EFFECT OF PERFORATIONS ON AXIALLY LOADED I-SECTION COLD-FORMED STEEL COLUMN

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ABSTRAK

Struktur keluli sejuk terbentuk adalah produk struktur keluli yang dibuat dengan membengkokkan kepingan rata keluli pada suhu bilik ke. Penggunaan keluli sejuk terbentuk adalah *Industrialised Building System (IBS)* yang menggalakkan mutu kerja yang tinggi dengan pembaziran yang minimum. Keluli sejuk terbentuk mempunyai pelbagai jenis bentuk berdasarkan fungsi mereka dalam kerja pembinaan. Terdapat tiga jenis bentuk iaitu bentuk terbuka tunggal, bentuk tertutup dan bentuk bina terbuka. Kajian ini menumpukan kepada bentuk bina terbuka. Struktur keluli sejuk terbentuk biasanya datang dengan kehadiran tebukan. Fungsi tebukan lubang atau bukaan yang dibuat pada keluli terbentuk sejuk untuk memudahkan kerja pembinaan. Ia biasanya disediakan dengan pelbagai bentuk dan saiz berdasarkan fungsinya seperti untuk menampung elektrik, paip dan penghawa dingin atau pemanas. Walau bagaimanapun, kehadiran tebukan boleh menyebabkan pengurangan kekuatan elemen komponen individu dan kekuatan keseluruhan anggota itu bergantung kepada kedudukan, saiz dan orientasi pembukaan. Kajian ini akan memberi tumpuan kepada kesan kedudukan dan bentuk tebukan pada kekuatan struktur tiang keluli terbentuk sejuk yang paksi dimuatkan. Satu siasatan experimen untuk keluli sejuk terbentuk tertakluk kepada mampatan loading untuk mengkaji kesan tebukan pada kapasiti beban ahli lajur terbina I-seksyen diadakan. Sebanyak 6 sampel yang mempunyai kedudukan tebukan yang berbeza telah diuji dalam eksperimen ini. Setiap ahli mempunyai ketebalan nominal sebanyak 1.6 mm, panjang 600 mm dan telah dimampatkan. Hasil daripada eksperimen ini menunjukkan bahawa beban muktamad setiap sampel amat berbeza pada kedudukan tebukan. Keputusan ini dipersembahkan dalam tiga bahagian yang beban vs anjakan menegak, beban vs anjakan mendatar dan tingkah laku lengkungan.

ABSTRACT

Cold-formed steel structure are steel structural product that are made by bending flat sheets of steel at ambient temperature into shapes. The application of cold-formed steel is an extent to the Industrialized Building System (IBS) that promotes high quality of work with minimum waste. Cold-formed steel comes with various type of section based on their function and purpose in construction work. There are three main type 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 or I-section. Structural members of cold-formed steel usually come with the presence of perforations. Perforations is a hole or opening that are made on the cold-formed steel to ease construction work. It usually provided with different shapes and size based on its function such as to accommodate electrical, plumbing and air conditioner or heating services. However, 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. This research will focus on the effect of position and shape of the perforations on the structural strength of the axially loaded cold-formed steel column. An experimental investigation of cold-formed steel subjected to compression loading to study the effect of perforations on the load capacity of column members of built-up I-section is held. A total of 6 samples that have different position of perforations were tested in this experiment. Each member has nominal thickness of 1.6 mm, column length of 600 mm and were compressed between a simply supported end at both end. The result of this experiment shows that the ultimate load of each sample varies greatly on the perforation position. The result is presented in three section which are load vs vertical displacement, load vs horizontal displacement and buckling behavior.

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LIST OF ABBREVIATIONS

AISI	American Iron Steel Institue
BS	Bristish Standard
FKASA	Fakulti Kejuruteraan Awam Dan Sumber Alam
FE	Finite Element
LOG	Logamatic Industries (sample code)
n.d.	No date

CHAPTER 1

INTRODUCTION

1.1 Background of Research

Cold-formed steel structure are steel structural product that are made by bending flat sheets of steel at ambient temperature into shapes. Currently, there are three methods involved in production of cold-formed steel which are folding, press barking and roll forming. These methods allow cold-formed steel to have diversity in shapes, sizes and applications. It also increases the yield strength and tensile strength of the cold-formed steel but these methods cause the ductility of cold-formed steel sections to decrease at the angular corner. The angular corner often has imperfections due to the method of producing the cold-formed steel itself. As shown in Figure 1.1, cold-formed steel is produced in various shape and section such as single open section, open built-up section and closed built-up section. For this research, open built-up section, also known as I section, will be used.

This research will also focus on the effect of perforations on the cold-formed steel. The cold-formed steel structure often come with perforations for the ease of construction works. Perforation is the opening made on the cold-formed steel to accommodate electrical wiring, plumbing, air conditioner, connections of structure etc.

The application of cold-formed steel is an extent to the Industrialised Building System (IBS) that promotes high quality of work with minimum waste. The application of cold-formed steel structure includes trusses, frame, doorways, beam, column etc. The usage of cold-formed steel is still limited in Malaysia but it is widely used in United States and Great Britain since it is introduced in 1850. Malaysia uses British Standard BS5950 as design reference.

Cold-formed steel are on high demand as it can be produced in large quantity with a control quality. It is a lot more light compared to hot-rolled steel and it is one of the material that has a highest strength-to-weight ratio. It gives more design option with better material used. Cold-formed steel is highly durable and provides resistant towards termites and rotting. Galvanized cold-formed steel also provides long-term corrosion resistant.

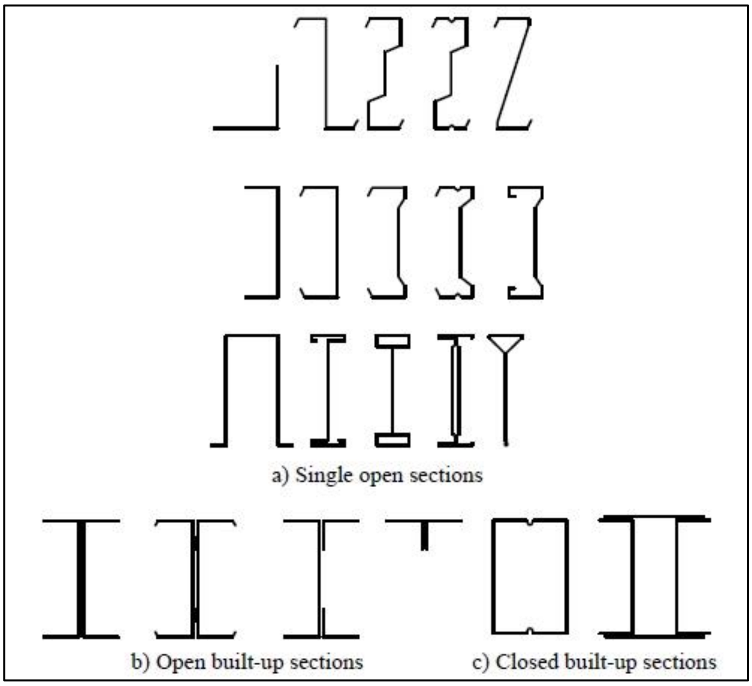

Figure 1.1 The diversity of shape for cold-formed steel

1.2 Problem Statement

Cold-formed steel members are often accommodated with perforations with different size and shape to ease the construction work. However, these perforations may affect the ultimate strength and elastic stiffness of the structural member. The ultimate strength and elastic stiffness also varies with the position of the perforations on the cold-formed steel structure.

In a structure as a column, cold-formed steel member is loaded in compression and their strength is restraint by buckling. There are various buckling behaviour that may be observe from a cold-formed steel structure which are local buckling, torsional buckling and flexural-torsional buckling. The buckling behaviour may also be affected by the position of perforations on the member.

1.3 Objective of Research

The objectives of the research are:

i. To determine the ultimate load of axially loaded built-up cold-formed steel column with perforations.

ii. To study the effect of perforations on the axial load of the axially loaded built-up cold-formed steel column.

iii. To study the failure mode and behaviour of axially loaded built-up cold-formed steel column with different perforation position.

1.4 Scope of Research

The scope of these research covers on the compression test for axially loaded built-up cold-formed steel with perforations. The experiment will be done at the laboratory. The scopes of work are:

i. Position of the perforations

ii. Support of the column

iii. The back-to-back sections of the cold-formed steel

1.5 Significant of Research

For this research, compression test will be conducted on multiple samples to determine the ultimate load of axially loaded built-up cold-formed steel column with perforations. These sample is different in term of it perforation position and slightly varies on their length, due to the imperfection of the cold-formed steel. The cold-formed steel that are going to be used in this experiment is a back-to-back cold-formed steel section.

By conducting this experiment, parameters such as elastic modulus, elastic limit, yield strength and ultimate strength can be determined. A better understanding towards the failure and buckling behaviour can also be gain by conducting this experiment. The buckling behaviour may differ as the perforation position is different between the samples.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Cold-formed steel is one of the two type of steel sections that are currently used in building construction. Cold-formed steel is composed of sections that are manufactured using various method of cold forming from steel sheet, plate or flat bar. The thickness of steel sheet or strip that are used in cold-formed steel structural member ranges from 0.378 mm to 6.35 mm.

By using cold forming work, various shape and sections can be produced to fit the needs of construction process. The shape and cross sections of cold-formed steel can be divided into three main category which are single open section, open built-up section and closed built up section. In this research paper, the experiment will be conducted on open built up section, also known as I-section, with perforations.

Cold-formed steel sections are widely used in car bodies, railway coaches, various type of equipment and others but the popularity of it in construction of building is rather increasing. In Malaysia, the application of cold-formed steel is still limited compared to other developing country as cold-formed steel sections are only used for roof trusses and purlin. Cold-formed steel holds many advantages that making it have a growing popularity in construction of building.

2.2 Method of Manufacturing

There are varieties of method in manufacturing of cold-formed steel but the three-main method are folding, press-barking and cold-rolling. These manufacturing methods can also be called cold-forming. Cold-forming is a term used to describe the manufacture of products by forming material from a strip or sheet of uniform thickness.

2.2.1 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. However, this method is not widely used as of it limitation of design and application. This is agreed by Chen and Liew (2003) that describe that this process has a very limited application in construction industries.

2.2.2 Press-Barking

Press-barking is widely used in manufacturing of cold-formed steel. The cold-formed steel is formed from a length of strip by pressing the strip between shaped dies to form a profile shape. Press-barking offers a greater variety of cross-sectional compared to folding. By using this method, each bend is formed separately. However, according to Chen and Liew (2003), press barking has certain limitations in it design. The profile geometry that can be formed and length of section that can be accommodate by this method is still limited.

2.2.3 Cold-Rolling

Cold-rolling is the main method that are used in producing cold-formed steel. It can produce a large volume of production thus, making it a more economical choice. In this method, the strip material is formed into the desired profile shape by folding it continuously through successive pairs of rolls. These rolls will bring the form of strip progressively closer to the final profile shape. The speed of rolling varies from 10 m per min up to 100 m per min. the speed depends on the complexity of profile.

This method eliminates the limitations that press-barking and folding method have. This is agreed by Chen and Liew (2003) that explain, cold-rolling can produce prismatic sections with a high degree of consistency and accuracy to any desired length.

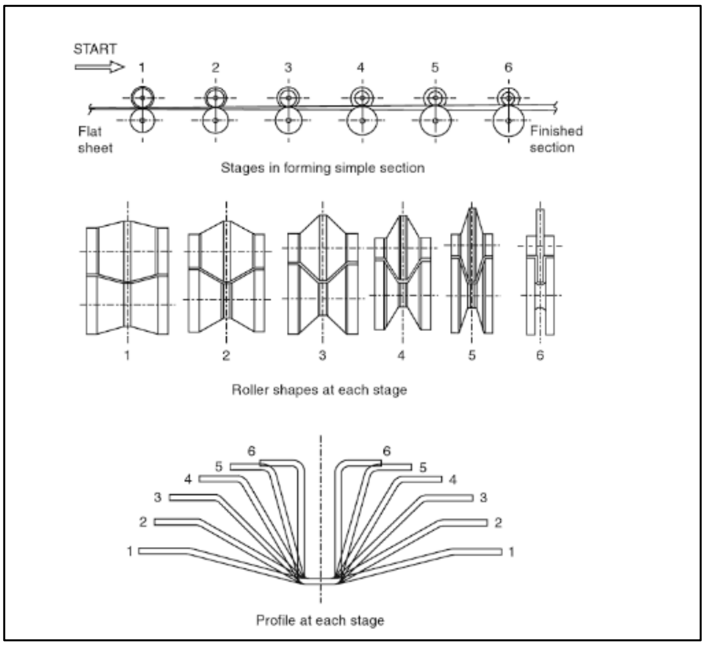

Figure 2.1 Stages of roll forming in simple section

Source: The Civil Engineering Handbook

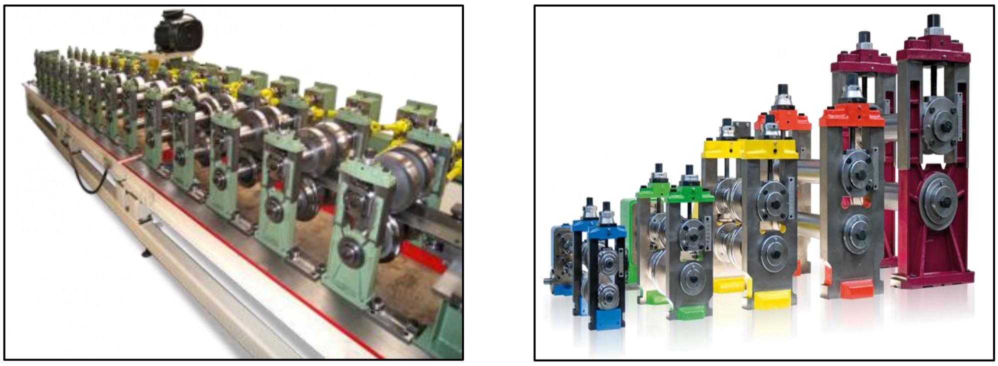

Figure 2.2 Roll forming machine

Source: Jidet.com

2.3 Advantages of Cold-Formed Steel

Cold-formed steel possesses many advantage when compared to other construction material such as hot-rolled steel, timber and conventional reinforcement concrete. These advantages help cold-formed steel to have its own reputation in construction industries.

2.3.1 Durable

As steel is an inorganic material, it is immune to termites, insects, rotting and fungi. Problems such as rotting and decomposition due to insect and fungal infection are eliminated with the use of cold-formed steel structure (Mahmood, 2007). Unlike conventional construction process, anti-termite spraying treatment is not necessary as the cold-formed steel highly durable and has an anti-termite resistance. According to Steel Framing Industry Association (n.d.), galvanized cold-formed steel provides long-term resistance to corrosion and can last hundreds of years without any deterioration. The protective layer and coating may give cold-formed steel a more attractive and pleasant silver finishing while avoiding messy requirement of painting on site (Mahmood, 2007).

2.3.2 High Strength and Stiffness

Cold-formed steel is made from sheet or strip steel thus it has a very lightweight. It also has the highest strength-to-weight ratio compared to other construction material. The action of forming, press barking or folding the cold-formed steel will subsequently develop the strength of the structure. The thinness of the material gives a huge advantage on cold-formed steel over hot-rolled steel as it has a higher strength-to-weight ratio (Kulatunga *et al.*, 2014). Because of cold-formed steel having a high strength and stiffness, it gives more diversity and flexibility in design while allowing design in longer spans with better material usage. Various section configurations can also be produced economically by both folding and press barking, resulting in the favourable strength-to-weight ratio (Yu, 2000; Wang *et al.*, 2016).

2.3.3 Versatility of Shape and Design

Cold-formed steel has variety of section design and this may ease the designing process of a project. Any desirable cross-sectional shape can be produced by cold rolling, such as T-section, Z-section, hat section and angle section (Mahmood, 2007 ; Zhang and Young, 2012 ; Kulatunga *et al.*, 2014). The versatility of the cross-sectional and section design gives the architect more flexibility in deciding the end design of a structure. Besides, Yu (2000) describes that the unusual sectional configuration can be produced economically.

2.3.4 Non-Combustibility of Material

Cold-formed steel is 100% non-combustible that it will not contribute to the spread or intensity of a fire unlike certain construction material. As a result, the design of cold-formed steel project can easily meet the code of fire resistance requirements. Moreover, height and area restrictions on combustible material does not apply on cold-formed steel. According to Steel Framing Industry Association (n.d.), cold-formed steel often translates into lower cost and extensive coverages for many types of construction insurance. The non-combustible properties of cold-formed steel results in lower insurance premium for a structure (American Iron and Steel Institute, 2010).

2.3.5 Cost Effectiveness

The cost effectiveness of using cold-formed steel covers from the phase of production, transporting, usage of material to the end of construction process. The method of manufacturing of cold-formed steel is simpler compared to hot rolled steel, making it more economical in the production. This is agreed by Wolford and Onstruction (1999) and Mahmood (2007) that conclude, the relative ease and simplicity of the bending operations results in the low price of the cold-formed steel while still having a return profit to be sooner than other construction material.

Next, cold-formed steel is easy to transport as it has a very lightweight. American Iron and Steel Institute (2010) described that the process of transporting the cold-formed steel is easy to handle as they can be nested and bundled hence reducing the required shipping and storage space.

Cold-formed steel also economical in terms of it material usage. Compared to hot rolled steel, cold-formed steel used less material to achieve a given strength and stiffness. This is agreed by Mahmood (2007) that described that the usage of material for a given strength and stiffness requirement is appeared to be much less than hot-rolled section.

Lastly, the construction period can also be reduce significantly compared to conventional method. By using cold-formed steel, the construction cycle is reduced and insurance cost is lower for builders and owners' due to the non-combustible properties of cold-formed steel (Steel Framing Industry Association, n.d.).

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.

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 2.3 is the sharp-yielding while on Figure 2.4, the gradual-yielding type. This is agreed by Yu and LaBoube (2010) that further explains, 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-underload method.

Tensile strength of cold-formed steel has a minor direct relationship to the design of member. Yu and LaBoube (2010) explains that 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. This ensure that the adequate safety is provided for the ultimate strength of tension member and connection.

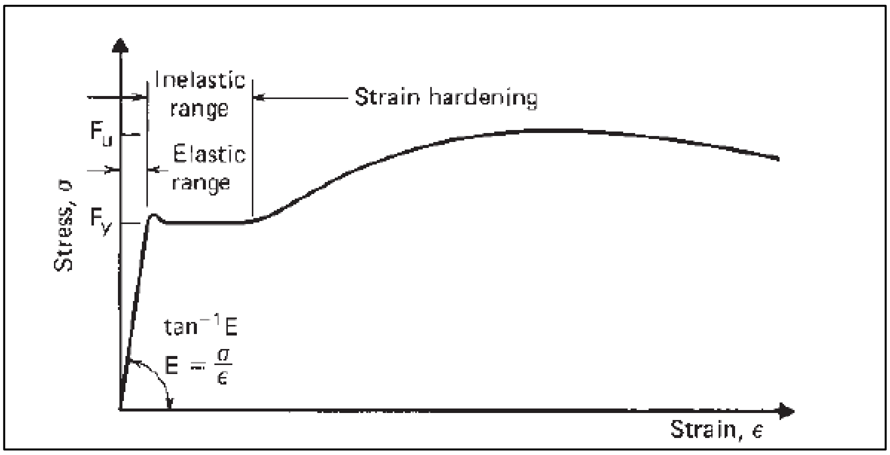

Figure 2.3 Sharp yielding

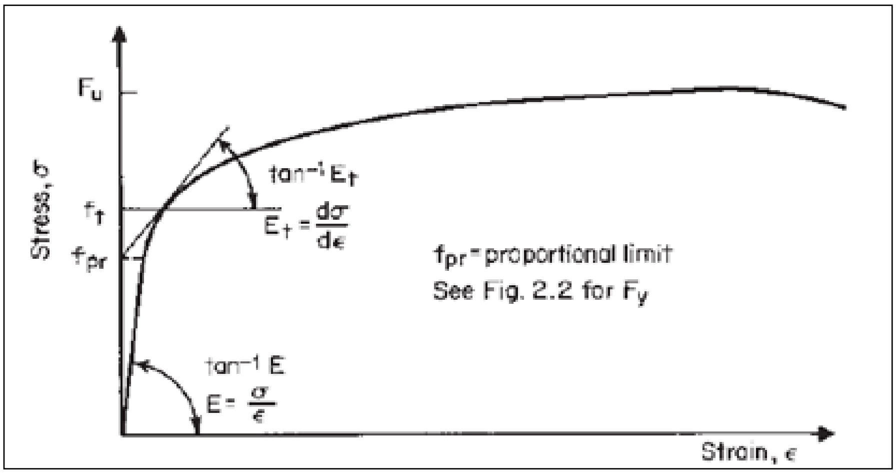

Figure 2.4 Gradual yielding

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 result 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. This is agreed by Yu and LaBoube (2010) that suggest the effect of mechanical properties on cold worked as shown in Figure 2.5.

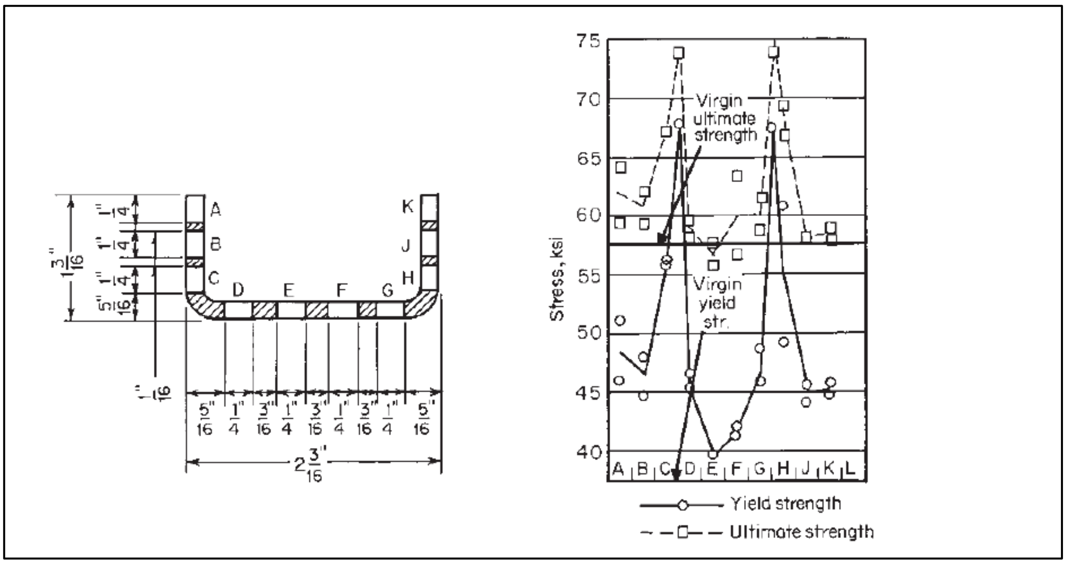

Figure 2.5 Effect of cold work on mechanical properties in channel cold-formed steel section

2.5 Buckling Behaviour

When cold-formed steel structural members are loaded in compression, it is often limited due to occurrence of failure mode. Although cold-formed steel is highly efficient in the usage of material, they are highly predicted to fail in various buckling mode. The complications due to characteristic of cold-formed steel is increase when the members are made slender. When designing a cold-formed steel structural member, these should be taken into consideration.

There are three main buckling mode that are common in cold-formed steel which are local buckling, torsional buckling and flexural-torsional buckling. This is agreed by Kulatunga and Macdonald (2013) and they further describe that there seems to be a consensus on these classifications of buckling modes but there is no consensus on the exact meaning of the modes themselves.

2.5.1 Local Buckling

Local buckling is the simplest buckling behaviour in cold-formed steel failure mode. Hancock (2003) explains that local buckling is a mode involving plate flexure alone without transverse deformation of the lines of intersection of adjoining plates. As seen in Figure 2.4, the deformation does not interfere on the intersection line of the adjacent plate elements.

There are many factors that contribute to local buckling of cold-formed steel column which are slenderness ratio of column, mechanical properties of cold-formed steel, effect of cold forming, effect of imperfections, shape of cross section etc. This is agreed by Kulatunga and Macdonald (2013) and they explain that due to this factor, cold-formed steel compression member can buckle locally before the applied load reached the overall collapse load of the column. Plus, the interaction effect of the local and overall column buckling is greatly dependent on the overall column strength.

2.5.2 Distortional Buckling

Distortional buckling is mode of buckling that involve change in cross-sectional shape. Zhao (2005) justify that distortional buckling is generally characterized by a flange distortion that occurs in simple channel or rack sections as seen in Figure 2.5. Distortional buckling also goes by the name of 'stiffener buckling' and 'local-torsional buckling'. This mode of failure is usually found at the flange or web in member with edge stiffened element.

The wavelength of distortional buckling lies between local buckling and global buckling which place it in the practical range of member length. Kulatunga and Macdonald (2013) pointed out that distortional buckling generally encourages failure more quickly than local buckling.

2.5.3 Flexural-Torsional Buckling

Flexural-torsional buckling is a mode of buckling in which long compression members bend and twist simultaneously. It usually occurs in long member that are loaded in compression and failure occur due to overall buckling. The cross-section that are familiar to flexural-torsional buckling is closed shape doubly symmetric, point symmetric or cylindrical shape. This is agreed by Kulatunga and Macdonald (2013) who further explains that when an open column section buckles in flexural-torsional mode, bending and twisting will occur simultaneously as seen in Figure 2.6.

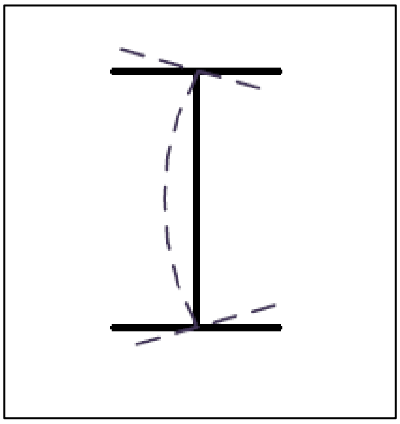

Figure 2.4 Local buckling

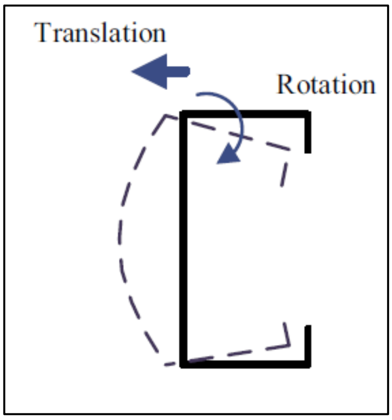

Figure 2.5 Distortional buckling

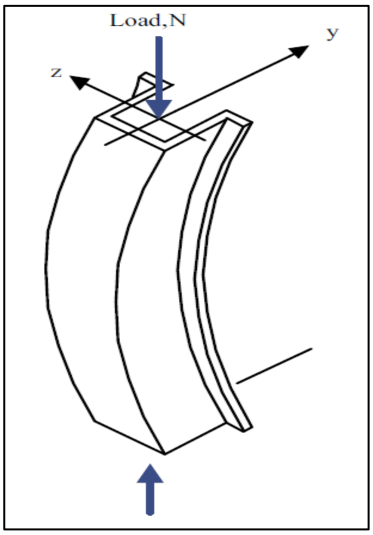

Figure 2.6 Flexural-torsional buckling

2.6 Classification of Section

Cold-formed steel comes with various type of section based on their function and purpose in construction work. These unique section is made possible by cold-forming method that were mentioned earlier in this research paper which are, press barking and 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 type of sections which are single open section, open built-up section and closed built-up section.

2.6.1 Single Open Section

Single open section is the basic shape that are produced by cold forming of cold-formed steel. It is roll-formed in a single operation from one piece of material. The example of single open section is Z-section and C-section. These section is usually used for construction of purlin and roof.

2.6.2 Open Built-up Section

Open built-up section is also known as I-section. It is a combination of two single open section that are being connected, usually by welding, and forming and I section. This is agreed by Yu (2000) that it is usually made by welding two channels back-to-back or by welding to angles to a channel. In this research paper, the test will be conducted on I-section.

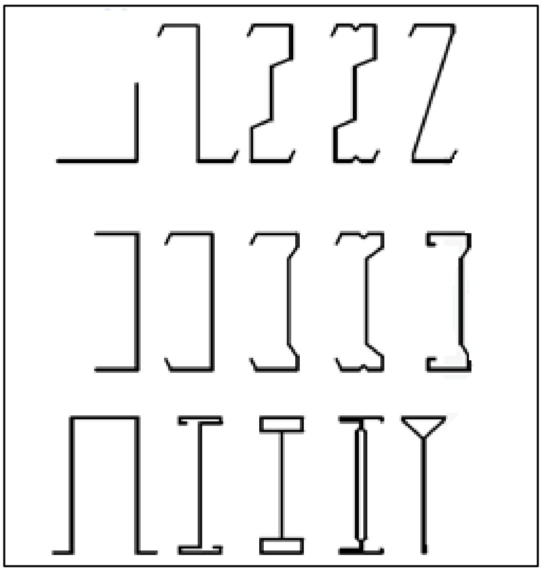

Figure 2.7 Single open section

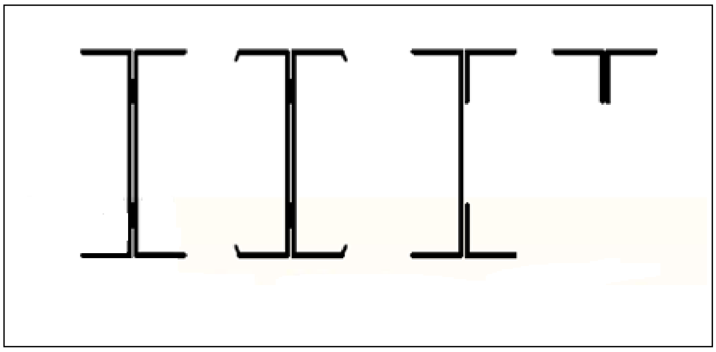

Figure 2.8 Open built-up section

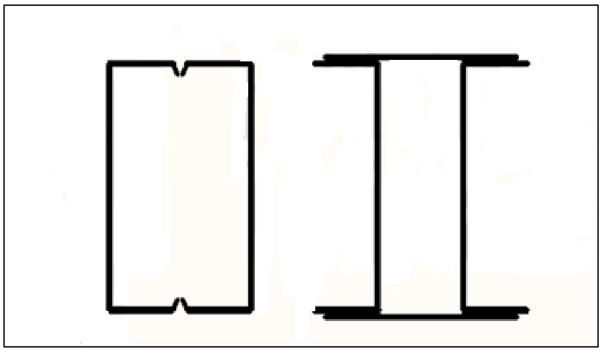

Figure 2.9 Closed built-up section

2.7 Perforations

Perforations is a hole or opening that are made on the cold-formed steel to ease construction work. As seen on Figure 2.7.1, 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 functions 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, 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 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. This is agreed by Chen and Liew (2003) 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 and shape of the perforations on the structural strength of the axially loaded cold-formed steel column.

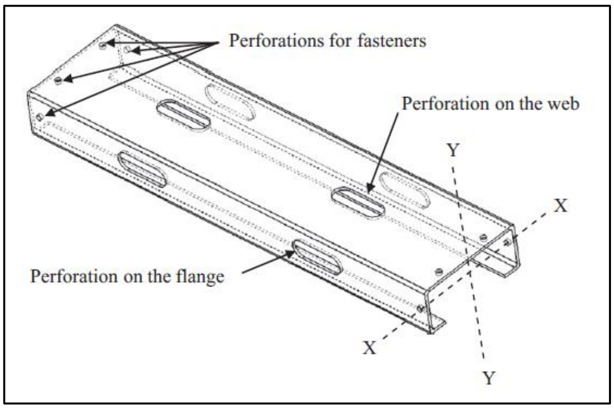

Figure 2.10 Perforations on cold-formed steel

2.8 Previous Research

Previous research that have been made by multiple researcher 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.

2.8.1 Behaviour of Cold-Formed Steel Built-Up I-Section

This research was done by T.A. Stone and R.A. LaBoube in 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 178mm and it is tested using universal testing machine. Pin connection was used at the top and bottom of the stud.

2.8.2 Investigation of Cold-Formed Steel Structural Members with Perforations of Different Arrangements Subjected to Compression Loading

The research that was done by M.P. Kulatunga and M. Macdonald back in 2013 focus on investigating cold-formed steel sections subjected to compression loading and to study the effect of perforation position on the load capacity of column members of lipped channel cross-section. However, these researches also are done through the method of Finite Element rather than just doing the laboratory experiment. The study showed that the ultimate load of the lipped channels under compression varied greatly with the perforation position. In this research, they have used British Standards – BS 5950 part 5:1998 for the recommendations for the design as it has a clear recommendation for the design of structural steelwork in building and related structure using cold-formed section of thickness up to 8mm. In their experimental investigation, the test specimens have a constant perforations size with different perforation position. The experiment that were done with applying load through a load bearing plate which represent the actual loading conditions. The displacement control method was employed to control the loading in stimulating the buckling behaviour observed. The experiment used flat-end boundary condition for all loading cases.

2.8.3 Load Capacity of Cold-Formed Column Members of Lipped Channel Cross-Section with Perforations Subjected to Compression Loading

This research was a collaboration between M.P. Kulatunga, M. Macdonald, J. Rhodes and D.K. Harrison in 2013. It was an investigation on the influence of perforations of various shape on the buckling behaviour of cold-formed column members of lipped channel cross-section. The experimental investigations are done to study the buckling behaviour of flat and fixed ended column and the result is compared and validate with the result of finite element analysis that is done simultaneously. These involved cold-formed steel lipped channel sections with perforations were tested to failure and all the sample used were cold-formed steel lipped C-section column. The fellow researcher has used two boundary conditions which are flat-end and fixed-fixed. They also used different column testing parameters such as perforation size, shape, position and end condition. In total, there are four set of specimen in this experimental investigation. The result of the experimental investigations was presented in a numerical result of load vs. displacement behaviour and it shown that the ultimate failure load of the lipped channels under compression varies greatly with the presence of the perforations.

2.8.4 Compression Test and Numerical Analysis of Web-Stiffened Channels with Complex Edge Stiffeners

This recent research was done in a cooperation between Chungang Wang, Zhuangnan Zhang, Daqian Zhao and Qingqing Liu back in 2016. Their papers describe a series of pin-ended compression test and numerical analysis of channels with complex edge stiffeners and two different type of web stiffeners. In the experimental investigation, axial and eccentric compression loading were imposed respectively on 18 and 12 specimens. The purpose of this paper is mainly to investigate the stability capacity, buckling mode and deformation behaviour of these specimens. The outcome of this experimental investigation was that the longitudinal intermediate stiffeners could reduce the web width-to-thickness ratio effectively and increase the stability capacity of members subjected to axial loading or eccentric loading with the eccentricity close to the web site

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 phase 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 "The Effect of Perforations on Axially Loaded I-section Cold-formed Steel Column" have been finalise, 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 source 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 axial load 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 600 mm length due to the limitation of height that the can be cater by the machine in the laboratory. The size of the section of each sample is 1.6 mm x 100 mm x 50 mm x13 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 M.P Kulatunga and M. Macdonald entitle "*Investigation of Cold-formed Steel Structural Members with Perforations of Different Arrangements Subjected to Compression Loading"* 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 three type which are the buckling behaviour of the sample, reading of axial load that are being applied to the sample and the displacements that were a result of the compression of the sample. 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 observe through presentation of picture of sample after the testing is done. For this testing, the result is then analyse and graph of load and 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 obtain 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 Preparation of I-shape Cold-Formed Steel Built-up Sections

In the preparation of the I-shape cold-formed steel built-up sections, two identical C-section columns were fastened together with self-drilling screws to form an I-section column. 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 C10016 that are 1.6 mm thick.

The perforations of the cold-formed steel are made using a circle shape with a diameter of 25 mm. As shown in Figure 3.1, there are three perforations made on each sample and these perforations are at different location on each sample. 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 50 mm each. The schematic detail of the screw spacing is presented in Figure 3.2.

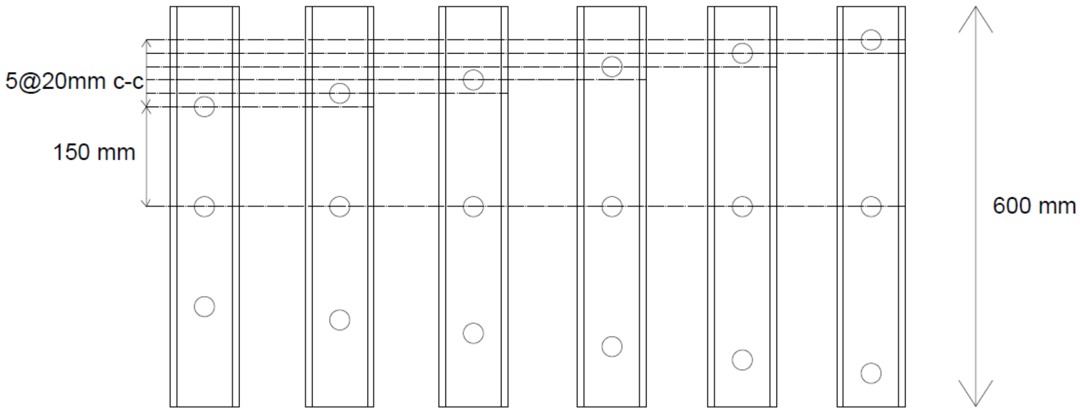

Figure 3.1 The perforation position

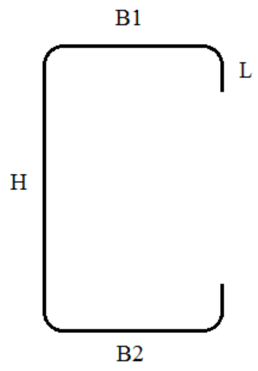

Figure 3.2 Dimensions of C-section sample

Table 3.1 Dimensions of C-section sample

C SECTION INDENTIFICATION	**DIMENSION (mm)**				
	H	B_1	B_2	L	t
LOG C10016	100	50	50	16	1.6

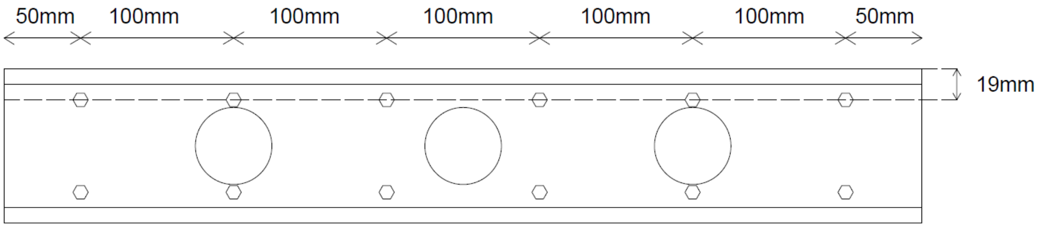

Figure 3.3 Screw spacing of the sample

3.2.1 Geometric Imperfection

In the preparation of the sample, the test members were carefully labelled so that the cross-sectional dimensions and the actual length of samples can be included. As cold-formed steel often experiences geometric imperfections due to the technic of folding the cold-formed steel to desired shape, the cold-formed steel that was received from the factory does not have accurate dimension in each sample.

The geometric imperfections could affect the ultimate load-carrying capacity, buckling mode and deformation of the axially loaded I-section cold-formed steel column later. The dimension of each sample is in Table 3.2. As the sample is in I-section, the dimension of each I-section sample consist of two dimensions from each C-section.

3.3 Compression Test

The experiment was done using a Universal Testing Machine that were available in Heavyweight Laboratory, FKASA. The machine can cater maximum axial load of 10,000 kN and the maximum height is one meter.

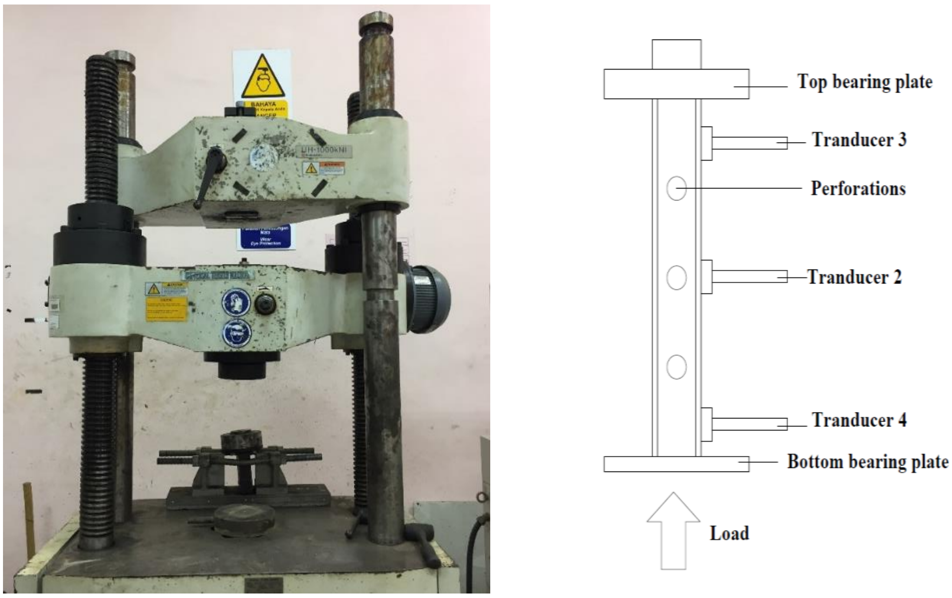

Figure 3.4 Universal testing Machine that are available in FKASA Heavyweight Laboratory

3.3.1 Test Setup and Procedure

There are four transducer that are used in this test. Three of it is placed on the sample while one was placed on the base plate of the universal testing machine. On the sample, the transducer is placed on top, middle and bottom of the sample. The function of the transducer is to calculate the horizontal displacement that were cause by the buckling of each sample. In this test, transducer 2 is placed at the middle, transducer 3 at the top while transducer is at the bottom of the sample. The details can be referred from Figure 3.4 and Figure 3.5. The placing of the transducer is according to the prediction of the buckling behaviour that were made prior the test by comparing with other research paper. As seen from Figure 3.6, the boundary condition used were simply supported as the sample does not have any rigid connection towards the machine.

The universal testing machine is setup and the displacement that are test in this testing is set to 6mm. This means, for every sample, the test will be end once the displacement of the sample that were caused by the axial load from the machine, reach 6mm. The result and data from each test will be provided into two set for each sample. The first set is from the data of axial load and vertical displacement from and the second set is from the data produced from the transducer which are the horizontal displacement. The thesis of M.P. Kulatunga and M. Macdonald (2012), T.A. Stone and R.A. LaBoube

(2005) and M.P. Kulatunga et. al., (2013) are being set as a reference through the execution of this project.

Figure 3.5 The placing of transducer from the front view

Figure 3.6 The placing of transducer from the side view

Figure 3.7 The boundary condition of the sample

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Analysis of Compression Test

The results from the compression test was measured from the maximum load that were applied on the sample before it buckles, buckling behaviour and the displacement of transducer. The data is presented through graph of load vs vertical displacement and load vs horizontal displacement where it compared the axial load and the displacement of the sample.

4.1.1 Load vs Vertical Displacement

For this part, the load applied on the sample is compared to the displacement that occur on the sample. As seen from Figure 4.1, the maximum axial load applied is on I4 with 212.45 kN while the lowest axial load was applied on I1 which is 151.262 kN. A graph of load vs displacement is plotted at the end of the test and it could be seen in Figure 4.2. Vertical displacement is the displacement that results from the compressing of the machine. The value shows the movement of the machine table in the act of compressing the cold-formed column.

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 centre, the maximum axial load applied decrease.

Table 4.1 Maximum axial load of each sample

Sample	Maximum axial load
I1	151.262 kN
I2	188.650 kN
I3	197.344 kN
I4	212.453 kN
I5	208.297 kN
I6	191.500 kN

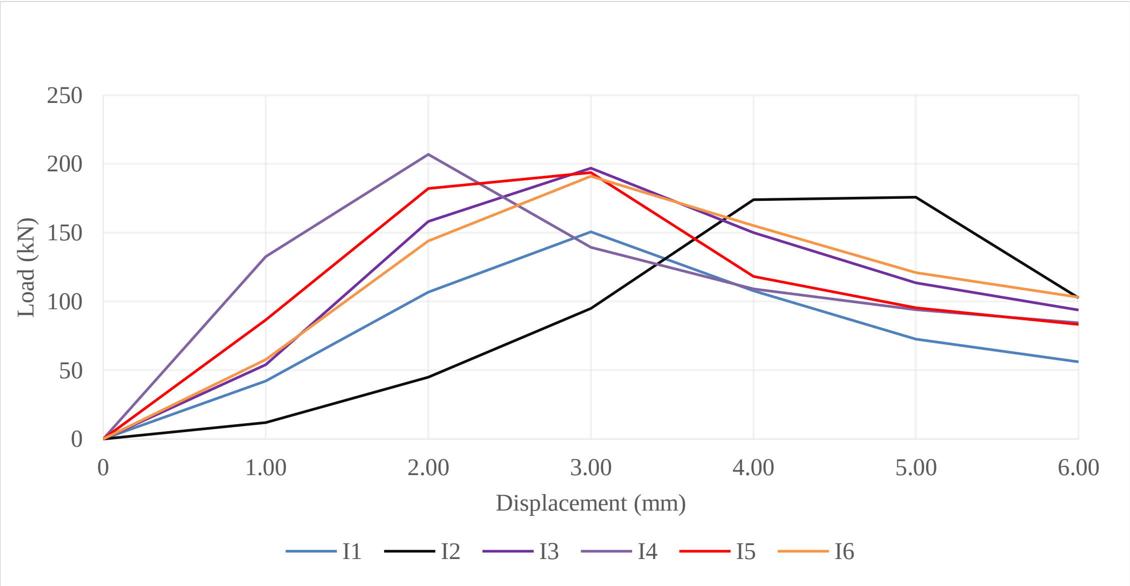

Figure 4.2 Load vs vertical displacement graph

4.1.2 Load vs Horizontal Displacement

The horizontal displacement is the corresponding data that were collected from the present of transducer that were place on three different point on the sample to measure the horizontal displacement. The data is presented though a load vs horizontal displacement graph where each graph represent each sample with three transducers attach to it. The graph of each sample is represented in a graph from Figure 4.3 until Figure 4.8 below.

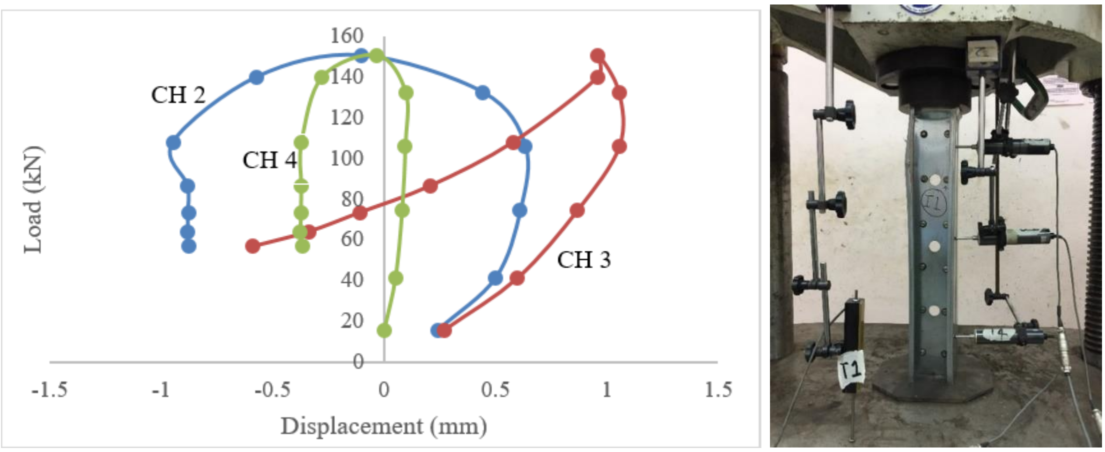

Figure 4.3 Sample I1

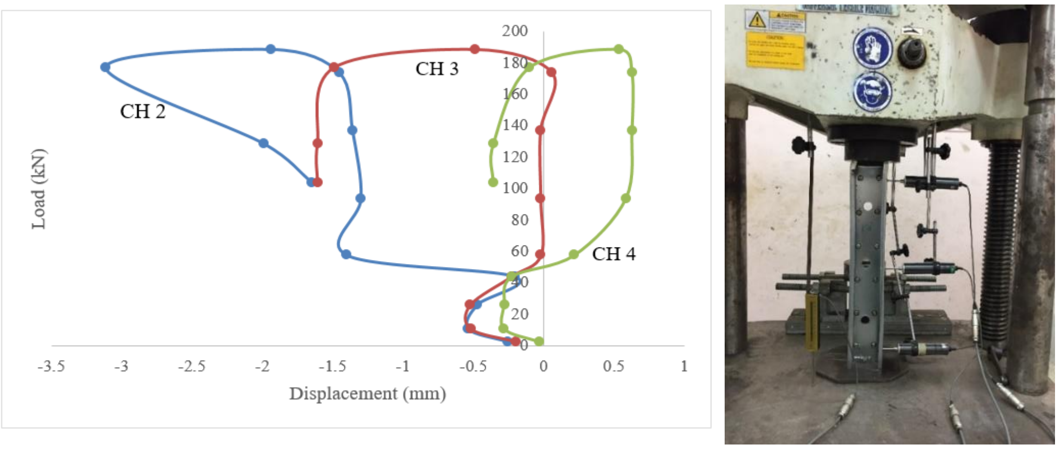

Figure 4.4 Sample I2

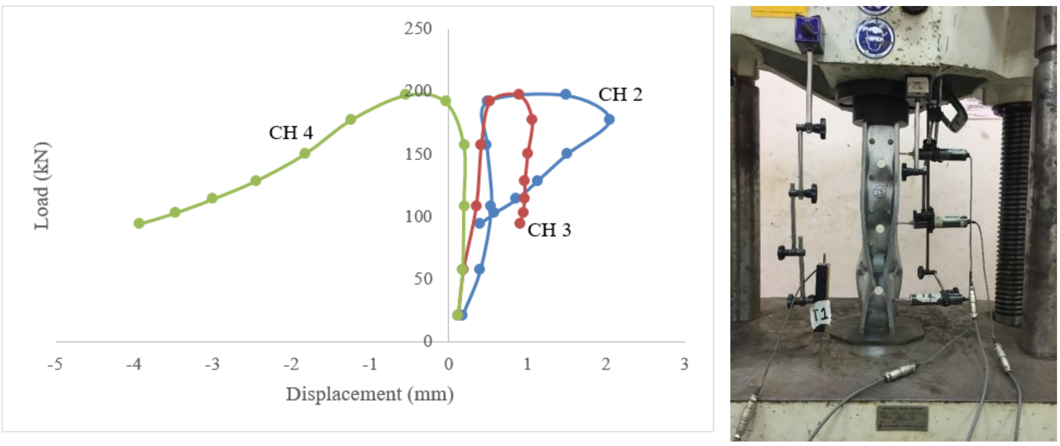

Figure 4.5 Sample I3

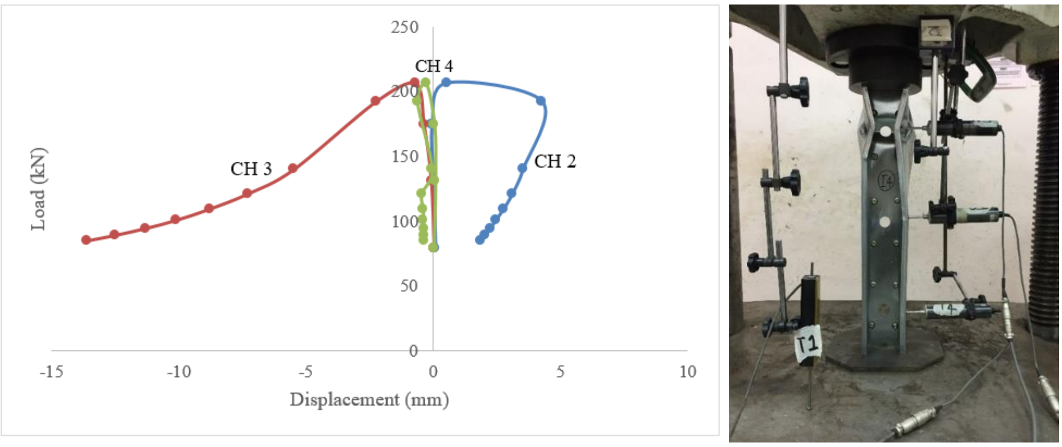

Figure 4.6 Sample I4

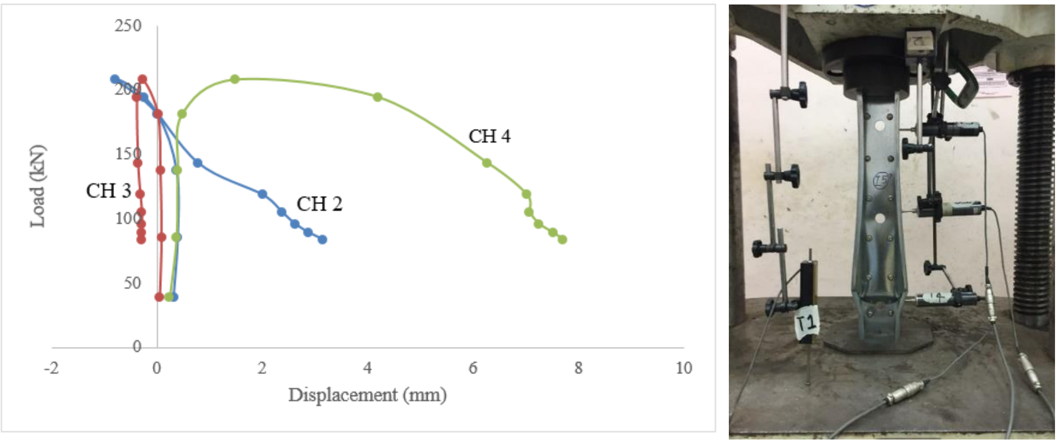

Figure 4.7 Sample I5

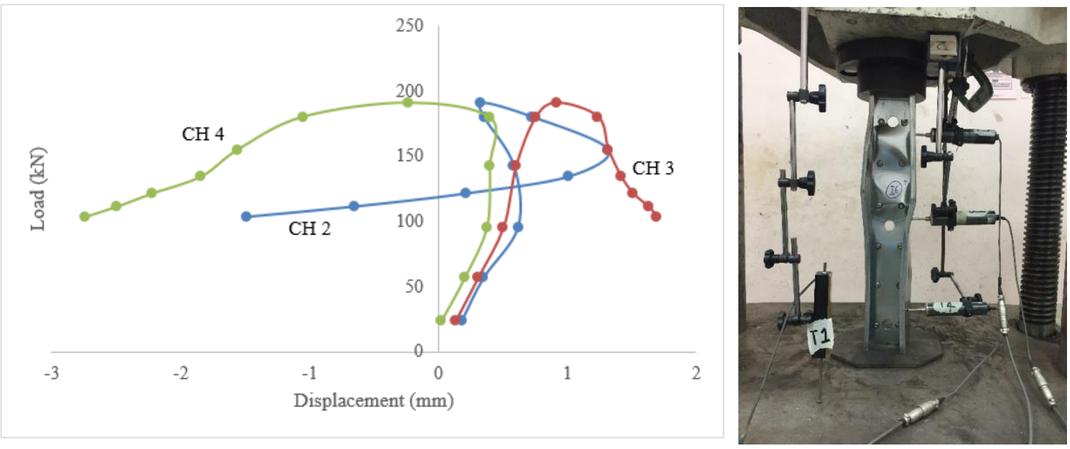

Figure 4.8 Sample I6

The maximum axial load for sample I1 is 151.26 kN and the maximum displacement is 0.959 mm which happen at the transducer CH 3 around the same time that maximum axial load is subjected to the sample. As seen from Figure 4.3, the graph intersects several times in the test. First, between CH 4 and CH 2 at load of 150.48 kN and again between CH 3 and CH 4 at the load of 63.79 kN.

For sample I2, the maximum axial load is 188.65 kN and the maximum displacement of the sample is -3.115 mm that happen after the maximum axial load is applied on the sample. As seen from Figure 4.4, the sample move into negative displacement for all three transducers until it reach the fourth point of load which are around 43.94 kN. After that, the graph diverges and only intersect again at the time maximum axial load is applied and it is between CH 2 and CH 3.

Sample I3 has a maximum axial load of 197.34 kN and a maximum displacement of -3.932 mm that happen at CH 4 at the end of the test. As seen from Figure 4.5, the graph intersects several times of the test. The first one is between CH 2 and CH 3 at load 57.31 kN. Towards the time when maximum axial load is applied, the graph intersects again between transducer CH 2 and CH 3 at load 191.89 kN and 197.02 kN.

Among all the sample tested in this project, sample I4 has the maximum axial load which is 212.45 kn. The maximum displacement of the sample is13.59 mm that happen at the end of the test at CH 3. As seen from Figure 4.6, the graph of CH 4 maintains around 0.4 until -0.5 which indicates that the bottom part of the sample did not move or buckle much through this test. However, CH 2 and CH 3 diverge into different direction towards the end of the test, producing the shape of buckle as seen above.

Sample I5 has a maximum axial load of 208.297 kN and a maximum displacement of 7.708 mm that happen at the end of the test. From Figure 4.7, up until the third point, the sample move into the same direction. However, CH 4 start to diverge to have positive displacement until the end of test.

The maximum load of sample I6 191.50 kN while the maximum displacement is -2.739 mm that happen in CH 4 at the end of the test. Unlike the other samples that buckle at the top or bottom of the cold-formed steel column, the buckling of sample I6 includes the mid-span of the short column. From Figure 4.8, the graph moves into the same direction until point number 4. Afterwards, CH 3 and CH 4 intersect at the load 179.55 kN, just before the maximum axial load is applied.

4.1.3 Buckling Behaviour of Samples

Overall, the samples show a series of local buckling and distortional buckling. Three of the samples which are I2, I3 and I5 buckles at the the bottom while the other buckle at the top. Figure 4.16 and Figure 4.17 shows the condition of all samples after the test from the front view and back view.

Figure 4.9 The condition of samples after the compression test (Front view)

Figure 4.10 The condition of samples after the compression test (Rear view)

CHAPTER 5

CONCLUSION

5.1 Conclusion

From the result of the experiment, several conclusions can be made. First, the position of perforations plays an important role in determining the ultimate load of the sample. As seen from the experimental result, the result varies greatly as the perforations position change. The result shows that, as the perforations position is placed nearing the support, the ultimate load of the sample will decrease. The position of perforations also must not be located near the centre of the sample, as it is the critical buckling position. Next, a short cold-formed steel column will fail in local buckling and distortional buckling. A short cold-formed steel column will only fail in either local buckling or distortional buckling. As seen from the buckling behaviour of the samples after the compression test, all sample experience distortional buckling.

5.1 Recommendation

There are few recommendations that can be used in future research regarding cold-formed steel column. First, use different size of section. In this research, only one section size is 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, to do an analysis of Finite Element. This research only used experimental investigation to study the effect of perforation on the axially loaded cold-formed steel column. The buckling behaviour can be predicted accurately using Finite Element (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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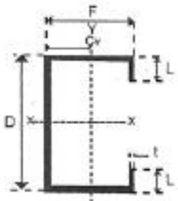
APPENDIX A
PREPARATION OF I-SECTION COLD-FORMED STEEL

APPENDIX B
PURCHASE SLIP OF THE SAMPLE



D = depth
F = flange
L = lip
t = thickness

High Tensile Galvanized C - Purlin Properties & Dimensions

C SECTION IDENTIFICATION	DIMENSION					AREA OF SECTION	MASS PER UNIT	2ND MOMENT OF AREA		SECTION MODULUS		RADIUS OF GYRATION		
	D	F_1	F_2	L	t			Ix	Iy	Zx	Zy	rx	ry	Cy
	mm	mm	mm	mm	mm	mm^2	kg/m	$10^6 mm^4$	$10^6 mm^4$	$10^3 mm^3$	$10^3 mm^3$	mm	mm	mm
LOG C10016	100	50	50	16	1.6	373	2.80	0.60	0.14	11.77	4.11	40.6	19.5	18.24
LOG C10020	100	50	50	16	2.0	422	3.45	0.76	0.18	14.84	5.46	41.9	20.3	18.60
LOG C10025	100	50	50	16	2.5	534	4.40	0.95	0.22	18.56	7.01	42.7	20.9	19.05
LOG C12516	125	50	50	16	1.6	408	3.10	1.00	0.15	15.72	4.29	50.0	21.4	11.08
LOG C12520	125	50	50	16	2.0	510	3.82	1.25	0.19	19.67	5.49	50.1	21.5	16.42
LOG C12525	125	50	50	16	2.5	638	4.89	1.56	0.24	24.56	7.13	50.1	21.6	17.35
LOG C15016	150	65	65	16	1.6	489	3.84	1.77	0.28	23.60	6.31	60.2	24.0	19.30
LOG C15020	150	65	65	16	2.0	608	4.77	2.19	0.35	29.20	7.74	60.0	23.9	19.60
LOG C15025	150	65	65	16	2.5	755	5.93	2.70	0.42	35.90	9.44	59.8	23.6	20.00
LOG C17516	175	75	75	16	1.6	564	4.47	2.79	0.43	31.89	8.03	70.3	27.7	22.10
LOG C17520	175	75	75	16	2.0	702	5.54	3.45	0.53	39.46	9.82	70.1	27.5	21.90
LOG C17525	175	75	75	16	2.5	873	6.89	4.26	0.65	48.72	11.97	69.9	27.3	21.70
LOG C20016	200	75	75	16	1.6	572	4.70	3.80	0.37	37.44	7.09	80.8	25.1	19.18
LOG C20020	200	75	75	16	2.0	689	5.74	4.75	0.45	46.80	9.39	82.5	25.4	20.16
LOG C20025	200	75	75	16	2.5	855	7.03	5.94	0.61	58.52	12.23	83.4	26.8	20.80
LOG C25020	250	75	75	18	2.0	540	6.69	7.63	0.58	61.08	10.08	95.3	26.3	18.83
LOG C25025	250	75	75	18	2.5	1050	8.34	9.52	0.73	76.18	12.85	95.2	26.4	18.85