AXIALLY LOADED OF COLD-FORMED STEEL COLUMNS WITH OPENING

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ABSTRAK

Kajian ini membentangkan mengkaji tingkah laku lengkokan tunggal C-seksyen sejuk terbentuk dengan pembukaan. Keluli sejuk terbentuk adalah istilah umum untuk produk yang dibuat oleh bergolek atau menekan keluli menjadi barang separuh siap atau siap pada suhu yang agak rendah. Kaedah ujian yang digunakan untuk eksperimen ini adalah ujian mampatan. Spesimen tiang telah dimampatkan antara plat galas dengan hujung rata. 7 spesimen dengan ketinggian 600 mm dengan satu tanpa bukaan dan 6 yang lain dengan bukaan telah digunakan dalam eksperimen ini. Bentuk bukaan yang digunakan adalah bulatan dan saiz bukaan yang digunakan adalah sama bagi setiap specimen iaitu 25 mm diameter untuk memastikan konsisten dalam setiap keputusan. Kekuatan beban muktamad seksyen keluli sejuk terbentuk dan mod kegagalan berbeza bergantung kepada kedudukan bukaan, di mana kesimpulan yang membuat berdasarkan perbandingan antara posisi bukaan. Transduser digunakan untuk membaca anjakan spesimen semasa ujian di mana graf telah diplot. Graf beban melawan pergerakan flange semasa ujian mampatan telah di plot. Jarak antara bukaan dan jarak bukaan daripada sokongan tidak memberi banyak perbezaan kepada keputusan dan ini mungkin kerana jarak antara bukaan yang tidak banyak perbezaan. Lengkokan tempatan dan lengkokan distortional boleh dilihat pada spesimen. Lengkokan tempatan hanya berlaku pada spesimen yang tidak mempunyai bukaan manakala bagi spesimen yang mempunyai bukaan, lengkokan distortional berlaku di mana flanged membengkok ke luar atau ke dalam dapat dilihat.

ABSTRACT

This paper presents study the buckling behavior of cold-formed single C-section with opening. 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. The method used for this experiment are compression test. The column specimens were compressed between bearing plate with flat ends. 7 number of specimens with height of 600 mm with one without opening and the other 6 with openings had been used in this experiment. The shape of openings used are circle and the size are keep constant that is 25 mm diameter to ensure the consistency in the result making. The ultimate load strength of the cold-formed steel section and failure modes differs depend on the position of the openings, where the conclusions are make on the basis of the comparisons between the positions of openings. Transducers used to read the displacement of the specimen during testing where the graph had been plotted. The load – displacement graph study the movement of the flange during compression test. The distance between openings and the opening distance from the support did make a difference to the results but the difference did not varies much due to the smaller distance between openings. Local buckling and distortional buckling can be seen at the specimen. Local buckling only happen at the specimen that did not has openings while for specimen that have openings, distortional buckling occurred where the flanged distort outward or inward can be seen.

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LVDT	Linear Vertical Displacement Transducer

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The construction industries has going through many changes and development towards the better and more advanced structures. Steel is one of the material of construction and is a basic ingredient needed in construction. In steel structures, there are two types of structural steel members that are hot-rolled steel members and cold-formed steel members. The hot-rolled steel members always being a popular choice of steel group and are widely used in construction industry but because of the several advantages of cold-formed over the hot-rolled steel sections, the use of cold-formed high strength steel structural members shown a rapid increase. Cold-formed steel structural members are commonly provided with holes to accommodate electrical and plumbing of building.

1.2 What is Cold-formed

Cold-formed steel members as shown in Figure 1.1 is formed in room temperature state and the steel product is formed by a steel strip or sheet of uniform thickness that combined together to formed a structure. The use of cold-formed steel section in others country can be found in rail transport, building and bridge construction and various type of equipment. In Malaysia, the common used of cold-formed steels are limited to a roof truss and framing. In construction industry, the cold-formed steel is being used in both non-structural and structural members. As non-structural members, the advantages are more on resistance to the rust because of the coating and aesthetic purposes because cold-formed can be coloured and design according to the interest. It is used as non-structural member for door and window farming, wall panelling and services. As structural members, the usage can be used as a truss members, beams, columns, and floor decking in steel concrete construction.

Cold-formed steel products are shaped from steel sheet, strip plate or flat bars by cold rolling-forming method or press braking method. They can be produced in large quantity in a limited time consumption and at high speed with consistent quality. The thickness of material formed together usually range in general between 0.70 mm to 3.5 mm. The critical elastic buckling loads are associated with local, distortional, and global buckling. Unlike heavy hot-rolled steel sections, cold-formed thin-walled sections tend to buckle locally at stress levels lower than the yield strength of the material when they are subjected to various loading conditions. However, failure modes are not commonly encountered in normal structural steel design specifications, and therefore, extensive testing is required to provide a guideline for the design of cold- formed thin-walled structural members.

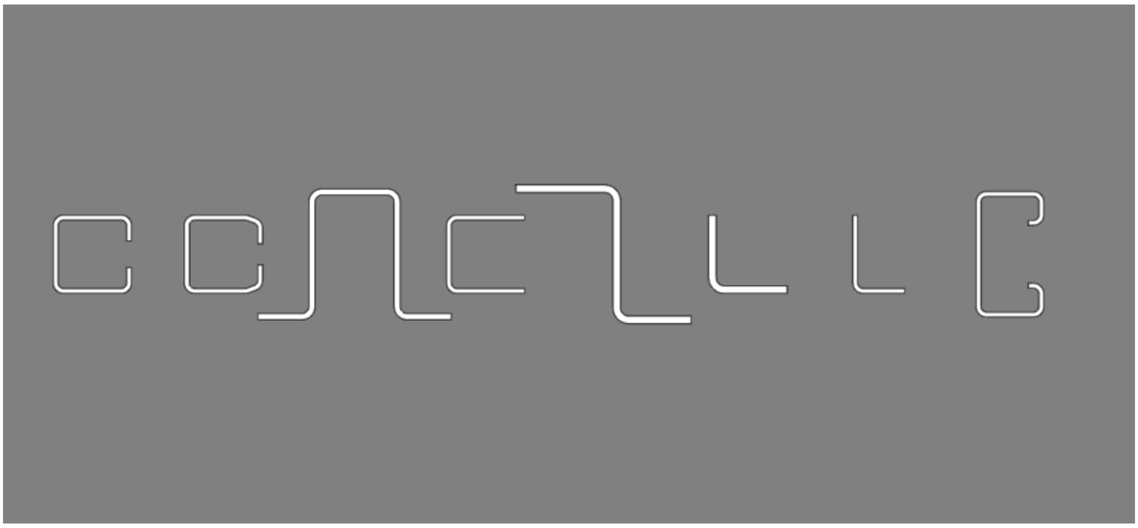


Figure 1.1 Example of cold-formed steel

Opening in cold-formed steel sections made specifically for fasteners such as bolts, screws, etc., may be neglected as openings are filled with material. However, for any other openings, the reduction in cross sectional area caused by theses openings should be taken into account. The ultimate strength and elastic stiffness of a structural member can vary with opening position, size, shape and orientation. In evaluation of the section properties of members in compression, openings need to be considered. The perforations can be divided by pre-punched or punched-on-site but mostly pre-punched are more favourable due to the problem that will rise later if the hole are not accurately made.

1.2.1 Example of Usage of Cold-formed Steel

Figure 1.2 House made up from cold-formed steel

Figure 1.3 Cold-formed steel framing

1.3 Problem Statement

Cold-formed steel structural members are commonly manufactured with holes to accommodate plumbing, electrical, and heating conduits in the walls and ceilings of buildings However, special properties of steel cold-formed members required special consideration when it come to the application in construction. Due to the variety of arrangement of openings, some special task of research to provide the practical design need to be done where the stability and strength are likely reduced by the existence of the perforations. Many problems had risen due to the existing of openings because the design process will be much more complicated and need extra study from the expert and already lead to the collapse of the building. This lead to the usage of the cold-formed steel with openings in the industry is limited and this can be changed with a lot of study by the expert.

Cold-formed steel with openings have their own advantages and disadvantages to the column and structure itself. Openings can be found in any desired shape of opening especially in circle, rectangular, oval or rectangle. The existence of opening will reduce the surface area of cold-formed steel and theoretically, their strength will likely to be reduced form the cold-formed without opening. The imperfection due to the residual stress because of folding the cold-formed steel are among the issue in this study. The yield stress that formed cannot be avoid because during forming the cold-formed, some stress need to be applied to make a desired shape of cold-formed.

The effect of strength of cold-formed due the compression also need to be taken into consideration because the strength will be likely decrease due to the openings. Experimental study needed to be done because there will be huge effect if the opening is being made because theoretically the opening will make the cold-formed have a less strength than cold-formed without opening. The structural behaviour of the cold-formed steel members characterized by different position of openings is not yet fully understood. Holes are generally assumed to decrease the elastic local buckling load of a flat plate loaded in uniform compression.

1.4 Research Objective

The main aim of this research is to study the condition of cold-formed steel section open C-section with opening under compression. In order to achieve this, several objectives are identified as follows:

i. To determine the ultimate load of axially loaded of single C section steel column.

ii. To study the ultimate load of C section column with different position of openings.

iii. To study the behaviour of failure mode of axially loaded column with different position of openings.

1.5 Research Scope

In this study, a series of column tests on cold-formed steel C-shaped open sections with edge and web stiffeners were conducted. The columns were compressed between fixed ends. Current design methods available to engineers for predicting the strength of cold-formed steel members with holes are prescriptive and limited to specific perforation locations, spacing, and sizes. The section of cold-formed that being tested is a single section and a short cold-formed steels are being used which range between 700 mm to 1000 mm with the thickness around of 1 to 2 mm. Eight specimen of cold-formed steel will be used with one does not have opening and the other seven will have an opening as shown in Figure 1.4. The shape of the opening used is circular shape. The position of opening of perforations at the cold-formed steel member also varies. The plate will be used as a base that will act as a support and will be welding together with one of the end of cold-formed and act as a fixed support. There will be 2 type of section size during experiment. The failure mode of axially loaded column with different position of perforations is tested by study the behaviour of the buckling mode of the cold-formed steel.

Figure 1.4 Example of cold-formed steel with different position of openings
Source: Kulatunga, M. and Macdonald, M. (2013)

1.6 Significance of Research

The finding of this study will contribute to the benefit of the construction industry. The behaviour of cold-formed steel when the perforations exist can be studied. The deformation of cold-formed at the different position of perforations also can be analysed by the experimental study. The data of either the column will show an effect if the position of perforations varies or not can be taken. The strength of the cold-formed steel will likely will change depend on the position of perforations. According to previous researcher, cold-formed tend to buckle locally at stress levels lower than the yield strength of the material when they are subjected to various loading conditions. However, the failure modes are not commonly encountered in normal structural steel design specifications, and therefore, extensive testing is required to provide a guideline for the design of cold-formed structural members.

CHAPTER 2

LITRATURE REVIEW

2.1 Introduction

The usage of cold-formed steel have been commonly used in the metal building construction industry for more than 40 years (Anbarasu, et. al., 2010). Development and usage of cold-formed steel structural members came to use in building construction in about the 1850s in the United States and Great Britain. However, they were not widely used in building structures until 1940 (Yu, 2000). The popularity of these products has increased in a drastic way in recent years due to their wide range of application, economy, ease of fabrication and high strength to weight ratios. Figure 2.1 shows the common shapes of cold-formed steel. Although there are many various shape that are available but C-sections are commonly used in light load and medium span situations such as roof systems, see in Figure 2.2.

In Malaysia, the cold-formed usage in building construction did not widely applicable until recently where the use of cold-formed steel in replacing hot-formed steel had been widely accepted. But, the usage of cold-formed still not widely used in construction due to the limitation of the specimen. Most local product in market has their own limitation due to the absent of opening. When the opening is being made, the limitation strength of cold-formed will likely will be changed. So, this study will show either the existing of opening will affect the strength of cold-formed steel.

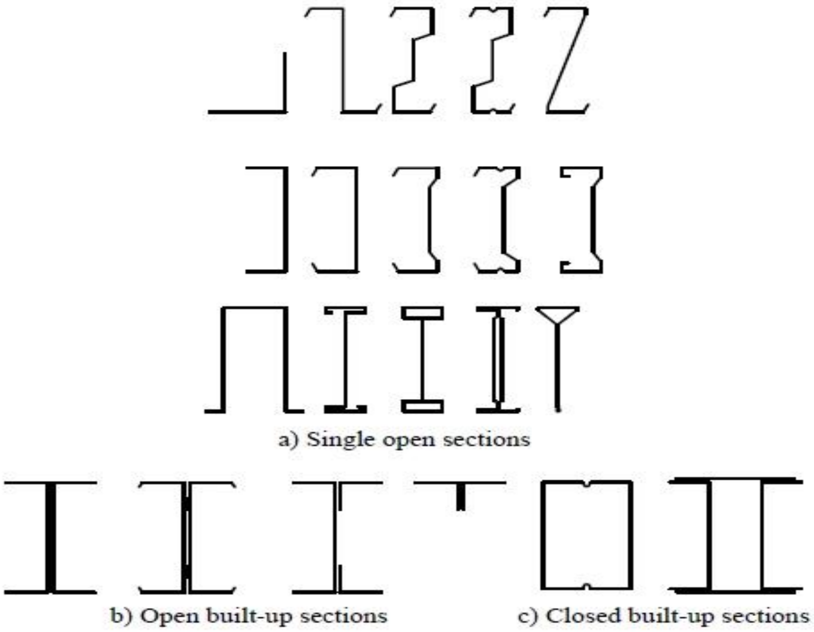


Figure 2.1 Common shapes for cold-formed steel

Figure 2.2 Roof system using cold-formed

2.2 Characteristic of Cold-formed Steel Members

Steel can be divided by hot-rolled steel and cold-formed steel. According to Satpute (2012), a cold-formed steel structure is the product made by bending flat sheets of steel at ambient temperatures into shapes which it can support more than the flat sheet themselves.

2.2.1 Cold-forming Process

Zhou (2017) stated that cold-formed steel members are manufactured by one of the three processes that are roll forming, folding and press braking. Roll forming consists of feeding a continuous steel strip through a series of opposing rolls to deform the steel plastically to form a desired shape. It is often used to produce sections where large quantities of a given shape are required. The shortcoming of roll forming is the high initial costs and the difficulty of changing to a different size section. Press baking normally involves producing one complete fold at a time along the full length of a section. Usually for sections with several folds, it is necessary to move the steel plate in the press and to repeat the pressing operation several times. Therefore press baking can be used to produce a variety shape with low volume production.

2.2.2 Cold-formed Steel Column

The design of cold-formed steel column is prepared on the basis of the 2001 edition of the North American Specification For The Design Of Cold-Formed Steel Structural Members and the 2002 edition of the AISI Cold-Formed Steel Design Manual.

2.2.3 Advantages of Cold-formed Steel

Anbarasu, et. al., (2010) indicate that, following advantage can be realized for cold-formed light gauge steel structural members in building construction:

a) Cold rolling can be employed to produce almost any desired shape to any desired length.
b) Pre-galvanized or pre-coated metals can be formed, so that high resistance to corrosion, besides an attractive surface finish, can be achieved.
c) All conventional jointing methods, for example riveting, bolting, welding and adhesive can be employed.
d) High strength to weight ratio is achieved in cold rolled products.
e) They are usually light making it easy to transport and erect
f) As compared with thicker hot rolled shapes, more economical design can be achieved for relatively light loads and/or short spans.

g) Unusual sectional configuration can be economically produced by cold-forming operation, and consequently favourable strength to weight ratios can be obtained.
h) Load carrying panels and decks can provide useful surfaces for floor, roof, and wall constructions, and in other cases they can provide enclosed cells for electrical and other conduits.

2.3 Imperfection of Cold-formed Steel

Compared with conventional structural column members, cold-formed steel, thin-walled, open cross-section column members have at least three competing buckling modes namely local, distortional, and Euler (flexural or torsional-flexural) buckling as illustrated in Figure 2.3 as stated by Anbarasu, et. al., (2010). 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 behaviour of hot-rolled steel where steel yielding is the leading design consideration There are two limit states for compression members that are yielding and overall buckling. Yielding is mainly an issue for compact and short columns. The yielding of the steel causes the failure of the entire column. For longer columns, it is likely that buckling will control rather than yielding of the member.

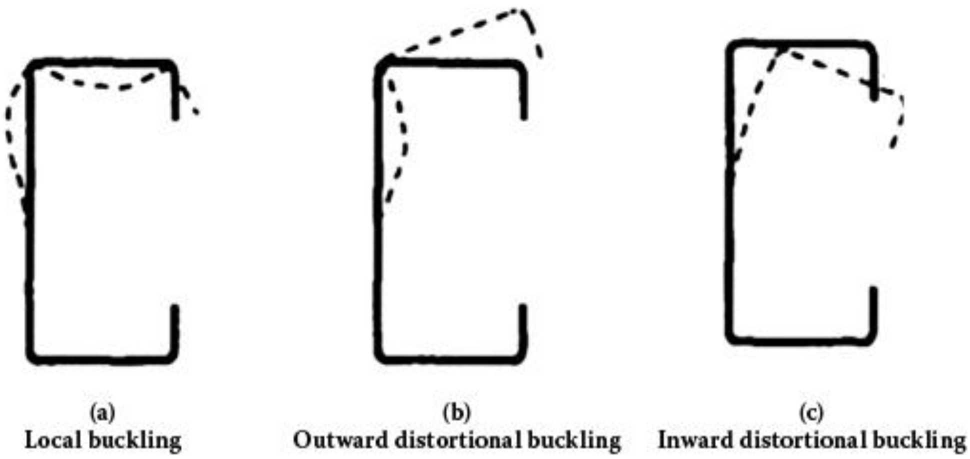


Figure 2.3 Type of buckling in cold-formed

2.3.1 Local Buckling

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

2.3.2 Distortional Buckling

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

2.3.3 Flexural - Torsional Buckling

Due to the smaller thickness the section have low torsional stiffness and their shear centre and centroid are located away from each other. This causes flexural-torsional buckling in which simultaneous bending and twisting in cold-formed steel occur.

2.4 The Design Standards for Axial Load

The Effective Width Method and Direct Strength Method (DSM) are the only two basic designs that are accessible now by the design codes including North American Specification for Cold-Formed Steel Structural members (AISI-2007). However, as structural shapes became more complex with additional lips and intermediate stiffeners, accurate computation of the effective widths of individual elements of the complex shapes becomes more difficult and inaccurate. The effective width method has its limitations in which it neglects the interaction of the compression elements of the sections. In order to overwhelm this problem, the Direct Strength Method (DSM) was developed. The Direct Strength Method is an alternative procedure for determining the strength or resistance and stiffness of cold-formed steel members either beams or columns (Zhang and Young, 2012).

2.4.1 Direct Strength Method

Moen and Schafer (2010) provided an introduction to the DSM approach for Cold-Formed Steel beams with holes and prevented the critical elastic buckling including presence of holes in the web and modified strength expressions to capture the strength reduction from yielding at the net section. Yu and Laboube (2010) indicated that the cold-formed steel compression members, due to the cross section shape, plat thickness and column strength, would fail in the following four limit states:

a) Yielding
b) Overall buckling including flexural buckling, torsional buckling and flexural-torsional buckling.
c) Local buckling (only occur in the individual compression element).
d) Distortional buckling for lip stiffened open section.

The Direct Strength Design Method, presented by Schafer (2008) is initially proposed in 1988 and has been adopted by the North American Cold-Formed Steel Specifications in 2004 as an alternative to the traditional EWM to estimate the compression and the flexural member strength, which can consider an interaction of local or distortional and overall buckling modes. This method does not require effective width calculations or iteration, but instead uses gross properties and the elastic buckling behaviour of cross section to calculate section or member strength.

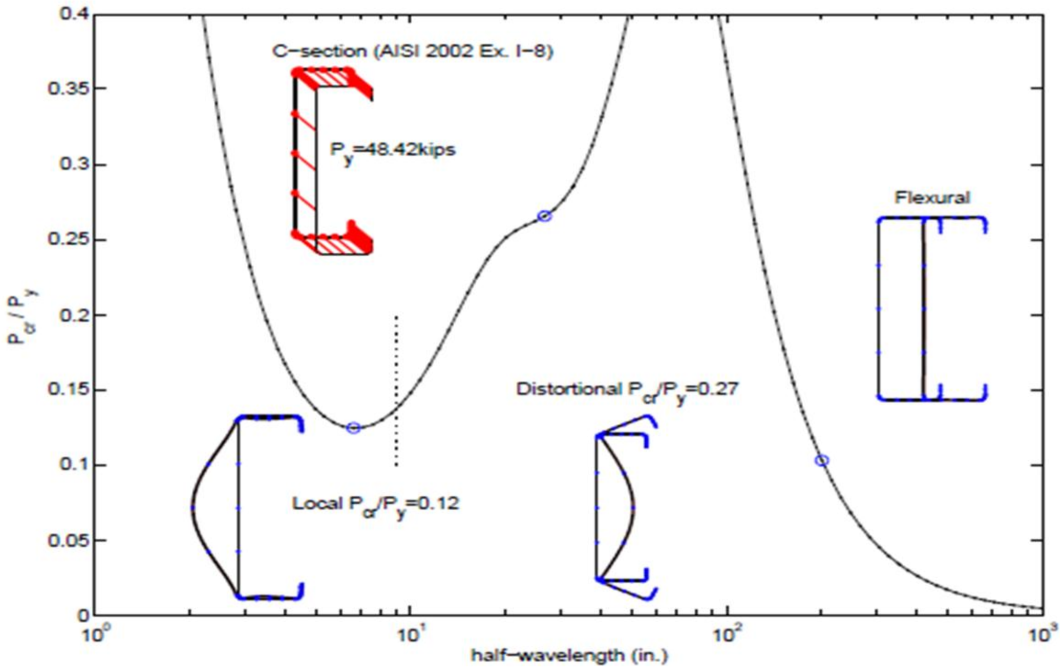


Figure 2.4 C-Section in Compression Showing Local, Distortional And Lateral-Torsional Buckling

Source: Direct Strength Method (DSM) Design Guide (2006)

2.5 Effect of Axially Loaded Cold-formed Steel Column

The critical elastic buckling loads will occur that are associated with local, distortional, and global buckling. The study by Kulatunga and Macdonald (2013) stated that it was found out that all of the columns tested failed by local and distortional buckling. The test results were compared with American (AISI-2007) and British Standards (BS5950-Part5) for the design of cold-formed steel structural members. Al-Jallad and Al-Thairy (2016) indicated that the reduction in the axial compressive strength of the column specimens caused by the presence of web openings is lower for the circular shape openings compared to that for rectangular and/or square shape web openings. The increasing number of web opening reduced the column axial stiffness owing to decreasing of the cross sectional area of the tested steel column.

Cold-formed steel compression members may be so proportioned that local buckling of individual component plates occurs before the applied load reaches the overall collapse load of the column. The interaction effect of the local and overall column buckling may result in a reduction of the overall column strength. Based on Yu, (2000), the influence of local buckling on column strength depends on the following factors:

a) The shape of the cross section
b) The slenderness ratio of the column
c) The type of governing overall column buckling (flexural buckling, torsional
d) buckling, or torsional–flexural buckling)
e) The type of steel used and its mechanical properties
f) Influence of cold work
g) Effect of imperfection
h) Effect of welding
i) Effect of residual stress
j) Interaction between plane components
k) Effect of perforations

2.6 Previous Research Paper

2.6.1 Experiment on Cold-formed Steel Columns with Holes

Test done by Moen. and Schafer (2008) describe a series of compression test performed on cold-formed steel column. The test results presented is to observe and quantify the relationship between elastic buckling steel columns with holes. Compression test were conducted on 24 short and intermediate length cold-formed steel columns with and without slotted web holes. For each specimen, a shell finite element eight buckling analysis was also conducted such that the influence of the boundary conditions and the hole on local, distortional and global elastic buckling response also be captured. Slotted web holes may modify the local and distortional elastic buckling half-wavelengths, and may also change the critical buckling load. Experimentally, slotted web holes are shown to have minimal influence on the tested ultimate strength in the specimens considered although post-peak ductility is decreased in some cases. Tangible connections are observed between elastic buckling and load-displacement response during the tests, including mode switching between local and distortional buckling. The columns are tested with friction-bearing boundary conditions where the columns ends are milled flat and parallel, and bear directly on steel plate. The presence of slotted holes caused only a slight decrease in the ultimate compressive strength of the tested columns, although the post-peak response and column ductility were influenced by the presence of slotted holes, the cross-section type, and the length member. In short columns, the slotted holes reduced the web buckling capacity, causing the column to rely more on the flanges and lip stiffeners to carry load with a distortional-type failure.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discuss the method involved in this study that is experimental compression test on short columns. The process of setting up the specimen during testing start by putting up the transducer first. After the transducer are placed, the specimen then is placed on the machine. Next, the transducer are put at the position according to the focussing study. Then, the loading rate of machine need to be set-up. The Universal Testing Machine will compressed the specimen until the machine are stop by the user according to displacement value study.

Research study by Kulatunga and Macdonald (2013) tittle, Investigation of cold-formed steel structural members with perforations of different arrangements subjected to compression loading, (2013) had been used as a standard to do the experiment and provided the basic guidance to develop all the research on cold-formed steel members. Seven specimens had been used where all specimens have different position of openings. The thickness and length of the specimens used are consistent to get an accurate results and to do comparisons.

The result of the performance and behaviour between cold-formed steel lipped single C section and the position of openings with the axial load applied to the cold-formed steel column were obtained by using the experimental study at the laboratory. .The experimental investigation was aimed at studying the influence of opening positions on the ultimate strength and the failure modes of lipped single C-section columns.

3.2 Experimental Investigation

Thin-walled cold-formed lipped channel sections subjected to compression loading were considered in the investigation. Figure 3.1 below show the overview of the flow process where the experiment will be conducted in Phase 2 and Figure 3.2 shows the rolled forming process of cold-formed at factory.

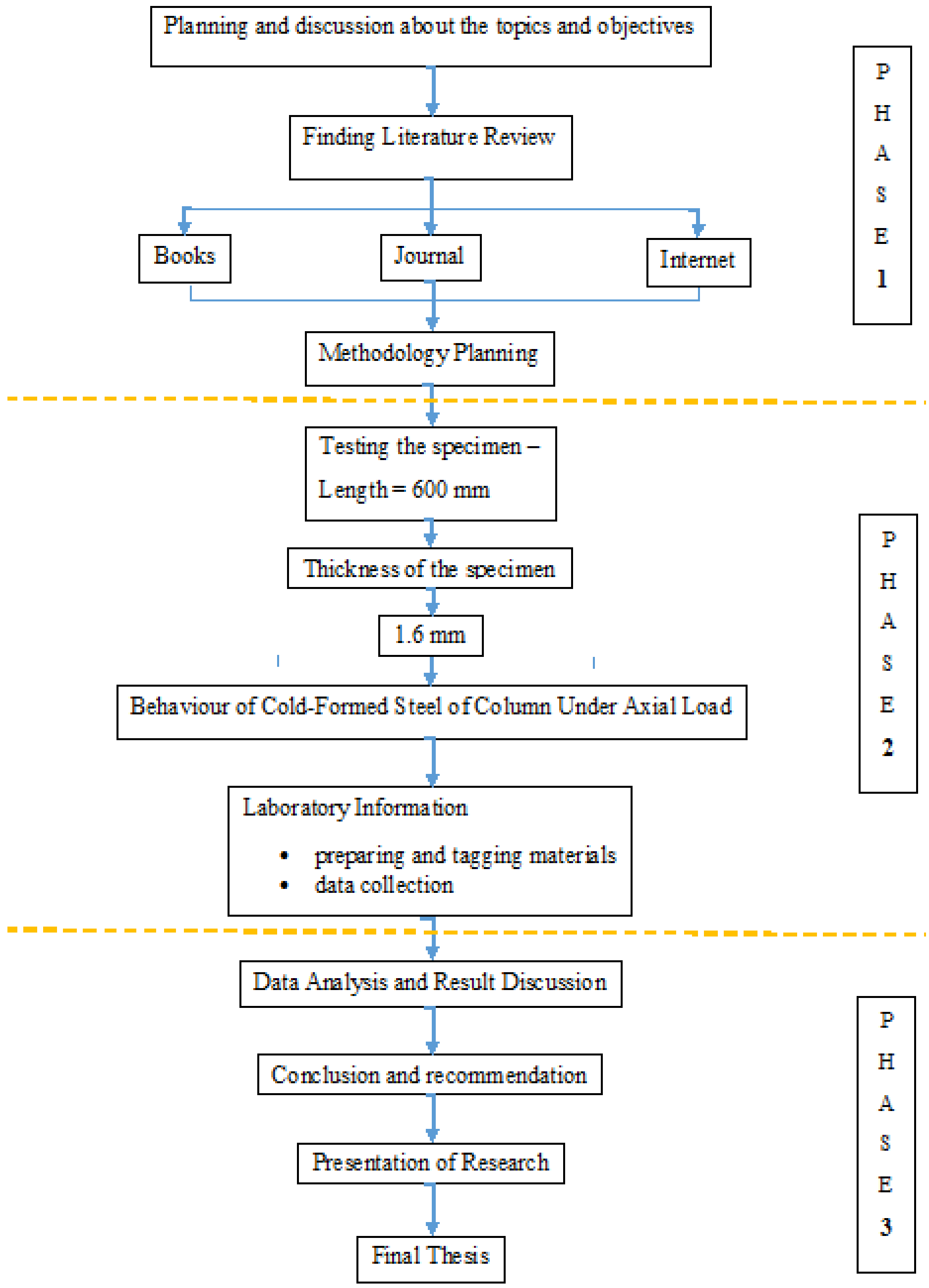


Figure 3.1 Project flow chart

Figure 3.2 Roll forming process of cold-formed steel

3.3 Material Selection

Cold-formed C section size are selected based on the previous researcher and the capability of the Universal Testing Machine at the laboratory. The maximum height of specimen that Universal Testing Machine can take is average 700 mm including the bearing plate.

3.4 Section Parameter

The parameters of the typical C-section cold-formed and their magnitudes are shown in Table 3.1.

Table 3.1 Parameter magnitudes of the cross-section

Parameter	Magnitude
Thickness, t	1.6 mm
Depth, H	100 mm
Flange, B	50 mm
Edge stiffener, L	14 mm

All the samples were 600 mm long and the tracks were made of material 1.6 mm thick. An inelastic buckling mode was expected during the test.

3.5 Operation Set-up and Loading

The machine that will be used to conduct this experiment is Universal Testing Machine and transducers. The Universal Testing Machine will read the displacement of the specimens. The loading rate that will be used is 0.5 mm per minute which it was the most suitable rate for this specimens according to the previous researcher. The data taken from this machine will be in the form of graph. The transducers are being used to read the reading of buckling mode of specimens. Four transducers will be used to take the accurate data. Figure 3.3 shows the series of cold-formed C section with various position of openings. The support being used for the specimen is flat end as shown in Figure 3.4, Figure 3.5 and Figure 3.

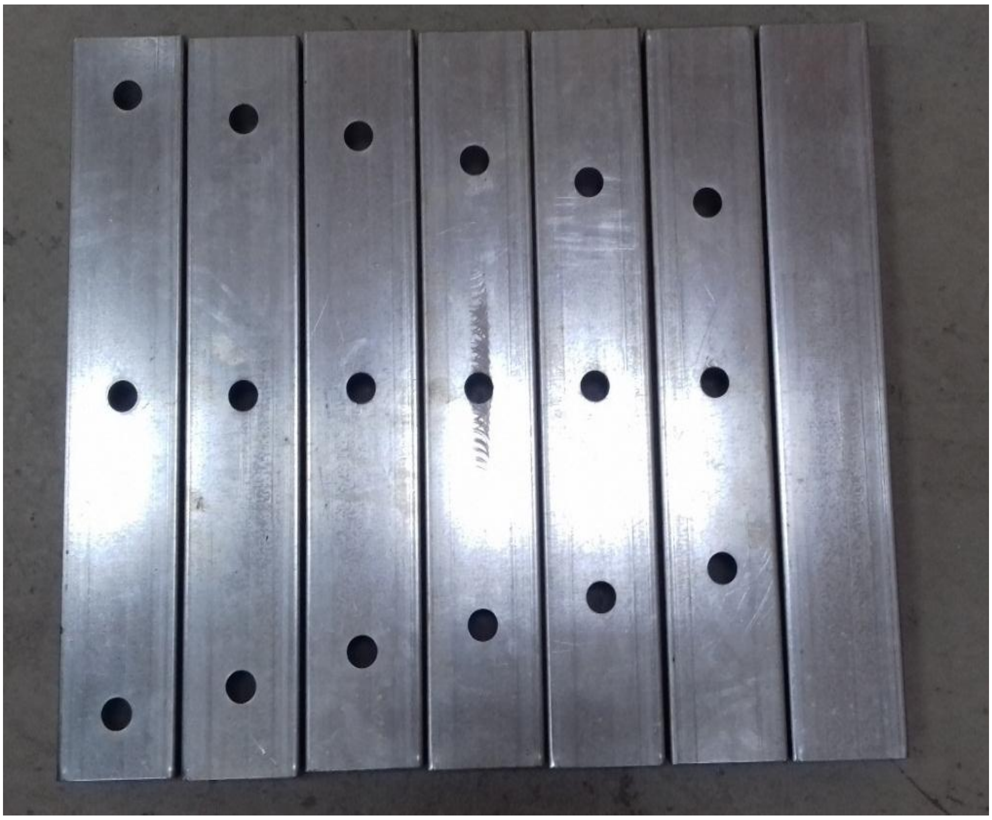
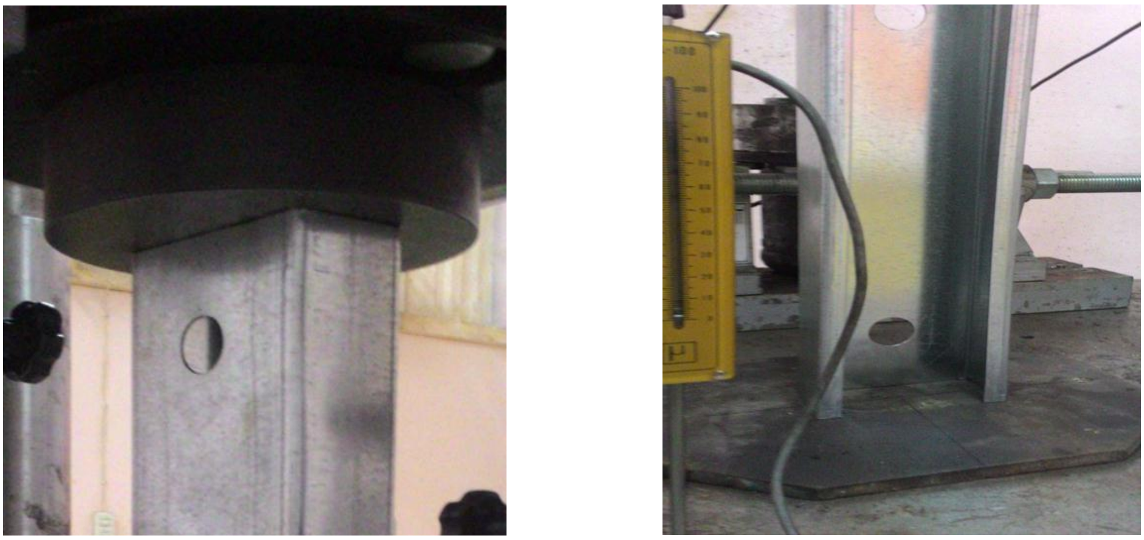


Figure 3.3 Series of cold-formed C section with various position of openings



(a) (b)

Figure 3.4 Picture (a) and (b) show the support at the top and bottom of the specimen

Figure 3.5 Bearing plate at the bottom

Figure 3.6 Bearing plate at the top

3.6 Schematic Diagram

The diagram of the specimens and machines used are describe by drawing. All dimensions are in millimetre (mm). The size of the openings was kept constant as shown in Figure 3.7 and the position of transducers also constant as in Figure 3.8. Opening positions were varied as illustrated in Figure 3.9 in order to investigate the effect of opening positions on the ultimate strength. A channel section without openings was also tested. The column lengths, cross- section dimensions, and perforation areas were kept constant, having a thickness of 1.6 mm and specimen length of 600 mm. Detail dimension of specimen is shown in Figure 3.9 and Figure 3.10. Figure 3.11 and Figure 3.12 show the setup of the transducers and the position of the specimen during testing. Figure 3.13 show the setup of apparatus in laboratory and Figure 3.14 show the machine used by previous researcher.

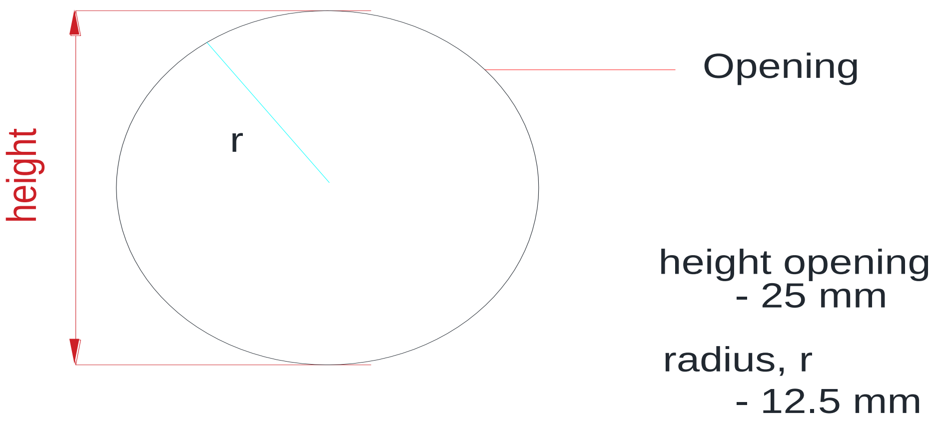


Figure 3.7 Schematic diagram of opening

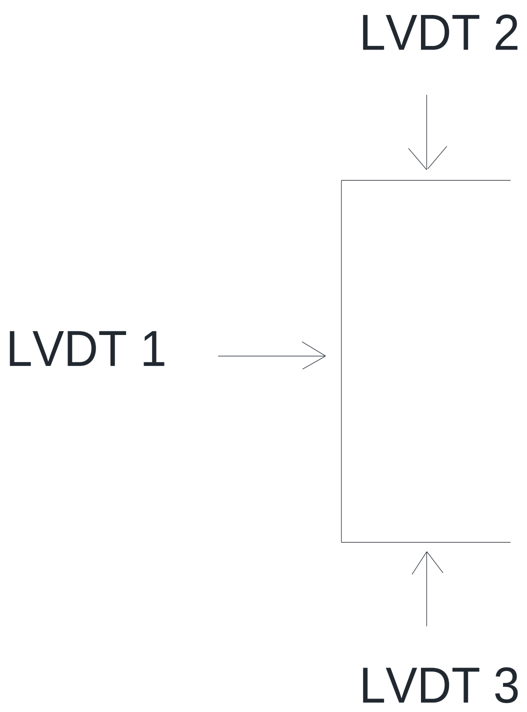


Figure 3.8 Schematic drawing of transducers position

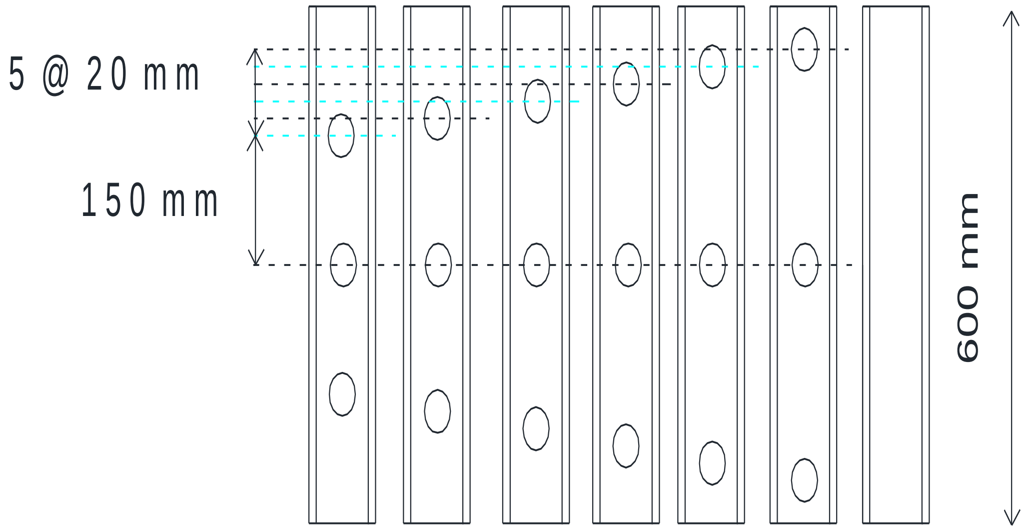


Figure 3.9 Schematic drawing of series of cold-formed C section

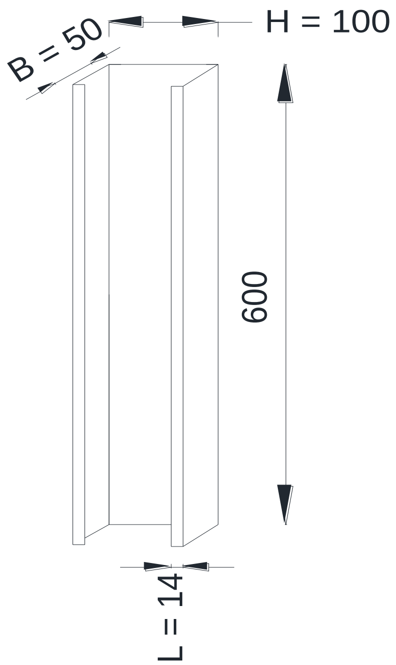


Figure 3.10 Schematic drawing of single C section column full section

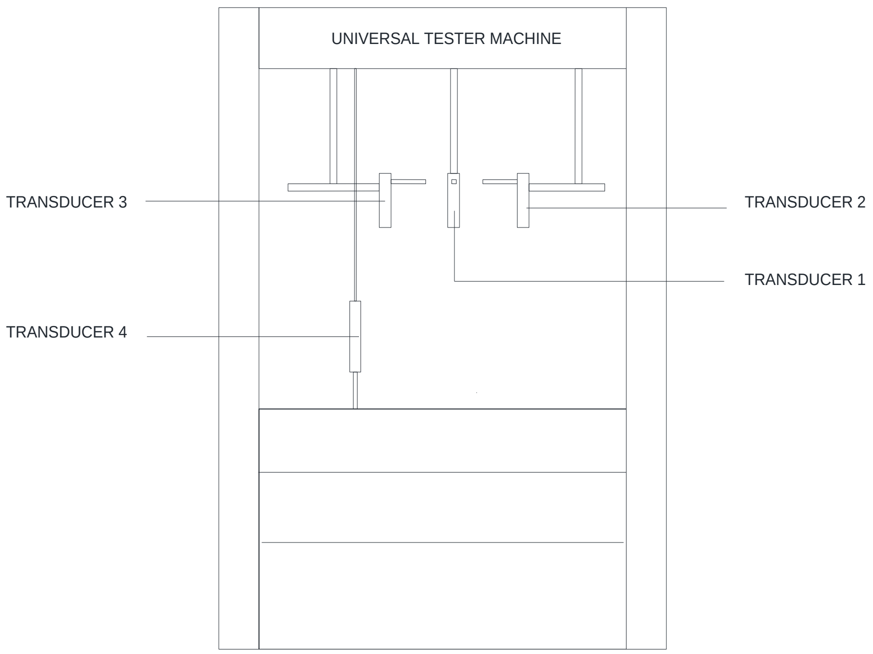


Figure 3.11 Universal testing machine and transducers set-up

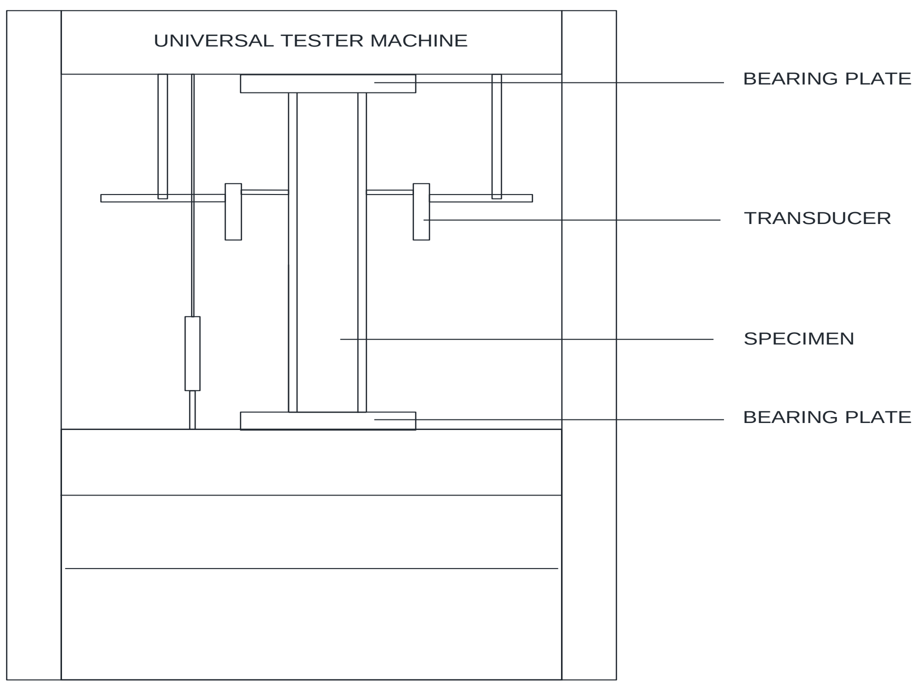


Figure 3.12 Schematic diagram of specimen set-up

Figure 3.13 Apparatus set-up in laboratory

Figure 3.14 Tinius Olsen testing machine

Sources: Kulatunga, M. and Macdonald, M. (2013)

CHAPTER 4

RESULT AND DISCUSSIONS

4.1 Introduction

The results obtained from compression test are presented in this chapter. Vertical and lateral displacement result of the specimen had been taken during testing. For lateral displacement, three transducer are placed at the upper support of the specimen which two at the both side of the flange of column and the other one at the middle of the web while for vertical displacement, one transducer had been placed at the bottom plate of specimen. Experimental investigation was aimed at studying the influence of opening positions on the ultimate strength and the failure modes of lipped C section columns. The size of opening was kept constant and opening positions were varied. The maximum displacement taken was keep constant that is 5 mm. The results of this experiment are presented in graphical method to give better visualize and understanding. The discussions were presented within the scope has been mentioned in the previous chapter.

4.2 Vertical Displacement

The vertical displacement transducer read the ultimate value of compression C section column. The measured specimen dimensions and experimental results were shown in Table 4.1 and Figure 4.1.

Table 4.1 Measured Specimen Dimensions and Experimental Results

No.	Thickness, t (mm)	Web, H (mm)	Flange, B (mm)	Lip, L_1 (mm)	Lip, L_2 (mm)	Length, L (mm)	H/t	B/t	H/B	Experimental ultimate load, P (kN)
C1	1.62	100.02	49.92	13.90	12.04	600	61.74	30.81	2.00	97.81
C2	1.62	100.08	49.88	14.12	12.22	600	61.78	30.79	2.00	99.50
C3	1.60	100.04	49.90	14.18	12.30	600	62.53	31.19	2.00	95.33
C4	1.62	99.98	50.08	13.86	12.44	600	61.72	30.91	1.99	97.06
C5	1.64	99.92	50.02	14.04	12.26	600	60.93	30.50	1.99	99.08
C6	1.64	99.86	50.10	14.14	12.18	600	60.89	30.55	1.99	101.54
C7	1.62	100.10	49.92	13.88	12.02	600	61.80	30.81	2.00	99.54

The ultimate strength values of compression members are illustrated in buckling behaviour by using linear vertical displacement transducer (LVDT) device. The highest ultimate load is specimen C-6 with 101.54 kN and the lowest ultimate load is specimen C-3 with 95.33 kN. The ultimate load for the specimen without opening and with opening did not varies much where all column have only slightly difference in reading of ultimate load. For the specimen without opening that is specimen C-1 the ultimate strength is 97.81 kN.

For summary, the position of openings play an important part in results produce. The reduction in area of steel columns will decreasing the ultimate load of that specimen. The position of opening from the support also affect the reading of ultimate load taken. The type of support used that is flat end affected the result due to the non-existing restraint at any axis during testing.

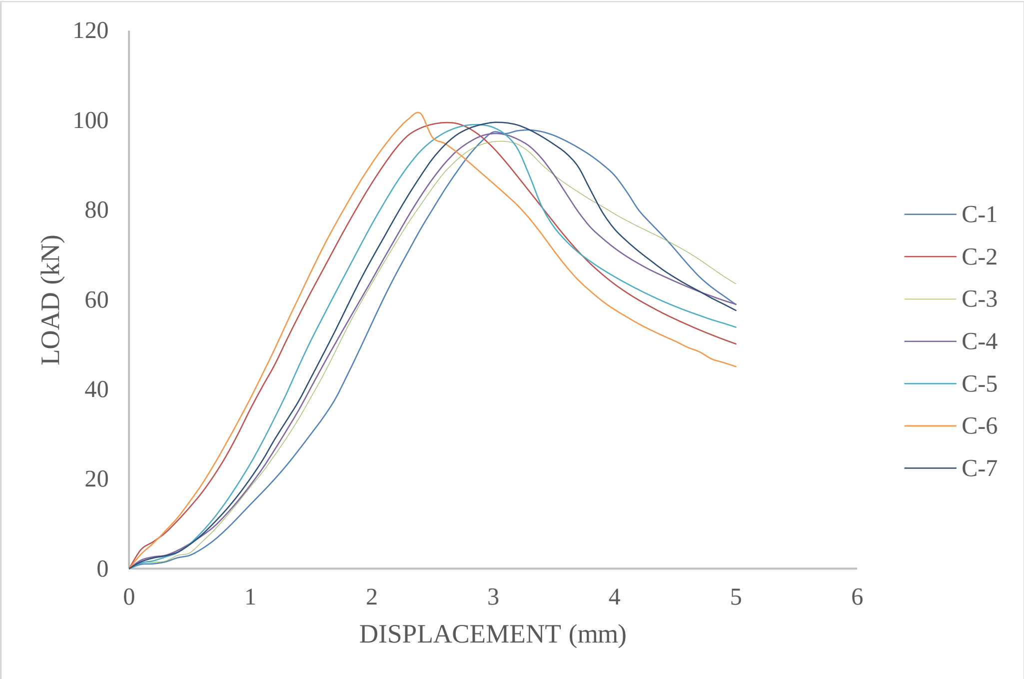


Figure 4.1 Load versus vertical displacement graph

4.3 Lateral Displacement

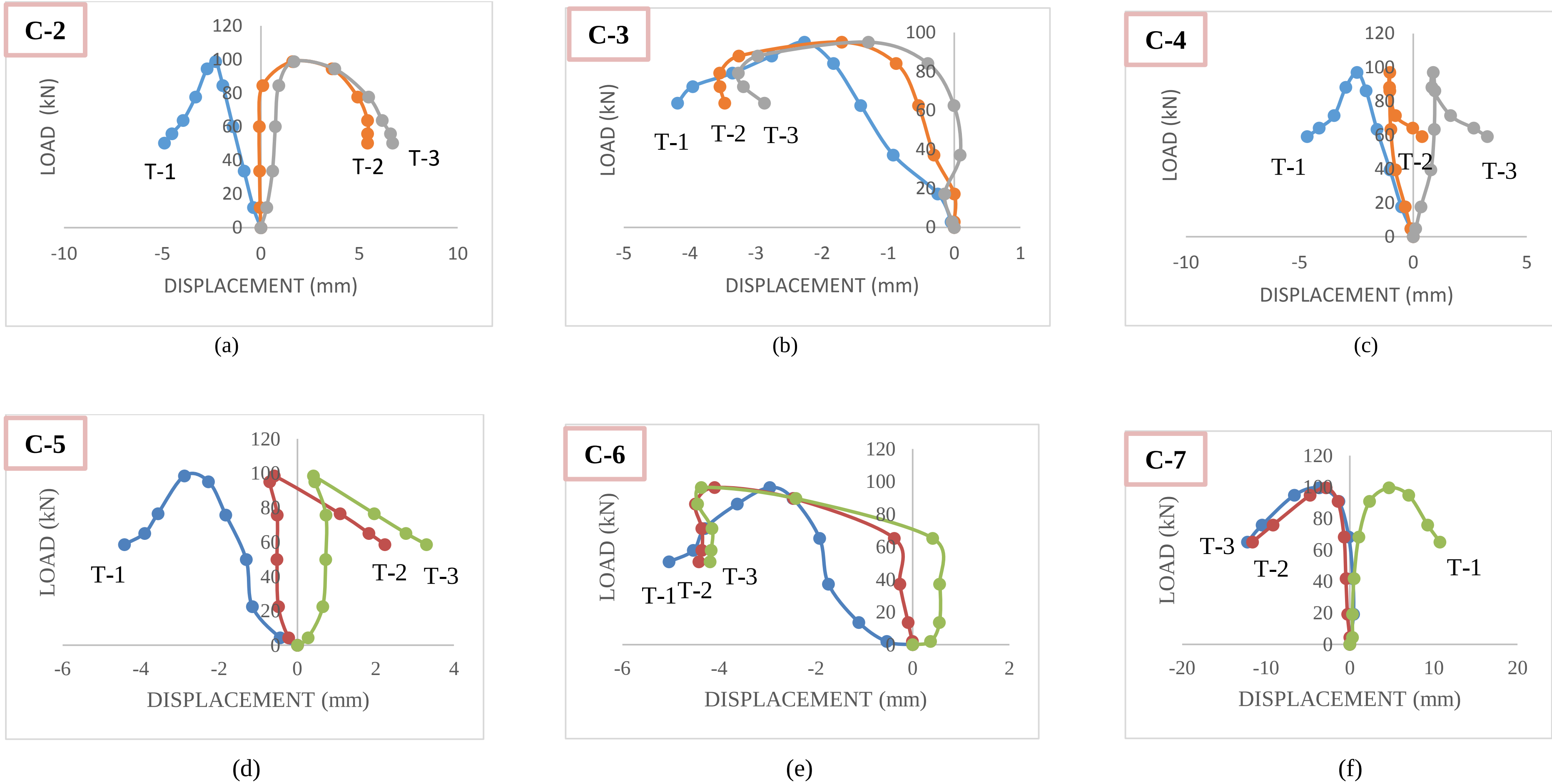


Figure 4.2 Load versus lateral displacement graph for all specimen

4.3.1 Specimen C-2

The specimen C-2 has the longest distance of the opening from the support but has the lowest distance between openings. From the Figure 4.3, it shows that from transducer 2 and transducer 3, it can be seen that the flange distort inward due to compression where the shape of lateral displacement uniform positively before maximum load at 1.8 mm displacement and continue to distort outward a little bit after maximum load. Transducer 1 is negative due to the movement of the web that distort outward. The movement of transducer is consistent and until maximum load happened, the transducer at the web continue to buckle outward.

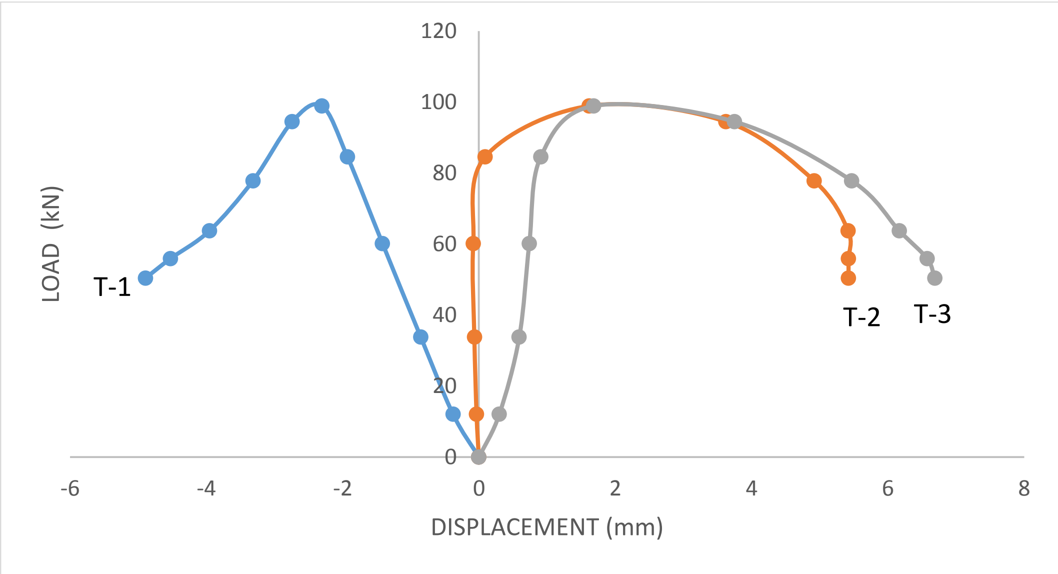


Figure 4.3 Load versus lateral displacement graph C-2

4.3.2 Specimen C-3

From the specimen C-3 it can be seen that the displacement value for all three transducers are negative where it show that the flange distort outward due to compression. From Figure 4.4, transducer 2 and transducer 3 show that the specimen had change in shape at the flange where the flange distort outward consistently until the specimen reach a peak of loading maximum at displacement of 1.5 mm. After reach the peak load, the flange of column buckle inward a little bit. Transducer 1 shows that the web of column had also buckle outward due to negative displacement. The displacement value increasing gradually show that the web of column buckle with increasing of load.

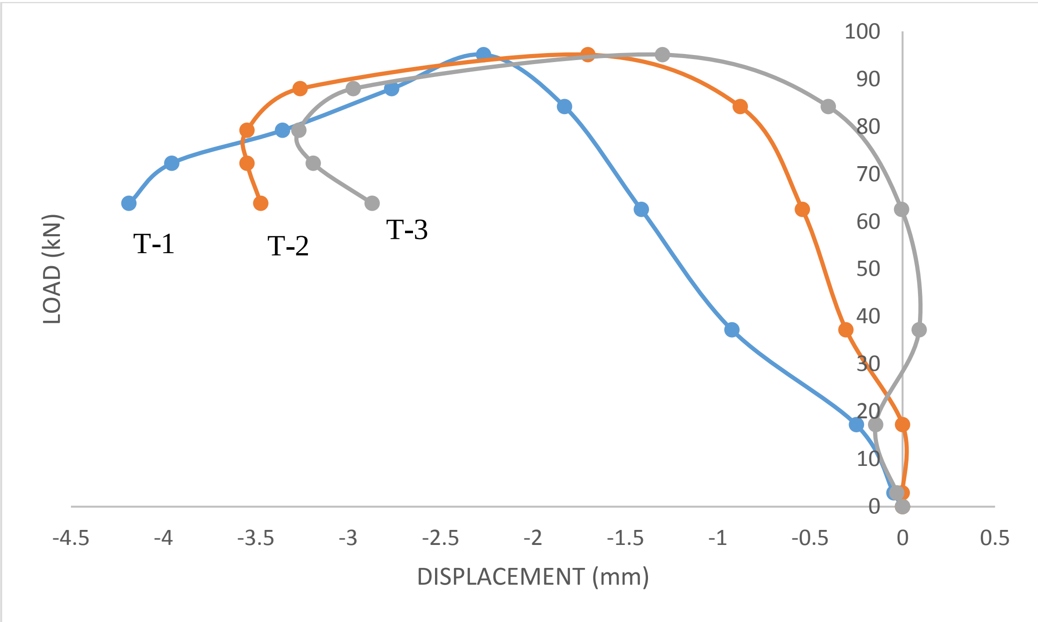


Figure 4.4 Load versus lateral displacement graph C-3

4.3.3 Specimen C-4

From the Figure 4.5 it shows on the specimen C-4 that the column buckled at the flange and distort inward due to compression. Transducer 2 and transducer 3 show that the reading of displacement are positive value. The displacement increasing gradually until reach peak loading load and continued to increase after peak load. Transducer 1 has a negative value shows that the web of column had buckle outward and gradually increase until 2 mm of displacement.

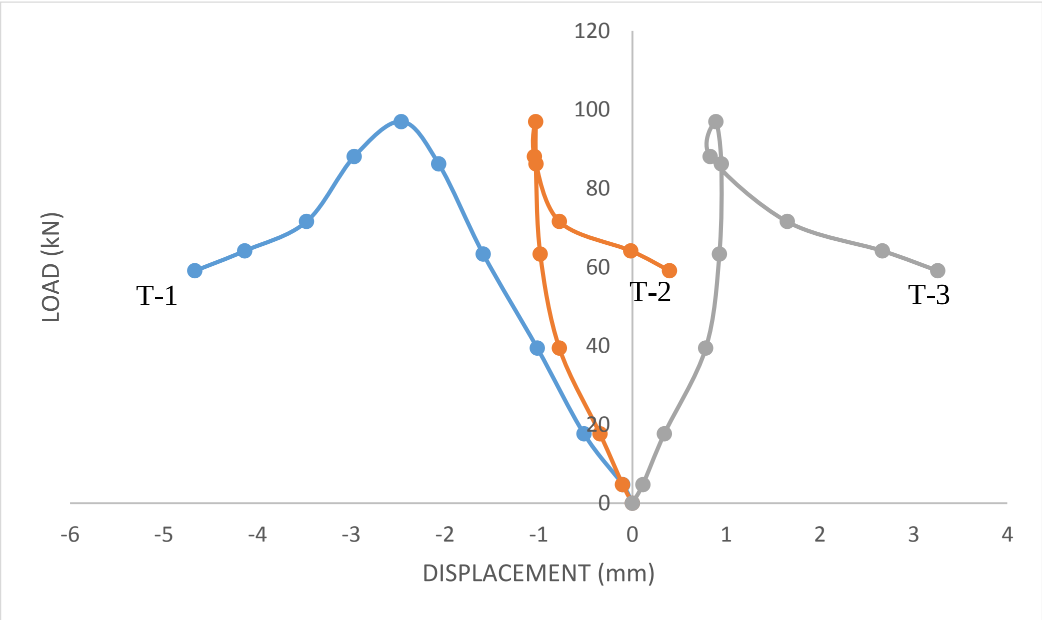


Figure 4.5 Load versus lateral displacement graph C-4

4.3.4 Specimen C-5

From Figure 4.6, it can be seen that the flange distort inward due to the compression where the displacement values are positive as seen at transducer 2 and transducer 3. It also show that the specimen had change in shape at the flange. The displacement value are not increasing much until the specimen had reach a peak load, then the displacement continued to increase gradually by distort inward. Transducer 1 show that the web of column had buckle outward where the displacement value is increasing gradually at negative value and at 2.8 mm of displacement of transducer 1, the web continued to distort outward.

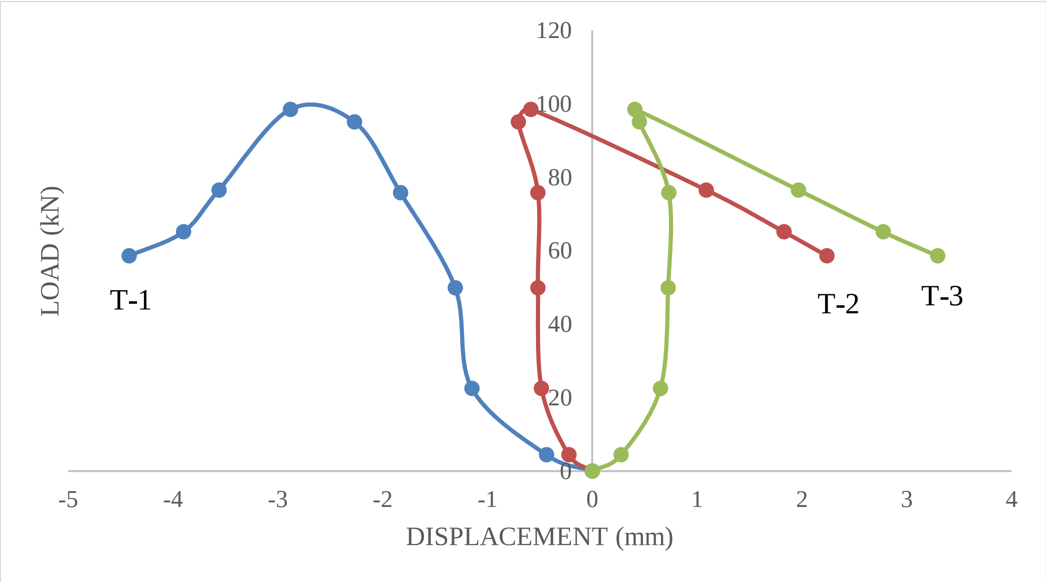


Figure 4.6 Load versus lateral displacement graph C-5

4.3.5 Specimen C-6

From the Figure 4.7, it shows from the specimen C-6 that the column buckled outward at the flange. It can be seen that the displacement value for transducer 2 and transducer 3 are negative. The displacement values increasing gradually until reach a peak load at 3 mm of displacement and stop increasing after that. Transducer 1 show that the web of column had also buckle outward due to the negative value of displacement. After a peak load, the web continued to buckle outward.

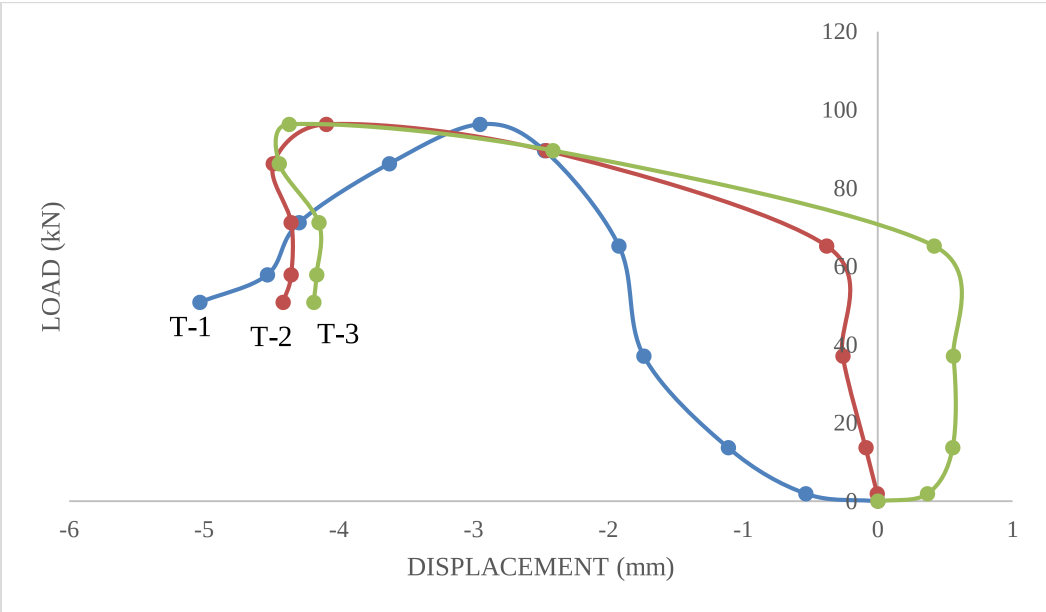


Figure 4.7 Load versus lateral displacement graph C-6

4.3.6 Specimen C-7

The specimen C-7 has the shortest distance of the opening from the support but has the longest distance between openings. From Figure 4.8, it can be seen that the flange distort outward due to compression where transducer 2 and transducer 3 shows that the shape of lateral displacement, uniform negatively. The displacement values continue to increasing after reach a peak load. Transducer 1 show that the web of column had buckle inward where the displacement value is positive and the peak load happened at 2.5 mm.

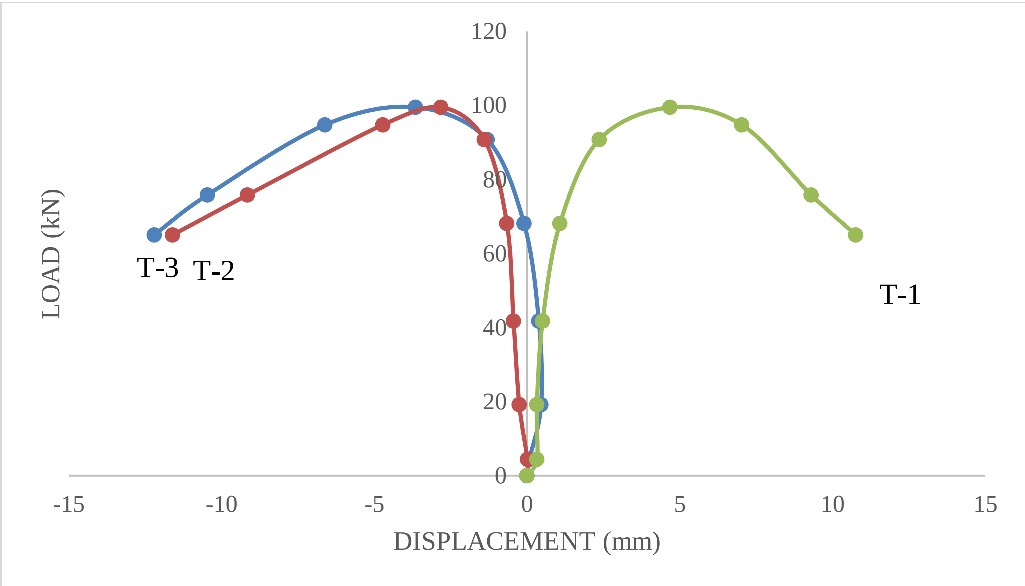


Figure 4.8 Load versus lateral displacement graph C-7

For the summary, lateral displacement of specimens varies and the range of displacement values are between 1.5 mm to 3.0 mm. The web of column distort outward for all specimen except for specimen C-7. The flange of column for specimen C-2, C-4 and C-5 distort inward while for specimen C-3, C-6 and C-7, the flange distort outward. After reach the maximum peak load, most specimen will continued to distort. The flange of columns distort due to the compression load from the machine continuously.

4.4 Failure Mode

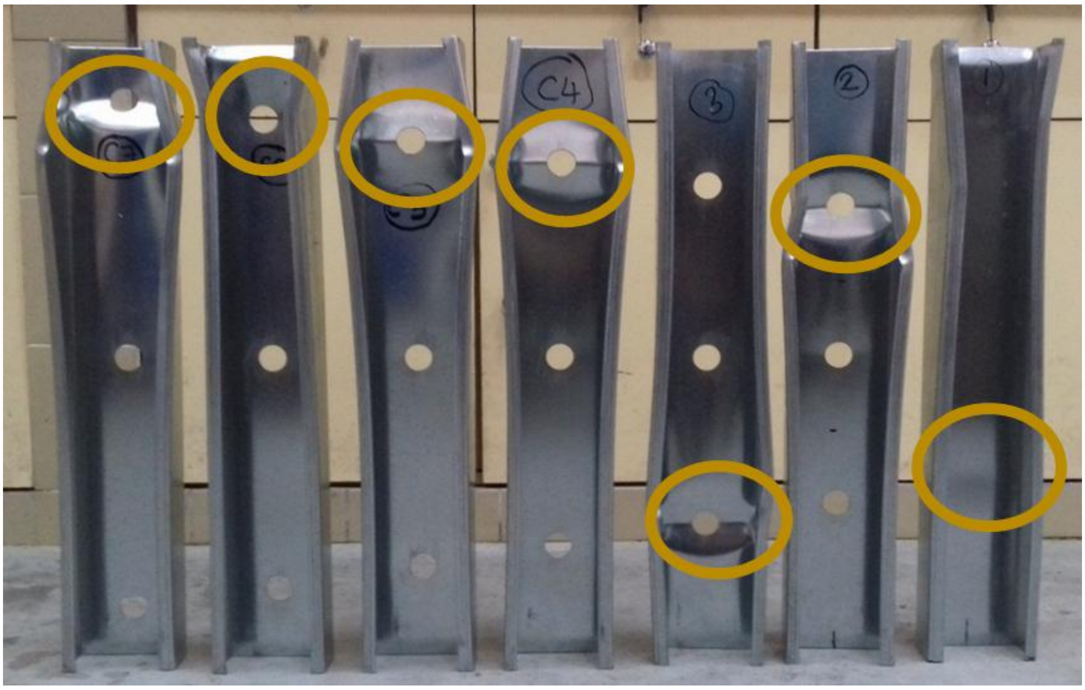


Figure 4.9 Front view

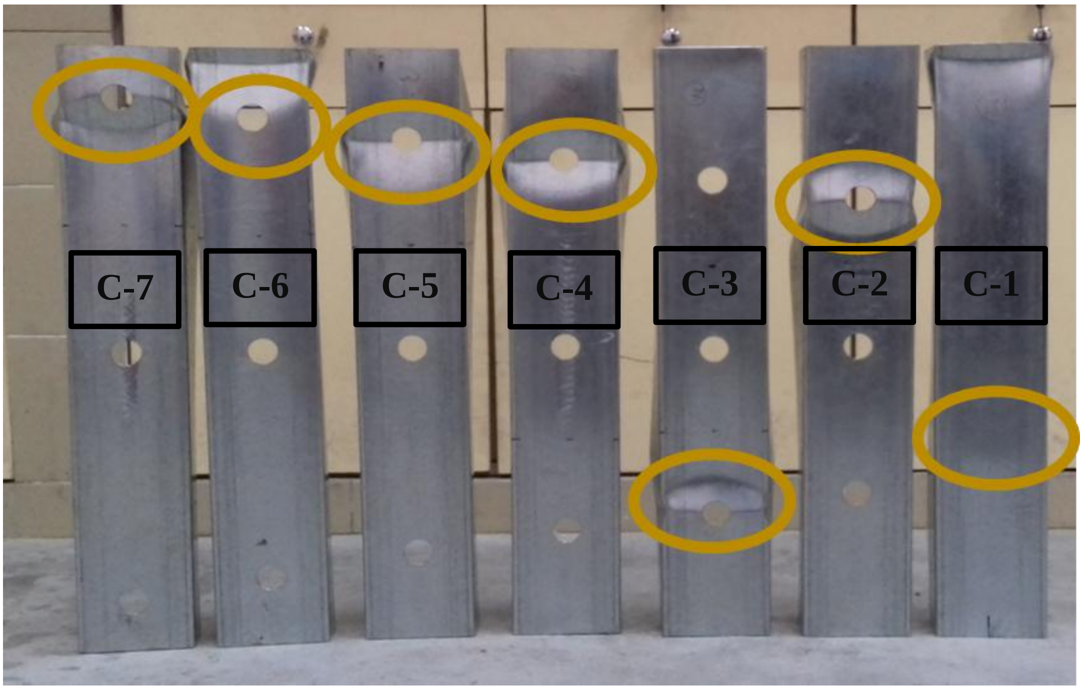


Figure 4.10 Back view

The experiment were using flat end supported where all specimen were compressed between two bearing plate. The failure mode of each specimen and all the changes in shape of steel columns were studied.

For specimen C-1, the C section column without opening, it only experienced local buckling behaviour. Local buckling behaviour can be seen at specimen C-1 where there is a wave appear at the web of the specimen as seen in Figure 4.9. The wavelength appear at the beginning of the stage of compression at the bottom of the column and the wavelength continue to appear until the column failed as shown in Figure 4.10.

Specimen C-2 has the longest distance of the opening from the support but has the lowest distance between openings. From the Figure 4.9, it shows from the specimen that the column buckle at the top opening and can be seen that the flange distort inward due to compression. The web of column also buckle at the upper opening near the support. The column experienced distortional buckling mode.

The specimen C-3 is the only column that buckled at the bottom support as shown in Figure 4.9. It can be seen that the flange distort outward due to compression and buckle at the lower opening near the support. The web of column also experienced change of shape where there web buckle and this show that the specimen C-3 experienced distortional buckling mode.

Specimen C-4 column buckled at the top opening. It can be seen that the flange distort inward due to compression. The web of column also failed at the opening and this can be seen at Figure 4.10. This show that specimen C-4 experienced distortional buckling mode.

The specimen C-5 shows that the column buckled at the top opening as seen in Figure 4.9. It can be seen that the flange distort inward due to compression. The web of column had buckle outward and this show that specimen C-5 experienced distortional buckling.

From the Figure 4.9, it shown from the specimen C-6 that the column buckled at the top opening. The change in shape at the flange happened where the flange distort outward due to compression. The specimen had change in shape at the upper support only and the web of column had also buckle outward as seen in Figure 4.10.

The specimen C-7 has the shortest distance of the opening from the support but has the longest distance between openings. From the Figure 4.9, it shown from the specimen that the column failed at the top opening and it can be seen that the flange distort outward due to compression. The web of column had buckle inward and this show that the specimen C-7 experienced distortional buckling.

For the summary, specimen C-1 and C-3 went through a failure at the bottom of the specimen while the other specimens went through a failure at the top opening. The columns for this experiment experienced local and distortional buckling. Local buckling behaviour can be seen at specimen C-1 where there is a wave appear at the web of the specimen. The wave appeared due to the load transferred to the column. Distortional buckling behaviour happened at specimen C-2. C-3, C-4, C-5 and C-6 and C-7. This failure mode can be seen where the flange and web buckle at the same time.

CHAPTER 5

CONCLUSION

5.1 Conclusion

From the overall project analysis and results that already being carried out, several conclusions that are made based on the results are:

a) The ultimate load for all specimens had been determined using Universal Testing Machine. The column without opening theoretically should has the highest ultimate load compared to specimens with openings.

b) The ultimate load of axially loaded cold-formed steel column with openings varies with the distance between openings but only cause a slight decrease in ultimate compressive strength of the tested columns

c) The buckling type of different position of opening can be predicted. The deformation response of the member with and without the hole is similar through the data test study, suggesting that the hole has a small influence on compression.

d) The failure mode of axially loaded columns with different position of openings also constant where all specimens are failed by local and distortional buckling. The deformation of peak load for the short column was less sensitive to the presence of openings, exhibit a mixed local-distortional failure mode.

5.2 Recommendation

Further studies on the research need to be conducted in the near future in order to come out with better and good results. Several recommendations are proposed for the future studies to achieve the objectives of this research as follow:

a) Distortional buckling can be prevented by increasing the web depth, but failure due to local buckling will likely to occur.
b) Use other type of support such as pin-pin or fixed-fixed at the both end of specimen to avoid twisting at the specimen.
c) Do not use stiffeners (lips) for the C columns.
d) Use different shape of openings such as rectangular, oval, or rectangle.
e) Use different type of material such as high yield steel or mild steel.
f) Use software such as ANSYS to compare the results in experimental study.

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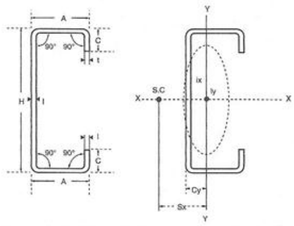
APPENDIX A

Lipped Channels – Available in Hot Rolled & Galvanized Material

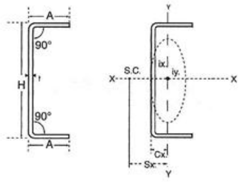
Source: Logamatic Industries (M) Sdn. Bhd.

JIS G 3350 SSC 400
SS 104



Dimension mm (in)		Sectional Area	Calculated Weight	Centre of Gravity		Secondary Moment of Area		Radius of Gyration of Area		Modulus of Section		Centre of Shear	
				Cx	Cy	Ix	Iy	ix	iy	Zx	Zy	Sx	Sy
HxAxC	t	cm^2	kg/m	cm	cm	cm^4	cm^4	cm	cm	cm^3	cm^3	cm	cm
250x75x25 (10x3x1)	4.5	18.92	14.9	0	2.07	1690	129	9.44	2.62	135	23.8	5.1	0
	4.0	16.95	13.3	0	2.07	1522	118	9.48	2.64	122	21.8	5.1	0
	3.2	13.73	10.8	0	2.08	1248	99.0	9.53	2.69	99.8	18.2	5.2	0
	3.0	12.91	10.1	0	2.08	1177	93.8	9.55	2.70	94.1	17.3	5.2	0
	2.3	10.00	7.85	0	2.08	921	74.8	9.60	2.73	73.7	13.8	5.3	0
250x75x20 (10x3x¾)	4.5	18.47	14.5	0	1.95	1639	117	9.42	2.52	131	21.0	4.8	0
	4.0	18.55	13.0	0	1.95	1480	107	9.46	2.54	118	19.3	4.9	0
	3.2	13.41	10.5	0	1.95	1214	89.9	9.51	2.59	97.1	16.2	4.9	0
	3.0	12.61	9.90	0	1.95	1145	85.3	9.53	2.60	91.6	15.4	4.9	0
	2.3	9.772	7.67	0	1.95	897	68.1	9.58	2.64	71.8	12.3	5.0	0
225x75x25 (9x3x1)	4.5	17.79	14.0	0	2.19	1310	125	8.58	2.65	116	23.6	5.3	0
	4.0	15.95	12.5	0	2.19	1184	115	8.62	2.68	105	21.6	5.4	0
	3.2	12.93	10.1	0	2.19	972	95.9	8.67	2.72	86.4	18.1	5.4	0
	3.0	12.16	9.54	0	2.19	917	90.9	8.68	2.73	81.5	17.1	5.5	0
	2.3	9.427	7.40	0	2.20	718	72.4	8.73	2.77	63.9	13.7	5.5	0
225x75x20 (9x3x¾)	4.5	17.34	13.6	0	2.05	1274	113	8.57	2.56	113	20.8	5.0	0
	4.0	15.55	12.2	0	2.06	1151	104	8.61	2.58	102	19.1	5.1	0
	3.2	12.61	9.90	0	2.06	946	87.2	8.66	2.63	84.1	16.0	5.1	0
	3.0	11.86	9.31	0	2.06	892	82.7	8.67	2.64	79.3	15.2	5.1	0
	2.3	9.197	7.22	0	2.07	700	66.1	8.72	2.68	62.2	12.2	5.2	0
200x75x25 (8x3x1)	4.5	16.67	13.1	0	2.32	990	121	7.71	2.69	99.0	23.3	5.6	0
	4.0	14.95	11.7	0	2.32	895	110	7.74	2.72	89.5	21.3	5.7	0
	3.2	12.13	9.52	0	2.33	736	92.3	7.79	2.76	73.6	17.8	5.7	0
	3.0	11.41	8.96	0	2.33	694	87.5	7.80	2.77	69.4	16.9	5.7	0
	2.3	8.852	6.95	0	2.33	545	69.7	7.85	2.81	54.5	13.5	5.8	0

JIS G 3350 SSC 400
SS 104



Dimension mm (in)		Sectional Area	Calculated Weight	Centre of Gravity		Secondary Moment of Area		Radius of Gyration of Area		Modulus of Section		Centre of Shear	
				Cx	Cy	Ix	Iy	ix	iy	Zx	Zy	Sx	Sy
HxAxA	t	cm²	kg/m	cm	cm	cm⁴	cm⁴	cm	cm	cm³	cm³	cm	cm
250x75x75	4.5	17.33	13.6	0	1.60	1502	82.9	9.31	2.19	120	14.1	3.7	0
	4.0	15.47	12.1	0	1.58	1348	74.5	9.33	2.19	108	12.6	3.7	0
	3.2	12.46	9.78	0	1.54	1096	60.6	9.38	2.20	87.7	10.2	3.7	0
	3.0	11.70	9.19	0	1.54	1032	57.0	9.39	2.21	82.5	9.56	3.7	0
	2.3	9.026	7.09	0	1.50	802	44.3	9.43	2.22	64.2	7.40	3.8	0
225x75x75	4.5	16.21	12.7	0	1.70	1166	80.6	8.48	2.23	104	13.9	3.9	0
	4.0	14.47	11.4	0	1.67	1048	72.4	8.51	2.24	93.1	12.4	3.9	0
	3.2	11.66	9.16	0	1.64	852	58.9	8.55	2.25	75.8	10.1	3.9	0
	3.0	10.95	8.60	0	1.63	803	55.5	8.56	2.25	71.3	9.45	3.9	0
	2.3	8.451	6.63	0	1.60	624	43.2	8.60	2.26	55.5	7.31	3.9	0
200x75x75	4.5	15.08	11.8	0	1.80	881	78.0	7.64	2.27	88.1	13.7	4.1	0
	4.0	13.47	10.6	0	1.78	792	70.1	7.67	2.26	79.2	12.3	4.1	0
	3.2	10.86	8.53	0	1.75	645	57.0	7.71	2.29	64.5	9.92	4.1	0
	3.0	10.20	8.01	0	1.74	608	53.7	7.72	2.29	60.8	9.32	4.1	0
	2.3	7.876	6.18	0	1.71	473	41.8	7.75	2.30	47.3	7.22	4.1	0
175x75x75	4.5	13.96	11.0	0	1.93	643	75.0	6.78	2.32	73.4	13.5	4.3	0
	4.0	12.47	9.79	0	1.91	578	67.4	6.81	2.32	66.1	12.1	4.3	0
	3.2	10.06	7.90	0	1.87	472	54.9	6.85	2.33	54.0	9.75	4.4	0
	3.0	9.454	7.42	0	1.86	445	51.7	6086	2.34	50.8	9.17	4.4	0
	2.3	7.301	5.73	0	1.83	347	40.2	6.89	2.35	39.6	7.10	4.4	0
150x65x65	4.5	11.93	9.37	0	1.71	400	47.9	5.79	2.00	53.4	10.0	3.7	0
	4.0	10.07	8.38	0	1.69	361	43.1	5.82	2.01	48.2	8.96	3.8	0
	3.2	9.623	6.77	0	1.65	296	35.2	5.86	2.02	39.4	7.26	3.8	0
	3.0	8.104	6.36	0	1.64	279	33.2	5.87	2.02	37.2	6.83	3.8	0
	2.3	6.266	4.92	0	1.61	218	25.9	5.90	2.03	29.1	5.30	3.8	0
125x50x50	4.5	9.459	7.43	0	1.31	212	21.6	4.73	1.51	33.9	5.85	2.8	0
	4.0	8.474	6.65	0	1.29	192	19.6	4.76	1.52	30.7	5.26	2.8	0
	3.2	6.863	5.39	0	1.25	158	16.0	4.80	1.53	25.3	4.28	2.8	0
	3.0	6.454	5.07	0	1.24	149	15.1	4.81	1.53	23.9	4.03	2.8	0
	2.3	5.001	3.93	0	1.21	117	11.9	4.85	1.54	18.8	3.13	2.8	0
100x50x50	4.5	8.334	6.54	0	1.46	125	20.1	3.87	1.55	24.9	5.67	3.0	0
	4.0	7.474	5.87	0	1.43	113	18.2	3.89	1.56	22.6	5.09	3.0	0
	3.2	6.063	4.76	0	1.40	93.6	14.9	3.93	1.57	18.7	4.15	3.1	0
	3.0	5.704	4.48	0	1.39	88.5	14.1	3.94	1.57	17.7	3.90	3.1	0
	2.3	4.426	3.47	0	1.36	69.6	11.1	3.97	1.58	14.0	3.04	3.1	0

Note- Minimum coating mass : 0.244kg/m (applicable for Galvanized Plain Channel only)
- Galvanized Plain Channel is made by hot - dip galvanized steel strip with extra - smooth surface.

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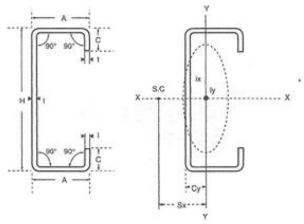

Dimension mm (in)		Sectional Area	Calculated Weight	Centre of Gravity		Secondary Moment of Area		Radius of Gyration of Area		Modulus of Section		Centre of Shear	
				Cx	Cy	Ix	Iy	ix	iy	Zx	Zy	Sx	Sy
HxAxC	t	cm^2	kg/m	cm	cm	cm^4	cm^4	cm	cm	cm^3	cm^3	cm	cm
200x75x20	4.5	16.22	12.7	0	2.19	963	109	7.71	2.60	96.3	20.6	5.3	0
(8x3x¾)	4.0	14.55	11.4	0	2.19	871	100	7.74	2.62	87.1	18.9	5.3	0
	3.2	11.81	9.27	0	2.19	716	84.1	7.79	2.67	71.6	15.8	5.4	0
	3.0	11.11	8.72	0	2.19	676	79.8	7.80	2.68	67.6	15.0	5.4	0
	2.3	8.622	6.77	0	2.20	531	63.7	7.85	2.72	53.1	12.0	5.5	0
175x75x20	4.5	15.09	11.8	0	2.33	702	105	6.82	2.63	80.3	20.2	5.6	0
(7x3x¾)	4.0	13.55	10.6	0	2.33	636	95.9	6.85	2.66	72.7	18.6	5.6	0
	3.2	11.01	8.64	0	2.34	524	80.5	6.90	2.70	59.9	15.6	5.7	0
	3.0	10.36	8.13	0	2.34	495	76.4	6.91	2.72	56.6	14.8	5.7	0
	2.3	8.047	6.32	0	2.35	389	61.0	6.96	2.75	44.5	11.8	5.7	0
150x65x20	4.5	13.07	10.3	0	2.10	441	69.2	5.82	2.30	58.8	15.7	5.0	0
(6x2½x¾)	4.0	11.75	9.22	0	2.11	401	63.7	5.84	2.33	53.5	14.5	5.0	0
	3.2	9.567	7.51	0	2.11	332	53.8	5.89	2.37	44.3	12.2	5.1	0
	3.0	9.008	7.07	0	2.11	314	51.1	5.90	2.38	41.9	11.7	5.1	0
	2.3	7.012	5.50	0	2.12	248	41.1	5.94	2.42	33.0	9.37	5.2	0
125x50x20	4.5	10.59	8.32	0	1.68	238	33.5	4.74	1.78	38.0	10.0	4.0	0
(5x2x¾)	4.0	9.548	7.50	0	1.68	217	31.1	4.77	1.81	34.7	9.38	4.0	0
	3.2	7.807	6.13	0	1.68	181	26.6	4.82	1.85	29.0	8.02	4.0	0
	3.0	7.358	5.78	0	1.69	172	25.4	4.83	1.86	27.5	7.56	4.1	0
	2.3	5.747	4.51	0	1.69	137	20.6	4.88	1.89	21.9	6.22	4.1	0
100x50x20	4.5	9.469	7.43	0	1.86	139	30.9	3.82	1.81	27.7	9.82	4.3	0
(4x2x¾)	4.0	8.548	6.71	0	1.86	127	28.7	3.85	1.83	25.4	9.13	4.3	0
	3.2	7.007	5.50	0	1.86	107	24.5	3.90	1.87	21.3	7.81	4.4	0
	3.0	6.608	5.19	0	1.86	101	23.4	3.91	1.88	20.2	7.45	4.4	0
	2.3	5.172	4.06	0	1.86	80.7	19.0	3.95	1.92	16.1	6.06	4.4	0
75x45x15	2.3	4.137	3.25	0	1.72	37.1	11.8	3.00	1.69	9.90	4.24	4.0	0
(3x1¾x3/5)	2.0	3.637	2.86	0	1.72	33.0	10.5	3.01	1.70	8.79	3.76	4.0	0
	1.6	2.952	2.32	0	1.72	27.1	8.71	3.03	1.72	7.24	3.13	4.1	0

Note- Minimum coating mass : 0.244kg/m (applicable for Galvanized Lipped Channel only)
- Galvanized Lipped Channel is made by hot - dip galvanized steel strip with extra - smooth surface.