BEAM TEST OF COLD-FORMED STEEL BUILT-UP OPEN SECTION WITH DIFFERENT NUMBER AND POSITION OF PERFORATIONS

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ABSTRACT

A cold-formed steel member include such products as purlins and girts for the construction of metal buildings, studs and joists for light commercial and residential construction, supports for curtain wall systems and also as a formed deck for the construction of floors and roof. Cold-formed steel comes with various type of section based on their function and purpose in construction work. This research will investigate the failure mode regarding the buckling behavior and the ultimate load of built-up cold-formed steel members with circular web holes. Structural members of cold-formed steel usually come with the presence of perforations. Perforation is a hole or opening that is made on the cold-formed steel to ease construction work. A total of 5 specimens with 20 mm holes diameters were tested under four-point bending test. The built-up open sections were assembled by self-tapping screws from either two lipped channels. Each member has nominal thickness of 1.2 mm, beam length of 1600 mm and supported with roller at both end. Reduction of ultimate loading and localized failure due to the presence of holes in the web plates of beams was observed in the tests. The result of this experiment shows that the ultimate load of each sample varies greatly on the number and position of perforation. The result is presented in two sections which are load vs displacement and buckling behavior.

ABSTRAK

Keluli yang terbentuk sejuk termasuk produk-produk seperti purlins dan girts untuk pembinaan bangunan logam, kancing dan gelang untuk pembinaan komersial dan kediaman ringan, sokongan untuk sistem dinding tirai dan juga sebagai dek terbentuk untuk pembinaan lantai dan bumbung. Keluli terbentuk sejuk mempunyai pelbagai jenis seksyen berdasarkan fungsi dan tujuan mereka dalam kerja pembinaan. Penyelidikan ini akan menyiasat mod kegagalan mengenai tingkah laku tenggelam dan beban muktamad keluli terbentuk sejuk yang dibentuk dengan lubang web bulat. Ahli struktur keluli terbentuk sejuk biasanya datang dengan kehadiran bukaan. Pembukaan adalah lubang atau pembukaan yang dibuat pada keluli terbentuk sejuk untuk memudahkan kerja pembinaan. Sejumlah 5 spesimen dengan diameter lubang 20 mm telah diuji di bawah ujian lenturan empat titik. Bahagian terbuka terbina dipasang oleh skru menegak sendiri dari dua saluran lipped. Setiap anggota mempunyai ketebalan nominal 1.2 mm, panjang rasuk 1600 mm dan disokong dengan roller pada kedua-dua hujungnya. Pengurangan pemuatan muktamad dan kegagalan setempat disebabkan oleh kehadiran lubang di plat web balok diperhatikan dalam ujian. Hasil daripada eksperimen ini menunjukkan bahawa beban muktamad setiap sampel sangat berbeza pada bilangan dan kedudukan perforasi. Hasilnya dibentangkan dalam dua bahagian iaitu beban vs anjakan dan tingkah laku.

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LIST OF ABBREVIATIONS

CFS	Cold-Formed Steel
AISI	American Iron and Steel Institute
FE	Finite Element

CHAPTER 1

INTRODUCTION

1.1 Introduction

The use of cold-formed steel members in building construction began in about the 1850s in both the United States and Great Britain. However, such steel members were not widely used in buildings until around 1940 (Steel, 2010). The earlier editions of the specification were based largely on the research sponsored by American Iron and Steel Institute (AISI) at Cornell University under the direction of George Winter since 1939. It has been revised subsequently to reflect the technical developments and the results of continuing research. Since 1946 the use and the development of thin-walled cold-formed steel construction in the United States have been accelerated by the issuance of various editions of the ‘‘Specification for the Design of Cold-Formed Steel Structural Members’’ of the American Iron and Steel Institute (AISI) (Steel, 2010).

Cold-formed steel construction materials differ from other steel construction materials known as hot-rolled steel. The manufacturing of cold-formed steel products occurs at room temperature using rolling or pressing. The strength of elements used for design usually governed by buckling. The construction practices are more similar to timber framing using screws to assemble stud frames. Cold-formed steel is widely used in buildings, automobiles, equipment, home and office furniture, utility poles, storage racks, grain bins, highway products, drainage facilities, and bridges. Its popularity can be attributed to ease of mass production and prefabrication, uniform quality, lightweight designs, economy in transportation and handling, and quick and simple erection or installation (Steel, 2010). These types of sections are cold-formed from steel sheet, strip, plate, or flat bar in roll forming machines, by press brake (machine press) or bending operations (Steel, 2010). The material thicknesses for such thin-walled steel members usually range from 0.373 mm to about 6.35 mm. Steel plates and bars as thick as 25.4 mm can also be cold-formed successfully into structural shapes.

A cold-formed steel member include such products as purlins and girts for the construction of metal buildings, studs and joists for light commercial and residential construction, supports for curtain wall systems and also as a formed deck for the construction of floors and roof (Steel, 2010). These products have enjoyed significant growth in recent years and frequently utilized in some shape in many projects today. Attributes such as strength, versatility, non-combustibility, and ease of production, make them cost effective in many applications. Cold formed steel has been used as the primary structure for flexural and compression member due to varieties of advantages such as high strength to weight ratio, high corrosion resistance, and ease of fabrication. The criteria need to be considered in improving the structural strength is the fabrication method. Fast and easy fabrication can produce an efficient structure. Built-up of normal cold-formed steel into new member with higher strength can be produced efficiently by attaching the normal steel using self-drilling screw (Muftah, Mohd Sani, Mohammad, & Tahir, 2014).

Cold-formed steel built-up cross-sections are commonly used in the building construction industry. Nowadays, several cross-sections can be built using standard single sections (C, U, Σ, etc.) available, including open built-up sections. Built-up cross-sections have several advantages over single sections. A built-up cross-section can span more distance, have a higher load bearing capacity and higher torsional stiffness. Moreover, the use of built-up cross-sections can be a major economic advantage since the whole manufacture process remains the same (Craveiro, Rodrigues, & Laím, 2016). There are many type of cold-formed steel shapes that used in construction. Figure 1.1 shows the various shape of cold-formed steel sections that have in building construction such as the usual shapes are channels of C-sections, Z-sections, angle and lipped channel. Moreover, C-sections and Z-sections are typically use in cold formed steel joists as shown in Figure 1.2.

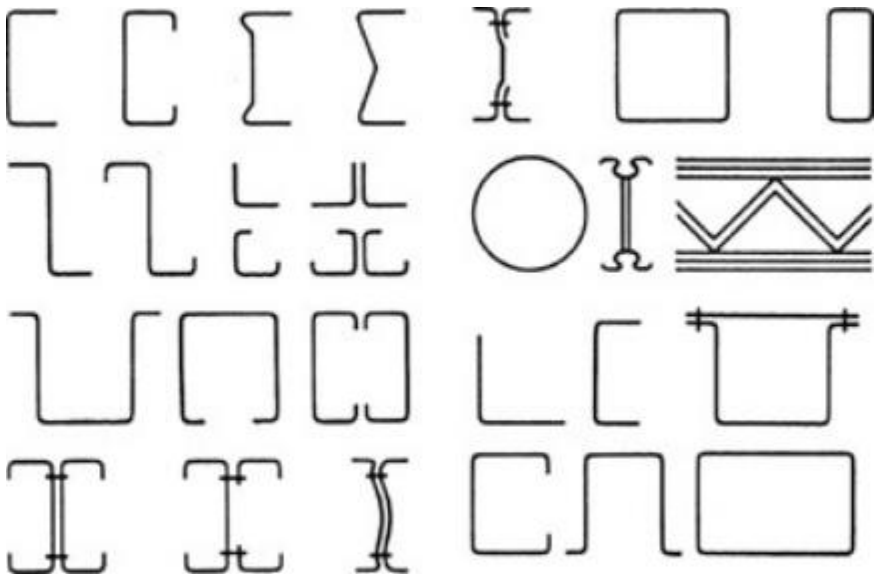

Figure 1.1 Various shape of cold-formed steel section

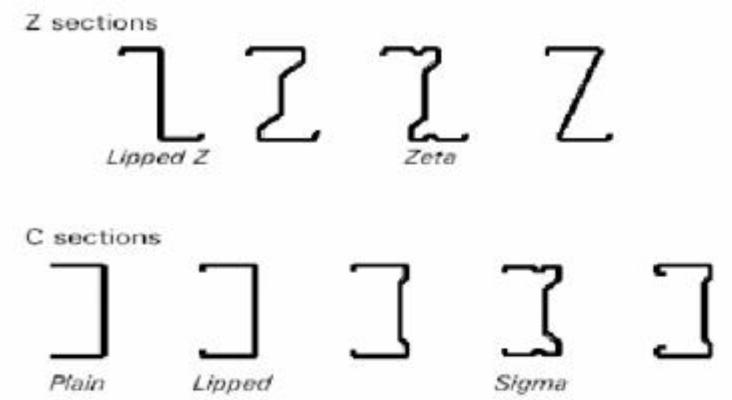

Figure 1.2 Common shapes for cold formed steel (C and Z section)

Cold-formed steel (CFS) are commonly used for floor joists and other structural members. However, these section beams are prone to fail by lateral torsional buckling due to the location of its shear center and centroid of the cross section. One way to overcome the problem is to connect two individual sections together to form double-symmetric built-up open section (Wang & Young, 2015). Besides, cold-formed steel also used as non-structural member for wall paneling, window frames, services and doorframes. As structural members, the usage includes beams, columns, truss members and roof sheeting. Figure 1.3 shows the model of beam formed with cold-formed steel section.

Figure 1.3 Model of cold-formed steel beam

1.2 Problem Statement

In building construction, there are primarily two types of structural steel work are the hot-rolled 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 or strip material. The manufacturing process involves forming the material by either press-braking or cold roll-forming to achieve the desired shape. Examples of the cold-formed steel are corrugated steel roof and floor decks, steel wall panels, storage racks and steel wall studs.

Holes or perforation can be found in most cold-formed steel structural components. For example, in low and midrise construction, evenly- spaced holes are place in the webs of cold-formed steel columns and beams, allowing electrical, plumbing, and heating services to pass through walls and ceilings (Moen & Schafer, 2009). It has agreed by (Kulatunga, Macdonald, Rhodes, & Harrison, 2014) that describe that the function of perforations is to facilitate various services in building. The strength and stability of the section will affected by the existence of the perforation, so some practical design need to be done due to variety of arrangement of opening. Cold-formed steel sections with the perforation may also exhibit local, distortional, and global buckling modes when they are subjected to bending loads (Yuan, Yu, & Li, 2017). However, because of the wide variety in the size and configuration of perforations, it is rather difficult to directly calculate the critical buckling stresses of perforated cold-formed steel section (Moen & Schafer, 2009). Existence of the perforation also will reduce the area of the cold-formed steel and it might risk because it can lead to the failure of the building. The strength and the buckling of the section can be examined in built-up open section.

The most common shape of holes is circular, although various shapes can be used for web opening in floor joists. Cold-formed steel joists of open sections such as C-sections and Z-sections can be used (Wang & Young, 2017). Cold-formed steel with openings have their characteristics and its advantages to the structure itself. The reducing of area of cold-formed section will reduced the strength of cold-formed steel without opening. Generally, the grades of carbon steel and high strength low alloy steel used for cold-formed steel products are characterized by two main properties that are the yield point and the tensile strength. Other important properties are ductility, hardness and weld ability.

The yield point of the steels commonly used for cold forming ranges from 230 to 380 MPa and may be higher. Tensile strength and ductility are important because of the way they relate to formability, and because of the local deformation demands of bolted and other types of connection. In members that include bolted connection or that, because of special design, may be subject to high stress concentrations, the tensile strength often must be taken into account.

1.3 Objective of Study

The main aim of this research is to study the cold-formed steel built-up open section with various web perforations under beam test. The objective are :

1. To determine the ultimate loading of built-up open section.

2. To investigate the flexural behavior of different number and position of perforations of built-up open section.

1.4 Scope of Study

In this study, a beam test of cold-formed steel of built up open section with web perforation were be conducted. There are five cases of testing which is the number and location of perforations will differentiate between the cases. It is to predict the load of cold-formed steel with perforation with specific perforation location, number, spacing and sizes. The section of cold-formed steel that has being tested is built-up open section with the thickness of 1.2 mm that in range of usually cold-formed steel sections which is as an important contributor to sustainable structures in the developed nations (Youns, Hassaneen, Badr, & Salem, 2016).

Overall of 10 single beam of cold-formed steel will be used. Two of beams were fastened together with self tapping screws to form five specimen of built-up open section beam. The numbers and position of perforation at the cold-formed steel members will be varies and the shape of perforation is in circular shape. Through the beam test of cold-formed steel, we can see the different type of buckling occurred due to the loading applied. It will show the behavior of steel whether failure happen or not. Besides, it will show what will happen to the steel, which is its strength, stability, also the buckling happen.

1.5 Significant of Study

Through the testing applied, the ultimate load of built-up open section can be determined. The effects of cold-formed steel at the different number and position of perforations also can be analyzed through the experiment. We can know the strength of beam when have an opening and can be compared with the beam that not have opening and it is depend on the numbers and position of the perforations. It also can see the flexural behavior of steel and mode of failure occurred.

Moreover, this testing will show a comparison with the theoretical values. Others than that, the result will be applied to the design requirements. In addition, we analyze the suitable requirement of the strength for each cold-formed steel beam.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Cold- formed steel members are extensively used in the building construction industry, especially in residential, commercial and industrial buildings. In recent times, the use of cold- formed high strength steel members has rapidly increased (Prakash, Samuel, Joanna, & Sakaria, 2014). Cold-formed steel is the common term for products made by rolling or pressing steel into semi-finished or finished goods at relatively low temperatures (cold working). Cold-formed steel goods are created by the working of steel billet, bar, or sheet using stamping, rolling including roll forming, or presses to deform it into a usable product. Cold-worked steel products, such as cold-rolled steel bar stock and sheet, are commonly used in all areas of manufacturing of durable goods, such as appliances or automobiles, but the phrase cold-formed steel is most prevalently used to describe construction materials.

In the construction industry both structural and non-structural elements are created from thin gauges of sheet steel. These building materials encompass columns, beams, joists, studs, floor decking, built-up sections and other components. The use of cold-formed steel members in the construction industry is motivated by the high structural efficiency of these profiles, namely by having an high strength/weight ratio, the wide range of shapes (cross-section shapes) and the low-cost of production and transportation (Eduardo & Rua, 2010).

Cold-formed steel sections can be widely used in many sectors of construction, including mezzanine floors, industrial buildings, commercial buildings and hotels and are gaining greater acceptance in the residential sector. However, the application of light steel framing has not been widely developed in Malaysia, due to the lack of research study on the local practice for such system. But, the popularity of cold-formed steel has increased in recent years due to their wide range of application, economy, ease of fabrication and high strength to weight ratios. Opening for the beam of cold-formed steel is being made in the market nowadays and it will affect the strength of steel itself. So, this research will know the existing of opening will affect the strength of cold-formed steel of built up open section. The shape of built-up open C-section is shown in Figure 2.1.

Figure 2.1 Shapes of built-up open C-section

2.2 Characteristics and Design Considerations of Cold-formed Steel Members

As compared with thicker hot rolled shapes, cold formed light members can be manufactured for relatively light loads or short spans. According to (Yu, 2000), unusual sectional configurations can be produced economically by cold forming operations, and consequently favorable strength to weight ratios can be obtained. Load carrying panel and decks can provide useful surface for floor, roof and wall construction, and in other cases they can also provide enclosed cells for electrical and other conduits. Load carrying panels and decks not only withstand loads normal to their surfaces, but they can also act as shear diaphragms to resist force in their own panels if they are adequately interconnected to each other and to supporting members.

2.2.1 Methods of Forming

In general, two manufacturing methods are used to produce various shapes of cold-formed steel sections. It is cold-roll forming and press brake operations.

2.2.1.1 Cold Roll-Forming

Roll forming is the method which enables the large scale production of cold-formed structural and non-structural steel profiles, allowing its competitiveness against other constructive solutions. The metal strip (sheet metal) is introduced through a succession of pairs of rollers that will deform it progressively, through several stages, before achieving the final shape. The inclusion of holes and slots can be performed prior or following the rolling process. The sections can be trimmed to the desired length before or after this process, being the dimensions only limited by transport and storage restrictions (Gomes, Nuno, Rosa, & Silvestre, 2012).

The cold roll-forming process consists of feeding a continuous steel strip through a series of opposing rolls to deform the steel plastically to form the desired shape. Figure 2.2 show a machine that used for cold roll-forming. A simple section may be produced by as few as six pairs of rolls but a complex section may require as many as 15 sets of rolls (Yu, 2000). This method usually used to produce cold-formed steel sections where a large quantity of a given shape is required.

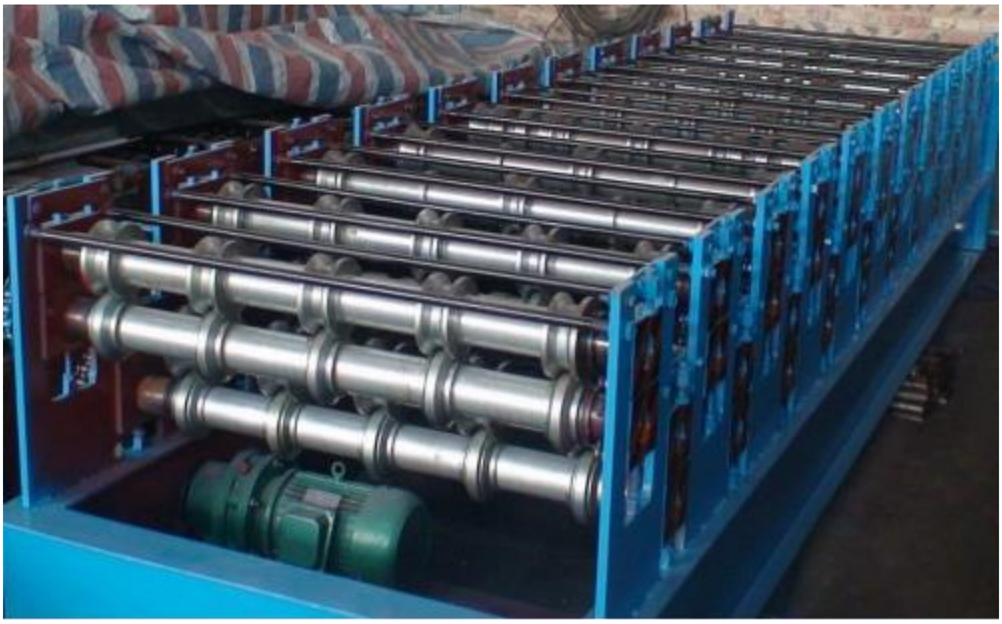

Figure 2.2 Cold roll-forming machines
Source: Yu (2000)

However, a significant limitation of this method is the time taken to change rolls for different size sections. Consequently, adjustable rolls are often used which allow a rapid change to a different section width or depth. From a structural point of view, roll-forming may produce a different set of residual stresses in the section and hence the section strength may be different in case where buckling and yielding interact. In cold forming, metal is formed at high speed and high pressure into tool steel or carbide dies. The cold working of the metal increases the hardness, yield, and tensile strengths.

2.2.1.2 Press Braking

In these processes, short lengths of strip are fed into the brake and bent or pressed round shaped dies to form the final shape. Usually each bend is formed separately and the complexity of shape is limited to that into which the die can fit (Structures & Ii, 2008).

The equipment in the press brake operation essentially consists of a moving top beam and a stationary bottom bed that produce one complete fold at a time along the full length of the section. This method is normally used for low volume production where a variety of shapes are required and the roll-forming tooling costs cannot be justified. However, this method has a limitation that it is difficult to produce continuous lengths exceeding approximately 5 metres.

2.2.2 Advantages of Cold-formed Steel

Cold-formed steel has advantages of attractive appearance, fast construction, low maintenance, easy extension, lower long-term cost, non-shrinking and non-creeping at ambient temperatures, no requirement of formwork, termite-proof and rot proof nature , uniform quality, non combustibility (Kubde & Sangle, 2018). It also agreed by (Steel, 2010) that say there are many advantages of cold-formed steel that includes:

1. Lightweight - Cold-formed steel components weigh approximately 35 % to 50 % less than their wood counterparts, which mean that they are easy to handle during construction and transportation.

2. High-strength and stiffness – As a result of the cold-forming process, cold-formed steel possesses one of the highest strength-to-weight ratios of any building material. This high strength and stiffness result in more design options, wider spans and better material usage.

3. Fast and easy erection and installation – Building components made of cold-formed steel can be fabricated with high accuracy in a plant and then assembled on job sites, which greatly increases erection efficiency and ensures construction quality.

4. Dimensionally stable material - Cold-formed steel does not expand or contract with moisture content. In addition, it does not split or warp as time goes by. Therefore, it is dimensionally stable. Cracked gypsum sheathed walls, nail head popping and other common problems with wood- framed structures can be virtually eliminated in buildings with cold-formed steel stud walls.

5. No formwork needed – The use of cold-formed steel decks eliminates the formwork for pouring concrete floor. In addition, composite action between the steel deck and con- crete increases floor strength and stiffness.

6. Durable material - Cold-formed steel is durable because it is resistant to termites and rotting. In addition, galvanized cold-formed steel products provide long-term resistance to corrosion.

7. Economy in transportation and handling - Lightweight cold- formed members or panels are easy to handle and trans- port. In addition, they can be nested and bundled, reducing the required shipping and storage space.

8. Non-combustible material - Steel is a non-combustible material and will not contribute fuel to the spread of a fire. This results in better fire resistance and lower insurance premiums.

9. Recyclable nature - Steel is North America's No. 1 recycled construction material, with a minimum 25 % recycled con- tent. Steel products used in construction are infinitely recyclable, with no degradation in structural properties. It can be recycled and reused. Steel-framed housing dramatically reduces the amount of trees consumed for residential construction, thus conserving one of nature's most precious resources.

10. Energy efficiency – A variety of color options for metal roofs and panels provides consumers with many choices to select products that save energy. For low-heating degree day climates (such as Miami), high-emissive white or light painted GalvalumeTM roofs display solar reflectance of at least 65 % and thermal emittance of 80 percent. This results in reducing air conditioning costs and the smog and pollution that are created by the production of that energy. For high-heating degree-day climates, on the other hand, heat gain can be obtained by using low-emissive unpainted GalvalumeTM roof and wall products, which reduce the load on the building's heating system and save energy.

2.3 Buckling Behavior of Cold-formed Steel

The major structural advantage of thin-walled structural members is the thinness of individual elements which leads to an extremely light-weight construction. However, the advantages of thin-walled members are often limited due to the occurrence of failure modes which sometimes are difficult to predict. Thin-walled steel structures are highly efficient in their use of material, but they are particularly sensitive to failure through various buckling modes (Kulatunga & Macdonald, 2013).

One of the biggest difficulties with cold-formed steel design is the prevention of member buckling. Because of the low thickness to width ratio, it is likely that the members will buckle at stresses that are lower than the yield stress when compressive, bearing, and shear bending forces are applied. Therefore, buckling is a major design consideration for all cold-formed steel, which is unlike the behavior of hot-rolled steel where steel yielding is the leading design consideration (Kang, Biggs, & Ramseyer, 2013).

Cold-formed steel members under high levels of compression may easily exhibit local (wall transverse bending only), distortional (both wall transverse bending and cross-section distortion) and global (lateral torsional) buckling (Laím & Rodrigues, 2016). The type of buckling of cold-formed is shown in Figure 2.3. Distortional and local buckling of a cold-formed steel member with holes is determined with the semi-analytical finite strip method, considering appropriate modifications to the element thickness and choice of buckling half-wavelength.

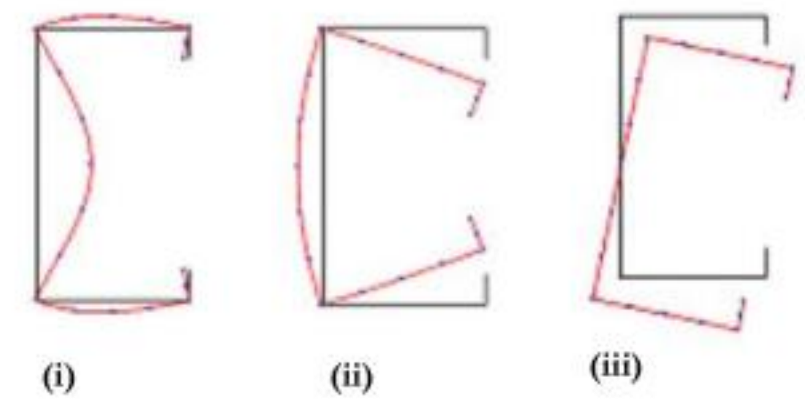

Figure 2.3 Cold roll-forming machines (Yu, 2000)

For this case, the identified buckling modes are:

i. Local Mode

ii. Distortional Mode

iii. Flexural-torsional Mode

2.3.1 Local Buckling

Local buckling is an extremely important facet of cold formed steel sections on account of the fact that the very thin elements used will invariably buckle before yielding. The buckles will form at the lower load with thinner of the plate. Individual elements forming cold-formed steel members are usually thin with respect to their width. Therefore, they are likely to buckle at a lower stress than yield point when they are subjected to compression, bending, shear or bearing forces. However, unlike one-dimensional structural elements, stiffened compression elements will not collapse when the buckling stress is reached, but they often continue to carry increasing loads by means of redistribution of stresses. The ability of these locally buckled elements to carry further load, known as post buckling strength, is allowed in the design to achieve an economic solution. various buckling modes (Kulatunga & Macdonald, 2013).

Local buckling involves significant distortion of the cross-section, but this distortion involves only rotation, not translation, at the fold lines of the member. The mode shapes for members with edge stiffened flanges such as those of the lipped cee or zee provide a direct comparison between the difference between local buckling and distortional buckling. Note the behavior at the flange/lip junction for local buckling only rotation occurs, for distortional buckling translation occurs (Behaviors, 2004).

In this buckling mode, the longitudinal axis of the member remains undeformed. The cross-section deformation is due to the bending of the member's inner walls. The outer walls present essentially rigid body displacements. The local buckling of the member depends on the most- likely to buckle of its walls. In simplified terms, local buckling of thin-walled members can be taken as the buckling of a plate whose edges (lines of intersection of adjoining plates of the member) are elastically restrained (Eduardo & Rua, 2010).

2.3.2 Flexural Torsional Buckling

Many of the steel shapes produced by cold-forming are monosymmetric open sections with their shear centre eccentric from their centroid as illustrated in Figure 2.4. The eccentricity of loads from the shear centre axis will generally produce considerable torsional deformation in the thin-walled beams as a result of flexural torsional buckling. The torsional rigidity is proportional to the material thickness, so that the cold-formed steel sections consisting of thin elements are relatively weak against torsion. Hence torsional stiffness of cold-formed steel members is an important criterion in the design of cold- formed steel sections to achieve an economic solution.

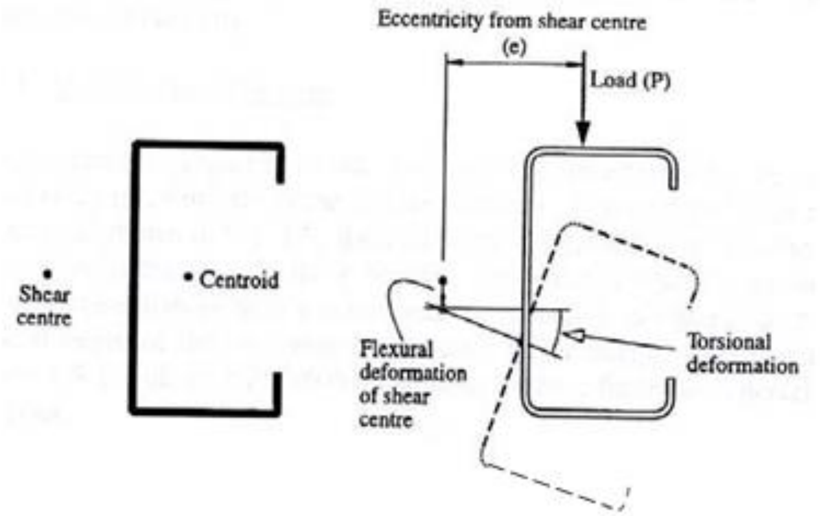

Figure 2.4 Torsional Deformations in Eccentrically Loaded Channel Beam

2.3.3 Distortional Buckling

The study of distortional buckling is still relatively recent. The earliest studies, based on analytical models were the basis to the first design codes that used distortional buckling considerations on the design of thin-walled steel structures. Distortional buckling is a mode characterized by the rotation of the member's flange at the flange/web junction, in members with edge stiffeners. Distortional buckling is associated with the presence of stiffeners. A channel member (cross-section without stiffeners) shows, in general, only one buckling mode: local (plate) mode. The presence of edge stiffeners improves the "performance" of the structural element, but leads to the occurrence of this second mode of instability (Eduardo & Rua, 2010).

Among various buckling modes, distortional buckling is a buckling mode that has recently been investigated. It is a buckling of the compression flange acting as a group of plates rather than as individual plates. The distortional buckling was less understood than the other forms of instability, and was deemed more pertinent to thinner sections of high strength steel. Distortional buckling was addressed within the code for the first time in the 2001 edition of American Iron and Steel Institute (AISI) Specification, and has not been updated until 2007. The importance of distortional buckling should not be underestimated as it is just as likely to occur as local buckling (Kang et al., 2013).

Laterally braced cold-formed steel beams generally fail due to local or distortional buckling. When the compression flange is not restrained by attachment to sheathing or paneling, such as in negative bending of continuous members such as joist and purlin, members are prone to distortional failures. However, distortional buckling remains a largely unaddressed problem in the main body of the North American Specification (AISI-S100-07, 2007). Only a limited amount of experimental data on unrestricted distortional buckling in bending is available, therefore a new series of distortional buckling tests was completed. The test details are selected specifically to insure that distortional buckling is free to form, but lateral buckling is restricted. Figure 2.5 show the distortional buckling of a channel section.

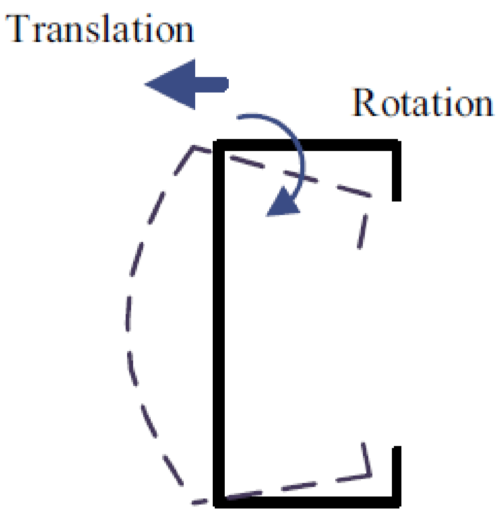

Figure 2.5 Distortional buckling of a channel section

2.4 Material and Mechanical Properties

The strength of cold-formed steel can be explained further through it material and mechanical properties. In a structural point of view, the most important properties of steel should be described in its yield point and strength, tensile strength, stress-strain relationship, modulus of elasticity and ductility.

The mechanical properties (yield point, tensile strength, and ductility) of this kind of steel sections mainly depend on the manufacture process which is known as cold working method. This method is used for strengthening of metal by plastic deformation, also known as strain hardening method (when the metal is strained beyond the yield point). This is because the cold-forming operation increases the yield point and tensile strength and at the same time decreases the ductility (Reza & Selvan, 2016).

2.4.1 Yield Point, Tensile Strength and Stress-Strain Curve

The strength of cold-formed steel structure majorly depends on the yield point or yield strength of the steel. But, there is exception on connections and cases where the elastic local buckling or overall local buckling is critical.

Generally, there are two types of stress-strain curve. The first curve as shown in Figure 2.6 is the sharp-yielding while on Figure 2.7, the gradual-yielding type. Hot-rolled steel usually experience sharp yielding where the yield stress is defined by level at which the stress-strain curve becomes horizontal. On the other hand, cold-formed steel always shows gradual yielding. In gradual-yielding, the stress-strain curve is rounded at the knee. The yield stress will then be determined by using either offset method or stress-under load method.

Tensile strength of cold-formed steel has a minor direct relationship to the design of member. The load carrying-capacities of cold-formed steel flexural and compression members are made limited by the yield stress or buckling stresses that are less than the yield stress of steel, especially for those compression elements that have a relatively large flat-width ration and compression members having relatively large slenderness ratio. However, there are exceptions on tension members and connections. This is due to the strength that depends on yield stress and tensile strength of the material. On this reason, there is special design considerations of ultimate strength includes by the North American Specification in the design of tension members and connection. These ensure that the adequate safety is provided for the ultimate strength of tension member and connection.

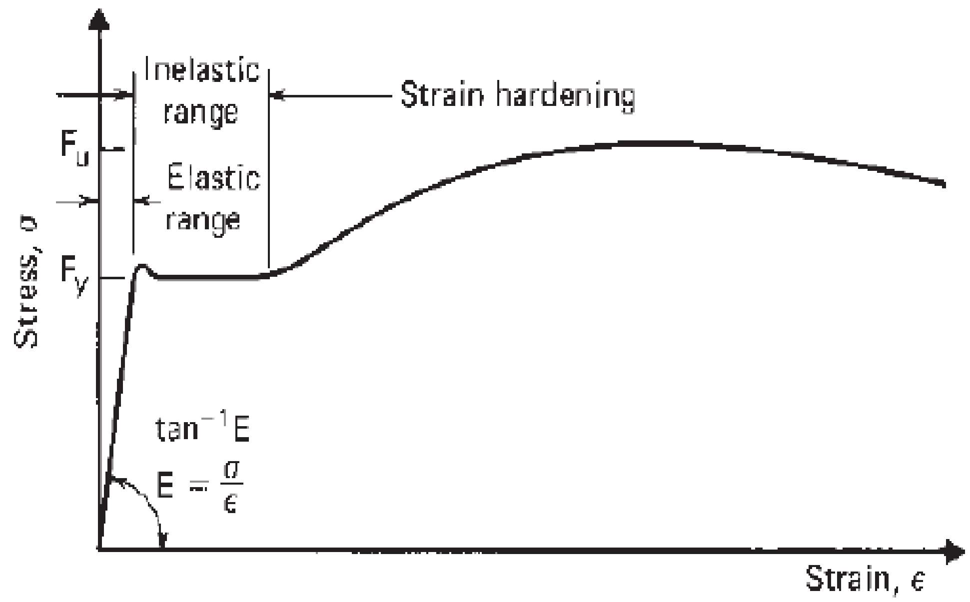

Figure 2.6 Sharp yielding

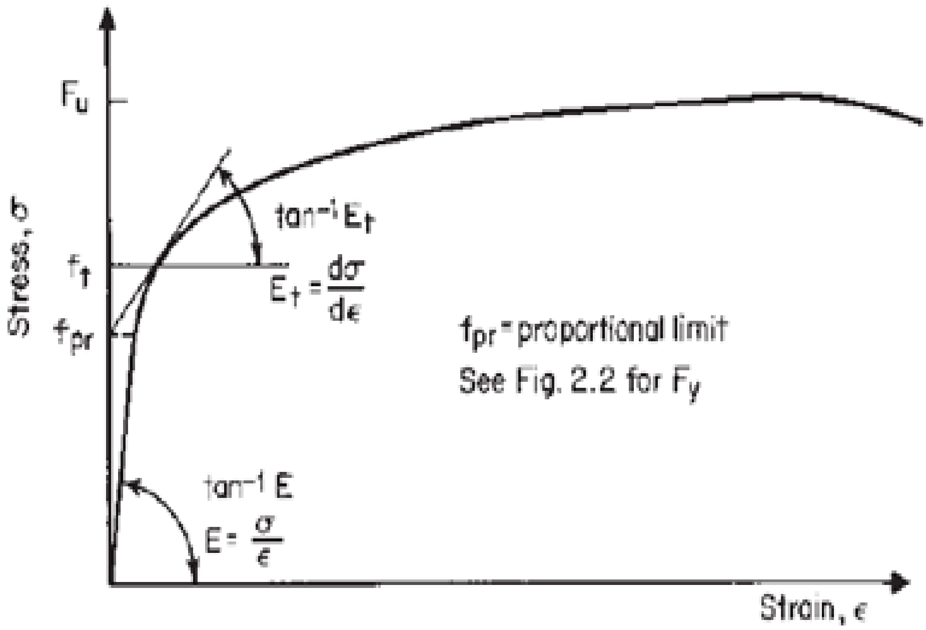

Figure 2.7 Gradual yielding

2.4.2 Increment of Strength from Forming of Cold-Formed Steel

Cold-formed steel originally made up of tiny sheet or strip that are bent or fold in ambient temperature. The mechanical properties of cold-formed steel sections are different before the cold forming is done. The cold forming operations increase the yield stress and tensile strength of the steel while simultaneously decrease the ductility of the cold-formed steel. The increase of tensile yield stress is smaller than the increase of tensile strength which results in the reduction in the spread between yield stress and tensile strength.

After the cold forming is done, the material in the corners of section has a higher degree than the material of flat elements. Thus, the mechanical properties are different across the cross section of the cold-formed steel. The effect of mechanical properties on cold worked as shown in Figure 2.8.

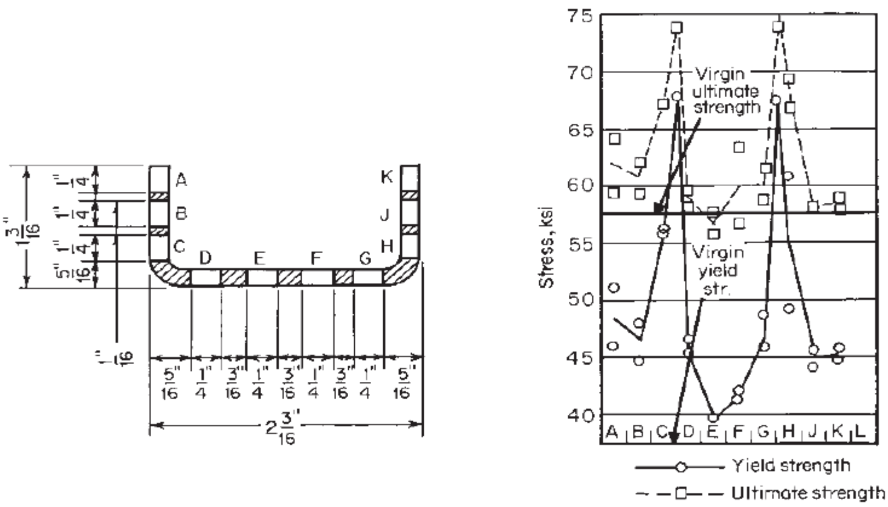

Figure 2.8 Effect of cold work on mechanical properties in channel cold-formed steel section

2.5 Classification of Section

Cold-formed steel comes with various type of section based on their function and purpose in construction work. This unique section is made possible by cold-forming methods that were mentioned earlier in this research paper which are, press braking and cold-roll forming. As a result, it offers a wide design option with little limitations and rising the popularity of cold-formed steel as a structural member. This is agreed by (Mahmood, 2007) that describe cold-formed steel to have a versatility of profile shape that can be produced in a controlled production line. There are three main types of sections which are single open section, open built-up section and closed built-up section. This research will be concentrating on open built-up section with different number and place of perforation.

2.5.1 Open Built-up Section

Open built-up section is a combination of two single open sections that are being connected, usually by screw to form built-up section. Four-point bending tests were conducted for cold- formed steel built-up open sections. The test setup of open section bolted on the flanges and clamped to the two sides of webs of the section, respectively, at the two loading points and the ends of each test specimen. The web stiffening plates were aimed to prevent the webs subject to load concentration and cause web crippling failure (Wang & Young, 2015).

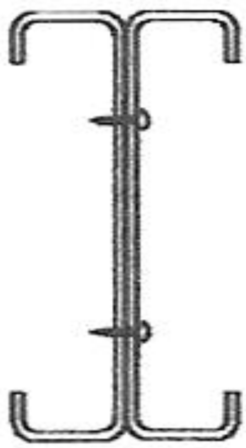

Figure 2.9 Open built-up section

2.6 Perforations

A perforation is a hole or opening that is made on the cold-formed steel to ease construction work. As seen on Figure 2.10, it usually provided with different shapes and size based on its function such as to accommodate electrical, plumbing and air conditioner or heating services. This is agreed by (Kulatunga et al., 2014) that describe that the function of perforations is to facilitate various services in building construction.

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, number, size and orientation of the opening. Exact analysis and design of steel with perforations elements are complex especially with unusual arrangements and shapes. Perforations on cold-formed steel are a major concern especially on a thin-walled structural members and the critical buckling loads for perforated plates and members have been studied by numerous investigators.

However, the strength is considered undisturbed if the perforations is made specifically to accommodate fasteners such as bolts and screws as the perforations will later be filled completely with the material. In The Civil Engineering Handbook that conclude, the presence of perforation that are specifically made for fasteners can be completely neglected on the basis that it will be filled with materials in any case. This research will focus on the effect of position, number and shape of the perforations on the structural strength.

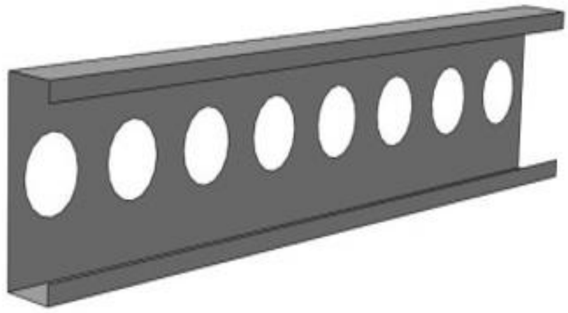

Figure 2.10 Perforation on cold-formed steel

2.7 Previous Research

Previous research that has been made by multiple researchers from around the globe has been referred to in completing this research. The reason of doing so is to strengthen the arguments and ensuring the quality in the outcome this research.

2.7.1 Beam test of cold-formed steel built-up section with web perforation

The research has been done by (Wang & Young, 2015). The aim of this study is to investigate the flexural behavior, including the ultimatemoment capacities and failure modes, of built-up cold-formed steel members with circular web holes. A total of 43 beams having ten crosssection sizes with different hole diameters were tested under four-point bending. The built-up sections were assembled by self-tapping screws from either two plain channels or lipped channels. Reduction of moment capacities and localized failure due to the presence of holes in the web plates of beams was observed in the tests.

2.7.2 Behaviour of Cold-Formed Steel Built-up Section

This research was done by (Stone & LaBoube, 2005) and it was done to study the behaviour of built-up cold-formed steel studs. This research has used North American Specification for the Design of Cold-Formed Steel Structural Members as their reference and the researcher also intended to determine if the AISI design methodology is valid for cold-formed steel members. This experimental study was performed at University of Missouri-Rolla concentrating on the behaviour of built-up compression members, specifically I-sections. The specimens tested in this investigation were constructed of C-shaped sections oriented back-to-back with edge stiffened flanges and track sections and the lengths of each specimens is 178 mm and it is tested using universal testing machine. Pin connection was used at the top and bottom of the stud.

2.7.3 Cold-formed steel built-up sections with web perforations subjected to bending

The investigation of flexural behaviour including the moment capacities and failure modes of cold-formed steel built-up sections with circular web holes has been done by (Wang & Young, 2017). The built-up sections included both I-shaped open sections assembled from two lipped channels back-to-back and box-shaped closed sections assembled from two plain channels face-to-face. The beam strengths obtained from the numerical analysis together with the available test data were compared with the design strengths calculated from the current direct strength method (DSM).

CHAPTER 3

METHODOLOGY

3.1 Work Flow Process

A work flow process has been framed before the project starts to ensure that the project run smoothly in the measured duration of time. These work flow process act as a guideline to make certain that the objective of the project is met and have a good result at the end of the project.

The work flow process of this project is divided into four main phases. The four phases indicates the importance and significant process that are important in establishing a good project with a good result at the end. The four phases are:

i. Phase 1: Preparation of literature review

ii. Phase 2: Planning and testing of sample

iii. Phase 3: Result and analysis

iv. Phase 4: Conclusion

3.1.1 Phase 1: Preparation of Literature Review

After the topic of Beam Test of Built-Up Open Section with Different Numbers and Position of Perforation have been finalize, the writing of literature review starts. Upon writing the literature review, one must gather information and knowledge to understand the topic better. The information provided in literature review must have accurate and useful information to ensure the objective of research may be obtained.

A well-written literature review will give good understanding to the person reading the research project paper later. The information and knowledge gather must only come from reliable source to ensure the quality and reliability of the complete research project later. There are three main sources that can be used in obtaining information which are previous journal and books, internet reading within reliable website and a direct discussion with supervisor and lecturers.

3.1.2 Phase 2: Planning and Testing of Samples

After completing the literature review, the methodology for the experimental investigation is planned. The sample is design and calculation of maximum loading is done to ensure that the machine available in the laboratory can cater with the design during the investigation. The sample used for this project has 1600 mm length due to the limitation of length that the can be cater by the machine in the laboratory. The size of the section of each sample is 50 mm x 100 mm x 20 mm. The size of section is also decided after further discussion with the supplier of the cold-formed steel and the size is change according to what the factory able to provide.

The testing of sample is made in the laboratory of Faculty of Civil Engineering and Earth Resources (FKASA) in Universiti Malaysia Pahang. Upon testing is made, a discussion is made with the technician involved to know further about the machine and how the testing is going to be conducted. As there are no standards that are available for the testing of steel, the research by Liping Wang and Beng Young entitle "Beam tests of cold-formed steel built-up sections with web perforations" is made as the main reference in conducting this experiment. The research was chosen as reference due to the factor of similarity between the samples used in the experimental investigation.

3.1.3 Phase 3: Results and Analysis

Upon completing the testing in the laboratory, the result and analysis phase may start. The result from the testing comes in two types which are the ultimate load on the beam test and the effect of the different number and position of perforation which is the buckling behaviour occured. Usually the data and result will be analyse by calculation, approximate graph, figure and table with the help of standard specification. On the other hand, the buckling behaviour is observed through presentation of picture of sample after the testing is done. For this testing, the result is then analyzed and graph of load and vertical displacement were plotted for each sample.

3.1.4 Phase 4: Conclusion

At the end of this research, conclusion is made based on the findings that were obtained from the experimental investigations. The conclusions made were corresponding and answering the objectives of the research. This phase should also summarise the whole research and giving recommendations for future improvements regarding the research topic.

3.2 Flowchart

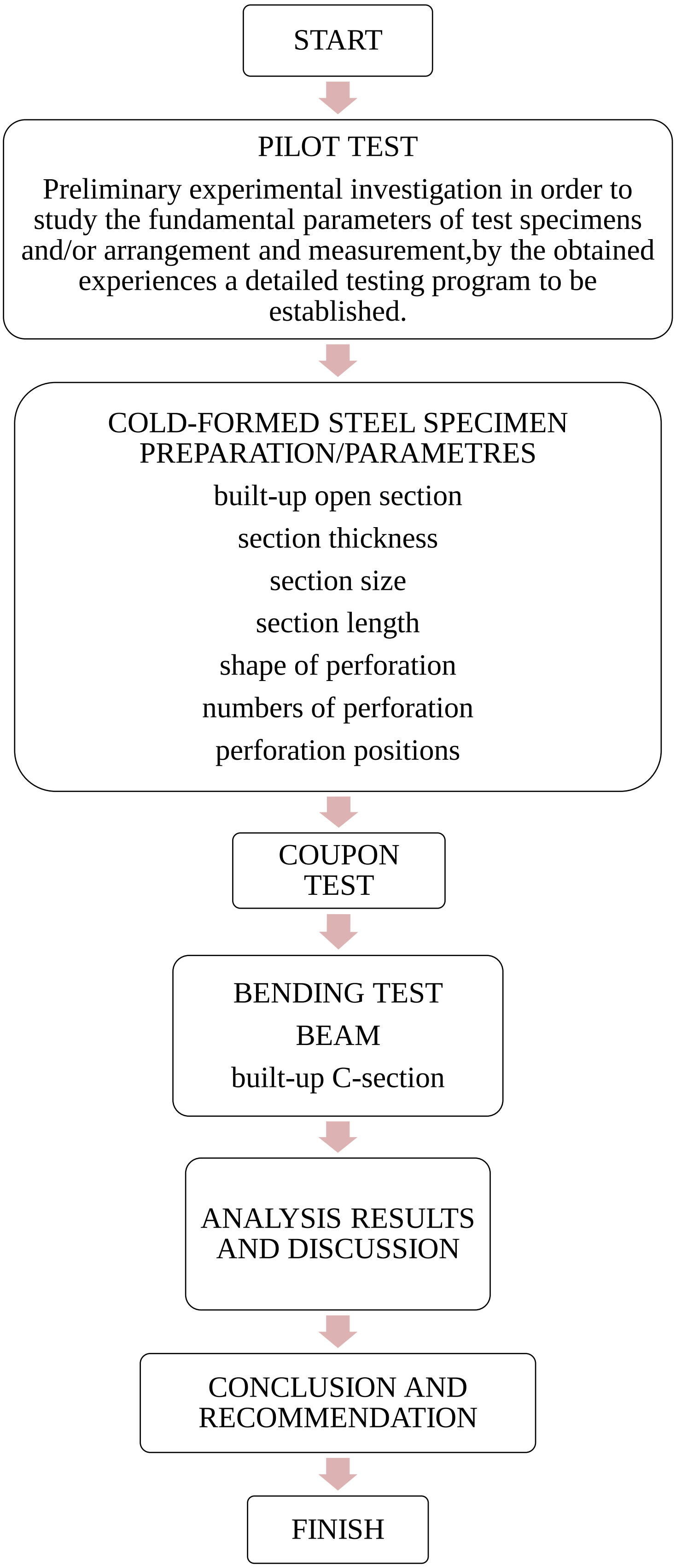

Figure 3.1 Flowchart

3.3 Preparation of Cold-Formed Steel Built-up Sections Beams

In this research, cold-formed C section has been used and the total of steel beam is 10 with five different cases. Two of cold-formed steel C-section beams were fastened together with self tapping screws to form built-up open section beam (Charles S. Davis, 1972). Table 3.1 shows the properties of the cold-formed steel that were used in this experimental investigation. The cold-formed steels were ordered and produced by Logamatic Industries (M) Sdn Bhd, a local company in Kuantan, Pahang. The section selected is LOG C10012 that is 1.2 mm thick.

The size of the beam is selected due to capability of the Loading Frame/Magnus Frame at the laboratory, so the sample of specimen used is 1600 mm length. Besides, the section size used in this research is 50 mm x 100 mm x 20 mm. The perforations of the cold-formed steel are made using a circle shape with a diameter of 20 mm and there is different numbers and position of perforation of built-up open section. Figure 3.1 shows the different numbers and position of perforation in cold-formed steel beam and Figure 3.2 shows the built-up open section diagram.

The screw spacing starts at 50 mm from one end with a constant gap of 100 mm later. The screw spacing is made constant for all samples while the diameter of the perforations was also fixed to 20 mm each. The schematic detail of the screw spacing is presented in Figure 3.3.

Figure 3.2 Cold-formed steel with various number and position of perforations

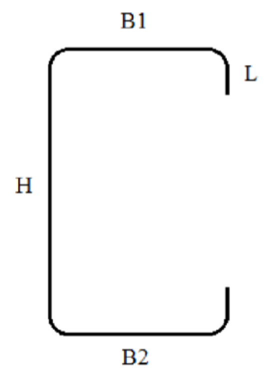

Figure 3.3 Built-up open section diagram

Table 3.1 Dimensions of C-section sample

C SECTION INDENTIFICATION	DIMENSION (mm)
H	100
B_1	50
B_2	50
L	20
t	1.2

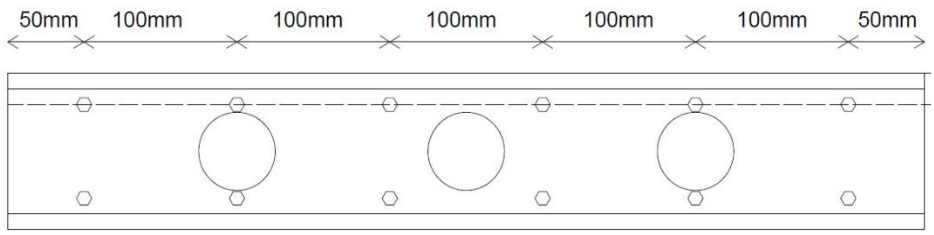

Figure 3.4 Screw spacing of the sample

3.3.1 Schematic diagram for testing

The diagram of the specimen used is described by drawing and all dimensions in this experiment are in milimetre (mm). The size of the opening is constant and the one of the schematic diagram of beam with perforation when receive the loading is shown in Figure 3.4. The varied number and position of perforation is to investigate the effect of the perforation on the ultimate load. In addition, it will compare by the number of perforations. The thickness and the length of specimen are kept constant which is 1.2 mm and 1600 mm respectively.

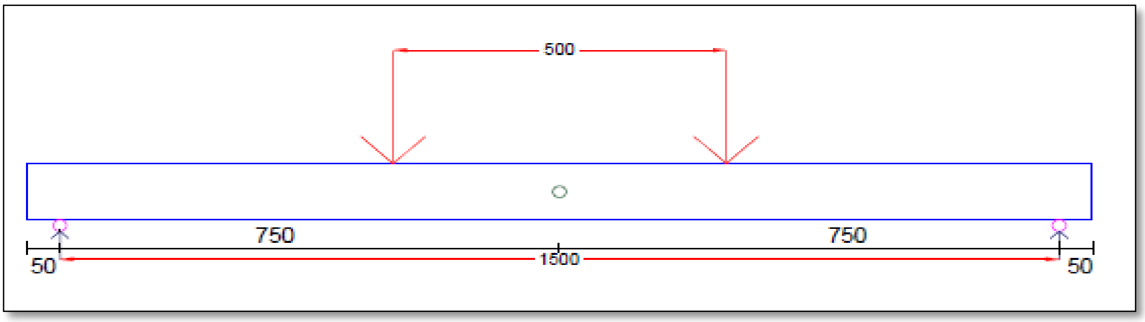

Figure 3.5 Schematic diagram of beam with perforation

3.4 Beam Test

Magnus Frame Machine has been used for the experiment in which available in Heavyweight Laboratory, FKASA and it shown in Figure 3.5. It has been used to test the steel beam perforation at the ultimate load. Figure 3.6 shows the driller used for making a perforation that will differentiate between the cases of the test. The generally used connection types in the cold-formed steel construction includes welds, bolts, screws, rivets and other special devices such as clinching, nailing and structural adhesives. The connection that used in this testing is self tapping screw as shown in Figure 3.7.

The four-point bending tests were conducted to obtain the ultimate load of each built-up section specimen (Laím, Rodrigues, & Silva, 2013). The beams were simply supported with a roller to roller distance of 1500 mm for all specimens. Half round bar was used as the two loading points. The distance between the two loading points was 500 mm for all beam specimens and the transducer is used in this experiment.

Figure 3.6 Magnus frame that used for beam testing

Figure 3.7 Driller for making a perforation

Figure 3.8 Self tapping screw

3.4.1 Test Setup and Procedure

There is one transducer that is used in this test and it is at the bottom of the specimen as shown in Figure 3.8. The arrangement of displacement transducer (LVDT) is identical to the four-point bending tests (Wang & Young, 2015). The function of the transducer is to calculate the vertical displacement that was cause by the buckling of each sample. The placing of the transducer is according to the prediction of the buckling behaviour that was made prior the test by comparing with other research paper.

The four-point bending tests were conducted to obtain the ultimate load of each built-up section specimen. The beams were simply supported with a roller to roller distance of 1600 mm for all specimens and the hinged support is simulated by round bar. It is allows both in-plane rotation and translation movement along the specimen. The distance between the two loading points was 500 mm for all beam specimens.

The loading frame was used to test the bending with two point load with different cases. The cases include varies numbers and position of perforation which is without perforation, at the centre, two, three and four holes. The test set up is shown in Figure 3.9 and Figure 3.10. The thesis of (Wang & Young, 2015)is being set as a reference through the execution of this project.

Figure 3.9 The placing of transducer

Figure 3.10 The test set up (front view)

Figure 3.11 The test set up (side view)

3.5 Data Analysis

From the experiment, the result can obtain with the ultimate load for built up open section. It can obtain by comparing the different numbers and position of perforation between the specimen. Besides, the failure mode which is buckling behavior that occur will be investigated during and after the testing and Figure 3.11 will show the type of buckling that occur after the testing. The buckling occur is depend on the presence of the numbers, size, spacing and location of the perforation (Ave, 2008).

Figure 3.12 Type of buckling behavior

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The result from the beam test was measured from the maximum load that was applied on the sample before it buckles and the buckling behaviour that occur during and after the experiment. The data is presented through graph of load vs vertical displacement where it compared the load and the displacement of the sample.

4.2 Load vs Vertical Displacement

For this part, the load obtained from the sample has been compared to the vertical displacement that occurs on the sample. As seen from Table 4.1, the maximum load obtained is 18.67 kN which is for sample with the three perforations while the lowest load is 16.53 kN which is for sample with the two perforations.

According to the result data, the result shows that when the perforations are located close to the support or when the perforations are closed to the loading applied, the ultimate load measured is decreasing. A graph of load vs vertical displacement is plotted at the end of the test and it could be seen in Figure 4.1 to Figure 4.5.

Table 4.1 Ultimate load of each sample

Samples name	Ultimate load (kN)
OH20T1.2-100-0H	17.03
OH20T1.2-100-1H	16.87
OH20T1.2-100-2H	16.53
OH20T1.2-100-3H	18.67
OH20T1.2-100-4H	17.73

The ultimate load is actually not predictable because of few reasons during the experim ent. It should be the higher ultimate load can be obtained from the beam without opening compare to the beam with opening. It is because of few reasons which are didn't use the stiffness plate during the experiment that may occur the imperfection. Furthermore, it is because of using a roller instead of half round bar that may cause the beam easily move around.

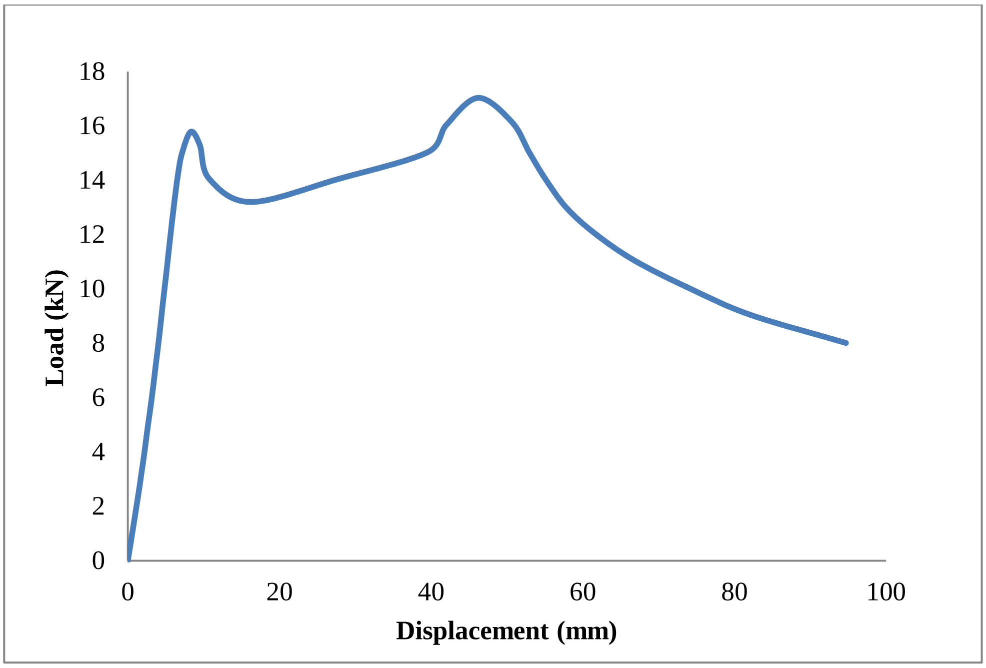

Figure 4.1 Sample OH20T1.2-100-0H

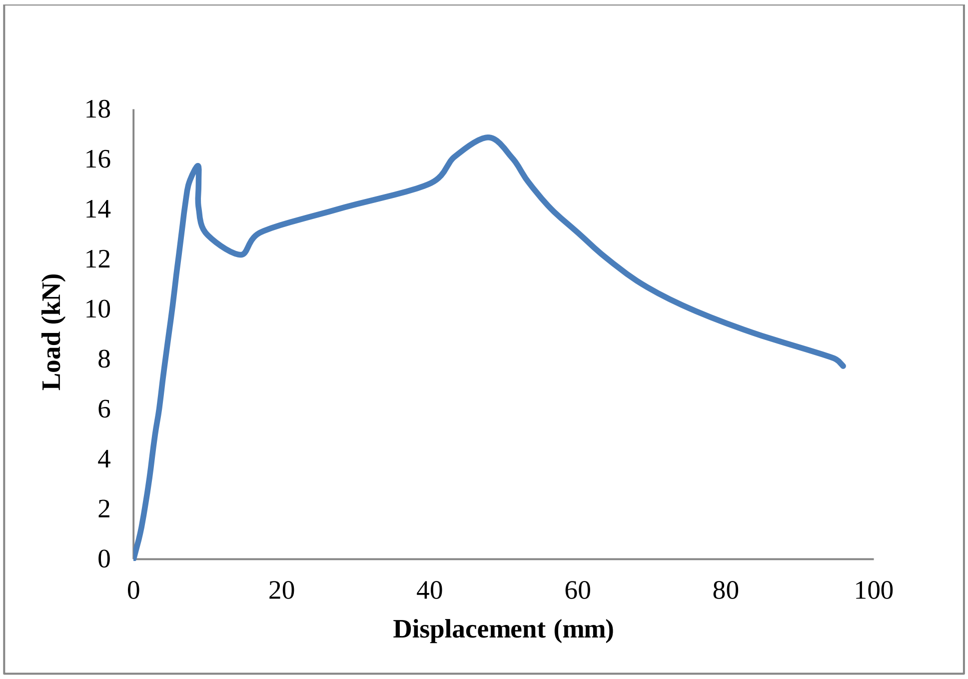

Figure 4.2 Sample OH20T1.2-100-1H

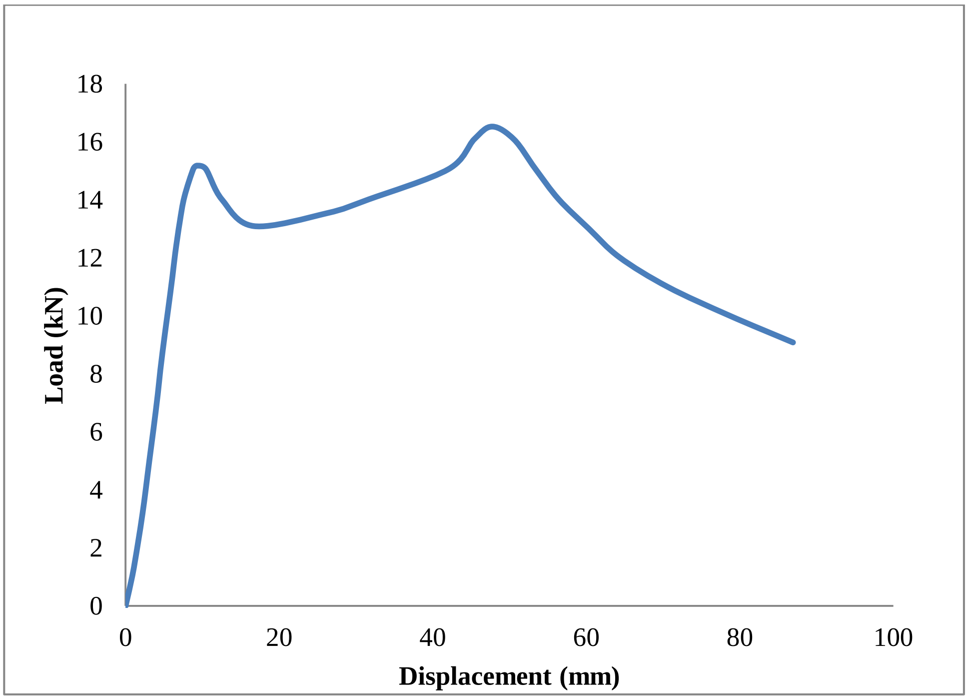

Figure 4.3 Sample OH20T1.2-100-2H

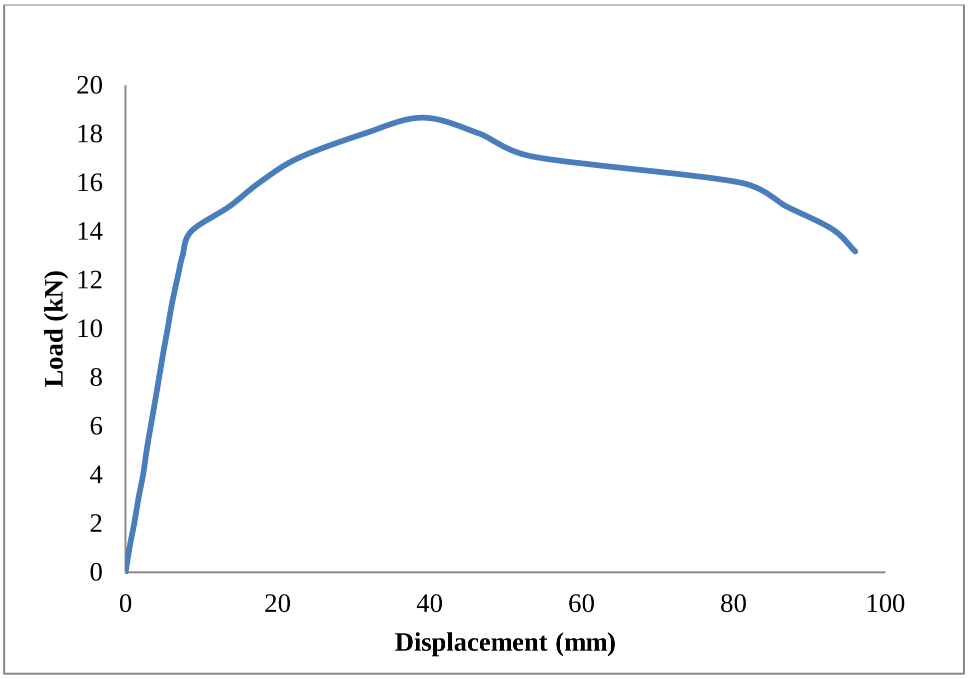

Figure 4.4 Sample OH20T1.2-100-3H

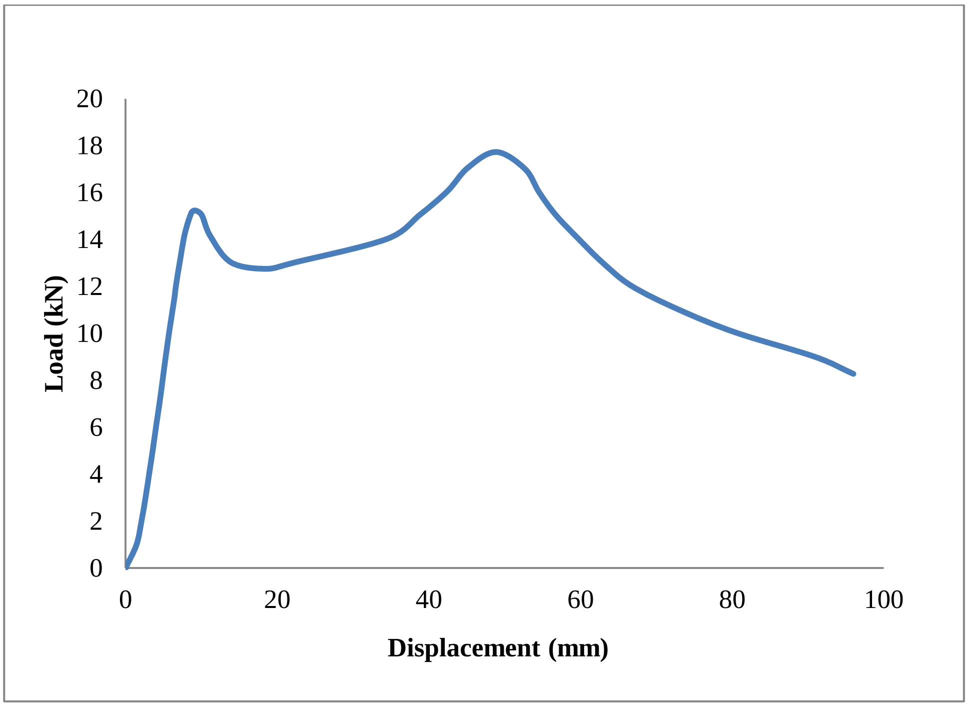

Figure 4.5 Sample OH20T1.2-100-4H

4.3 Buckling Behaviour of Samples

The samples show a buckling behaviour occurs which is the effect on the beam during and after the experiment. There are three type of buckling happen which are local buckling, flexural torsional buckling and distortional buckling. All the samples are show that the all of buckles happen on the specimen. Table 4.2 shows the failure modes that occur on each sample during and after the experiment.

Table 4.2 Failure mode of each sample

Samples name	Ultimate load (kN)
OH20T1.2-100-0H	L+F+D
OH20T1.2-100-1H	L+F+D
OH20T1.2-100-2H	L+F+D
OH20T1.2-100-3H	L+F+D
OH20T1.2-100-4H	L+F+D

L=local, F=flexural, D=distortional

4.3.1 Local buckling of open sections using lipped channels with holes

In this experiment, local buckling mostly occurred at initial of the testing. Figure 4.6 to Figure 4.8 show that the initial local bucklimg that happen in the testing. Initial local buckling is occurred when the loading start to applied to the steel beam.

Figure 4.6 Initial local buckling during experiment (side view)

Figure 4.7 Local buckling at the middle of the beam at peak of the experiment

Figure 4.8 Local buckling at the middle of the beam after experiment (post – peak)

4.3.2 Flexural torsional buckling of open sections using lipped channels with holes

Figure 4.9 and Figure 4.10 show the flexural torsional buckling that occurred at peak and post – peak of the experiment. It is happen along the beam that shows the beam twistly rotate.

Figure 4.9 Flexural torsional buckling along the beam at peak of the experiment

Figure 4.10 Flexural torsional buckling along the beam after experiment (post – peak)

4.3.3 Distortional buckling of open sections using lipped channels with holes

The testing shows that the distortional buckling occurred at the both end of the specimen during and after the experiment. It has been shown in Figure 4.11 and Figure 4.12.

Figure 4.11 Distortional buckling occur at peak of the experiment

Figure 4.12 Distortional buckling occur after experiment (post – peak)

CHAPTER 5

CONCLUSION

5.1 Conclusion

A test program on cold-formed steel built-up section beams with web perforations has been presented. The test specimens were assembled by self-tapping screws from two lipped channels. Web holes were located on each channel of the built-up specimens in the moment span with the hole diameter of 20 mm. The simply supported beams were tested under four-point bending. A total of 5 specimens were tested in this research.

The result from the beam test shows that the ultimate load is depend on the number and the position of perforations itself either it is at the near midspan or near the support. The maximum load is obtained from the sample that have three balance perforations along the beam which is the perforations is not located at the support or the loading applied.

Furthermore, the position of perforations must not be located near the centre of the sample, as it is the critical buckling position. The presence of web perforations was also found to initiate the failure for all built-up open section beams in the tests. The result shows that all specimen has experienced all the buckling behavior at the peak of the testing.

5.2 Recommendation

There are few recommendations that can be used in future research regarding cold-formed steel beam. First, use different size of section. In this research, only one section size has been used. In future research, multiple size of section can be used to study on the effect of size of section in the buckling behaviour of the sample. This is relevant to the various section used by the construction industry as part of the precast component. Considering different type of section or an innovation of new geometrical section may contribute to new effective section that may apply in future.

Next, use different perforation shape and size. As the construction industry may use different perforation shape and size to cater the need of construction, future research can be done to study the effect of different shape and size of the perforations on the ultimate load and the buckling behaviour of the sample. Lastly, do an analysis of Finite Element (FE) to compare with the experimental to get accurate result. This research only used experimental investigation to study the effect of perforations of cold-formed steel beam. The buckling behaviour can be predicted accurately using FE. The used of FE in the research can help give additional information and the comparison of ultimate load and displacement of the sample can be done.

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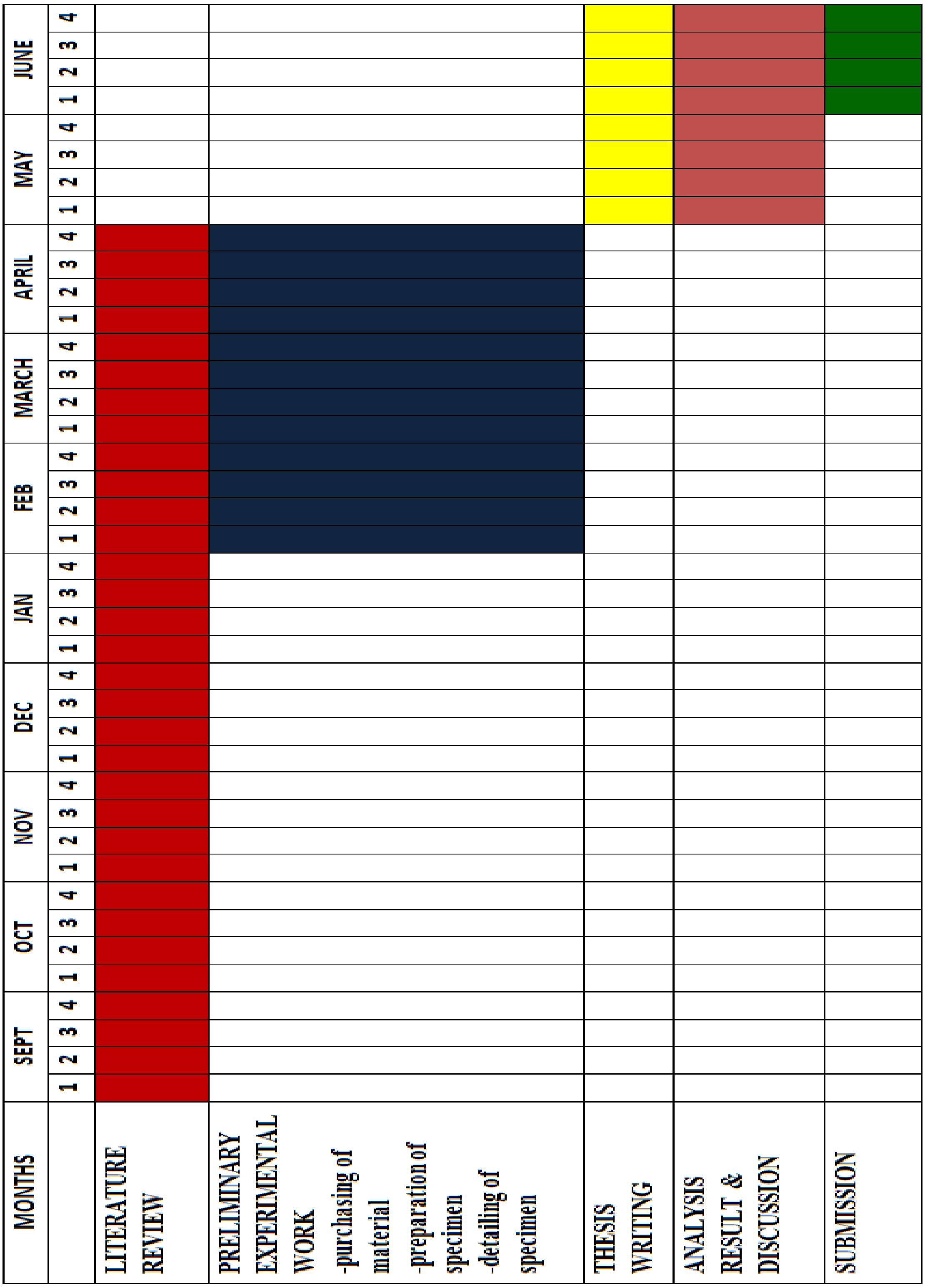
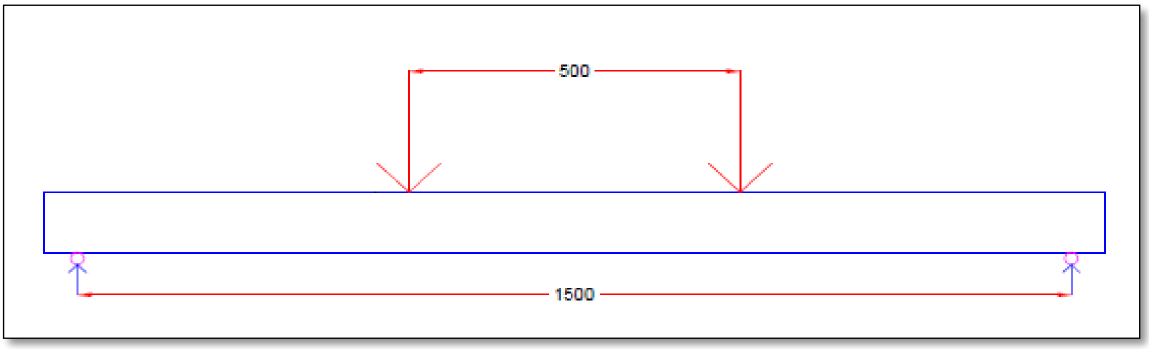
APPENDIX A
GANTT CHART



APPENDIX B
SAMPLE OF TESTING

CASE 1 : BUILT-UP OPEN SECTION BEAM WITHOUT OPENING.

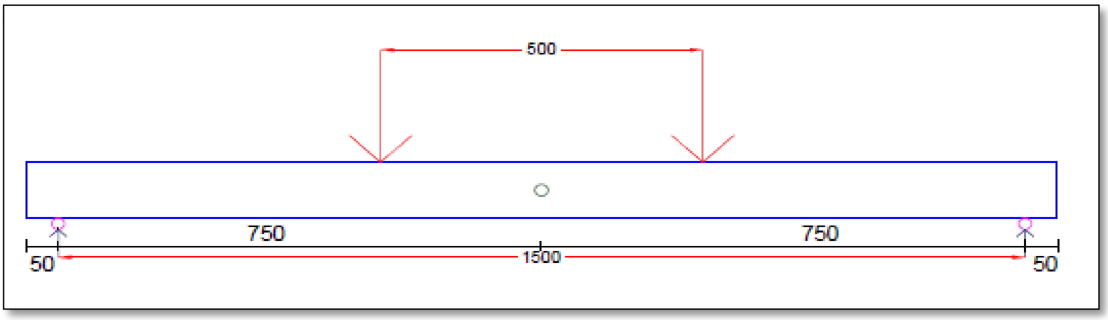


TEST SET-UP

AT PEAK CONDITION

AT POST – PEAK CONDITION

CASE 2 : A SINGLE OPENING AT THE MIDDLE OF THE BEAM.

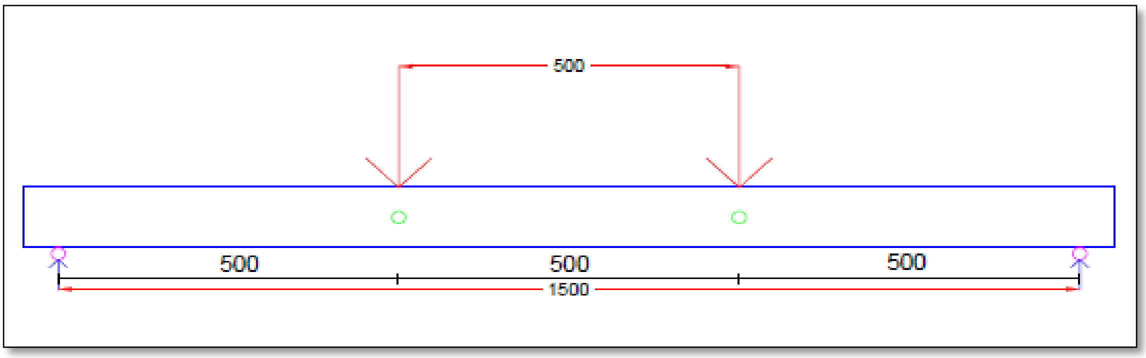


TEST SET-UP

AT PEAK CONDITION

AT POST – PEAK CONDITION

CASE 3 : TWO PERFORATION WITH THE SPACING OF 500MM FROM THE MIDDLE OF THE BEAM TO THE OPENING FOR EACH SIDE.

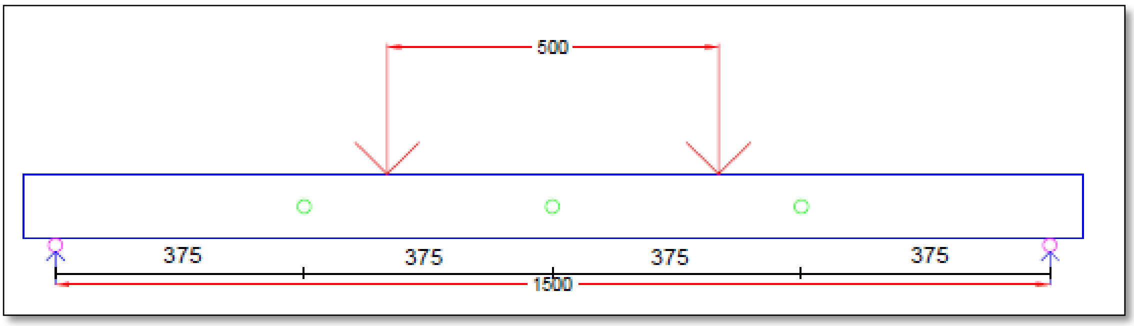


<u>TEST SET-UP</u>

AT PEAK CONDITION

AT POST – PEAK CONDITION

CASE 4 : THREE PERFORATION WITH THE SPACING OF 375MM FROM THE MIDDLE OPENING TO THE OPENING FOR EACH SIDE.

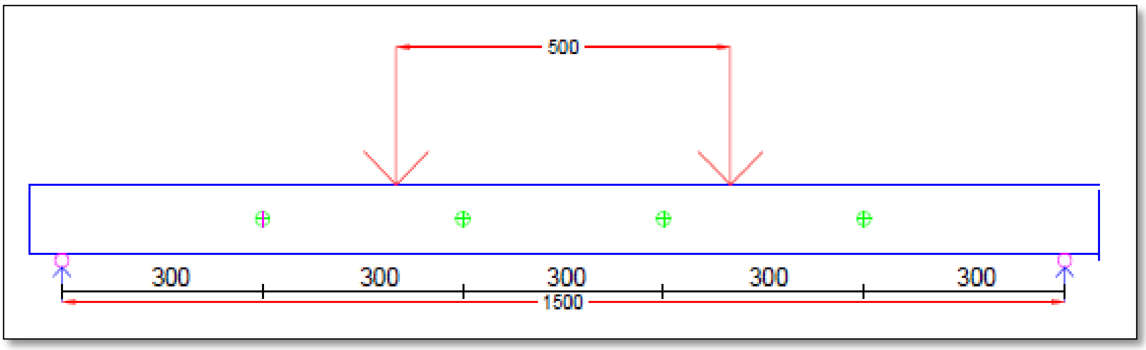


TEST SET-UP

AT PEAK CONDITION

AT POST – PEAK CONDITION

CASE 5 : FOUR PERFORATION WITH THE SPACING OF 300MM FROM THE MIDDLE OF THE BEAM TO THE OPENING EACH SIDE.



<u>TEST SET-UP</u>

AT PEAK CONDITION

AT POST – PEAK CONDITION

APPENDIX C
PREPARATION OF BUILT-UP OPEN SECTION