-section produced by cold roll-forming can be held within very close dimensional tolerances, normally plus or minus 0.4 mm. Hence, the members are usually uniform in cross-section.

2.5.2 Press Brake Operation

This method is preferable when the section to be formed is of simple configuration, and with relatively wide plate components(MARINO WARE, 2016). It is usually used if the required quantity is less than 1000 linear meters. The equipment used in the press brake operation consists of a moving top beam and stationary bottom bed, on which dies app1icab1e to the particular cold formed steel shape are mounted. In general, press beds are 1imited to a length up to 3 meters. Some of the more powerful machines can form section up to 8 meters in length (Walker, 1975).

2.5.3 Folding

Folding method is the simplest method of cold-forming. The production involved series of bends (folding) of sheet of material. From this method, a short length of cold-formed steel with a simple geometry can be produced. In addition, there are a lot of advantages such as improved parts quality, simplified handling and increase productivity by reducing handling and set-up-times and increased flexibility lower production costs (and after-treatment costs). However, this method is not widely used as of it limitation of design and application.

There are other 1ess popu1ar ways of co1d-forming. A method used for manufacturing simple sections such as angles, Z-sections, and channels is the bending brake operation. However, it is not suitable for more complex sections. Other production methods for cold-forming include drawing and extrusions. These methods are not economical in mass production of prismatic steel sections and are not common1y used.

2.6 Perforation

In practice, perforations are either pre-punched or punched on-site on the cold-formed sections, to pass through conduits and utility ducts (MacDonald & Kulatunga, 2013). The presence of perforations in a structural member has often created a number of problems and drawbacks and complicates the design process. In general the effect of perforations made specifically for fasteners such as bolts, and screws. On the overall strength of a structure may be neglected as holes are filled with material. However, any other openings or perforations generated and not filled with replacement material creates a reduced cross sectional area and cross sectional properties and this should be taken into account in any analysis. The effect of perforations on the structure is examined by testing and analysis.

Leading design rules for cold-formed s1eel members with perforations are largely based on empirical formulae which have been developed by numerous researchers in the past, and are limited to certain perforation sizes, shapes, orientations and positions. These limitations have created a number of problems and can decrease the reliability of cold-formed steel sections in the building construction industry (Moen and Schafer, 2009). The results of the investigations of cold-formed steel structural members with perforations, previously conducted by various researchers, have found that a concentrated load that may potentially cause deformation of the structure is applied over perforations. However, it has been identified that due to the shape of the perforations and the thickness of the sections and for other practical reasons, reinforcement of these perforations in thin-walled members is not possible.

Test done by (Moen and Schafer, 2009), describe a series of compression test performed on cold-formed steel column. The test results presented is to observe and quantify the relationship between elastic buckling steel columns with holes. Slotted web holes may modify the local and distortional elastic buckling half-wavelength, and may also change the critical buckling load. Experimentally, slotted web holes arc shown to have minimal influence on the tested ultimate strength in the specimens considered although post-peak ductility is decreased in some cases. Tangible connections are observed between elastic buckling and load-displacement response during that tests, including mode switching between local and distortional buckling. The columns arc tested with friction-bearing boundary conditions where the columns ends are milled flat and parallel, and bear directly on steel plate. The presence of slotted holes caused only a slight decrease in the ultimate compressive strength of the tested columns, although the post-peak response and column ductility were influenced by the presence of slotted holes, the cross-section type, and the length member. In short columns, the slotted holes reduced the web buckling capacity, causing the column to rely more on the flanges and lip stiffeners to carry load with a distortional-type failure.

The presence of perforations may cause a reduction in strength of individual component elements and the overall strength of the member depending on the position, size and orientation of the opening. Exact analysis and design of steel with perforations elements are complex especially with unusual arrangements and shapes. According to (Yu and Laboube, 2010), perforations on cold-formed steel are a major concern especially on a thin-walled structural members and the critical buckling loads for perforated plates members have been studied by numerous investigators.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, it would be discussed about the method that be used involving this research. The apparatus that would be used was The Universal Testing Machine that function to compress (applying axial load) the specimens. The specimens used are directly ordered from factory with specific design and details. The testing samples were made in the laboratory of Faculty of Civil Engineering and Earth Resources (FKASA) in University of Malaysia Pahang. The samples used by this research has 600 mm in length due to the limitation of height that can be cater by the machine in the laboratory. The base plate need to weld both sides as it is consider to be fixed-end.

Upon testing was made, a discussion was made with the technician involved to know further about the machine and how the testing would be conducted. As there are no standards that are available for the testing of steel, the research by (Kulatunga & Macdonald, 2013) was made as the main reference in conducting this experiment. The research was chosen as reference due to factor of similarity between the samples used in the experimental investigation.

At the end of this research, the results that were obtained showed the performance and behavior of cold-formed steel single C-section against different size and with or without an opening. Other than that, the behavior of buckling such as elastic buckling, failure mode and post-buckling also will be obtained. The reading of maximum axial load that are being applied to the specimens also can be acquired. The experimental investigation was aimed at studying the influence of opening on the ultimate strength and the failure mode of single C-section stub columns. This research should be summarize the whole research and gives recommendations for future improvements regarding the research topic.

3.2 Flow Chart

The flow of this research would based on the phase which are phase 1, phase 2 and phase 3. From these phases, the flow of this research would be smother as we can see the ways to the end.

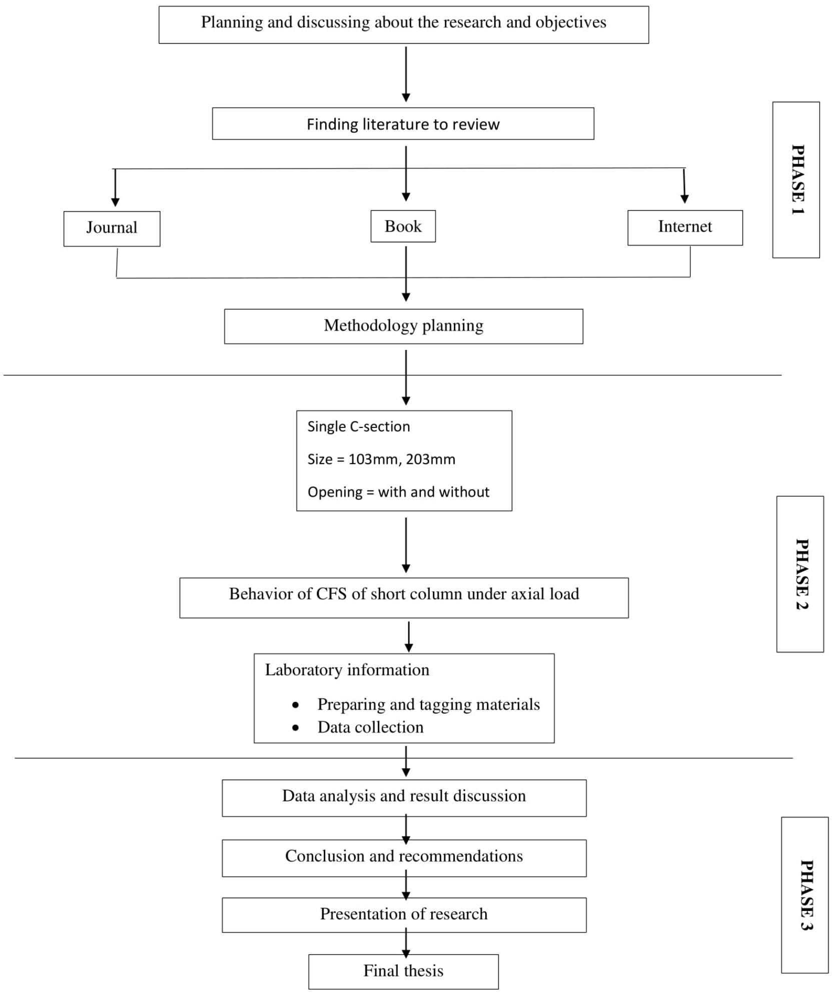

Figure 3. 1: Flow chart of the research

3.3 Research Design and Parameter

In this research, the design of specimens was in specific details so that the factory can provided the correct material. The sample used for this research has 600 mm length due to to the limitation of height that can be cater by the machine in the laboratory. The design and naming convention of the specimens can be refer from Table 3.1, Table 3.2 and Figure 3.2.

Table 3. 1: Section parameter

Parameter	Magnitude
Length	600 mm
Depth	103 mm, 203 mm
Thickness	1.2 mm, 2.0 mm
Opening	with/without opening
Section	Single C-section

Table 3. 2: Naming convention of the specimens

Thickness(mm)	Depth(mm)	Name	
		No Hole	With Hole
1.2	103	SC-1.2-103-NH	SC-1.2-103-H
	203	SC-1.2-203-NH	SC-1.2-203-H
2.0	103	SC-2.0-103-NH	SC-2.0-103-H
	203	SC-2.0-203-NH	SC-2.0-203-H

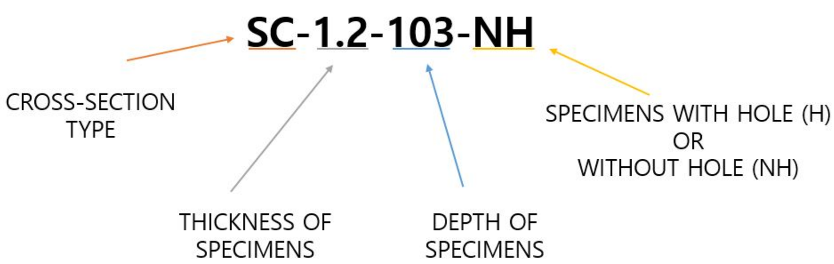

Figure 3. 2: Naming convention

3.4 Research Procedure

This research procedure conducted at FKASA laboratory at University Malaysia Pahang by using Universal Testing Machines. The process of setting up the specimen during the testing start by making cross-line at the centre of the bottom part as guide to position the specimens. Continue by putting up the transducers which are vertical and horizontal at both sides of the specimens. Next, the transducer are put at the position according to the focusing study. Then, the loading rate of machine need to be set-up. The loading rate that will be used was 0.5 mm per minute which it was the most suitable rate for this specimens according to previous researchers.

The Universal Testing Machine will compressed the specimens until the total vertical displacement of compression reached 6mm. the data taken from this machine will be in form of graph. The horizontal transducers are being used to read the reading of buckling mode of specimens. The support being used for the specimens is fixed-end support. Thesis by Kulatunga & MacDonald (2013), S. Vijayanand & Anbarasu (2017) are being set as reference through the execution of this research.

Figure 3. 3: Positioning of specimens and transducers in Universal Testing Machine

Figure 3. 4: Welding work of specimens

Figure 3. 5: Drilling of specimens

Figure 3. 6: Single C-section steel specimens

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The results for this research was measured from the maximum load applied to the specimens, buckling behavior (failure mode) and the displacement of all three transducers. The data is analyzed and presented through tables and graph of load against vertical displacement and load against horizontal displacement where it compared the axial load and the displacement of the sample. Comparison of maximum load of each specimen series also were presented in graph to show a vivid comparison.

From the research, the overall result can refer Table 4.1. The ultimate load was obtained by specimen without opening compare to with an opening. For the type of opening, specimens without opening has a higher ultimate load compare to specimens with an opening. In addition, for the size of the specimen, the 203 mm has higher ultimate load than the size with 103 mm. For the behavior of failure mode, all the specimens seems to experience local, distortional and warping buckling.

Table 4. 1: Overall result of the research

SPECIMEN		PEAK LOAD (kN)	FAILURE BEHAVIOUR		
			INITIAL	PEAK	POST
SC-1.2-103	NH	41.0187	DB	WbM	WbT
	H	41.4875	DM	WrM/WbM	WbM
SC-1.2-203	NH	45.0000	WrM	Wb	DB
	H	48.1270	WrM	Wb	DB
SC-2.0-103	NH	102.0750	WrB	WrT/WbB	DB
	H	87.0000	DT	WrM/WbM	WbM
SC-2.0-203	NH	105.7000	WrB	WbM	DM
	H	105.0875	WrM	WrM/WbM	WrM

4.2 Test of Compression on Series 1 (SC-1.2-103)

4.2.1 Compressed Test on SC-1.2-103-NH

At the initial stage where the loading was applied, distortion buckling occurred at the bottom of the specimen based on observation (Figure 4.1). The specimen failure was at 41.0187 kN due to buckling of web at the middle of the specimen (Figure 4.3). From the overall observation. The web buckling occurred at the top was obviously showed the failure of the specimen (Figure 4.4).

For the load vs vertical displacement graph (Figure 4.6), the ultimate axial load applied was 41.0187 kN with 2.019 mm displacement. Vertical displacement is the displacement that results from compressing of the machine. The value shows the movement of the machine table in act of compressing the cold-formed column.

The maximum axial load for this sample is 41.0187 kN and the maximum displacement is 0.787 mm which happen at transducer T2. As seen from the Figure 4.7, the graph intersect once in the test. Intersection between T2 and T3 occurred at 0.42 mm displacement. The negative value in the graph represent the flange of the column buckled inward while positive value means the flange buckled outward. The result shows that local buckling behavior at middle and top of the specimen.

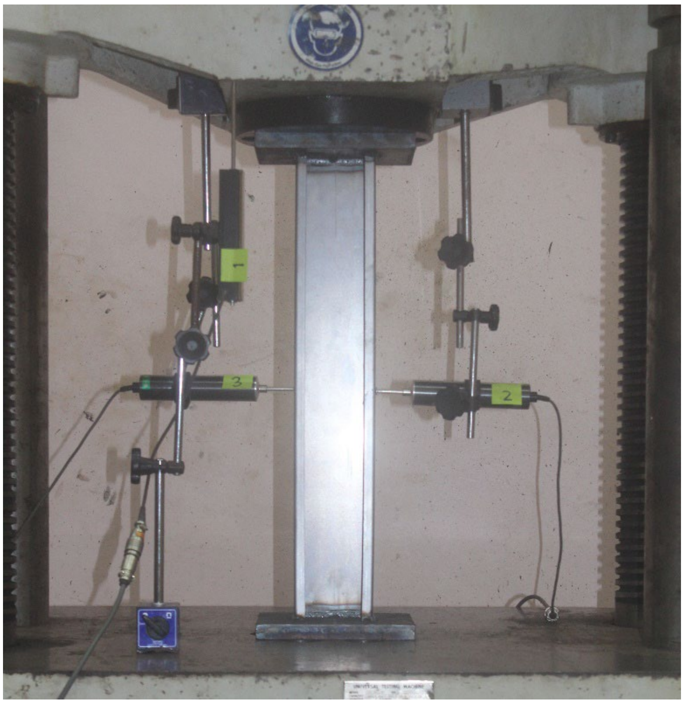

Figure 4. 2: At zero loading

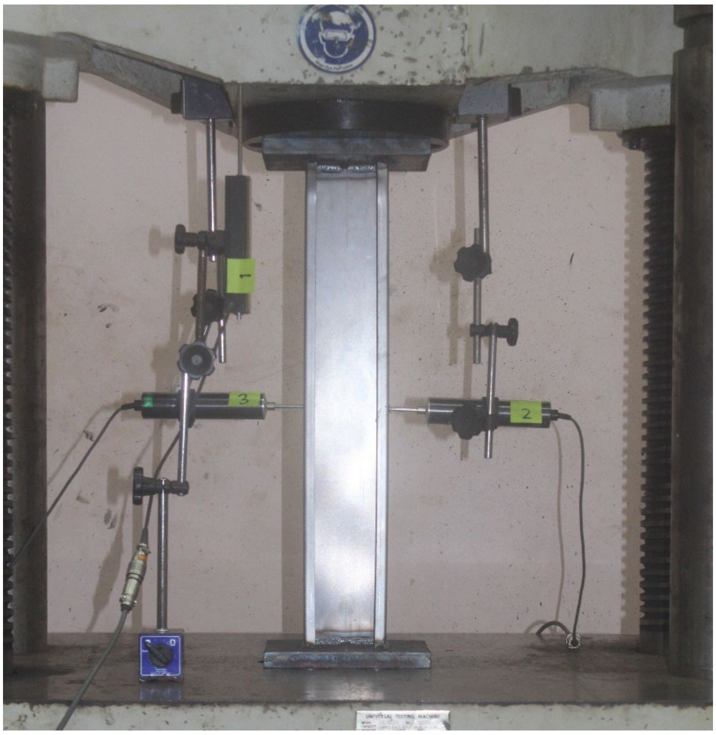

Figure 4. 1: Initial buckling

Figure 4. 3: Peak load

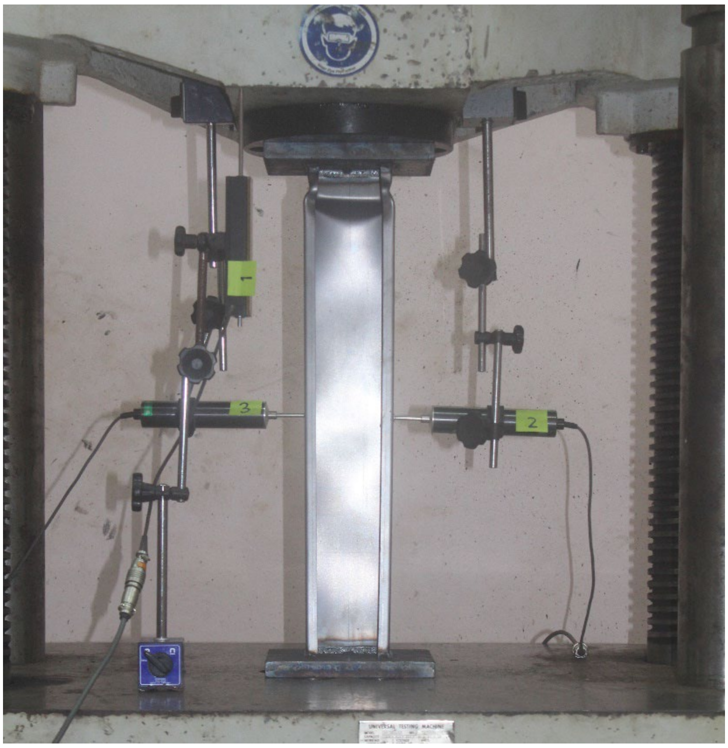

Figure 4. 4: Post-load buckling

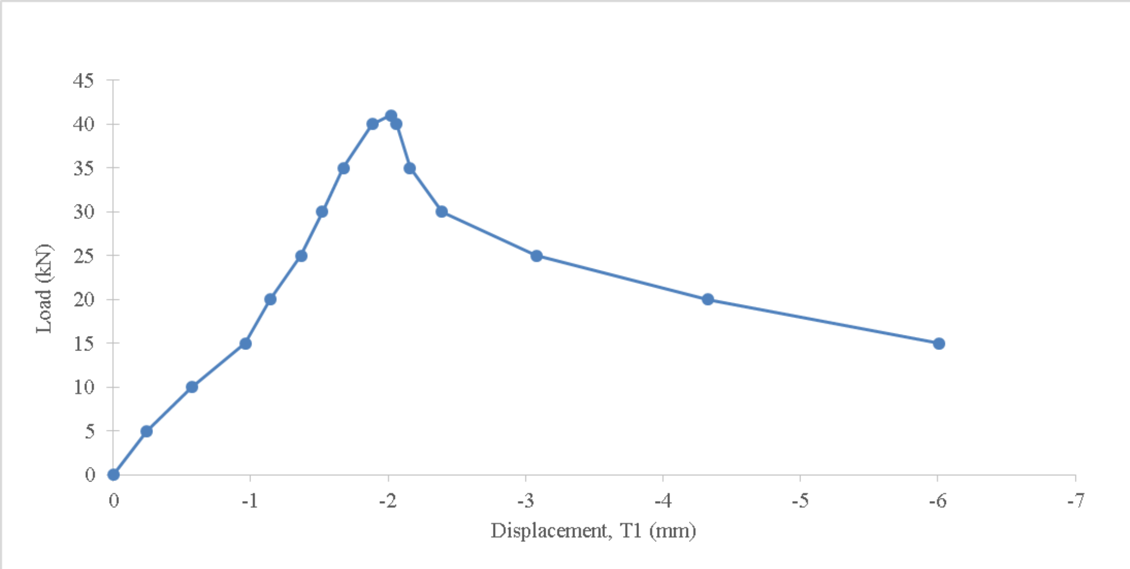

Figure 4. 6: Load vs Verticall Displacement Graph

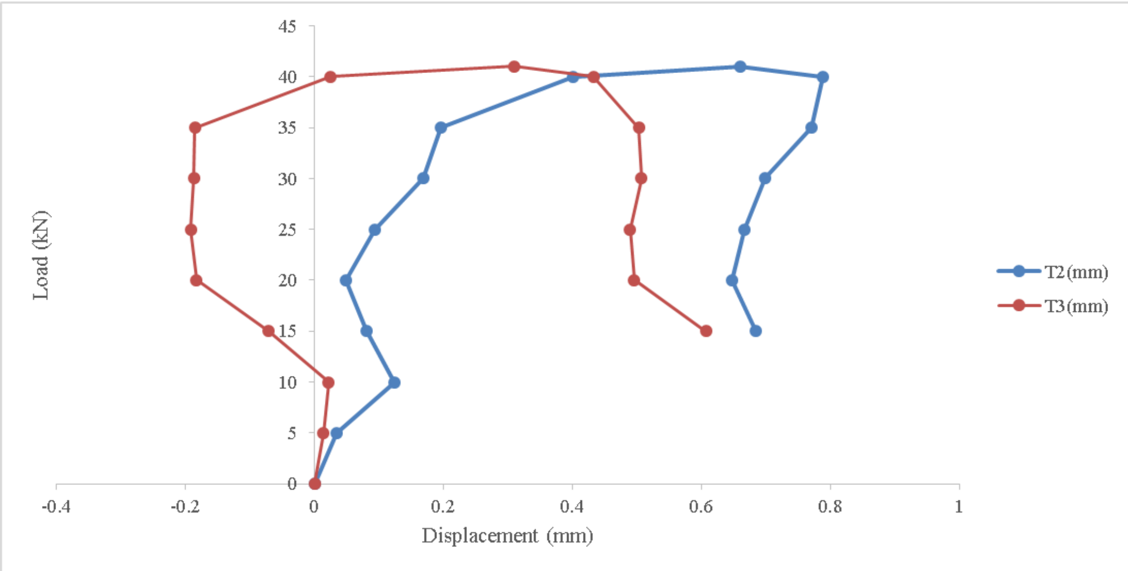

Figure 4. 5: Load vs Horizontal Displacement Graph

4.2.2 Compressed Test on SC-1.2-103-H

At the initial stage where the loading was applied, the initial buckling was occurred at the middle of the column where the hole is situated (Figure 4.8). The specimen failure was at 41.4875 kN due to local, distortional buckling and warping at the middle of the column (Figure 4.9). Even the column show warping type of failure at the beginning, the mode of failure of this specimen showed the flange buckled inward or distortion at the middle at post-load. (Figure 410).

For load vs vertical displacement graph (Figure 4.11), the ultimate axial load applied was 41.4875 kN with 1.508 mm displacement. For this sample, the maximum axial load is 41.4875 kN and the maximum horizontal displacement is -10.571 mm showed by transducer T2. As seen from the Figure 4.12, the sample move exponently to positive side before gradually move toward negative right after the maximum load. From the result observation made that distortional occurs at middle front of the specimen, local and distortion occur at the middle of the specimen.

Figure 4. 7: At zero loading

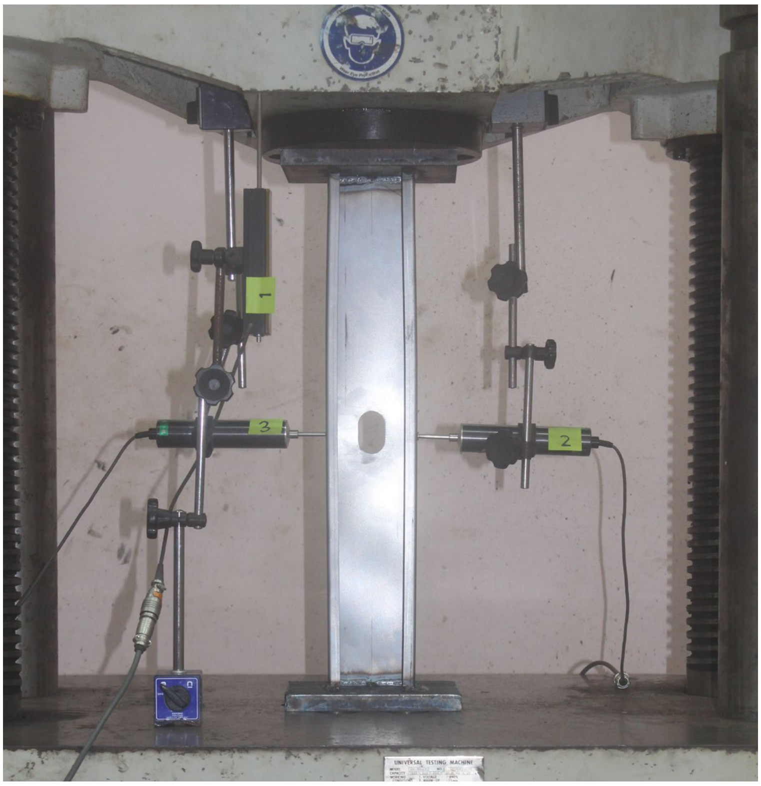

Figure 4. 8: Initial buckling

Figure 4. 9: Peak load

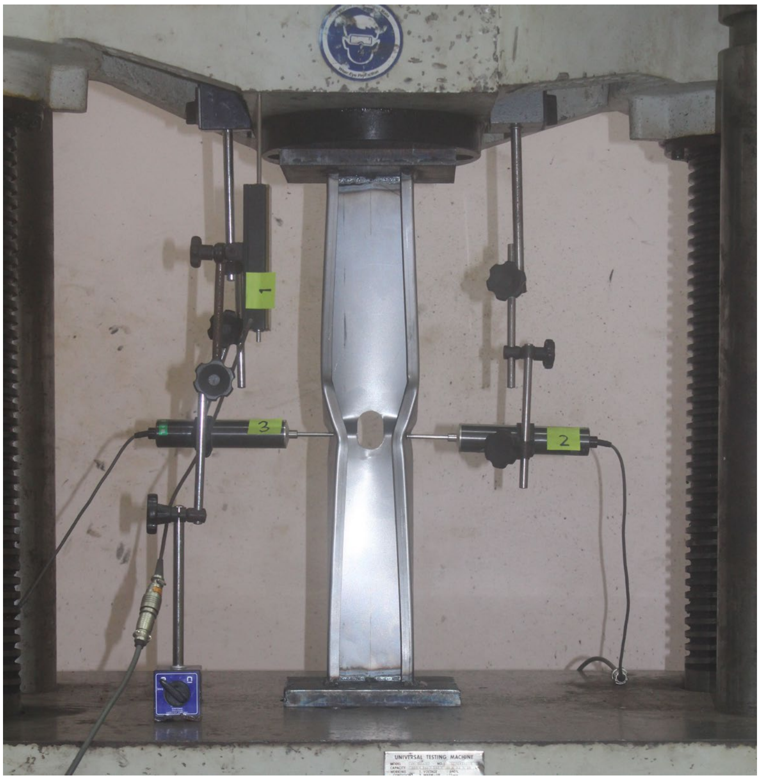

Figure 4. 10: Final post-buckling

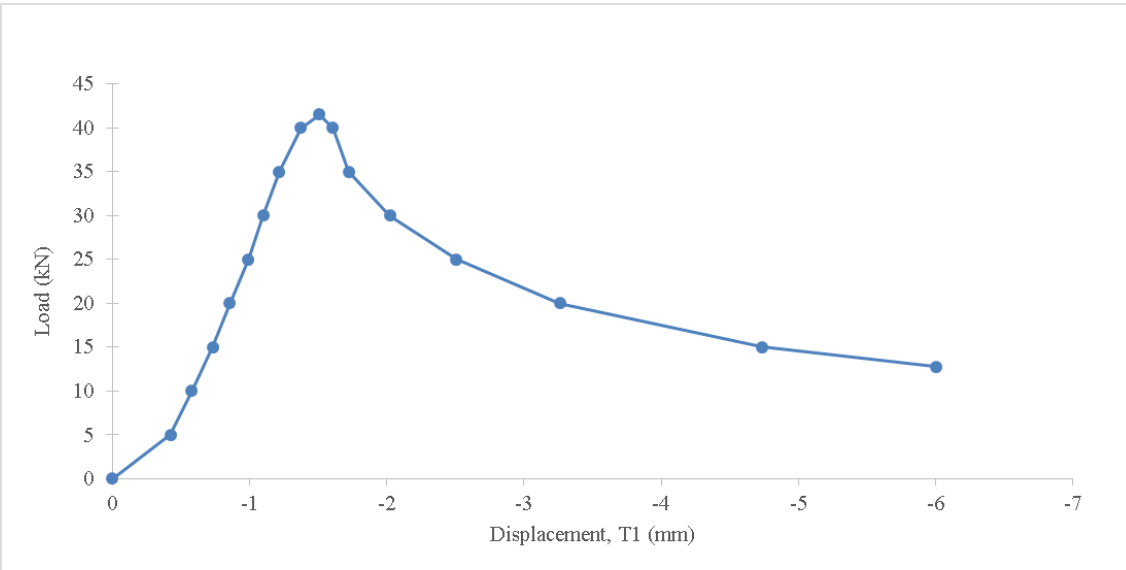

Figure 4. 11: Load vs vertical displaacement graph

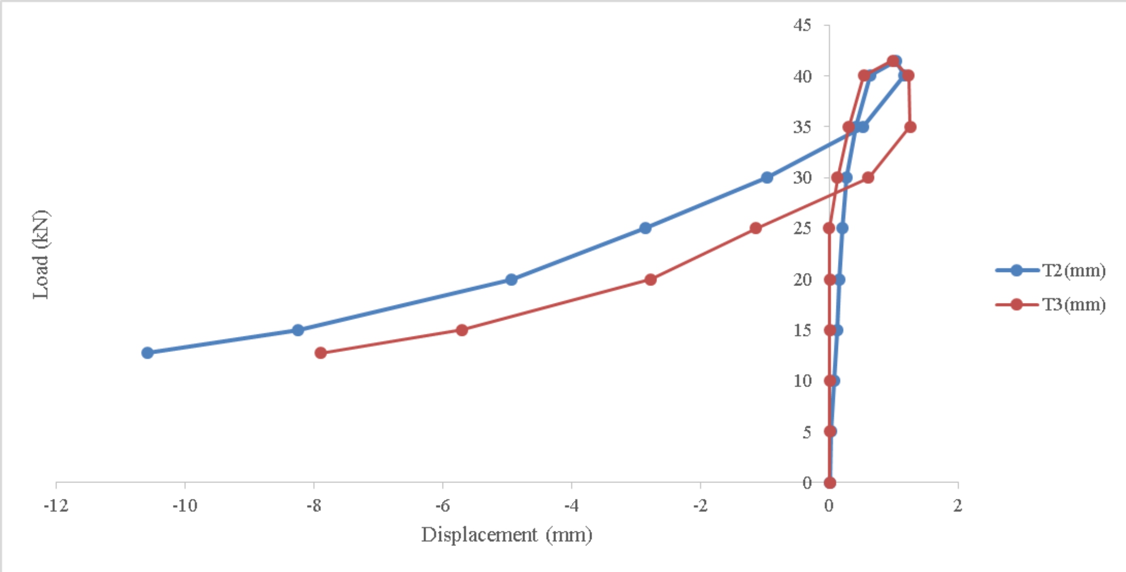

Figure 4. 12: Load vs horizontal displacement graph

4.2.3 Comparison between SC-1.2-103-NH and SC-1.2-103-H

The result for Series 1 compression test was unexpected and quite unique as the ultimate axial load obtained from both specimen showed the SC-1.2-103-H has a higher value than SC-1.2-103-NH. Figure 4.13 showed a better view of the comparison. This problem had been encountered before by (Seong, 2009), in his paper stated that the problem was caused by the steel plate at one end was not welded properly. The steel plate was slightly tilted to the backside of the column, resulting the load applied was not uniformly. This would lead to reduction of the ultimate axial load due to loading was not transferred thoroughly the steel column. The column would tend to fail even with a low load applied. A tilted steel plate could make the Universal Testing Machine were not in fully contact with the specimen during the testing were conducted.

Upon inspection on both specimens, the blame of this faulty can be put on specimen SC-1.2-103-NH as the steel plate on one of the specimen's ends are found to be tilted to front of the specimen. This could be the major cause of the faulty as the position of the steel plate play a major role in this research.

Figure 4. 13: Comparison on axial load

4.3 Test of Compression on Series 2 (SC-1.2-203)

4.3.1 Compressed Test on SC-1.2-203-NH

At the initial stage where the loading was applied, there is local buckling occur and warping at the middle of the column (Figure 4.14). The specimen failure was at 48.172 kN due to further warping and local buckling (Figure 4.17). From the overall observation, the warping occurred at the middle was obviously showed the failure of the specimen (Figure 4.16).

From the load vs vertical displacement graph (Figure 4.19), the ultimate load applied was 48.172 kN with 1.327 mm displacement. For this specimen, it has a maximum axial load of 48.172 kN and a maximum displacement of 10.655 mm showed by transducer T2 at the end of the test (Figure 4.18). Results shows displacement exponentially increase towards positive and further gradually move to positive after the peak load. From the figure specimen shows warping at the middle and local occur at the top of the specimen after the end of the experiment.

Figure 4. 15: At zero loading

Figure 4. 14: Initial buckling

Figure 4. 17: Peak load

Figure 4. 16: Final post buckling

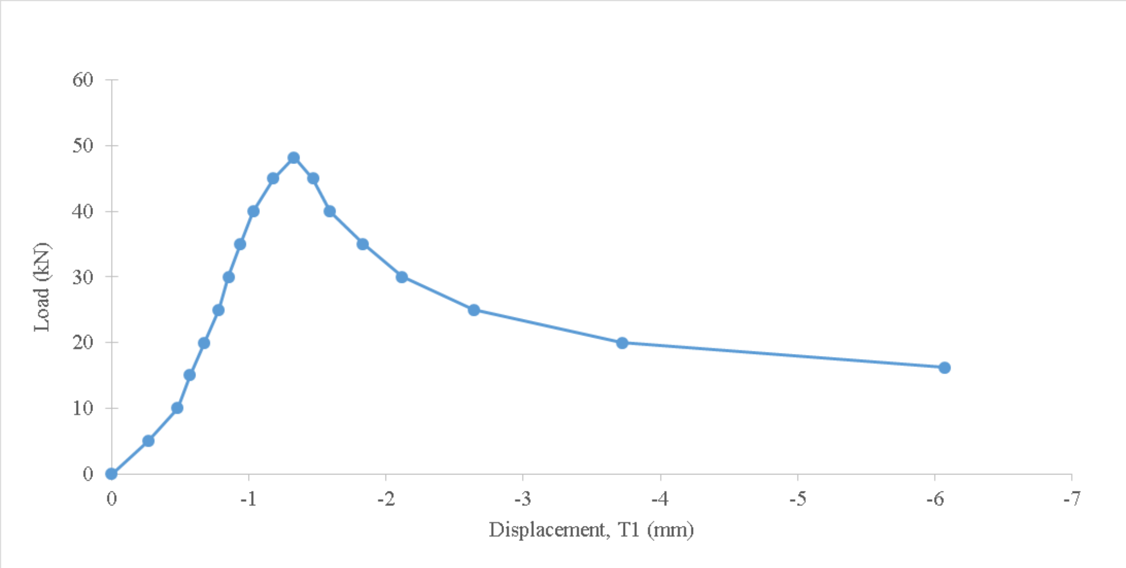

Figure 4. 19: Load vs vertical displacement graph

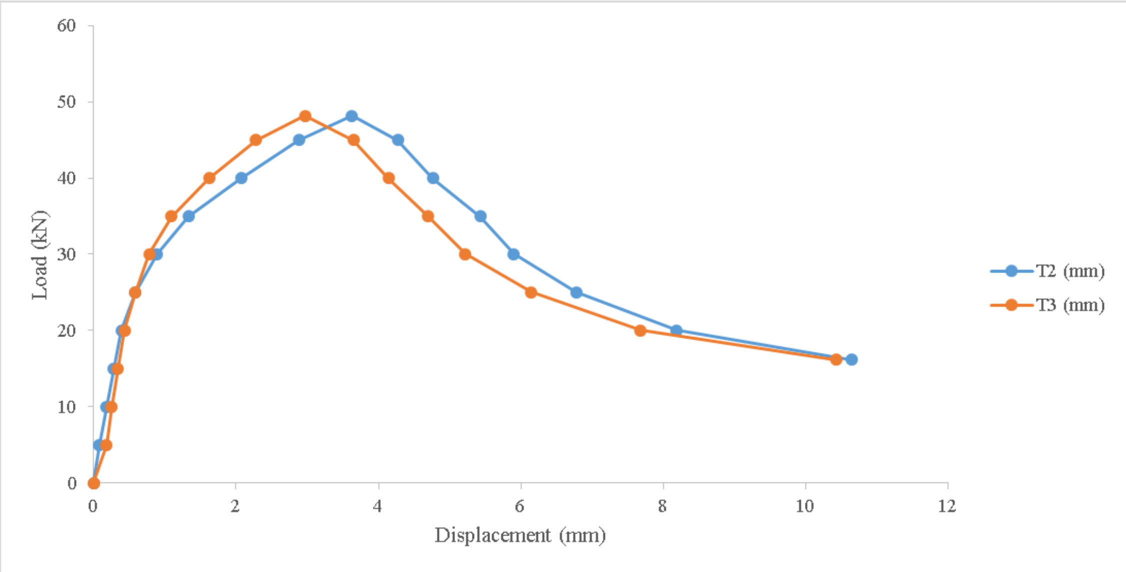

Figure 4. 18: Load vs horizontal displacement graph

4.3.2 Compressed Test on SC-1.2-203-H

At the initial stage where the loading was applied, there is local buckling occur and warping at the middle of the column (Figure 4.22). The specimen failure was at 45 kN due to further warping and local buckling (Figure 4.21). From the overall observation, the warping occurred at the middle was obviously showed the failure of the specimen (Figure 4.24).

From the load vs vertical displacement graph (Figure 4.23), the ultimate load applied was 45 kN with 1.67 mm displacement. For this specimen, it has a maximum axial load of 45 kN and a maximum displacement of 9.753 mm showed by transducer T3 at the end of the test (Figure 4.25). Results shows displacement exponentially increase towards positive and further gradually move to positive after the peak load. From the figure specimen shows warping at the middle and local occur at the top of the specimen after the end of the experiment.

Figure 4. 20: At zero loading

Figure 4. 22: Inital buckling

Figure 4. 21: Peak load

Figure 4. 24: Final post-buckling

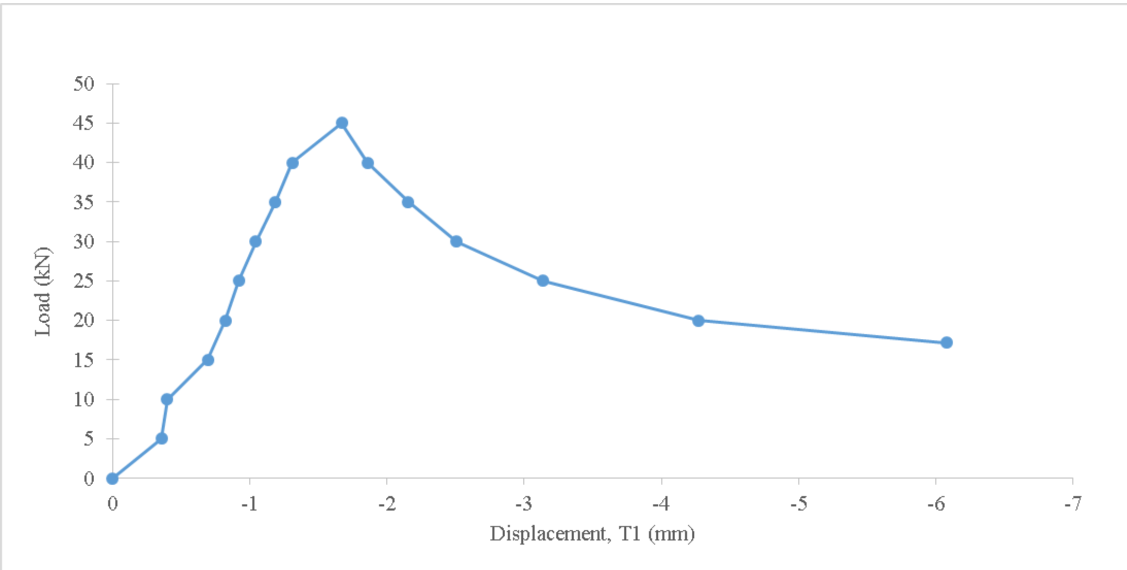

Figure 4. 23: Load vs vertical displacement graph

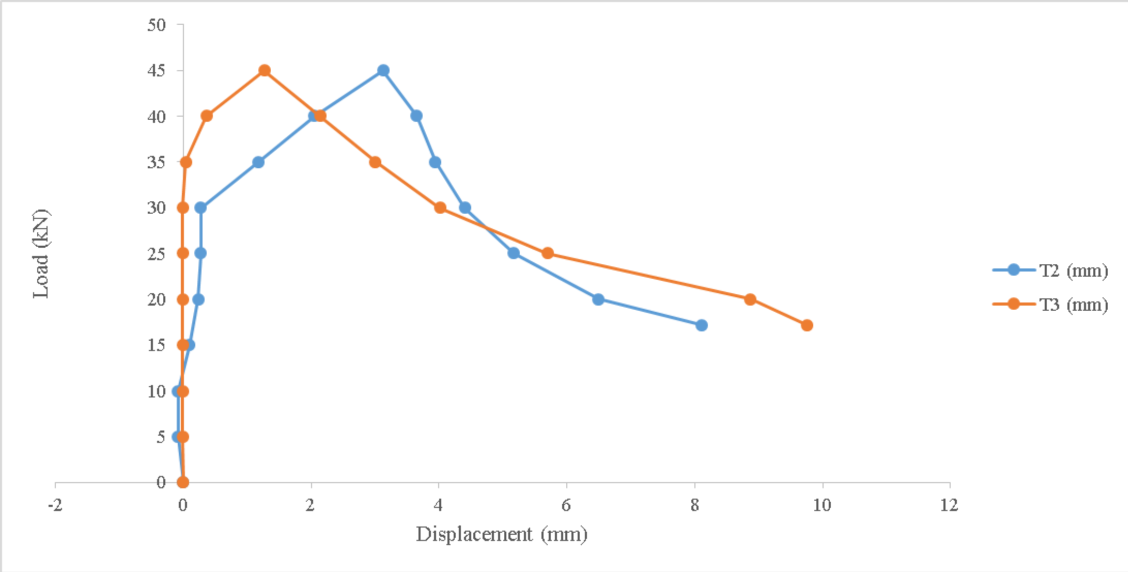

Figure 4. 25: Load vs horizontal displacement graph

4.3.3 Comparison between SC-1.2-203-NH and SC-1.2-203-H

The result of Series 2 experiment were expected as the ultimate strength for SC-1.2-203-H is lower than SC-1.2-203-NH in 6.25% difference. Figure 4.26 showed a better view for the comparison. Both load applied on the specimens were increased in the same rate before SC-1.2-203-H stopped at 45 kN while SC-1.2-203-NH continue to increase until 48.172 kN before dropped gradually toward the end of experiment.

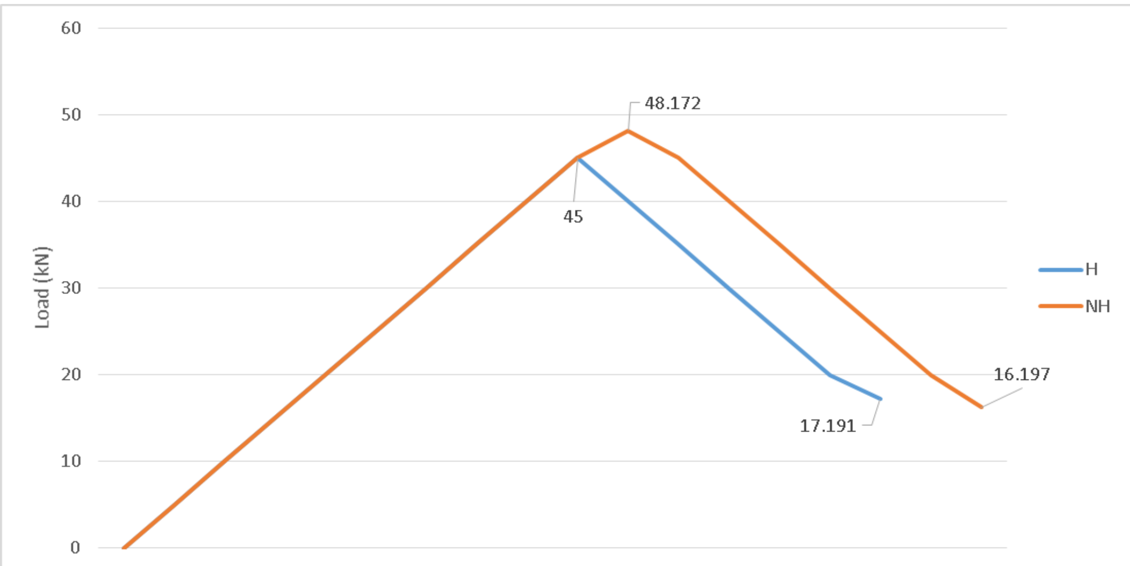

Figure 4. 26: Comparison on load applied

4.4 Test of Compression on Series 3 (SC-2.0-103)

4.4.1 Compressed Test on SC-2.0-103-NH

At the initial stage where the loading was applied, there is local buckling occur and warping at the middle of the column (Figure 4.29). The specimen failure was at 102.075 kN due to further local buckling (Figure 4.28). From the overall observation, the distortion buckling occurred at the bottom was obviously showed the failure of the specimen (Figure 4.31).

From the load vs vertical displacement graph (Figure 4.30), the ultimate load applied was 102.075 kN with 1.509 mm displacement. For this specimen, it has a maximum axial load of 102.075 kN and a maximum displacement of 0.965 mm showed by transducer T2 at the end of the test (Figure 4.32). The mode of failure for this specimen were hardly to be observed by naked eyes because they buckling were very little and the displacement were not even exceed 1 mm as shown in Figure 4.32. Results shows displacement were unique as it goes to positive before maximum loading was applied and gradually move to negative after it reached maximum loading. From the figure specimen shows distortion and local at the bottom near the support of the specimen after the end of the experiment.

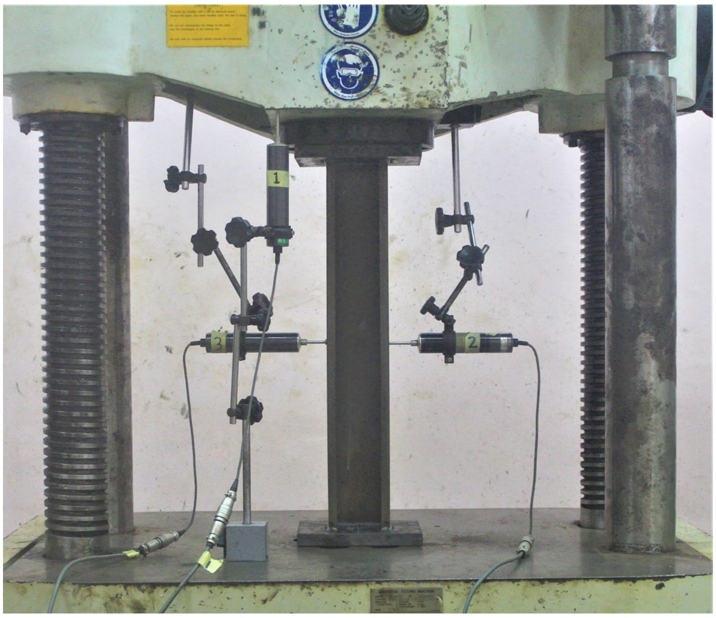

Figure 4. 27: At zero loading

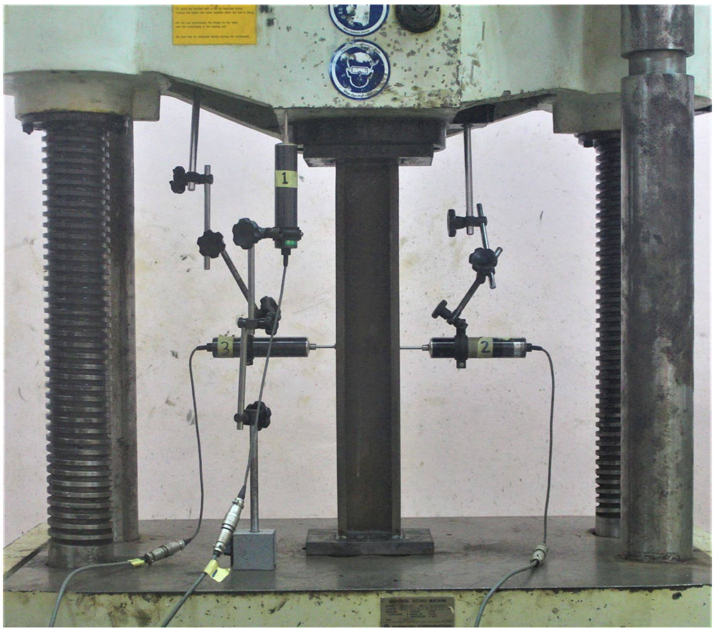

Figure 4. 29: Initial buckling

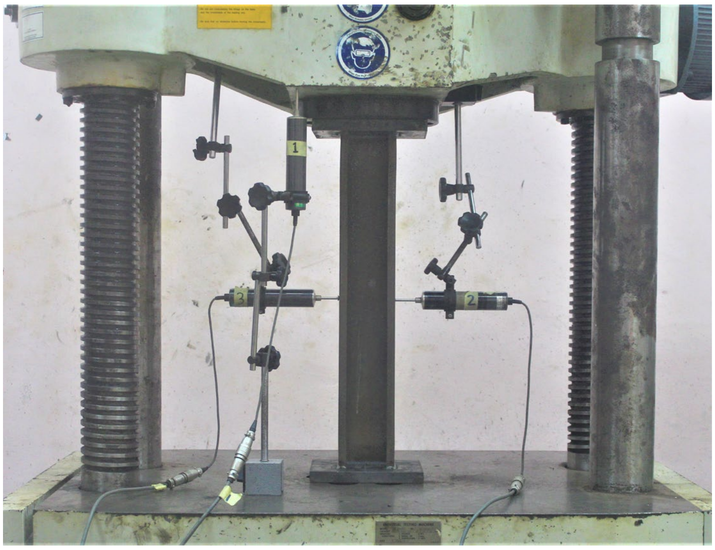

Figure 4. 28: Peak load

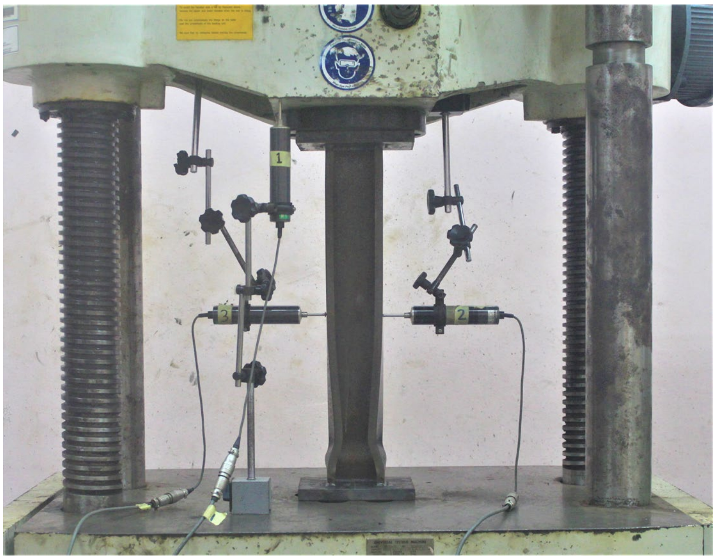

Figure 4. 31: Final post-buckling

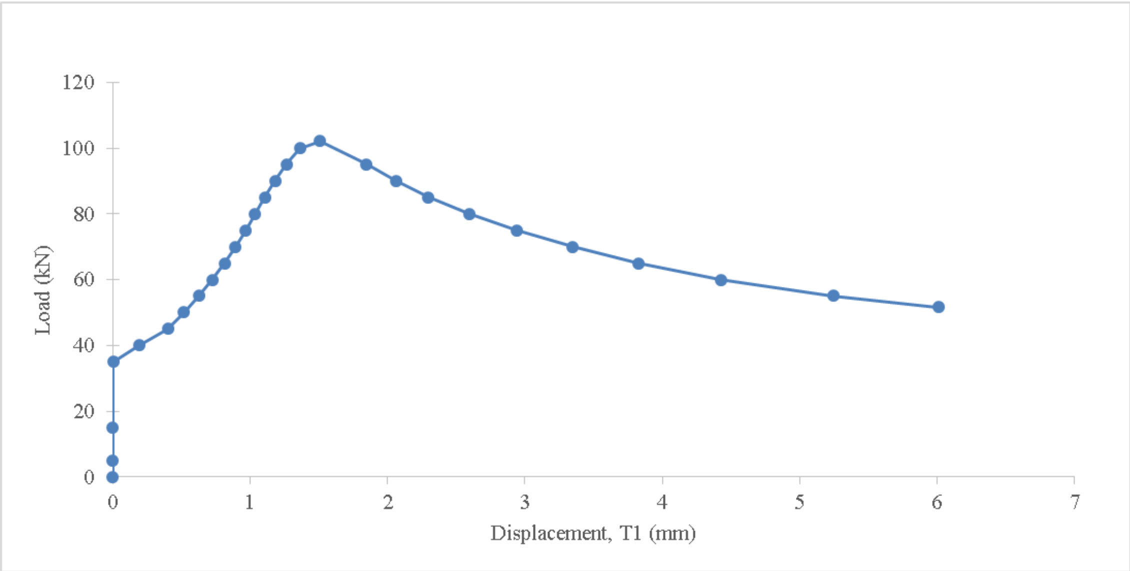

Figure 4. 30: Load vs vertical displacement graph

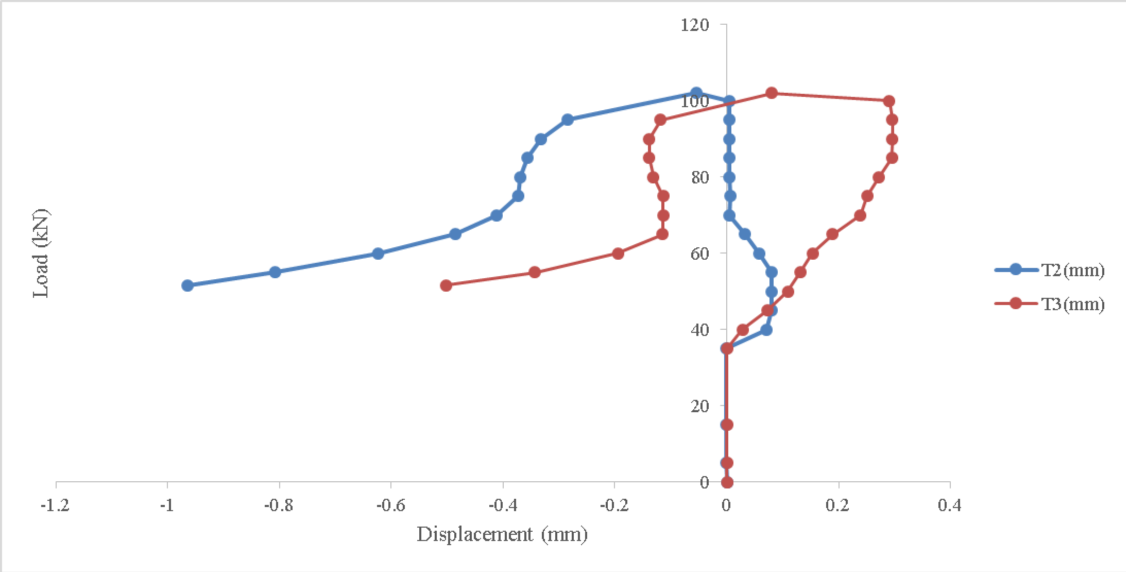

Figure 4. 32: Load vs horizontal displacement graph

4.4.2 Compressed Test on SC-2.0-103-H

At the initial stage where the loading was applied, there is local buckling occur and warping at the middle of the column (Figure 4.33). The specimen failure was at 87 kN due to further local buckling (Figure 4.36). From the overall observation, the warping buckling occurred at the bottom was obviously showed the failure of the specimen (Figure 4.35).

From the load vs vertical displacement graph (Figure 4.38), the ultimate load applied was 87 kN with 1.407 mm displacement. For this specimen, it has a maximum axial load of 87 kN and a maximum displacement of 9.41 mm showed by transducer T2 at the end of the test (Figure 4.37). The mode of failure for this specimen were hardly to be observed by naked eyes because they buckling were very little and the displacement were not even exceed 1 mm as shown in Figure 4.37 before it reached maximum load. Results shows displacement were unique as both transducer T2 and T3 decrease slowly but not exceed -1 mm before it goes to positive right after maximum loading was reached. From the figure specimen shows warping and local at the bottom near the support of the specimen after the end of the experiment.

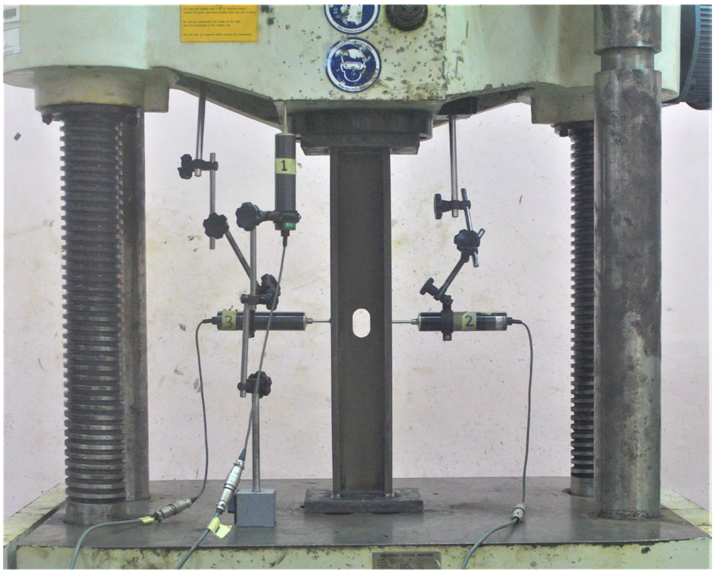

Figure 4. 34: At zero loading

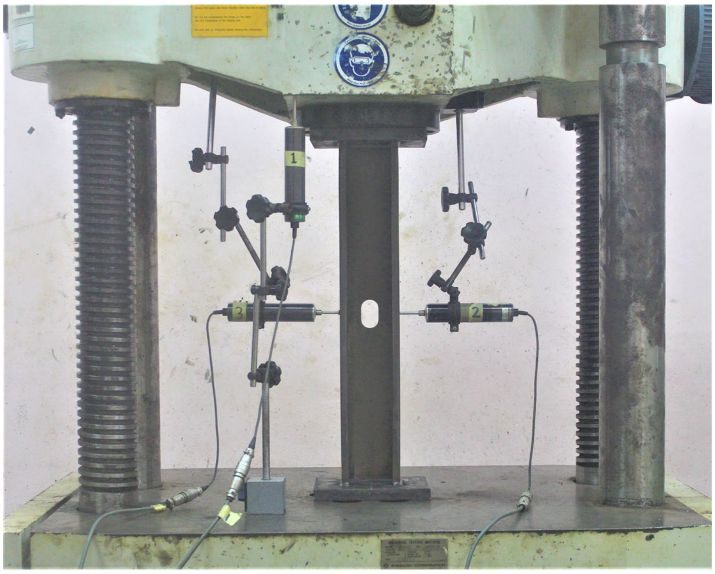

Figure 4. 33: Initial buckling

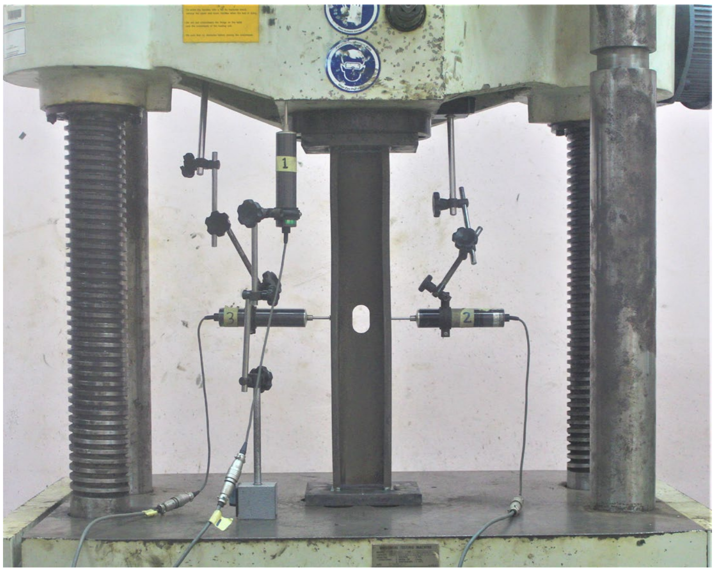

Figure 4. 36: Peak load

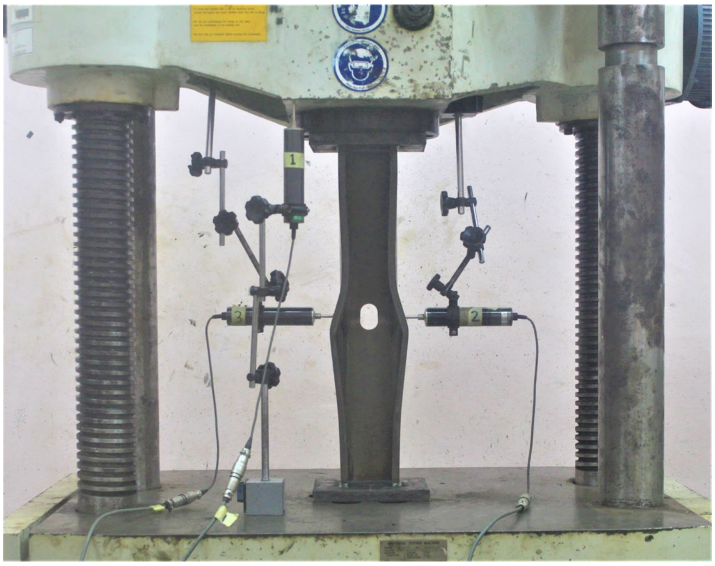

Figure 4. 35: Final post-buckling

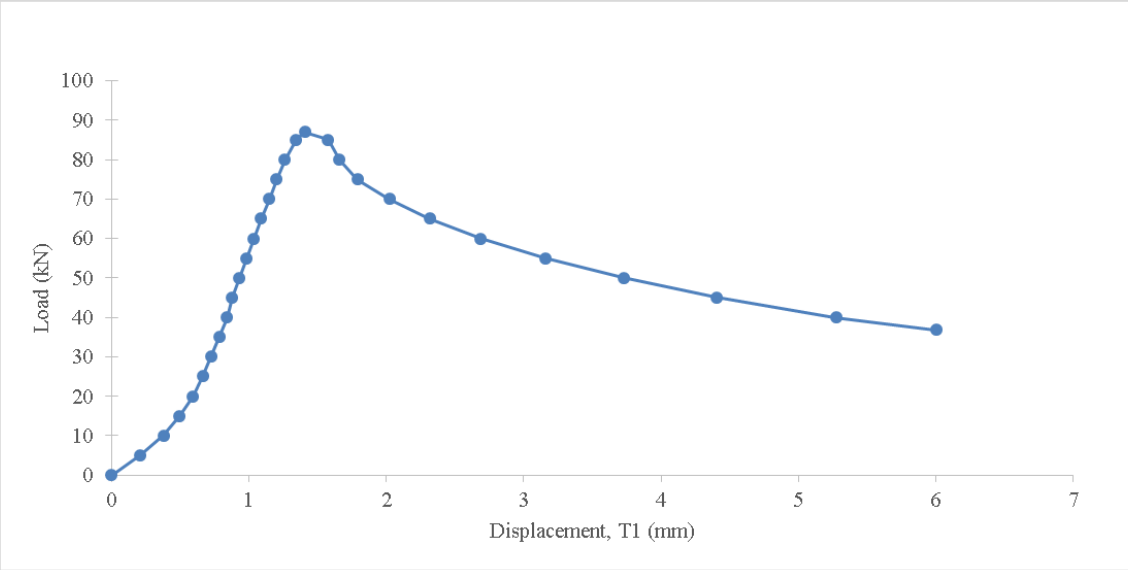

Figure 4. 38: Load vs vertical displacement graph

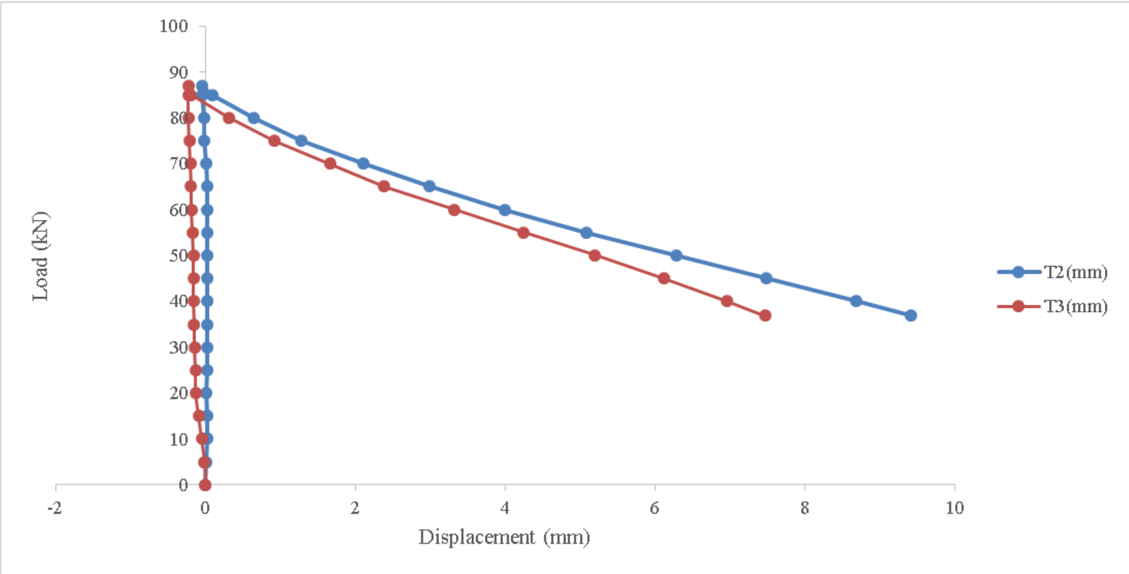

Figure 4. 37: Load vs horizontal displacement graph

4.4.3 Comparison between SC-2.0-103-NH and SC-2.0-103-H

The result of Series 3 experiment were expected as the ultimate strength for SC-2.0-103-H is lower than SC-2.0-103-NH in 17.33% difference. Figure 4.39 showed a better view for the comparison. Both load applied on the specimens were increased in the different rate before SC-2.0-103-H stopped at 87 kN while SC-2.0-103-NH continue to increase until 102.075 kN before dropped gradually toward the end of experiment.

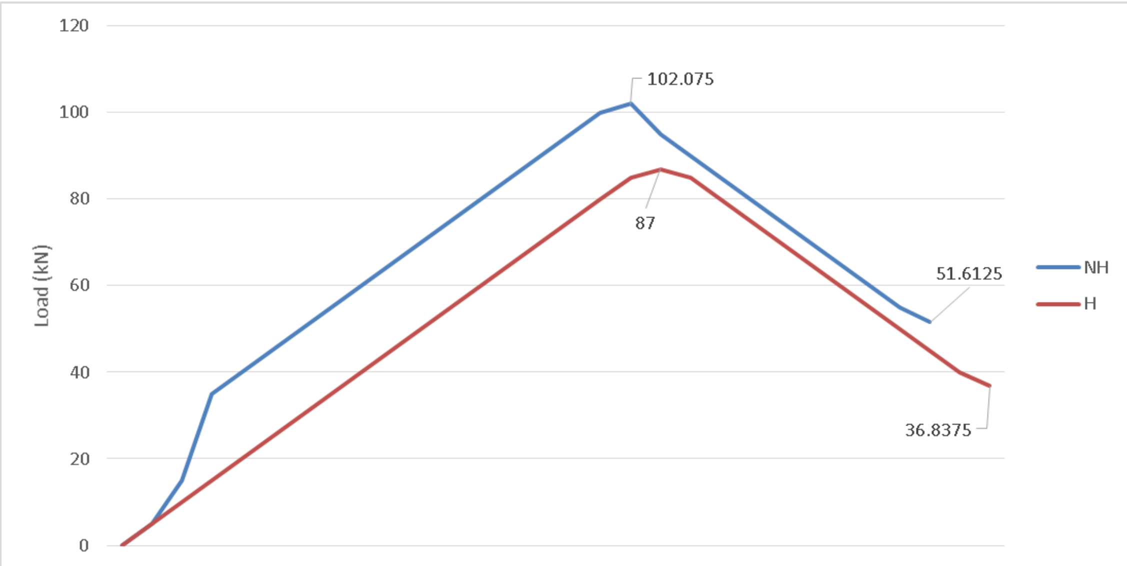

Figure 4. 39: Comparison on axial load applied

4.5 Test of Compression on Series 4 (SC-2.0-203)

4.5.1 Compressed Test on SC-2.0-203-NH

At the initial stage where the loading was applied, there is local buckling occur and warping at the top of the column (Figure 4.42). The specimen failure was at 105.7 kN due to further local buckling and warping at top (Figure 4.41). Toward the end of the testing, distortion and local occurred at the bottom of the column and was obviously showed the failure of the specimen (Figure 4.44).

From the load vs vertical displacement graph (Figure 4.43), the ultimate load applied was 105.7 kN with 1.271 mm displacement. For this specimen, it has a maximum axial load of 105.7 kN and a maximum displacement of 5.548 mm showed by transducer T3 before the end of the test (Figure 4.45). Results shows displacement were unique as both transducer T2 and T3 increase slowly, meaning the column get warped at the middle but it slightly decrease right before the test were ended. This could happen because distortion occurred at the bottom part of the column and it pulling the middle flange to distort as well. From the figure specimen shows distortion and local at the bottom the support of the specimen after the end of the experiment.

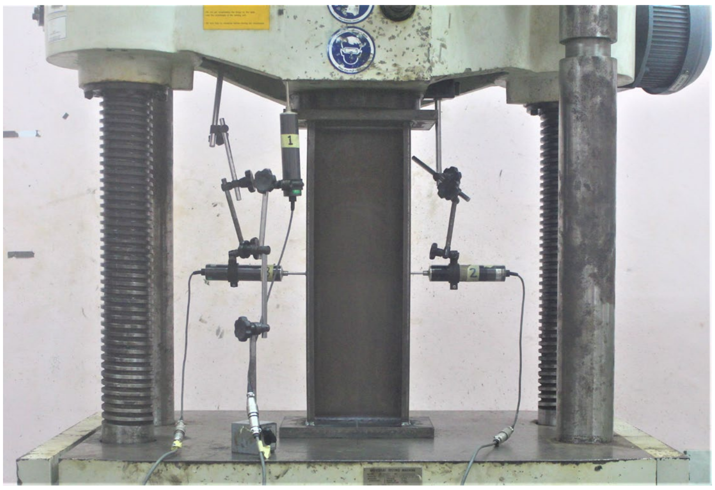

Figure 4. 40: At zero loading

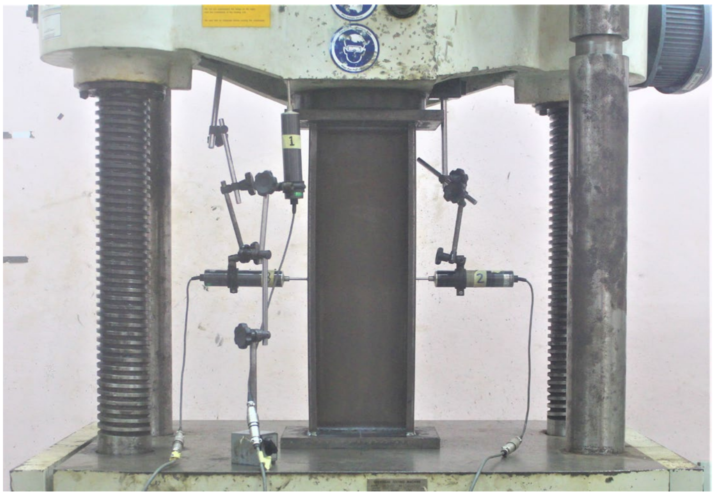

Figure 4. 42: Initial buckling

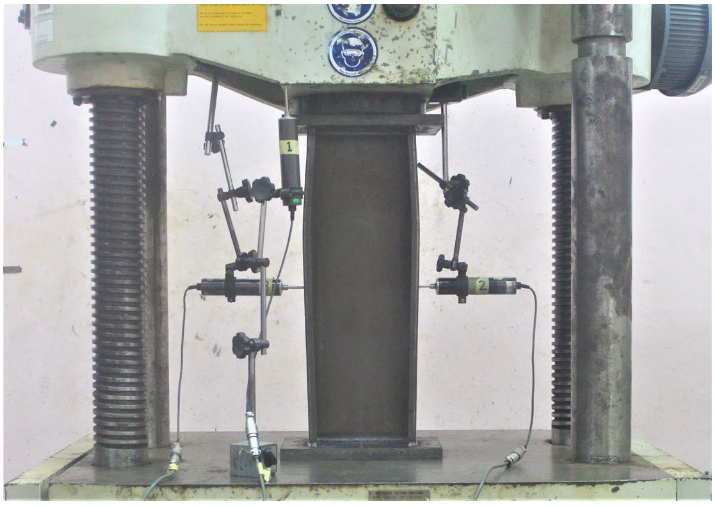

Figure 4. 41: Peak load

Figure 4. 44: Final post-buckling

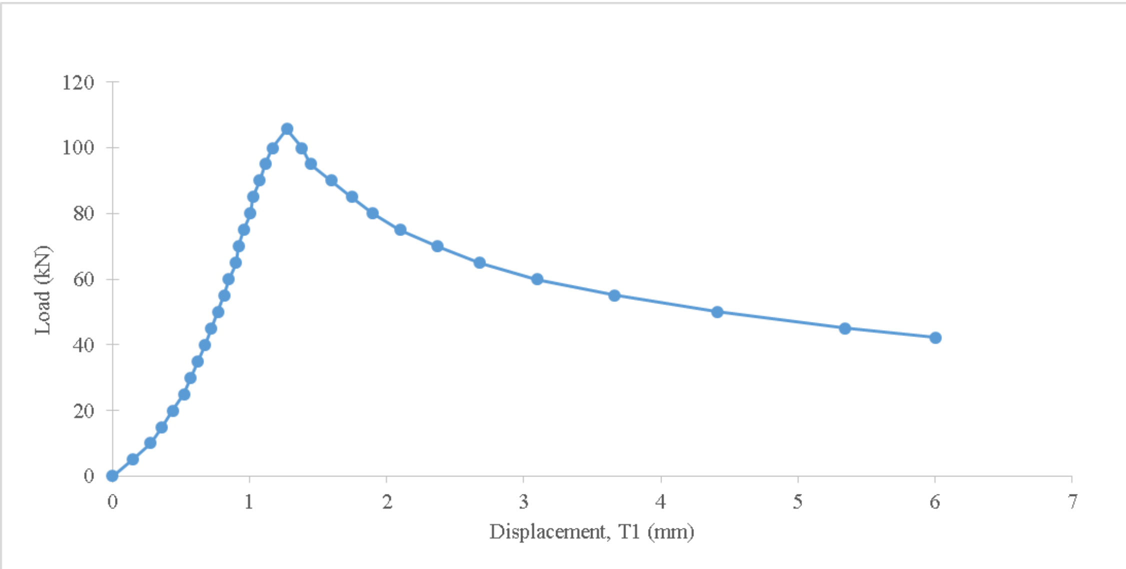

Figure 4. 43: Load vs vertical displacement graph

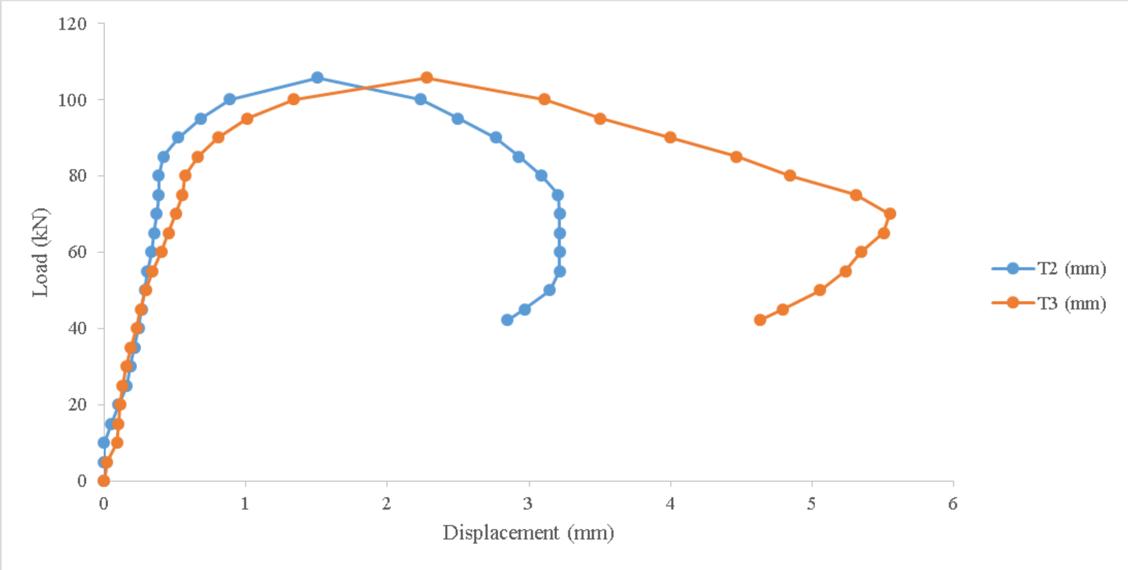

Figure 4. 45: Load vs horizontal displacement graph

4.5.2 Compressed Test on SC-2.0-203-H

At the initial stage where the loading was applied, there is local buckling occur and warping at the top of the column (Figure 4.__). The specimen failure was at 105.0875 kN due to further local buckling and warping at top (Figure 4.__). Toward the end of the testing, distortion and local occurred at the bottom of the column and was obviously showed the failure of the specimen (Figure 4.__).

From the load vs vertical displacement graph (Figure 4.__), the ultimate load applied was 105.0875 kN with 1.025 mm displacement. For this specimen, it has a maximum axial load of 105.0875 kN and a maximum displacement of 8.988 mm showed by transducer T3 right at end of the test (Figure 4.__). Results shows displacement were unique as both transducer T2 and T3 were increase rapidly, before it slowing the pace after the maximum load was reached. From the figure specimen shows warping and local at the middle of the specimen after the end of the experiment.

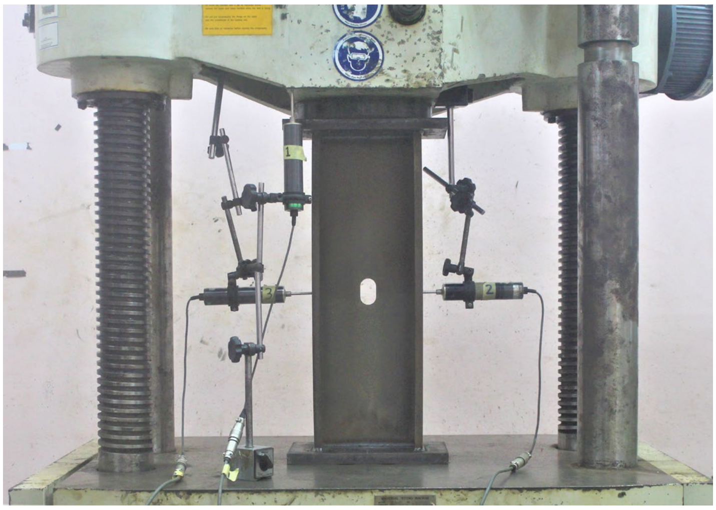

Figure 4. 47: At zero loading

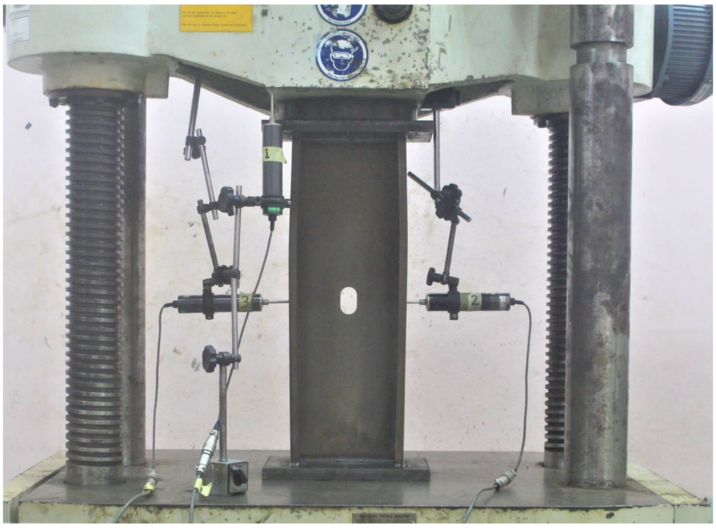

Figure 4. 46: Initial buckling

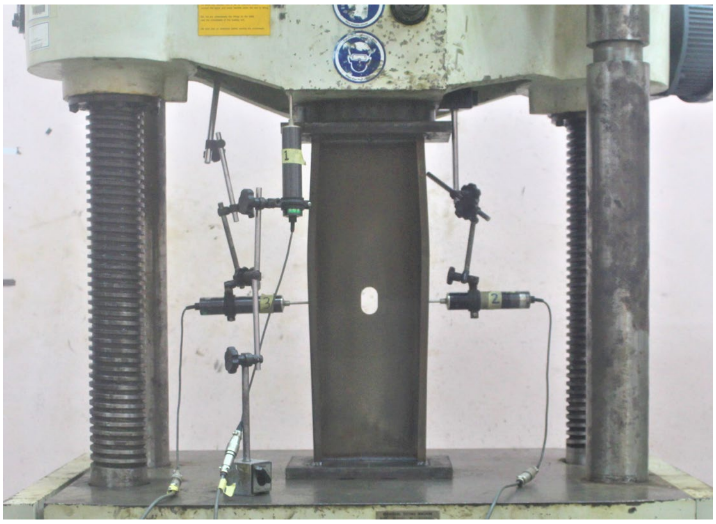

Figure 4. 49: Peak load

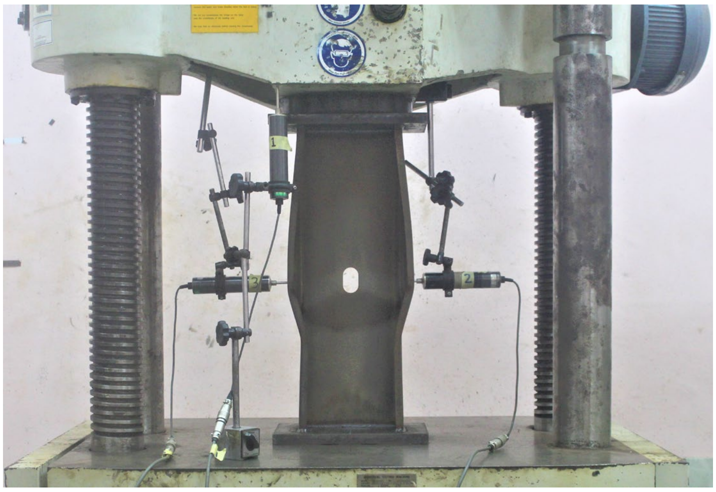

Figure 4. 48: Final post-buckling

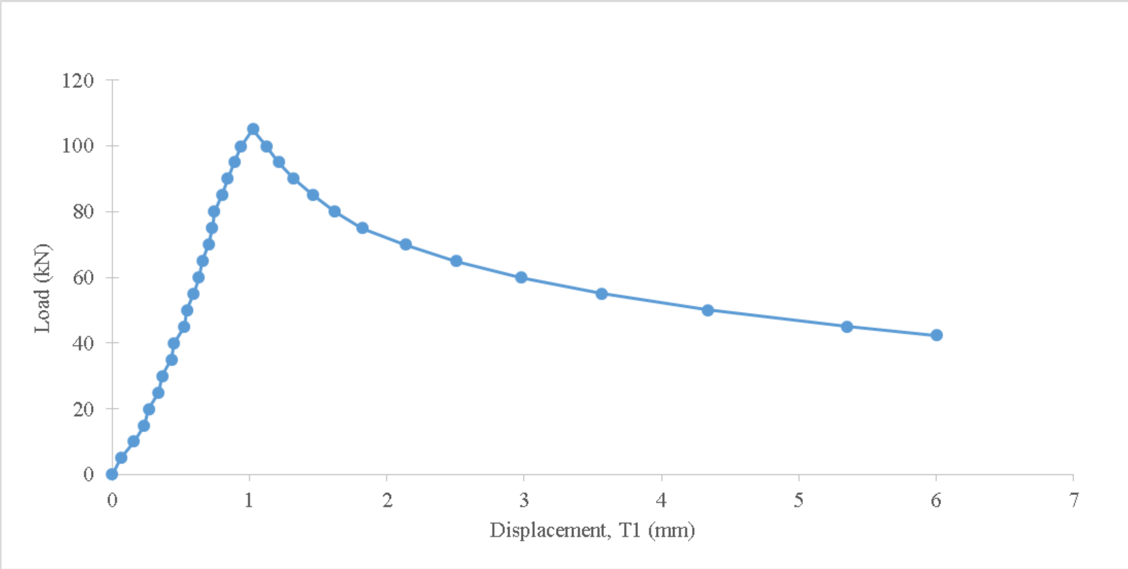

Figure 4. 51: Load vs vertical displacement graph

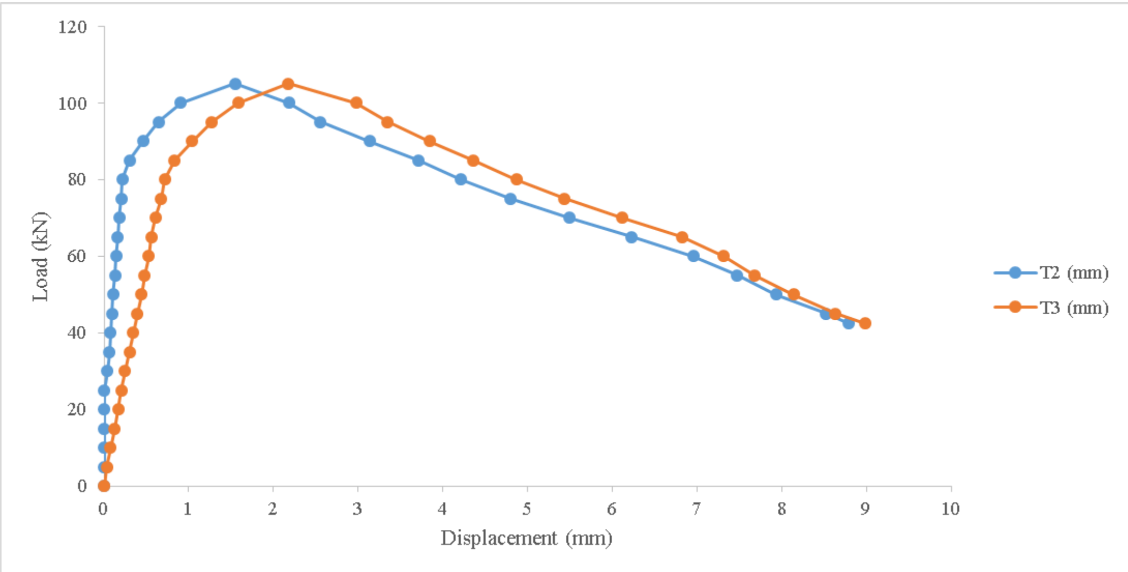

Figure 4. 50: Load vs horizontal displacement graph

4.5.3 Comparison between SC-2.0-203-NH and SC-2.0-203-H

The result of Series 4 experiment were unexpected as the difference of both ultimate strength was not significant and near the same. The difference is only 0.58%, that is equal to 0.6125. Figure 4.52 showed a better view for the comparison. Both load applied on the specimens were increased and decrease in the same rate throughout the experiment.

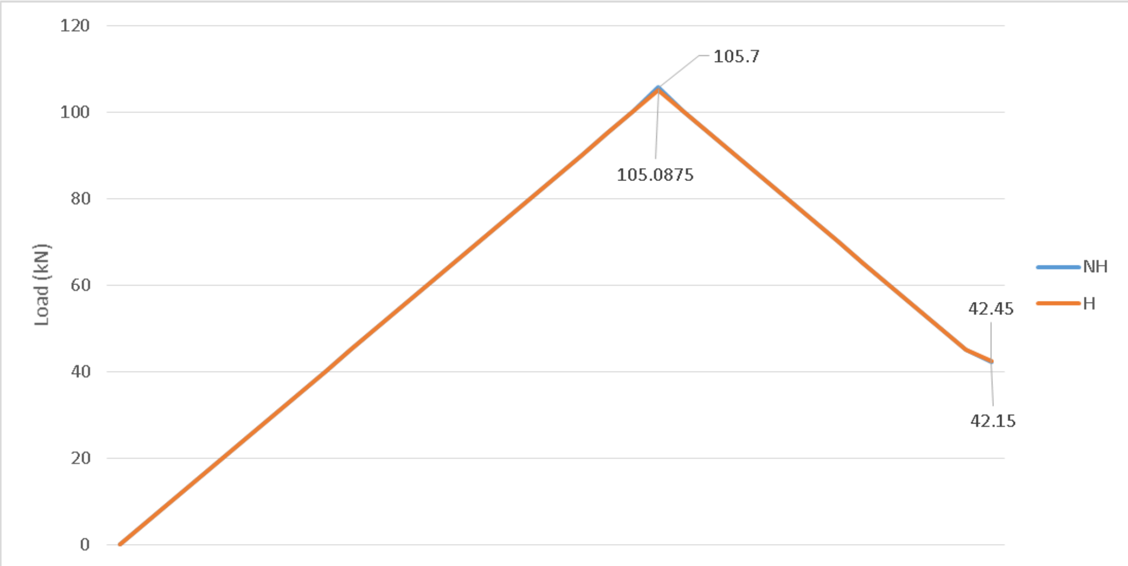

Figure 4. 52: Comparison on axial load applied

CHAPTER 5

CONCLUSION

5.1 Conclusion

From the overall results that obtained, it can be conclude that all of the specimens failed due to distortional buckling, either its flange buckle inward or outward. This is because that if the width to thickness ration increases, local buckling and distortional buckling capacity decreases. From the failure mode, it can be observed that few parameters play a crucial role for a cold-formed steel to fail under this mode. Among the parameters are the size of specimens (depth and thickness) and presence of opening.

For the ultimate load, most of the specimens without an opening has a higher strength compare to specimens with an opening. The presence of hole make the strength of the specimen decrease because it has a relatively low sensitivity of the specimen. In addition, the size of the specimen which is 203 mm have a higher strength than 103 mm specimen. The specimen with 2.0 mm thickness also have a greater strength than 1.2 mm specimens. This is because the bigger the size, the specimens would have a greater second moment of area due to farther distribution of material from axis of cross section. Thus, resulting a higher value of radius of gyration.

Last but not least, there are few important matters to notice which are:

i- Any initial physical changes (buckling)

ii- Transducer are very sensitive equipment and easy to changes the date even with a slight movement on the specimen.

5.2 Recommendation

i- To introduce web & flange stiffener to prevent local buckling & web crushing in thin walled section.

ii- Distortional buckling can be prevented by increasing the web depth. But failure due to local buckling is likely to occur.

iii- Longer lipped will enhance the distortional buckling strength. The highest distortional buckling strength can be achieved when flange width is equal to lipped length.

iv- Specimens should be polish properly before initiating test to get a vivid view on physical changes (buckling) of the specimens.

v- Use finite element analysis to get a better understanding on failure mode.

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