AXIALLY LOADED OF COLD-FORMED STEEL SECTION WITH OPENING

RUZAIM BIN RUSLAN

B. ENG (HONS.) CIVIL ENGINEERING

UNIVERSITI MALAYSIA PAHANG

UNIVERSITI MALAYSIA PAHANG

DECLARATION OF THESIS AND COPYRIGHT

Author's Full Name : RUZAIM BIN RUSLAN

Date of Birth : 07 OCTOBER 1995

Title : AXIALLY LOADED OF COLD-FORMED STEEL SECTION WITH OPENING

Academic Session : 2017/2018

I declare that this thesis is classified as:

☐	CONFIDENTIAL	(Contains confidential information under the Official Secret Act 1997)*
☐	RESTRICTED	(Contains restricted information as specified by the organization where research was done)*
☑	OPEN ACCESS	I agree that my thesis to be published as online open access (Full Text)

I acknowledge that Universiti Malaysia Pahang reserves the following rights:

1. The Thesis is the Property of Universiti Malaysia Pahang
2. The Library of Universiti Malaysia Pahang has the right to make copies of the thesis for the purpose of research only.
3. The Library has the right to make copies of the thesis for academic exchange.

Certified by:

(Student's Signature)	(Supervisor's Signature)
951007-11-5139 New IC/Passport Number Date:25 JUNE 2018	KHALIMI JOHAN BIN ABD HAMID Name of Supervisor Date: 25 JUNE 2018

NOTE : * If the thesis is CONFIDENTIAL or RESTRICTED, please attach a thesis declaration letter.

SUPERVISOR’S DECLARATION

I hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Bachelor in Civil Engineering.

Full Name : KHALIMI JOHAN BIN ABD HAMID
Position : SUPERVISOR
Date : 25 JUNE 2018

STUDENT’S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

Full Name : RUZAIM BIN RUSLAN
ID Number : AA14070
Date : 25 JUNE 2018

AXIALLY LOADED OF COLD-FORMED STEEL SECTION WITH OPENING

RUZAIM BIN RUSLAN

Thesis submitted in fulfillment of the requirements
for the award of the
Bachelor Degree in Civil Engineering

Faculty of Civil Engineering and Earth Resources
UNIVERSITI MALAYSIA PAHANG

JUNE 2018

ACKNOWLEDGEMENTS

In the name of Allah, The Most Gracious and the Most Merciful

Alhamdulillah, all praises to Allah for the strengths and His blessing in completing this thesis. Immeasurable appreciation and deepest gratitude for the help and support are extended to the following person who in one way or another have contribute in making this study possible. Special appreciation goes to my supervisor, Mr Khalimi Johan bin Abd Hamid, for his supervision and constant support. His invaluable help of constructive comments and suggestions throughout the thesis works have contributed to the success of this research.

To my parents, RUSLAN BIN ISMAIL and ZAIRIDAH ANI BINTI MOHAMMAD who always keep me in their prayer day by day. To my siblings who always support behind me. To know that their support and blessing is with me at all time is one of the thing that keep me going on the day that I feel like giving up on myself.

To all my friends especially HAFIZI, WAN IZZUAN and IZZUDDIN who are with me from the start of the project through up and down. Their keen interest and encouragement were a great help throughout the course of this research work. The journey is made easy with all of you by my side and I will always remember that. All these memories we shared in completing our project and through our four years in UMP will always be something that I will treasure for life.

I humbly extend my thanks to all concerned person who co-operated with me in this regard.

May all the kindness and support will return to you in some way in the future. Thank you

ABSTRAK

Unsur struktur keluli yang terbentuk sejuk telah digunakan secara meluas dalam industri pembinaan dan telah muncul sebagai penyelesaian ekonomi pilihan untuk bangunan komersial dan perindustrian satu tingkat. Bahagian terbina dalam keluli terbentuk sejuk biasanya digunakan sebagai unsur mampatan untuk membawa beban yang lebih besar apabila seksyen tunggal tidak mencukupi. Walau bagaimanapun, bahagian yang dibina menunjukkan beberapa tingkah laku yang unik yang kod-kod semasa tidak mempunyai peruntukan yang komprehensif. Ini adalah samar-samar kerana tingkah laku keluli bergulung panas berbeza daripada keluli terbentuk sejuk. Penyelidikan ini akan menumpukan pada bahagian terbina terbuka atau bahagian I. Ahli struktur keluli terbentuk sejuk biasanya datang dengan kehadiran perforasi. Tebukan adalah lubang atau pembukaan yang dibuat pada keluli terbentuk sejuk untuk memudahkan kerja pembinaan. Ia biasanya dilengkapi dengan bentuk dan saiz yang berbeza berdasarkan fungsinya seperti menampung elektrik, paip dan penghawa dingin atau perkhidmatan pemanasan. Di samping itu, sangat sedikit kajian telah dijalankan untuk mengkaji bahagian terbina keluli terbentuk sejuk seperti back-to- lajur C-channel belakang tanpa jurang, lajur C-saluran belakang dengan lajur jurang, battened, dan berlapis. Oleh itu, matlamat penyelidikan ini adalah untuk menentukan beban utama keluli terbentuk sejuk dengan dan tanpa membuka melalui kajian eksperimen. Sejumlah 8 sampel diuji dalam eksperimen ini. Setiap sampel mempunyai ketebalan nominal 1.2 mm dan panjang lajur 600 mm yang sama, tetapi jenis seksyen yang berlainan yang merupakan seksyen tunggal dan seksyen terbina, dan diameter panjang web yang berbeza iaitu 103 mm dan 203 mm. dimampatkan di antara hujung yang disokong hanya pada kedua-dua hujungnya. Hasil percubaan ini menunjukkan bahawa beban muktamad setiap sampel sangat berbeza pada kedudukan perforasi dan panjang web. Hasilnya dibentangkan dalam tiga bahagian yang merupakan beban berbanding anjakan menegak, beban vs. anjakan melintang dan tingkah laku tenggelam.

ABSTRACT

Cold-formed steel structural elements have been widely used in the construction industry and have emerged as a preferred economical solution for single-storey commercial and industrial buildings. Cold formed steel built-up sections are commonly used as compression elements to carry larger loads when a single section is insufficient. However, the built-up sections exhibit some unique buckling behaviors which the current codes do not have comprehensive provisions. This is ambiguous as the behavior of hot rolled steel is different from cold formed steel. 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 In addition, very few studies have been carried out to study cold formed steel built-up sections such as back-to-back C-channel column without a gap, back-to-back C-channel column with a gap, battened, and laced columns. Thus, the aim of this research is to determine the ultimate load of cold-formed steel with and without opening through experimental studies. A total of 8 samples were tested in this experiment. Each sample has a nominal thickness of 1.2 mm and the same length of 600 mm columns, but different types of sections that are single sections and built-in sections, and diameters of web lengths of 103 mm and 203 mm. compressed between the supported end only at both ends. The result of this experiment shows that the ultimate load of each sample varies greatly on the perforation position and the web length. The result is presented in three section which are load vs. vertical displacement, load vs. horizontal displacement and buckling behavior.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

LIST OF ABBREVIATIONS

BS	British Standard
CFS	Cold-Formed Steel
DBB	Distortional buckling at bottom support (back)
DBF	Distortional buckling at bottom support (front)
DMF	Distortional buckling at middle span (front)
DTB	Distortional buckling at top support (back)
DTF	Distortional buckling at top support (front)
FE	Finite Element
FKASA	Fakulti Kejuruteraan Awam dan Sumber Alam
LBF	Lateral Buckling
LGD	Local Distortional Global
LVDT	Linear Vertical Displacement Transducer
WBF	Warping buckling at bottom support (front)
WMB	Warping buckling at middle span (back)
WMF	Warping buckling at middle span (front)
WTB	Warping buckling at top support (back)

CHAPTER 1

INTRODUCTION

1.1 Introduction

In steel structures, there are two types of structural steel members which the hot-rolled and cold-formed steel. The hot-rolled steel members always preferred as the 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 (CFS) structural members are commonly provided with holes to accommodate electrical and plumbing of building. CFS 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 CFS 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 CFS are limited to a roof truss and framing.

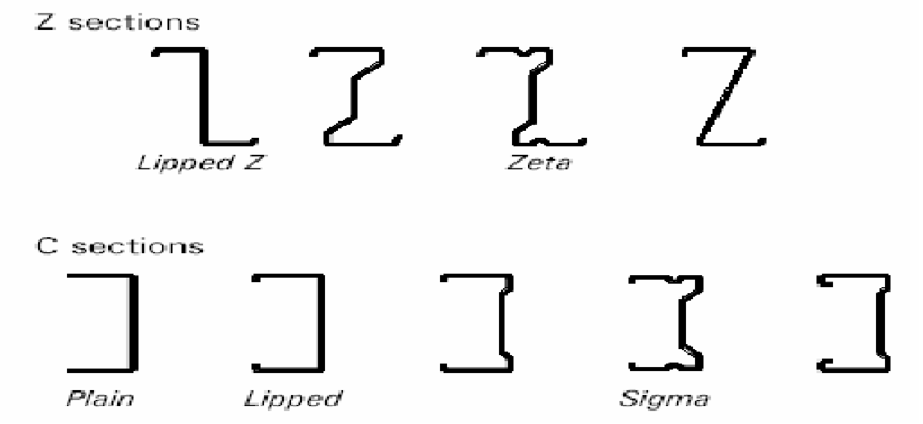


Figure 1.1 Cold-formed steel members

Source : (Crisan, et al., 2012)

CFS 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.

The use of cold formed steel (CFS) structures in residential construction has become increasingly popular all over the world in recent decades and is now a highly competitive alternative to traditional structural systems. The increase in the CFS construction is due to the ongoing development and improvements in the field, the consequential availability of more cost-effective solutions and the broad recognition of the advantages of CFS framing (Figure 1.2). Some of the widely acknowledged advantages of CFS framing are lighter weight, reduces transport and handling costs, and ease of prefabrication and mass production.

Figure 1.2 Uses of CFS framing

Source : (Dinis, et al., 2012)

Opening in CFS sections made specifically for fasteners such as bolts, screws, etc., may be neglected as openings are filled with material (Figure 1.3). However, for any other opening, the reduction in cross sectional area caused by these opening should be taken into account. The ultimate strength and elastic stiffness of a structural member can vary with opening, size, and shape. 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.

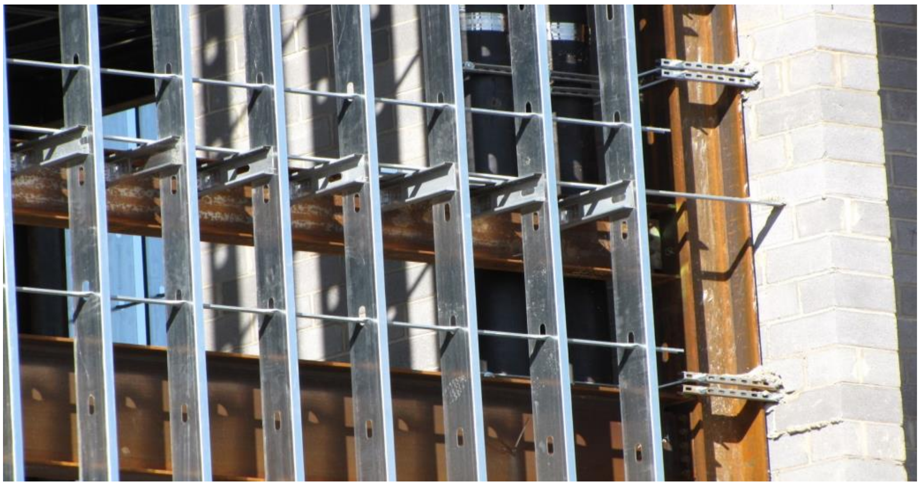


Figure 1.3 Cold-formed steel with openings

Source : (Dinis, et al., 2012)

1.2 Problem Statement

CFS structural members are commonly manufactured with holes such as joist/beams, for piping, electrical-wiring, plumbing, and bracing. Typically, it is manufactured with different shapes, and sizes. In particularly, large openings on the web are preferred by the contractors as the mechanical and electrical works become more and more complex in today's building industry. Besides, it's also facilitate various services in building construction. Due to the variety of size, and shapes, some task of research to provide the practical design need to be done where the strength is likely reduced by the existence of the perforation. Many problems had risen due to the existing of opening 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.

The second problem is the buckling behaviours (failure modes) for build-up section. Extensive studies have been conducted on the structural response of individual C-section cold-formed members affected by local distortional (LD) and local distortional global (LGD) interactions and have proved that the occurrence of LD and LDG interactions result in a substantial strength erosion. Seems there is no research concerning the structural behaviour of the built-up section columns affected by LD and LDG interactive failure modes. Therefore, additional researches on such a problem are still required. In addition, the influence of connection for build-up section. It seems that not only the cross-sectional geometry determines the strength of the members. The response strongly depends of the type of connection pieces and their effects on the overall buckling length and quality of interconnection.

1.3 Research Objective

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

1. To determine the ultimate load of axially loaded of cold formed steel single and build-up C-section short column.

2. To study the failure mode of axially loaded with opening.

1.4 Research Scope

For this research, a several of specimen of single and build-up C-section of CFS short column were conducted. As we can see nowadays, there are a lot of design of cold formed steel that can be used by engineers with different strength. The support will be used by using a base plate as a fixed support (welding at the end both of CFS).

The scope of these research covers on the compression test for axially loaded single and built-up C-section of CFS. The experiment will be done at the laboratory. The scopes of work are:

i. Single and build-up C-section.

ii. With and without opening.

iii. The size of the specimens.

1.5 Significance of Research

For this research, it will be conducted by doing compression test on series of specimens of single and build-up C-section of CFS short column to determine the maximum load of axially loaded. These sample are different in term of type of section which are single and build-up, with and without opening, and size of the specimens which are 103mm and 203mm. By conducting this experiment, its can alter the elastic stiffeners and ultimate strength of a structural member. In addition, it can improve the understanding about distortional buckling, post-buckling, and collapse behaviours. As we know the failure modes affected by type of section, with and without opening, and different sizes of each samples. As a result, special research need to conduct to be a guideline to design the cold-formed steel structural members.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Cold-formed thin-walled members are used in building industry in many fields. The probably largest area of use is in conventional – mainly industrial – steel structures as secondary and tertiary load-bearing elements – purlins, sheeting – on a steel or reinforced concrete primary structure (Jakab, 2009), and (Schafer, 2008). Cold-formed members are extensively used in North-America and Australia/New Zealand in residential housing (Figure 2.1) as primary load-bearing structures; light-gauge building systems are gaining on popularity and compete with the traditional building material, wood.

Landesmann (2013) indicates that advances in fabrication versatility and low production costs have prompted the cold-formed steel industry to search for novel cross-section shapes that are structurally more efficient (higher strength-to-weight ratios), even if this goal is achieved at the expense of geometrical simplicity.

There are several examples of multi-storey office buildings (Figure 2.2) with a primary load-bearing system consisting entirely of cold-formed members as well. Another large area of use is composite slabs, where trapezoidal sheeting and cold-formed sections are used as tension and a thin concrete slab as compression parts resulting in light floor systems applicable in buildings made of cold-formed members or in refurbishment. Cold-formed members are also extensively used in warehouse racks.

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

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

Source: Moen & Schafer (2008).

Figure 2.2 Roof system using cold-formed

Source: Moen & Schafer (2008).

2.2 Method of Forming

There are three methods generally used in the manufacture of cold-formed steel sections which are cold-rolling, folding, and press braking operation. According to Zhou (2017), 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 Cold-Rolling

The method of cold roll forming has been widely used for the production of building components such as individual structural members, and some roof, floor, and wall panels and corrugated sheets. It is also employed in the fabrication of partitions, frames of windows and doors, gutters, downspouts, pipes, agricultural equipment, trucks, trailers, containers, railway passenger and freight cars, household appliances, and other products. Sections made from strips up to 36 in. (915 mm) wide and from coils more than 3000 ft. (915 m) long can be produced most economically by cold roll forming.

The machine used in cold roll forming consists of pairs of rolls (as Figure 2.3) which progressively form strips into the final required shape. A simple section may be produced by as few as six pairs of rolls. However, a complex section may require as many as 15 sets of rolls. Roll setup time may be several days. The speed of the rolling process ranges from 20 to 300 ft. /min (6 to 92 m/min). The usual speed is in the range of 75 to 150 ft. /min (23 to 46 m/min). At the finish end, the completed section is usually cut to required lengths by an automatic cut off tool without stopping the machine. Maximum cut lengths are usually between 20 and 40 ft. (6 and 12 m).

Figure 2.3 Cold Roll Forming Machine

Source: Zhou (2017).

As far as the limitations for thickness of material are concerned, carbon steel plate as thick as in. (19 mm) can be roll-formed successfully, and 3–4 stainless steels have been roll-formed in thicknesses of 0.006 to 0.30 in. (0.2,to 7.6 mm). The size ranges of structural shapes that can be roll-formed on, standard mill-type cold roll forming machines are shown in Figure 2.4. The tolerances in roll forming are usually affected by the section size, the product type, and the material thickness. Figure 2.5 gives the fabrication tolerances as specified by the Metal Building Manufacturers Association (MBMA) for cold-formed steel channels and Z-sections to be used in metal building systems. All symbols used in the table are defined in Figure 2.6.

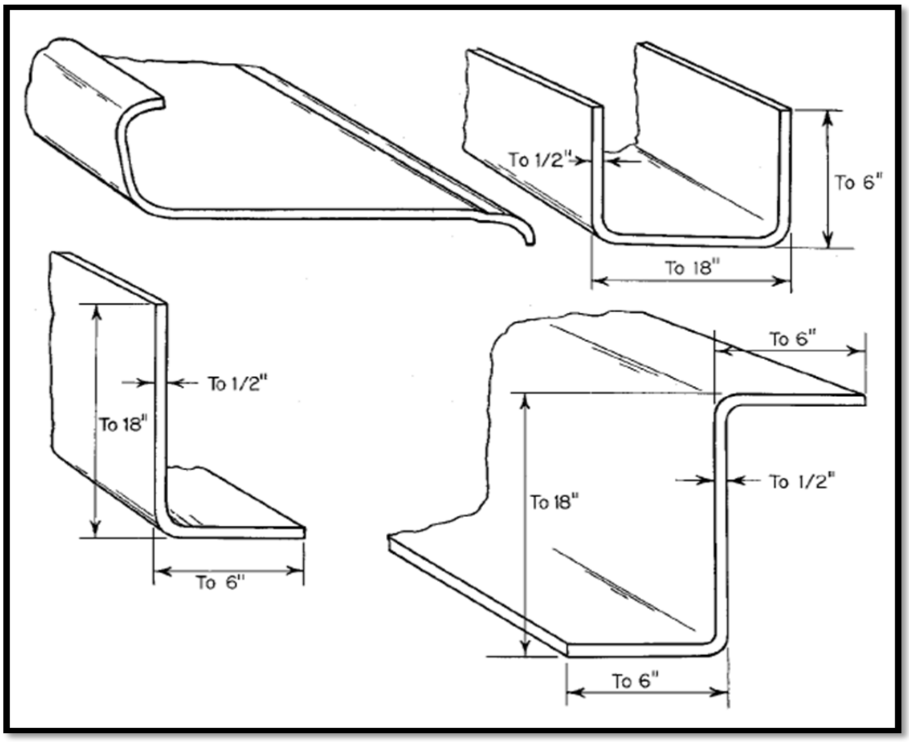
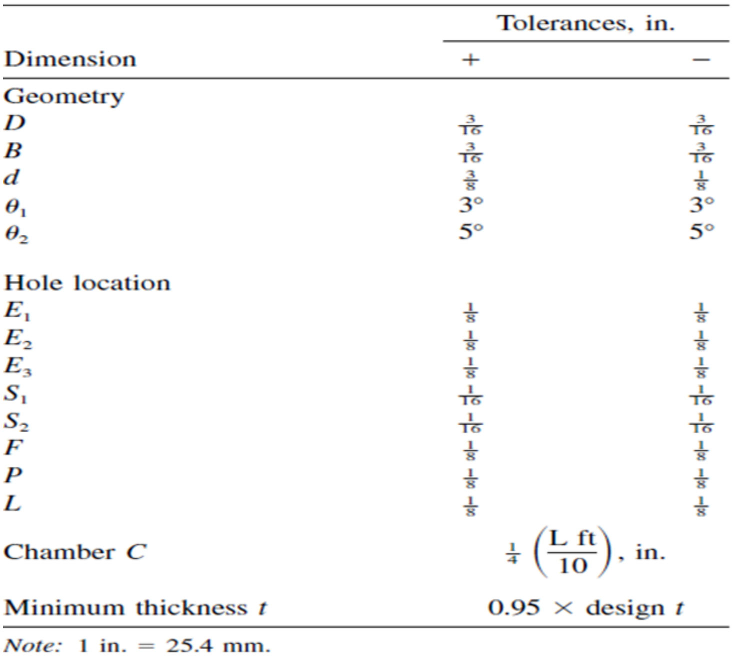


Figure 2.4 Size Ranges of Typical Roll-Formed Structural Shapes

Source: Zhou (2017).



Dimension	Tolerances, in. +	Tolerances, in. −
Geometry		
D	$\frac{3}{16}$	$\frac{3}{16}$
B	$\frac{3}{16}$	$\frac{3}{16}$
d	$\frac{3}{8}$	$\frac{1}{8}$
θ_1	3°	3°
θ_2	5°	5°
Hole location		
E_1	$\frac{1}{8}$	$\frac{1}{8}$
E_2	$\frac{1}{8}$	$\frac{1}{8}$
E_3	$\frac{1}{8}$	$\frac{1}{8}$
S_1	$\frac{1}{16}$	$\frac{1}{16}$
S_2	$\frac{1}{16}$	$\frac{1}{16}$
F	$\frac{1}{8}$	$\frac{1}{8}$
P	$\frac{1}{8}$	$\frac{1}{8}$
L	$\frac{1}{8}$	$\frac{1}{8}$
Chamber C	$\frac{1}{4}\left(\frac{\text{L ft}}{10}\right)$, in.	
Minimum thickness t	0.95 × design t	

Note: 1 in. = 25.4 mm.

Figure 2.5 MBMA Table on Fabrication Tolerances

Source: Jakab & Dunai (2008).

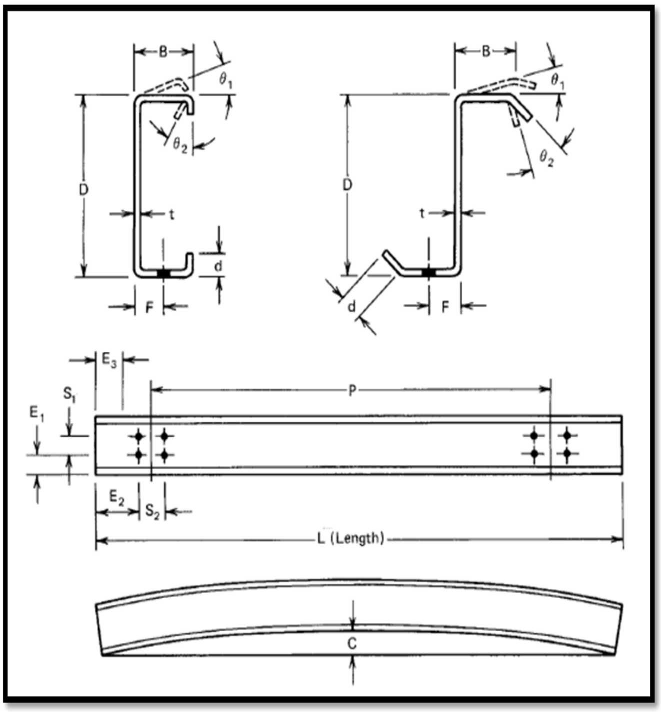


Figure 2.6 Symbols used in MBMA
Source: Kulantunga & MacDonald (2013).

2.2.2 Press Brake Operation

The press brake operation may be used under the following conditions:

1. The section is of simple configuration.
2. The required quantity is less than about 300 linear ft. /min (91.5 m/min).
3. The section to be produced is relatively wide [usually more than 18 In. (457 mm)] such as roof sheets and decking units.

The equipment used in the press brake operation consists essentially of a moving top beam and a stationary bottom bed on which the dies applicable to the particular required product are mounted (Vardakoulias, 2015), as shown in Figure 2.7. Simple sections such as angles, channels, and Z-sections are formed by press brake operation from sheet, strip, plate, or bar in not more than two operations. More complicated sections may take several operations. It should be noted that the cost of products is often dependent upon the type of the manufacturing process used in production. In addition to the strength and dimensional requirements, a designer should also consider other influencing factors, such as formability, cost and availability of material, capacity and cost of manufacturing equipment, flexibility in tooling, material handling, transportation, assembly, and erection.

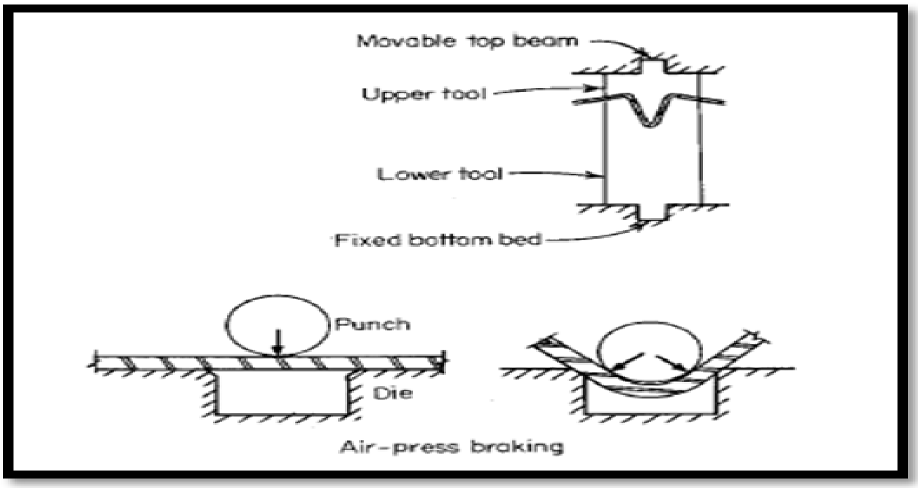


Figure 2.7 Press-braking
Source: Vardakoulias (2015).

2.2.3 Folding

Folding method is the simplest method of cold-forming. The production involved series of bends (folding) of sheet of material. From this method, a short length of cold-formed steel with a simple geometry can be produced. In addition, there are a lot of advantages such as improved parts quality, simplified handling, and increase productivity by reducing handling and set-up-times, and increased flexibility lower production costs (and after-treatment costs). However, this method is not widely used as of it limitation of design and application. The folding machine can be refer Figure 2.8.

Figure 2.8 Folding Machine

Source: Meiyalagan (2010).

2.3 Application of Cold-Formed Steel

Cold forming has the effect of increasing the yield strength of steel, the increase being the consequence of cold working well into the strain hardening range. These increases are predominant in zones where the metal is bent by folding. The effect of cold working is thus to enhance the mean yield stress by 15-30 %. For purposes of design, the yield stress may be regarded as having been enhanced by a minimum of 15 %.

According to Meiyalagan (2010), there are a lot advantages for CFS structural members in building construction which are the cross sectional shapes are formed to close tolerances and these can be consistently repeated for as long as required. Cold rolling can be employed to produce almost any desired shape to any desired length. Pre-galvanized or pre-coated metals can be formed, so that high resistance to corrosion, besides an attractive surface finish, can be achieved. High strength to weight ratio is achieved in cold rolled products, they are usually light making it easy to transport and erect as compared with thicker hot rolled shapes, more economical design can be achieved for relatively light loads and/or short spans.

Unusual sectional configuration can be economically produced by cold-forming operation, and consequently favourable strength to weight ratios can be obtained. 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. Load carrying panels and decks not only withstand loads normal to their surfaces, but they can also act as shear diaphragms to resist force in their own planes if they are adequately inter connected to each other and to supporting members.

2.4 Behaviours under Axial Compression

Meiyalagan (2010) indicates that non symmetric open web cross sections (whose centroid does not coincide with shear centre) will undergo flexural torsional buckling. Single symmetric sections will likely to fail flexural buckling, or flexural torsional buckling depending on their actual sizes (Figure 2.9). Double symmetrical members, may be susceptible to lateral torsional buckling (flexural buckling) due to the presence of the imperfections. Pure torsional buckling modes are likely to occur for point symmetric sections in which the shear centre and centroid coincides. Lateral torsional buckling (or flexural torsional buckling) FT is a combination of flexural buckling (F) and torsional buckling (T). Long columns fail in flexural or flexural – torsional buckling and short columns in distortional buckling.

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

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

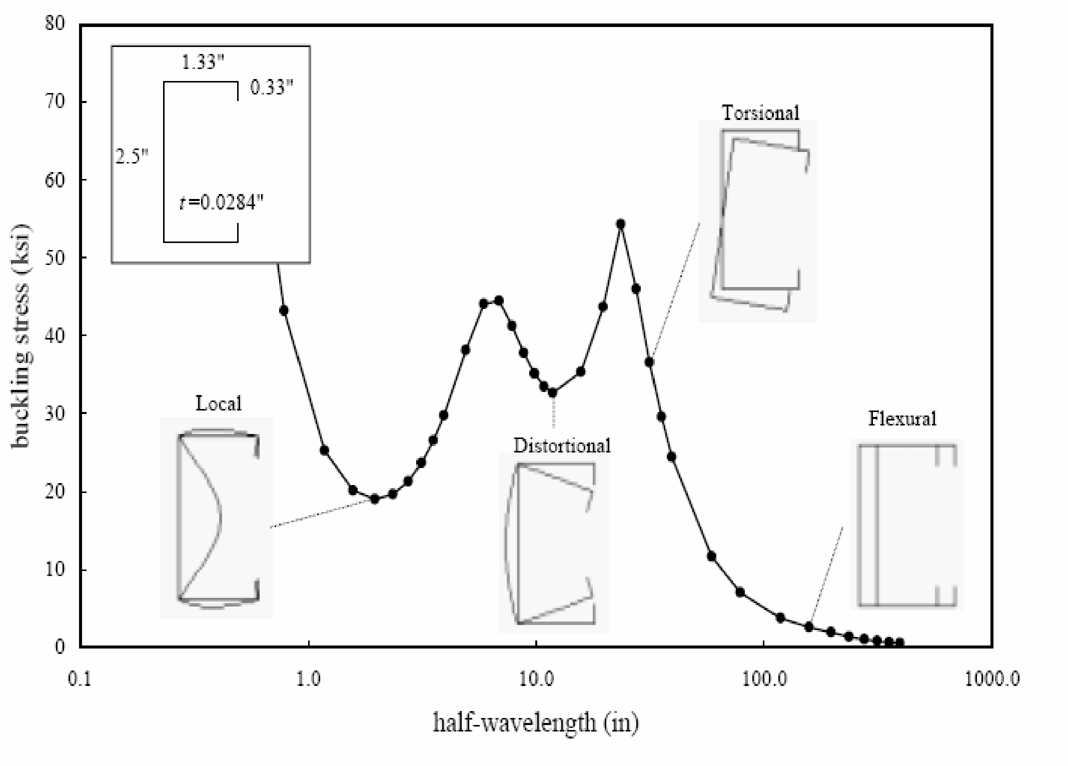


Figure 2.9 Mode of failure for CFS

2.4.1 Local Buckling

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

2.4.2 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.

2.4.3 Torsional - Flexural Buckling

When an open section column buckles in the torsional flexural mode, bending and twisting of the section occur simultaneously. The section translate in the x and y direction and rotates an angle about the shear centre. The critical buckling load (refer Figure 2.10) is the smallest value of the three roots of P_{cr},

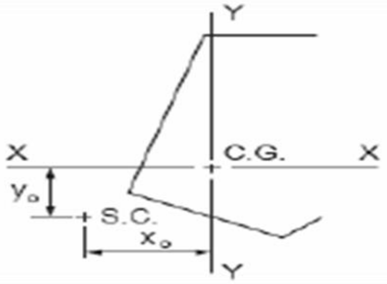


Figure 2.10 Torsional buckling of CFS

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 Kulantunga & MacDonald (2013) stated that it was found out that all of the columns tested failed by local and distortional buckling. (Al-Jallad & Al-Thairy, 2016) Indicates 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.

According to Crisan, et al. (2012), both test and numerical simulations have proven the negative influence of interaction between distortional and overall buckling in the case of these particular types of rack sections. This leads to a medium to very strong interaction, which reduces significantly the capacity in compression of the members. In principal, considering the results obtained for the interaction range from both tests and the numerical simulations, the perforations are increasing he c erosion coefficient and the aim perfection factor values, but not as much as expected. Real sections tend to have a higher capacity than the one obtained via numerical simulations due to:

- The real imperfections are lower than those recommended by codes and literature
- In real cases, the imperfections randomness partially compensates each other, while in numerical simulation they are cumulatively applied.

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:

- The shape of the cross section
- The slenderness ratio of the column
- The type of governing overall column buckling (flexural buckling, torsional buckling, or torsional–flexural buckling)
- The type of steel used and its mechanical properties
- Influence of cold work
- Effect of imperfection
- Effect of welding
- Effect of residual stress
- Interaction between plane components
- Effect of perforations
- Effect of the type of section
- Effect of the base plate

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 two main type of sections which are single open section and open built-up section

2.6.1 Single 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.

M. P. Kulatunga, et al. (2013) indicates that the CFS sections offer one of the highest load capacity-to-weight ratios among the various structural components currently in the market. It also offers economy in production, transportation and handling. CFS sections with edge stiffened flanges have three types buckling specifically local buckling, distortional buckling and Euler’s buckling (flexural or flexural-torsional), generally called as global buckling.

2.6.2 Build-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.

Based on the research by Georgievaa et al. (2012), built-up CFS members usually have symmetric cross-sections, higher strength and better resistance against out-of-plane movement. Because the production method remains unchanged, composed CFS members are a relatively cheap alternative to single profiles, which easily fail in overall buckling, if not laterally supported. Built-up solutions are adopted in practice, regardless of the lack of design rules to predict the member strength.

Whittle & Ramseyer (2009) specifies that built- up members be designed with a modified slenderness ratio if shear forces are induced between the weld or screw connectors. The section also introduces a minimum fastener strength requirement and a fastener spacing requirement for built-up members.

According to Lu, et al.(2017), the structure response of the cold-formed built-up I-section column was significantly affected by the occurrence of local distortional and local-distortional-global interactions. The complex multiple interactions effects resulted in a significant strength erosion for the tested built-up columns. The local buckling cannot be restrained for cold-formed I-section columns when the screw spacing is larger than the local buckling half-wavelength of the corresponding C-section parts. Under such a circumstance, the local buckling strength of the cold-formed built-up I-section column is approximately two times of that of the corresponding C-section parts.

2.7 Perforations

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

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

Test done by Moen (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. 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.

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 & 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.

CHAPTER 3

METHODOLOGY

3.1 Introduction

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

Upon testing was made, a discussion was made with the technician involved to know further about the machine and how the testing would be conducted. As there are no standards that are available for the testing of steel, the research by M.P. Kulatunga and M. Macdonald entitle “Investigation of Cold-formed Steel Structural Members with Perforations of Different Arrangements Subjected to Compression Loading” was 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.

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

3.2 Flow Chart

The flow of this research would based on the phase which are phase 1, phase 2, and phase 3 (refer Figure 3.1). From this phase, the flow are smoother to carry out as we can see the ways of this research at the end.

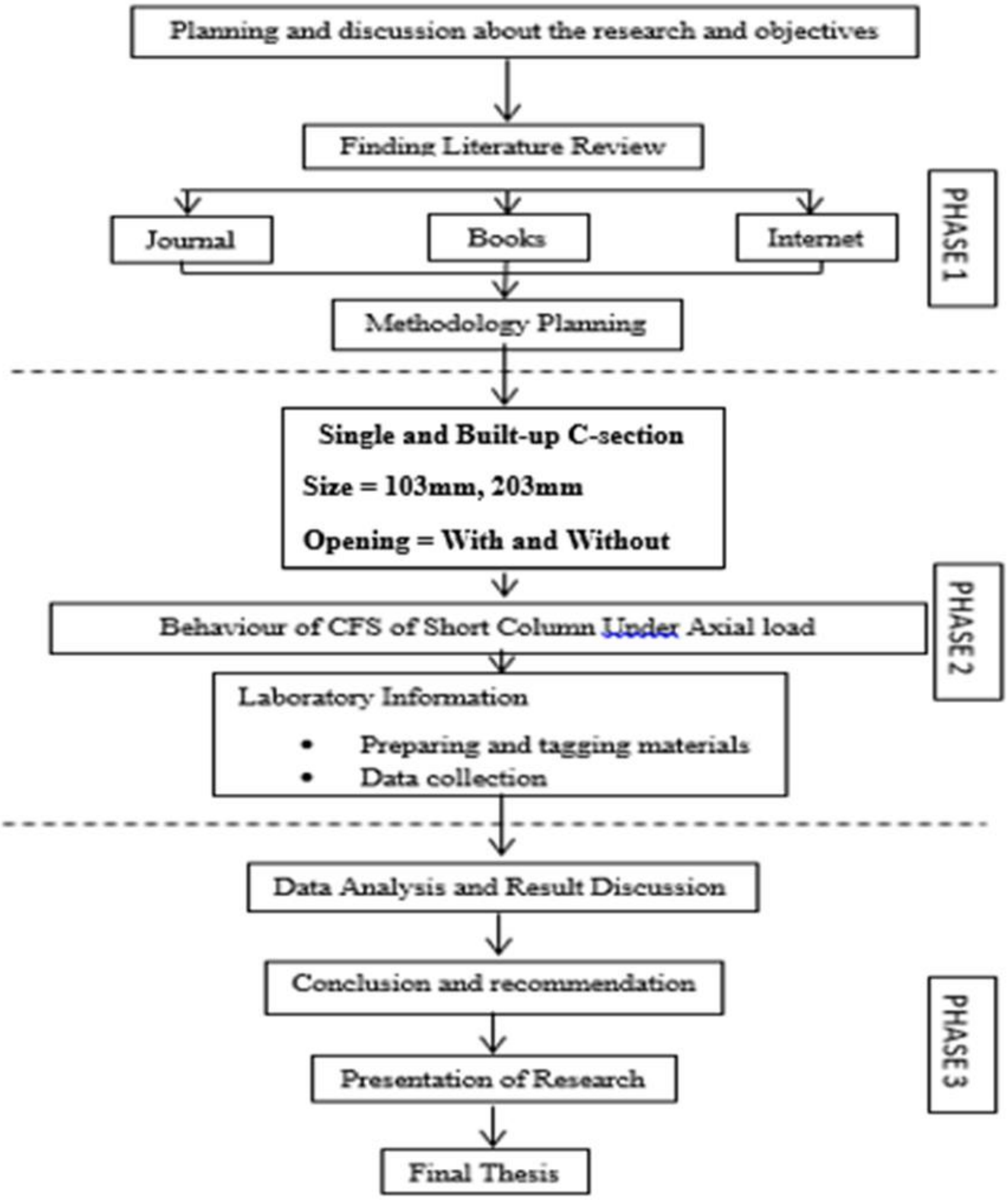


Figure 3.1 Project Flow Chart

3.3 Research Design and Parameter

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

Table 3.1 Section Parameter

Parameter	Magnitude
Length	600mm
Diameter	103mm , 203mm
Thickness	1.2mm
Opening	With and Without Opening
Section	Single and Built-up Section

Table 3.2 Naming Convention of the Specimens

Without Opening	With Opening
103 – A1 – SC	103 – A2 – SC
203 – A1 – SC	203 – A2 – SC
103 – A1 – BC	103 – A2 – BC
203 – A1 – BC	203 – A2 - BC

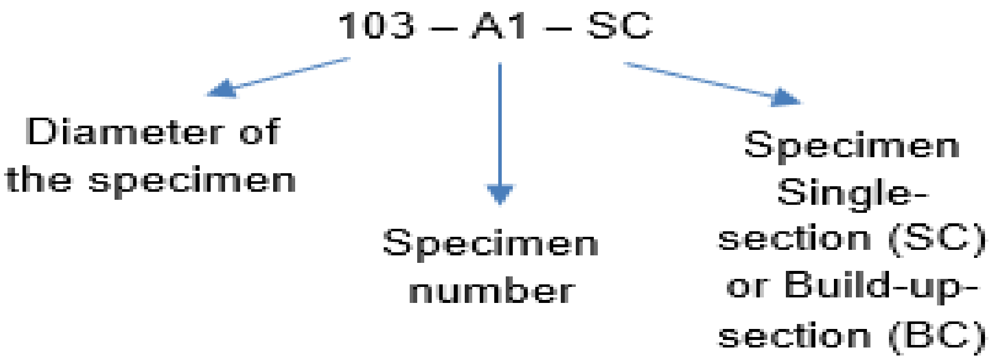


Figure 3.2 Naming Convention

3.4 Research Procedure

This research conducted at FKASA laboratory at University Malaysia Pahang by using Universal Testing Machines. The process of setting up the specimen during testing start by making cross-line at centre of the bottom to make easy to place the specimen with permanent position. Continue by putting up the transducers which are vertical and horizontal at both sides. 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 loading rate that will be used was 0.5 mm per minute which it was the most suitable rate for this specimens according to the previous researcher.

The Universal Testing Machine will compressed the specimen until the machine are stop by the user according to displacement value study. The Universal Testing Machine will read the displacement of the specimens. 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. The support being used for the specimen is fixed end. The thesis of Kulantunga & MacDonald (2013), S.Vijayanand & Anbarasu (2017) and MacDonald & Kulatunga (2013) are being set as a reference through the execution of this project. Refer to Figure 3.3 – 3.16 show the procedure to prepare the specimens with details by schematic diagram.

Figure 3.3 Labels the Naming Convention of Specimens

Figure 3.4 Drilling the Specimens to form Build-up Section

Figure 3.5 Welding the Base Plate to be Fixed-Ends

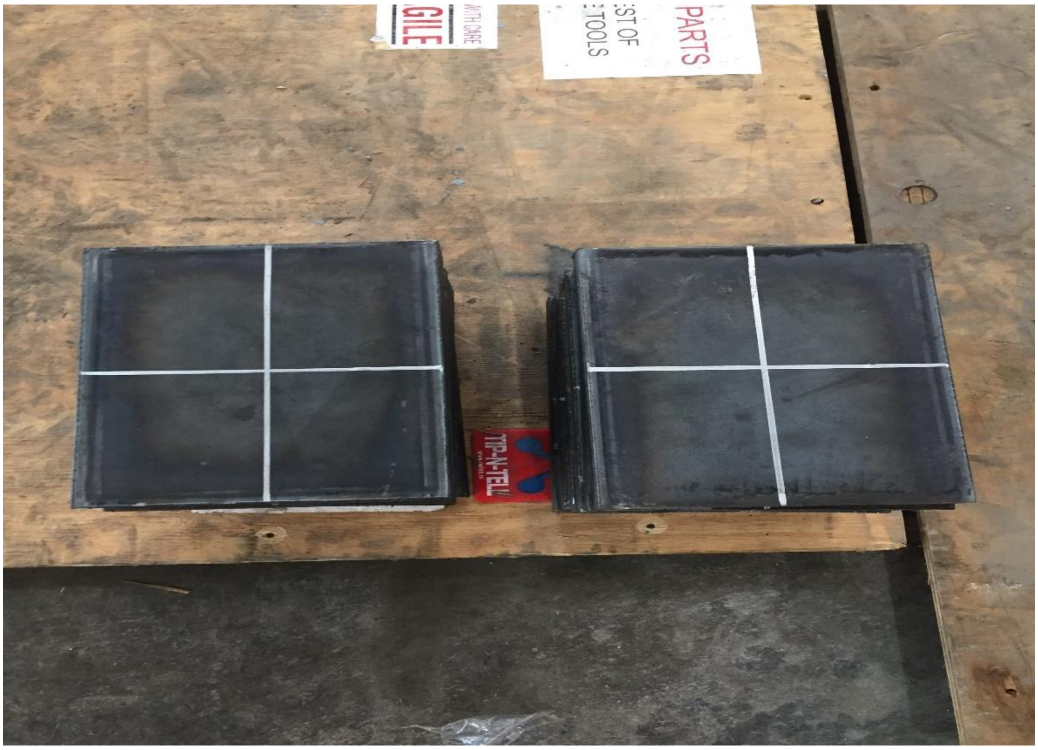


Figure 3.6 The Base Plate that will be used.

Figure 3.7 The Support Condition of the Specimen

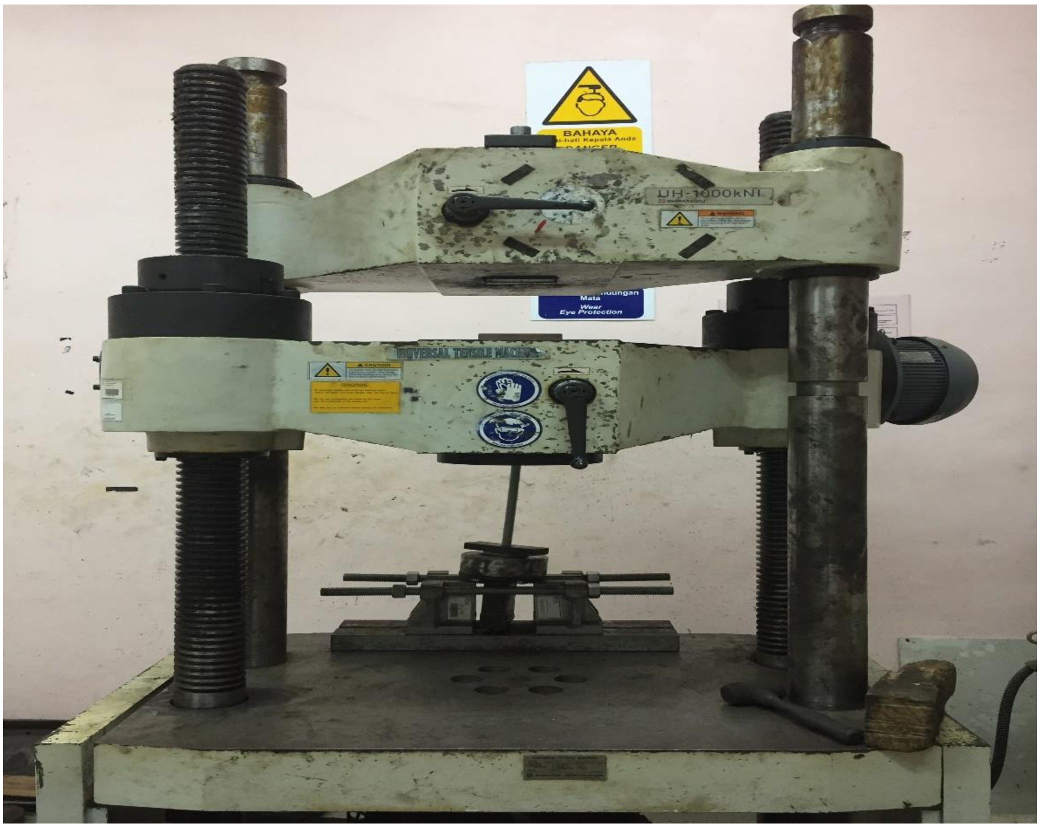


Figure 3.8 Universal testing Machine that are available in FKASA laboratory

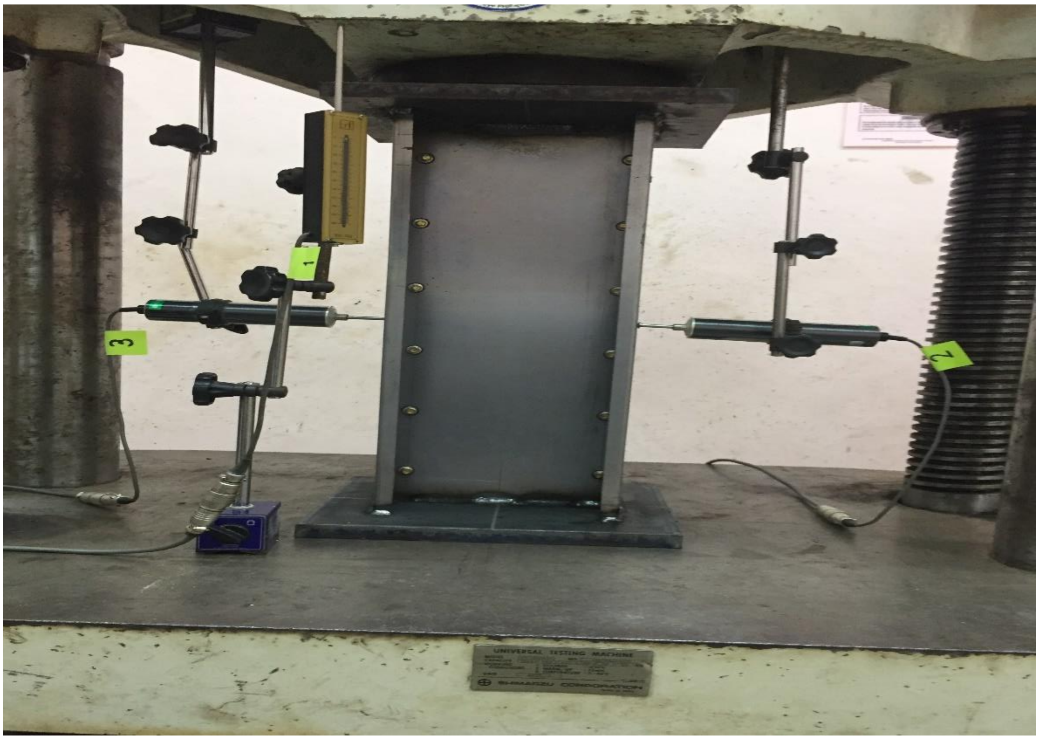


Figure 3.9 The Placement of Transducers and Specimens

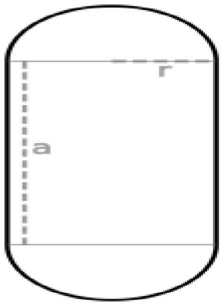
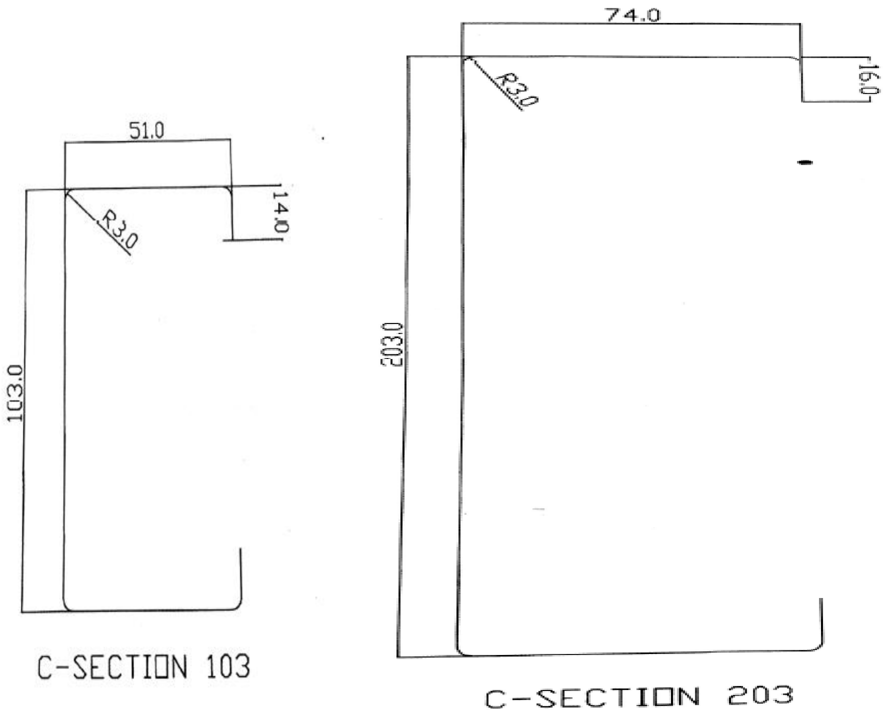


Figure 3.10 The Shape of opening of the specimens

Figure 3.11 The Self-Drilling Screws that will be used to form Built-up Section



C-SECTION 103

C-SECTION 203

Figure 3.12 Schematic Diagram of the Specimens

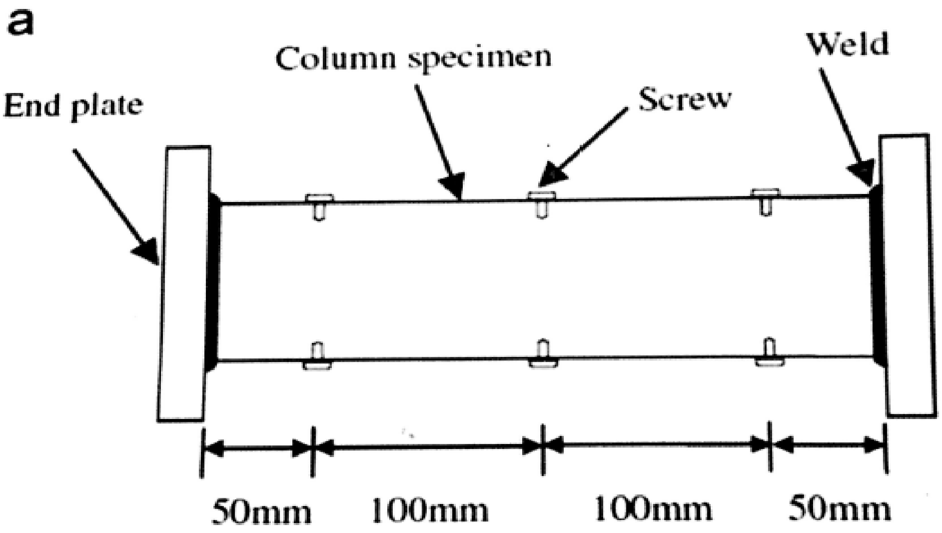


Figure 3.13 The Positions and Displacement of the Screws

Source: Lu, et al. (2017).

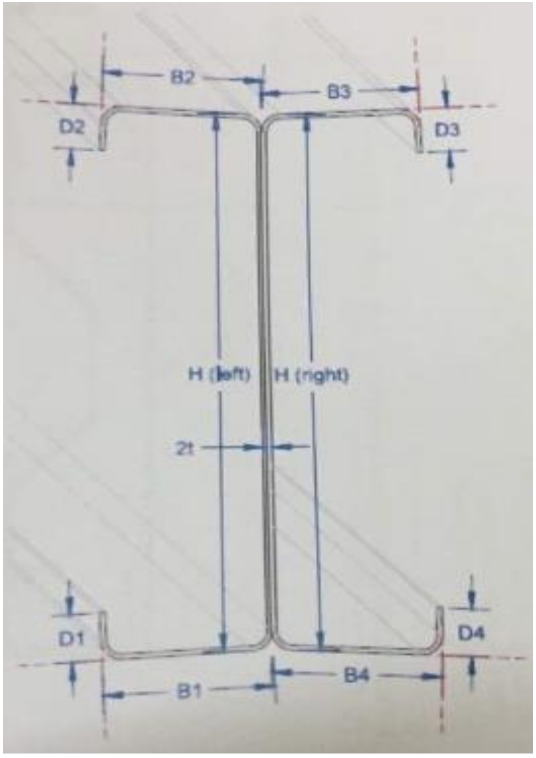


Figure 3.14 Schematic Diagram for Built-up Section

Source: Lu, et al. (2017).

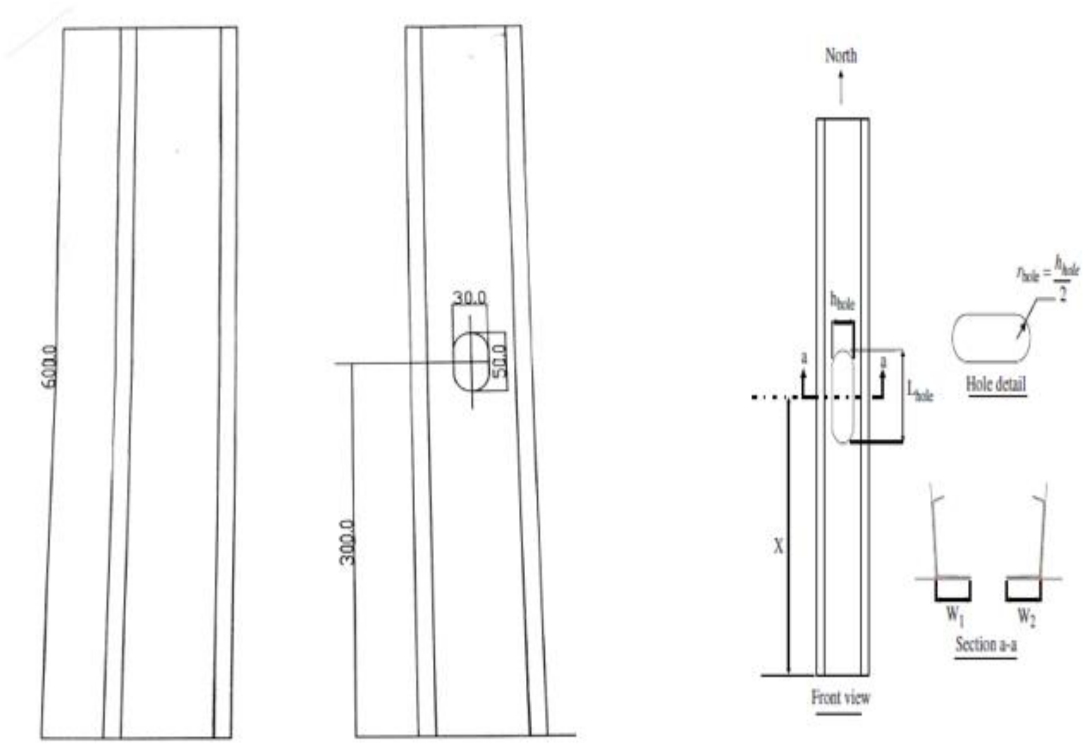


Figure 3.15 Schematic Diagram of the position of the Opening.

.

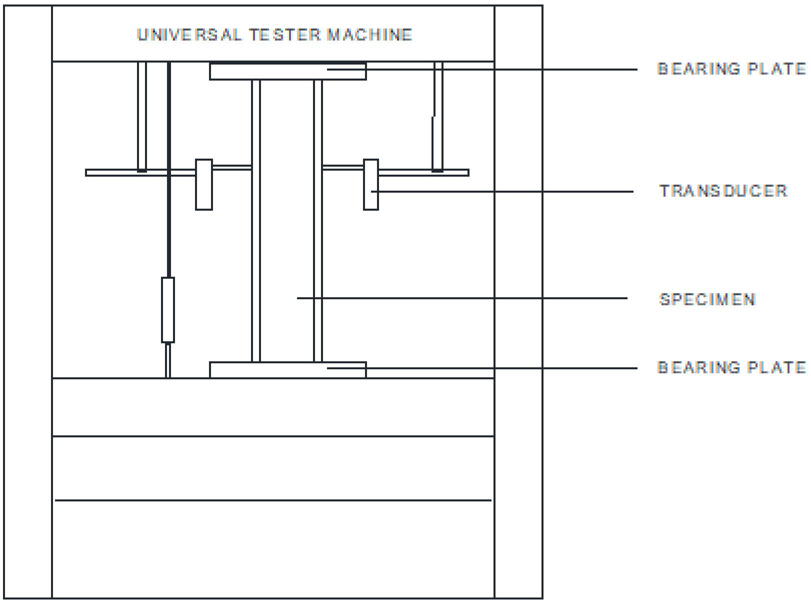


Figure 3.16 Schematic Diagram of the position of the Opening

CHAPTER 4

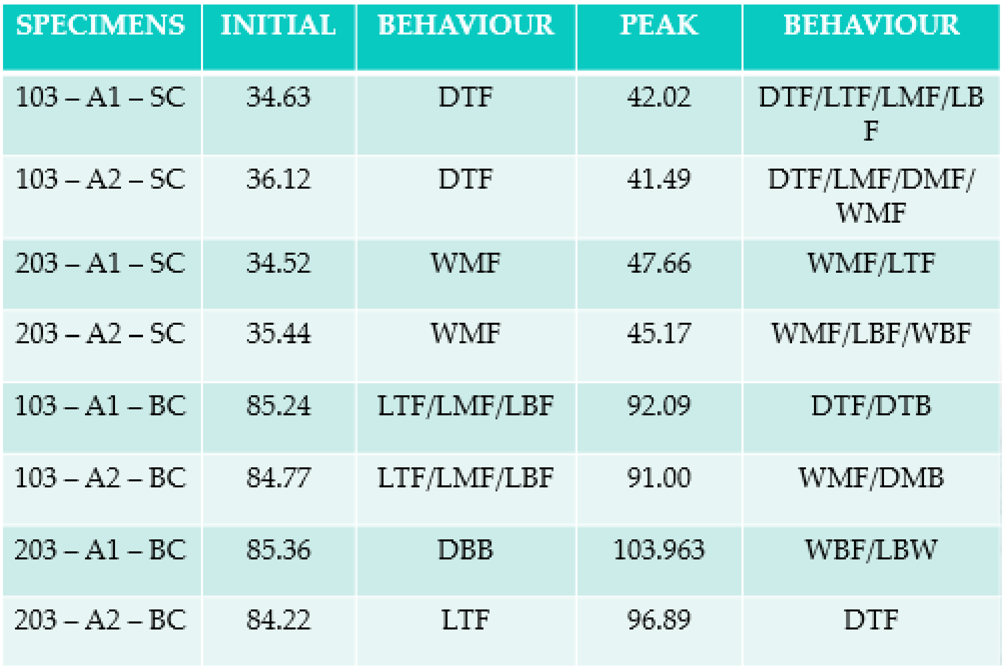
RESULTS AND DISCUSSION

4.1 Introduction

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 against vertical displacement and load against horizontal displacement where it compared the axial load and the displacement of the sample.

From this research, the overall result can refer Figure 4.1. The ultimate load was obtained by specimen without opening compare to with opening. For the type of section, the built-up section obtained higher ultimate load compare to single section. In addition, for the size of the specimen, the size with 203mm has higher ultimate load than the size with 103mm.

For the behaviour of failures mode, all the specimen seems to experience local, distortional and warping buckling. From the overall result obtained, the cause of unexpected result (imperfection) might be causes by the transducers (LVDT) that easily to move/rotate and give effects to the reading. Besides, the initial load reading are difficult to obtain an accurate value caused by observed the initial buckling are difficult. Moreover, the reading from the data logger for each of the transducers are not compatible with the reading from universal testing machine.



SPECIMENS	INITIAL	BEHAVIOUR	PEAK	BEHAVIOUR
103 – A1 – SC	34.63	DTF	42.02	DTF/LTF/LMF/LBF
103 – A2 – SC	36.12	DTF	41.49	DTF/LMF/DMF/WMF
203 – A1 – SC	34.52	WMF	47.66	WMF/LTF
203 – A2 – SC	35.44	WMF	45.17	WMF/LBF/WBF
103 – A1 – BC	85.24	LTF/LMF/LBF	92.09	DTF/DTB
103 – A2 – BC	84.77	LTF/LMF/LBF	91.00	WMF/DMB
203 – A1 – BC	85.36	DBB	103.963	WBF/LBW
203 – A2 – BC	84.22	LTF	96.89	DTF

Figure 4.1 Overall Result

4.2 Test on Compression Single Section

4.2.1 Compressed on 103 – A1 – SC

The result for this specimen was as an expected. At the initial stage where the loading was applied, the initial load was 34.63 kN and the observation at specimen occurred distortional buckling at the top of the specimen (Figure 4.3). The specimen failure was at 42.02 kN due to local and distortional buckling (Figure 4.4). From the overall observation, the distortional buckling occurred at the top was obviously showed the failures of the specimen (Figure 4.5).

For the load vs vertical displacement graph (Figure 4.6), the ultimate axial load applied was 42.02 kN with 2.019 mm displacement. 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 CFS short column.

The maximum axial load for this sample is 42.02 kN and the maximum displacement is 0.789 mm which happen at the transducer CH. As seen from Figure 4.7, the graph intersects once in the test. Intersect between CH2 and CH3 at 0.45 mm displacement. The result shows that local buckling behaviour at top, middle and bottom of the specimen and distortional buckling also occur at top of the specimen.

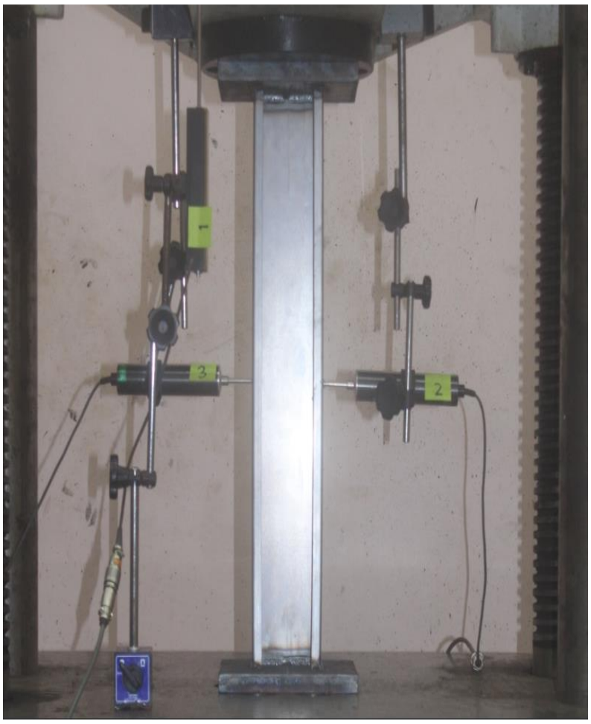


Figure 4.2 At Zero Loading

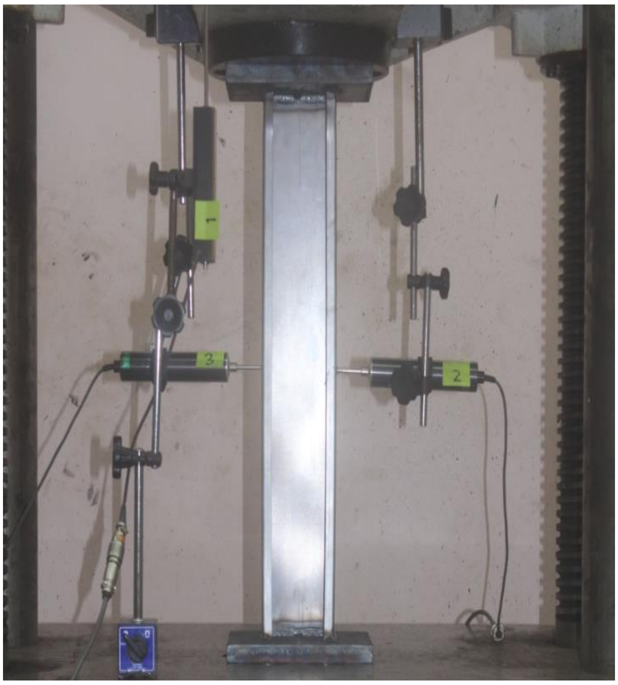


Figure 4.3 Initial Buckling

Figure 4.4 Peak Load

Figure 4.5 Final Post-Buckling

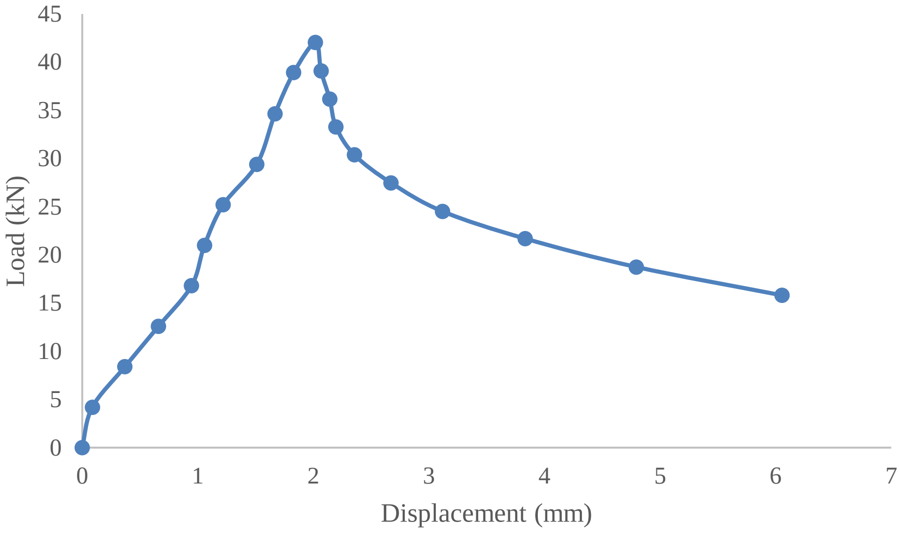


Figure 4.6 Load vs Vertical Displacement Graph

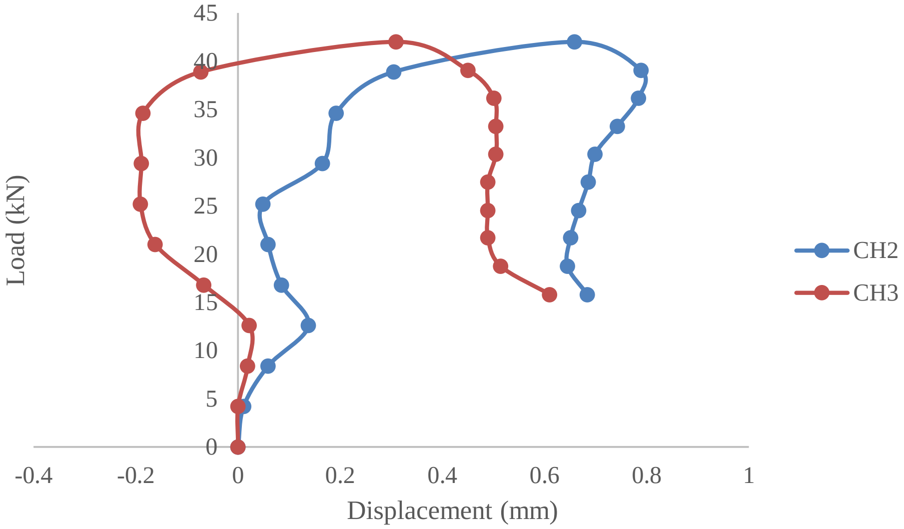


Figure 4.7 Load vs Horizontal Displacements Graph

4.2.2 Compressed on 103 – A2 – SC

The result for this specimen was as an expected. At the initial stage where the loading was applied, the initial load was 36.12 kN and the observation at specimen occurred distortional buckling at the top of the specimen (Figure 4.9). The specimen failure was at 41.49 kN due to local, distortional buckling and warping (Figure 4.10).

From the overall observation, the warping and distortional buckling occurred at the mid were obviously showed the failures of the specimen (Figure 4.11).

For the load vs vertical displacement graph (Figure 4.12), the ultimate axial load applied was 41.49 kN with 1.599 mm displacement. For this sample, the maximum axial load is 41.49 kN and the maximum displacement of the sample is -10.668 mm that happen after the maximum axial load is applied on the sample. As seen from Figure 4.13, the sample move into negative displacement for CH2 and CH3 transducers until it reach the failure. It shows that the displacement is slowly moving towards negative after the maximum load. From the result observation made that distortional occurs at top and middle front of the specimen, local and warping occur at the middle of the specimen.

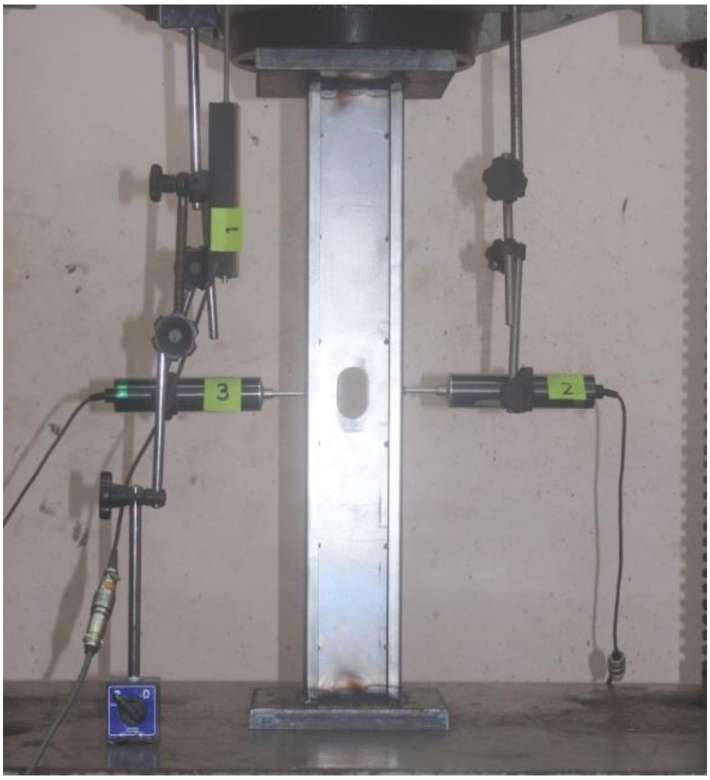


Figure 4.8 At Zero Loading

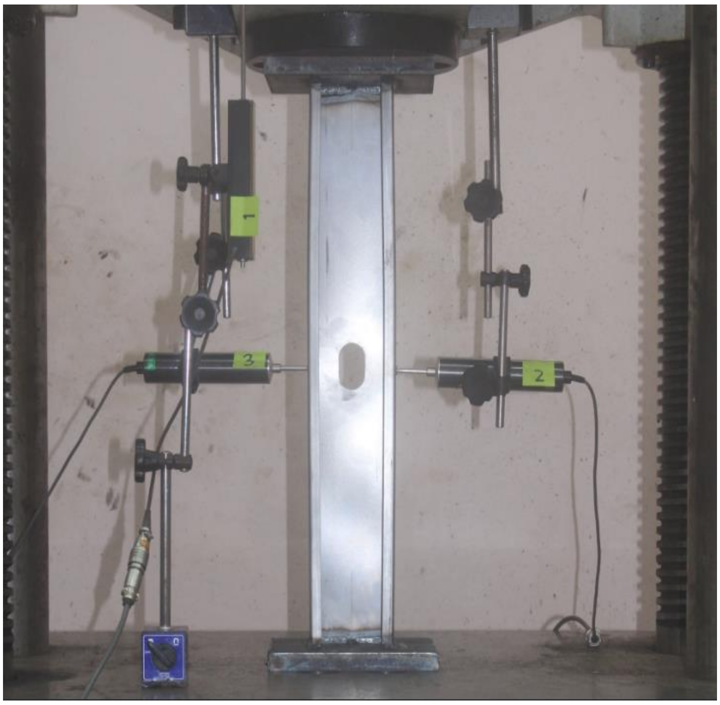


Figure 4.9 Initial Buckling

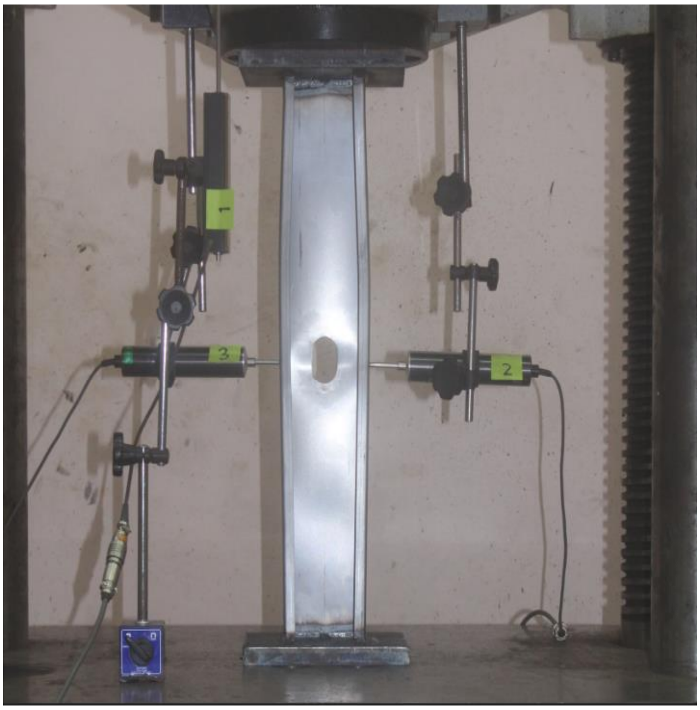


Figure 4.10 Peak Load

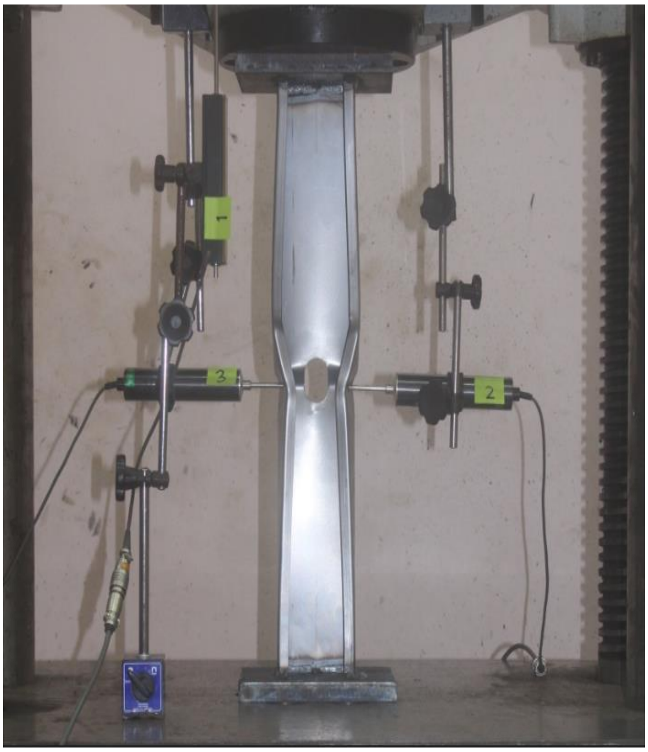


Figure 4.11 Final Post-Buckling

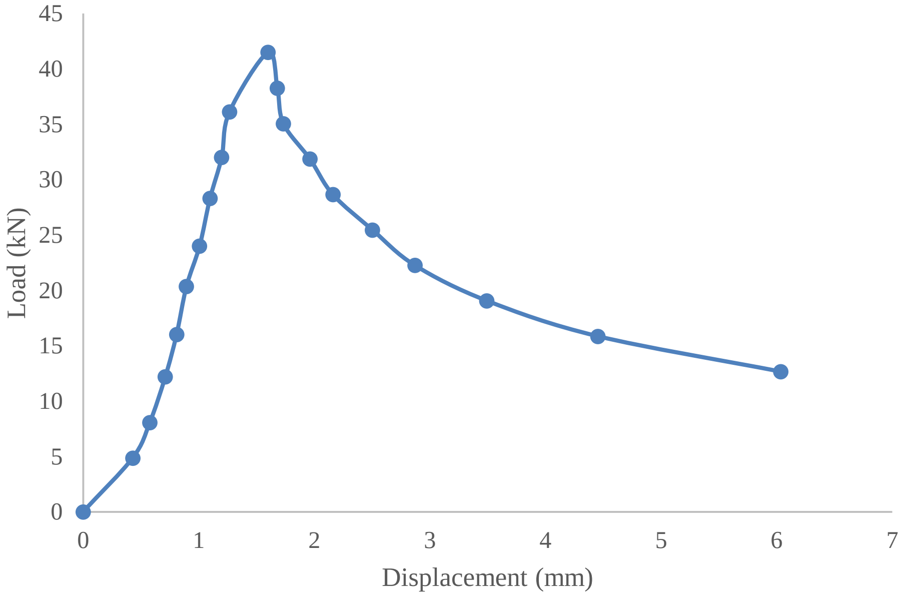


Figure 4.12 Load vs Vertical Displacement Graph

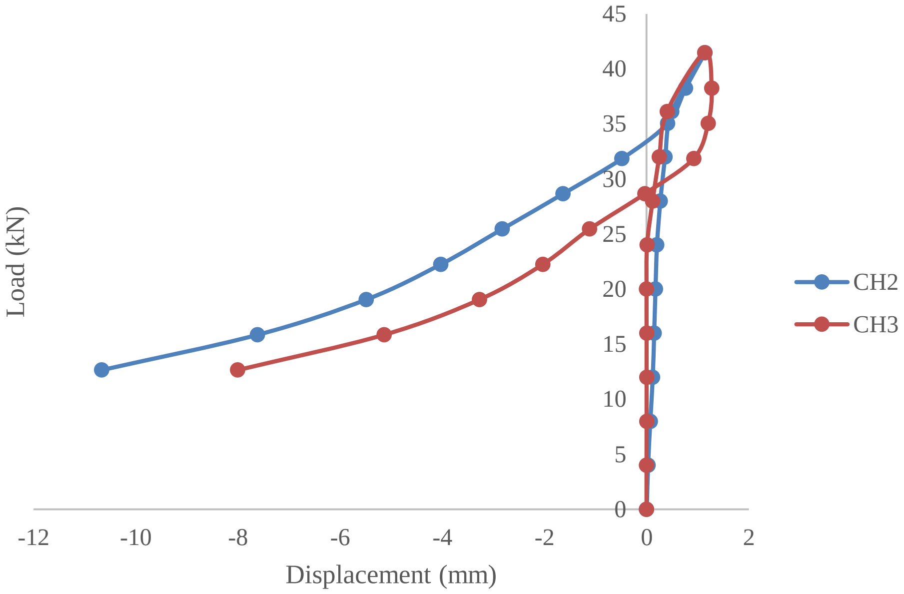


Figure 4.13 Load vs Horizontal Displacements Graph

4.2.3 Compressed on 203 – A1 – SC

The result for this specimen was as an expected. At the initial stage where the loading was applied, the initial load was 34.52 kN and the observation at specimen occurred warping at middle of the specimen (Figure 4.15). The specimen failure was at 47.66 kN due to warping and local buckling (Figure 4.16). From the overall observation, the warping occurred at the middle was obviously showed the failures of the specimen (Figure 4.17).

For the load vs vertical displacement graph (Figure 4.18), the ultimate axial load applied was 47.66 kN with 1.561 mm displacement. For this sample, it has a maximum axial load of 47.66 kN and a maximum displacement of 8.999 mm that happen at CH 3 at the end of the test. As seen from Figure 4.19, the graph intersects a few times of the test. Results shows displacement moving towards positive displacement for the two transducers. From the figure specimen shows warping at the middle and local occur at top of specimen after the end of experiment.

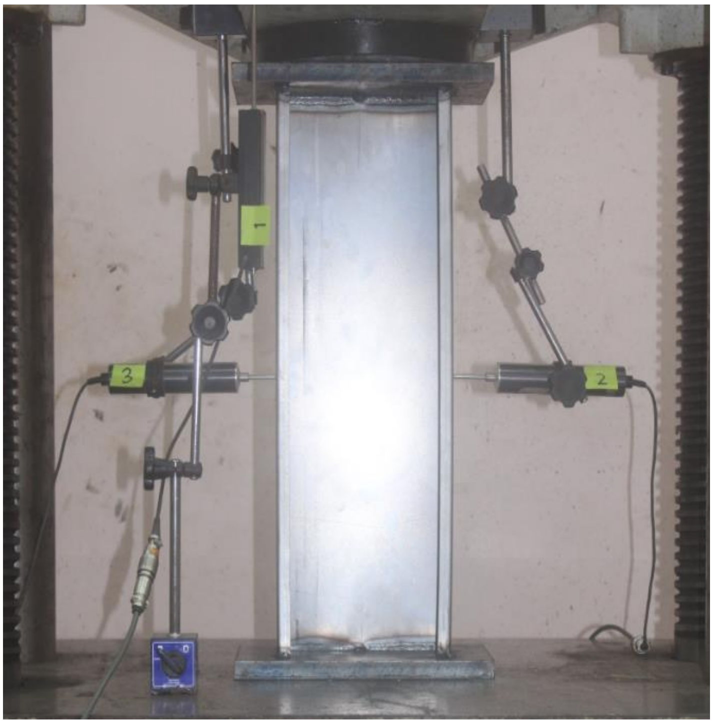


Figure 4.14 At Zero Loading

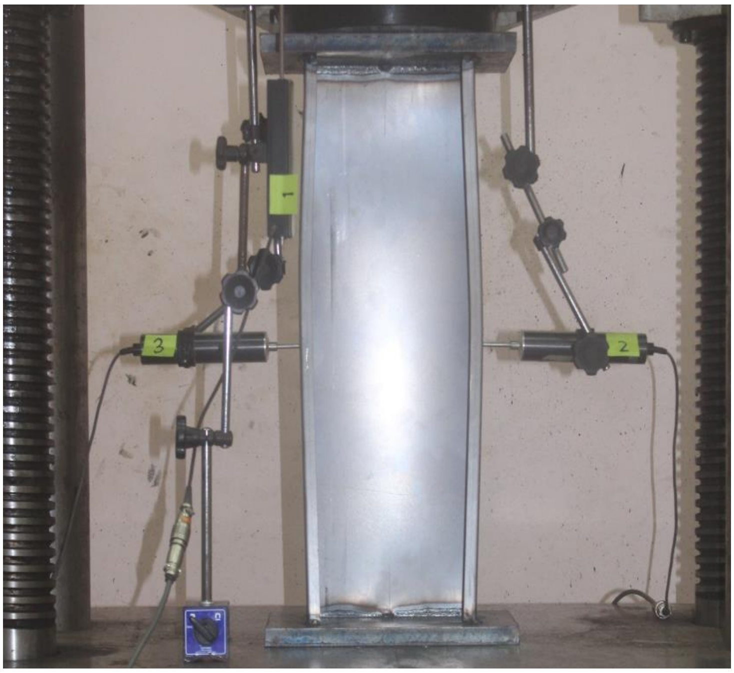


Figure 4.15 Initial Buckling

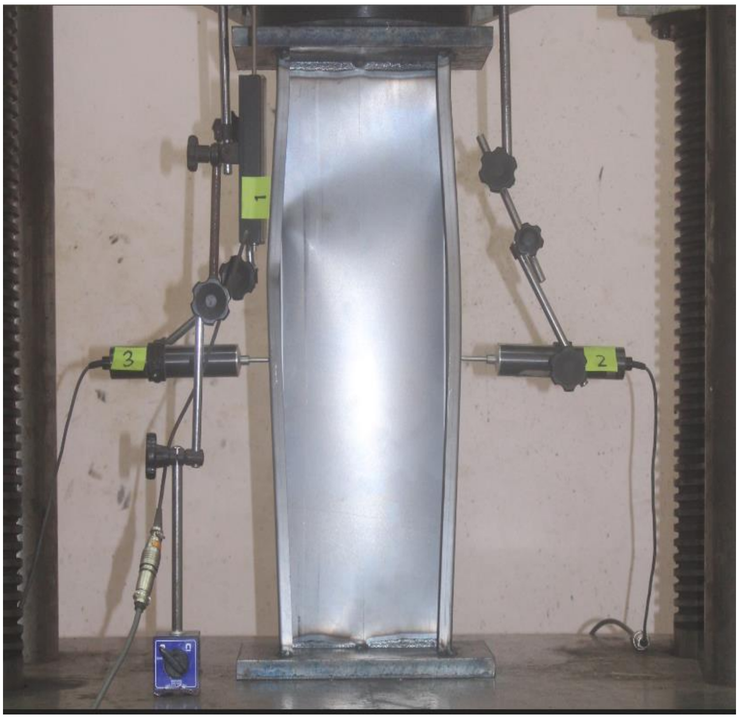


Figure 4.16 Peak Load

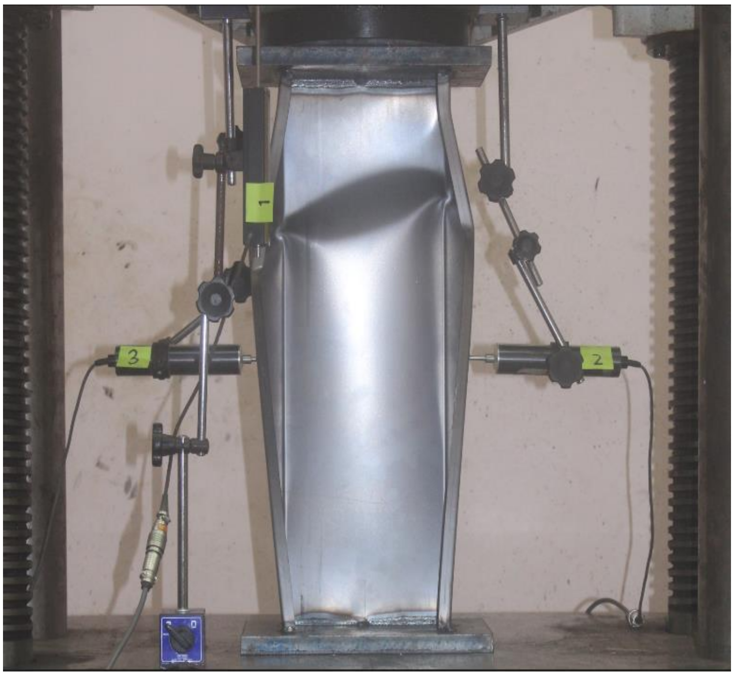


Figure 4.17 Final Post-Buckling

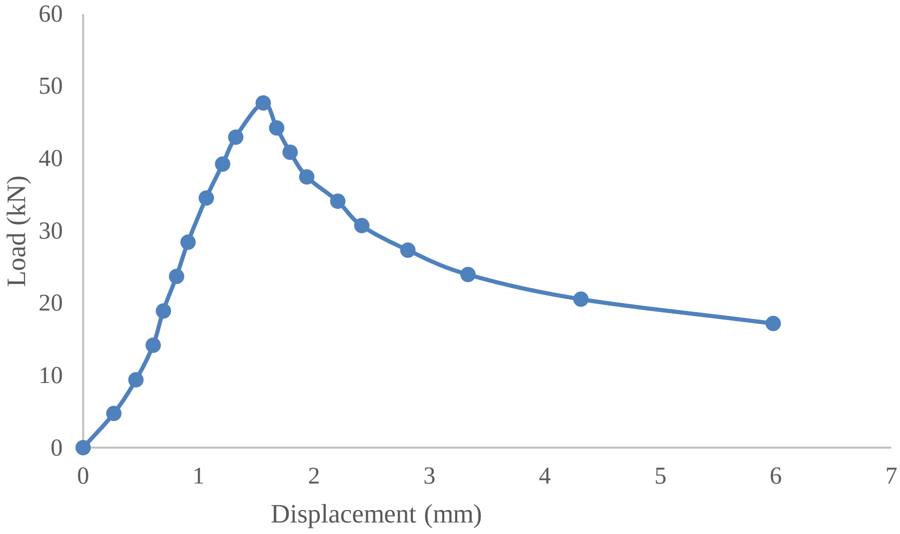


Figure 4.18 Load vs Vertical Displacements Graph

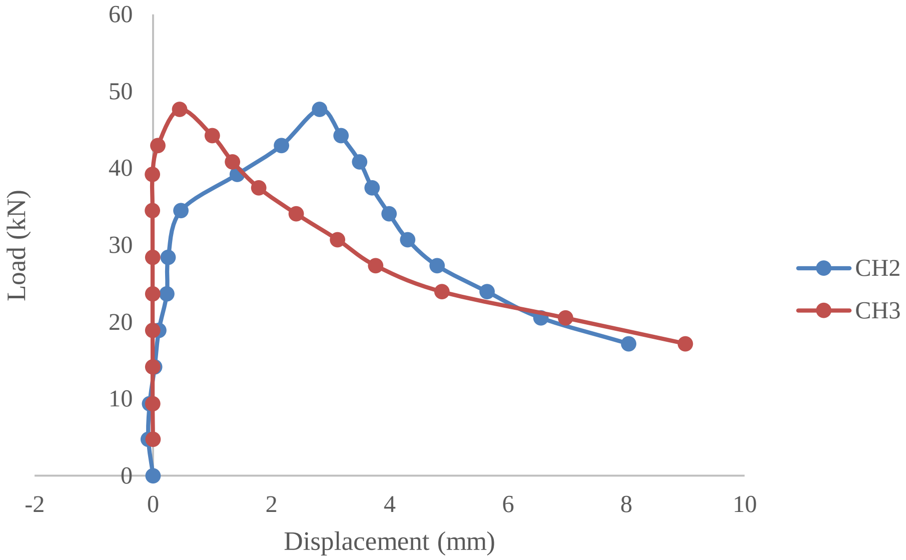


Figure 4.19 Load vs Horizontal Displacements Graph

4.2.4 Compressed on 203 – A2 – SC

The result for this specimen was as an expected. At the initial stage where the loading was applied, the initial load was 35.44 kN and the observation at specimen occurred warping at the middle of the specimen (Figure 4.21). The specimen failure was at 45.17 kN due to warping and local buckling (Figure 4.22). From the overall observation, the warping occurred at the middle was obviously showed the failures of the specimen (Figure 4.23).

For the load vs vertical displacement graph (Figure 4.24), the ultimate axial load applied was 45.17 kN with 1.202 mm displacement. Sample 203-A2-SC has a maximum axial load of 45.17 kN and a maximum displacement of 10.322 mm that happen at the end of the test. From Figure 4.25, the sample move into the same direction at the end of the result where it move to positive displacement. At the end of the result the specimen shows warping at mid and bottom, and local happens at bottom.

Figure 4.20 At Zero Loading

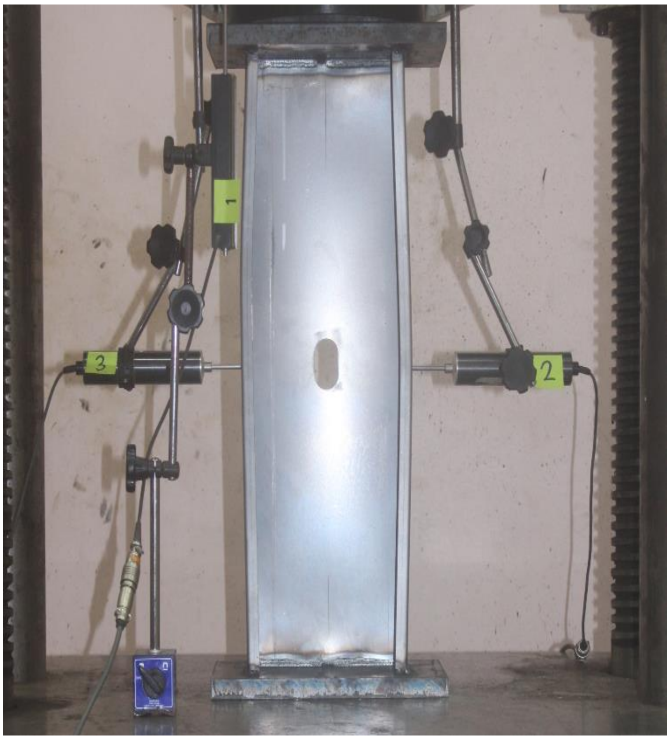


Figure 4.21 Initial Buckling

Figure 4.22 Peak Load

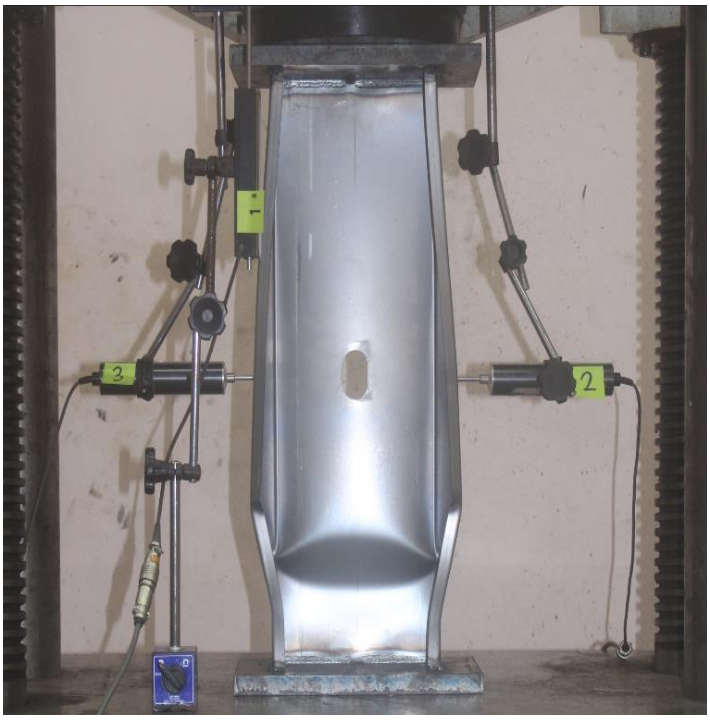


Figure 4.23 Final Post-Buckling

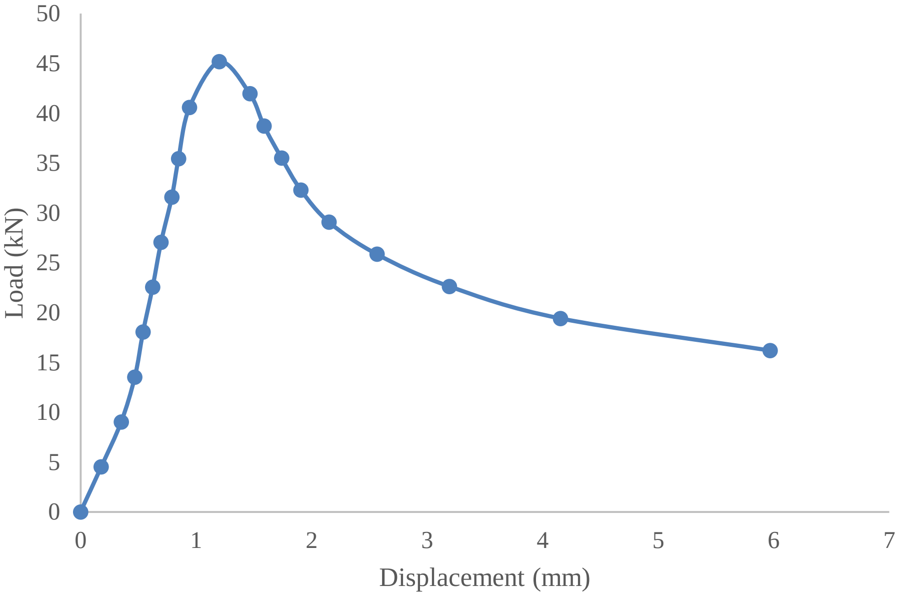


Figure 4.24 Load vs Vertical Displacement Graph

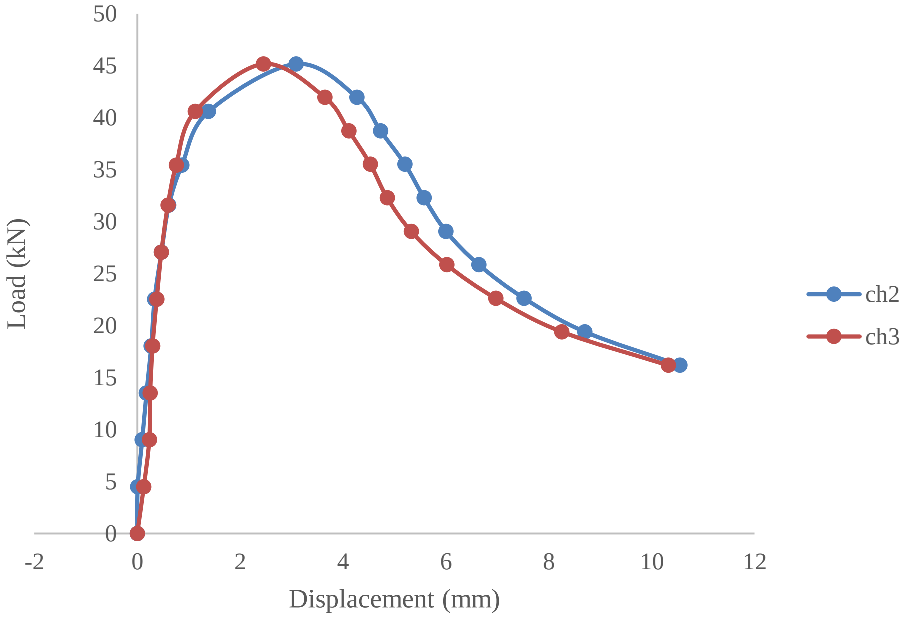


Figure 4.25 Load vs Horizontal Displacements Graph

4.3 Test on Compression Built-up Section

As expected result, the ultimate load for built-up section specimens were higher than the single section.

4.3.1 Compressed on 103 – A1 – BC

The result for this specimen was as an expected. At the initial stage where the loading was applied, the initial load was 85.24 kN and the observation at specimen occurred local buckling at overall of the specimen (Figure 4.27). The specimen failure was at 92.09 kN due to local and distortional buckling (Figure 4.28). From the overall observation, the distortional buckling occurred at the top was obviously showed the failures of the specimen (Figure 4.29).

For the load vs vertical displacement graph (Figure 4.30), the ultimate axial load applied was 92.09 kN with 1.614 mm displacement. Maximum load for this sample is 92.09 kN and the maximum displacement for this sample is at CH 3, -0.388 mm which occur at 73.68 kN axial load. The graph shows that at maximum load (Figure 4.31), displacement at CH2 and CH3 are at similar distances where place at both negative position for CH2 and positive position for CH3. At the end of the test shows that specimen are having distortional buckle at the top for both front and backside of the specimen.

Figure 4.26 At Zero Loading

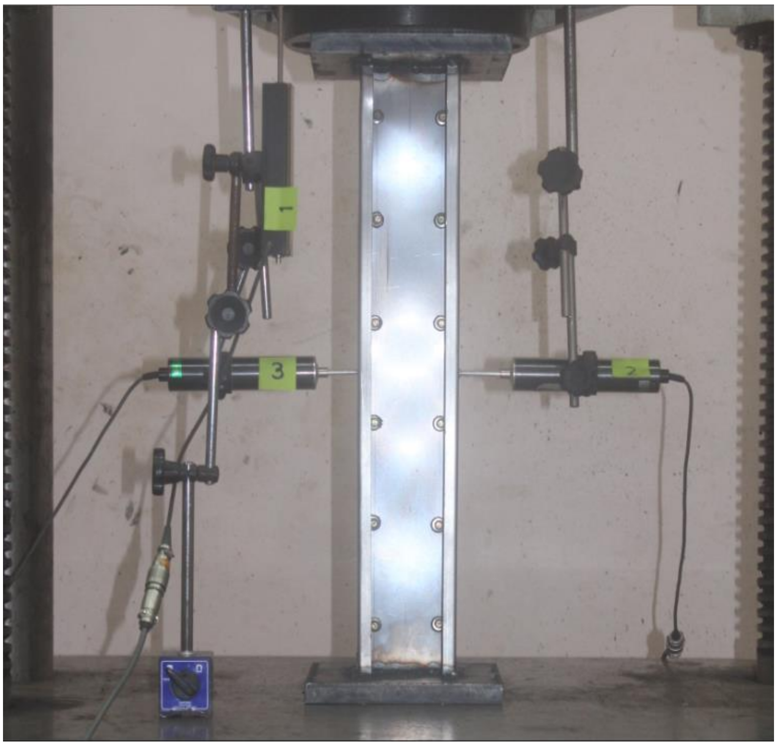


Figure 4.27 Initial Buckling

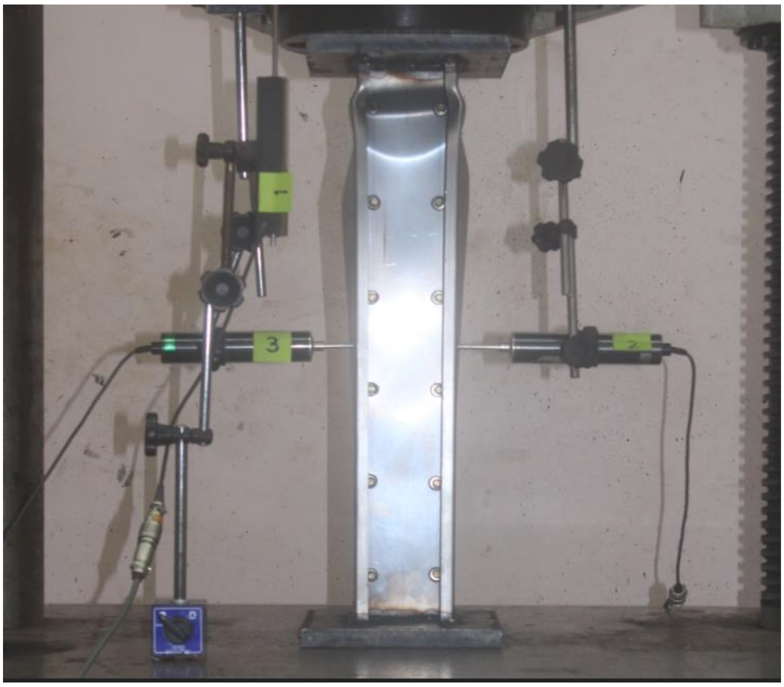


Figure 4.28 Peak Load

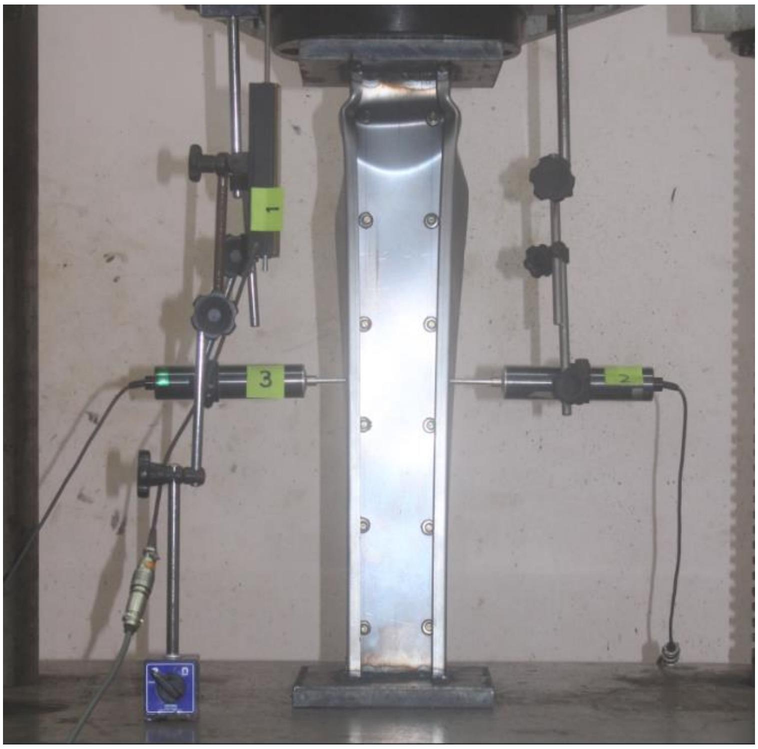


Figure 4.29 Final Post-Buckling

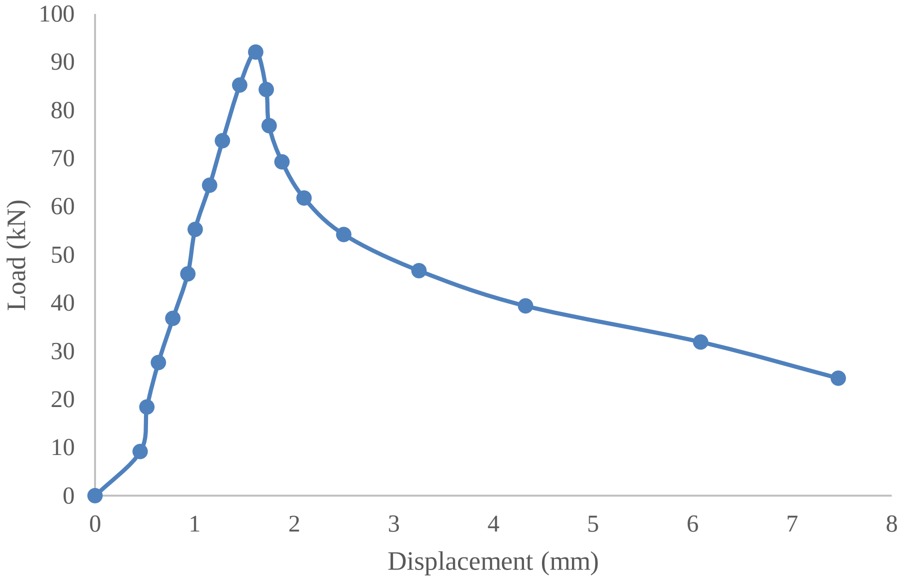


Figure 4.30 Load vs Vertical Displacement Graph

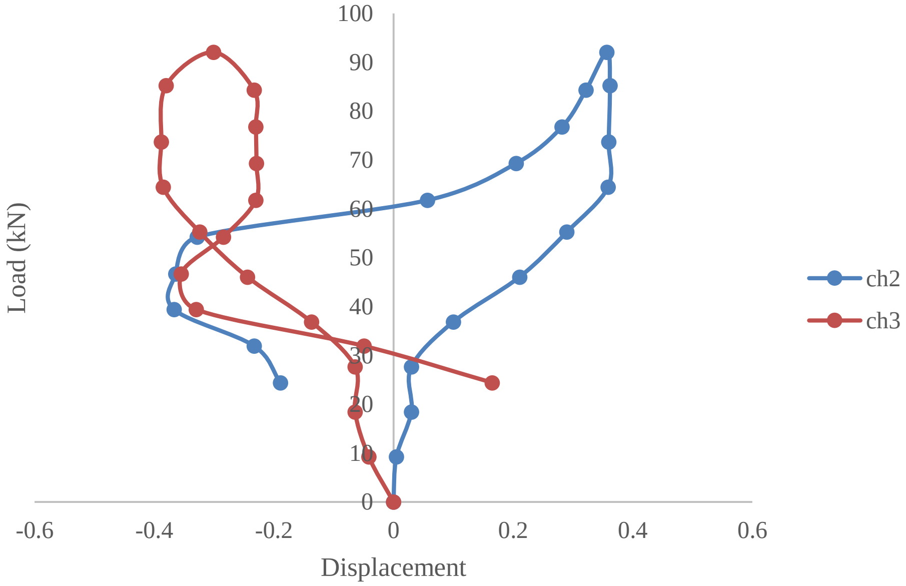


Figure 4.31 Load vs Horizontal Displacements Graph

4.3.2 Compressed on 103 – A2 – BC

The result for this specimen was as an expected. At the initial stage where the loading was applied, the initial load was 84.77 kN and the observation at specimen occurred local buckling at overall of the specimen (Figure 4.33). The specimen failure was at 91.00 kN due to warping and distortional buckling (Figure 4.34). From the overall observation, the warping and distortional buckling occurred at the middle were obviously showed the failures of the specimen (Figure 4.35).

For the load vs vertical displacement graph (Figure 4.36), the ultimate axial load applied was 91.00 kN with 0.971 mm displacement. From the charts shows that maximum load occur at 91.0 kN and the maximum displacement at 10.115 mm for CH2. There’s several times of intersection line of the CH2 and CH3 before the maximum load occurs and after the maximum load occurs. From the charts can be shown that at maximum load CH2 and CH3 are at the similar displacement. In Figure 4.37, it’s occur warping at the middle front of the specimen and distortional at middle of backside the end of the test.

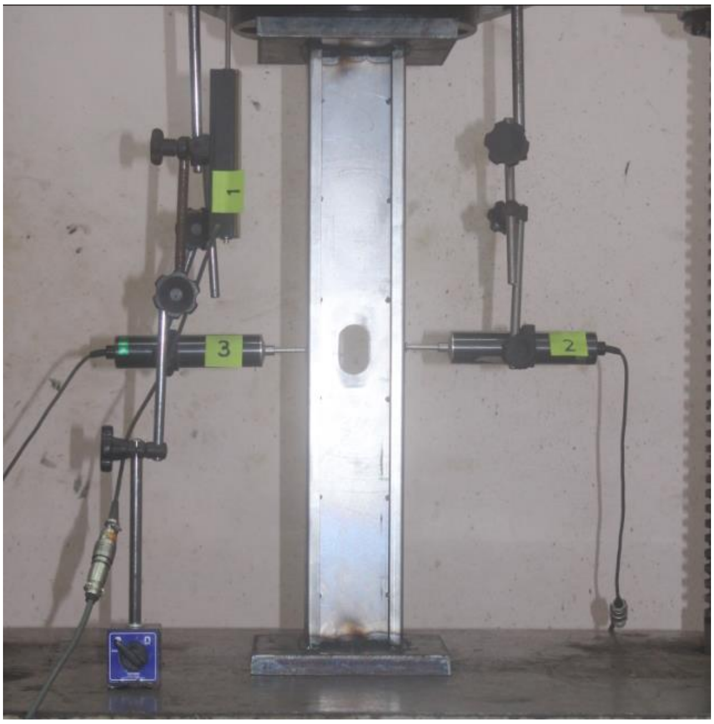


Figure 4.32 At Zero Loading

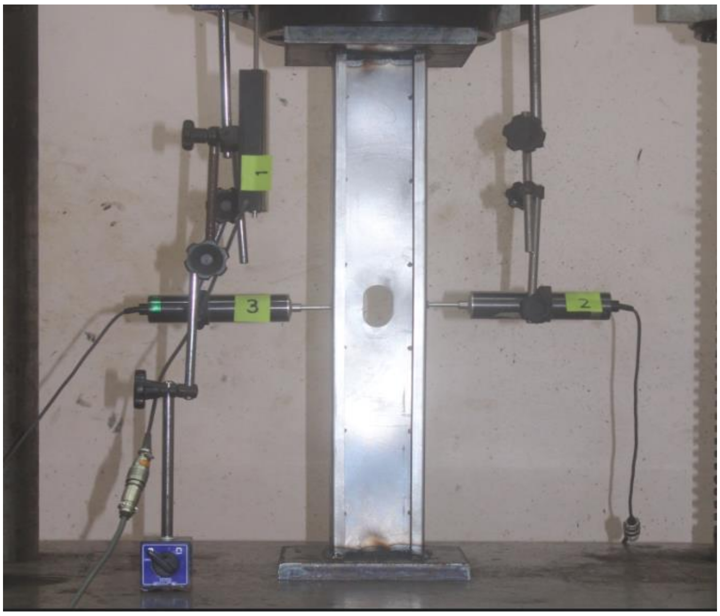


Figure 4.33 Initial Buckling

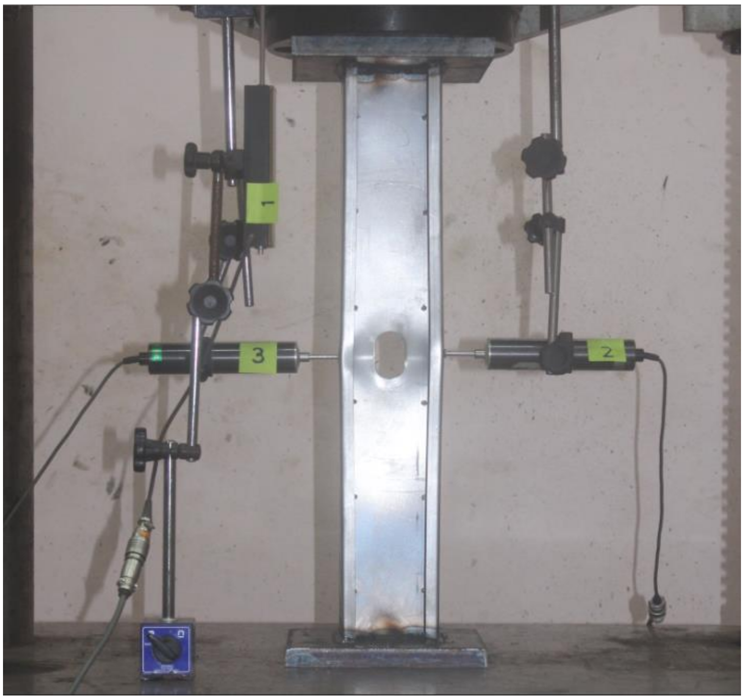


Figure 4.34 Peak Load

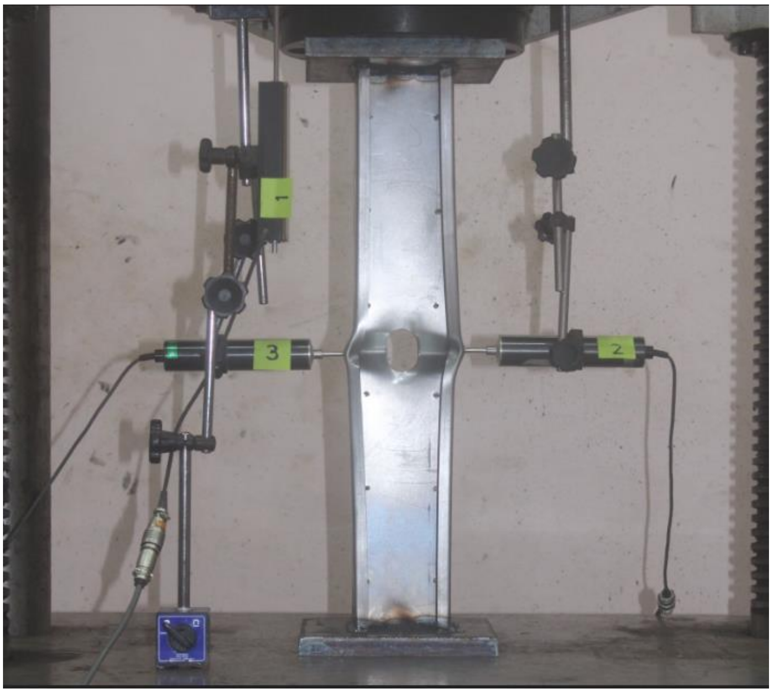


Figure 4.35 Final Post-Buckling

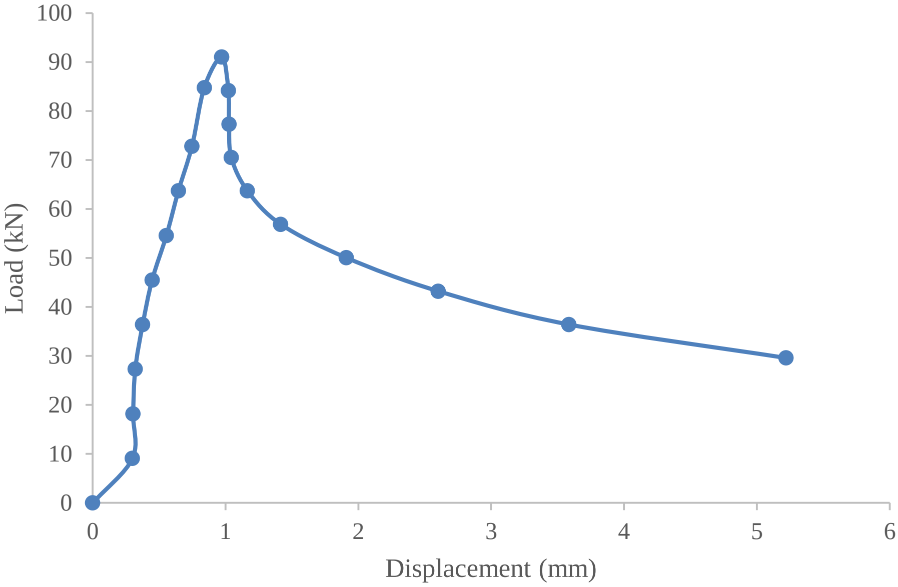


Figure 4.36 Load vs Vertical Displacement Graph

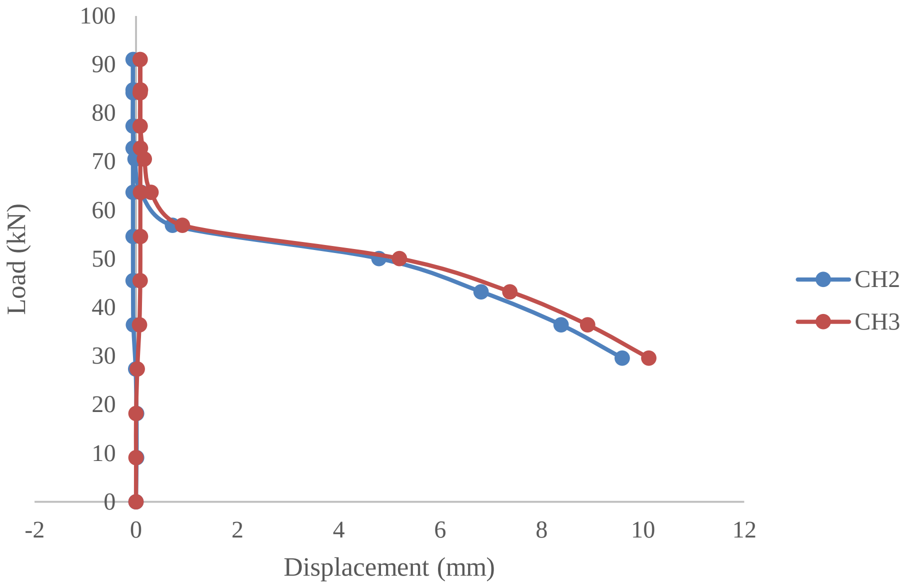


Figure 4.37 Load vs Horizontal Displacements Graph

4.3.3 Compressed on 203 – A1 – BC

The result for this specimen was as an expected. At the initial stage where the loading was applied, the initial load was 85.36 kN and the observation at specimen occurred distortional buckling at the bottom of the specimen (Figure 4.39). The specimen failure was at 103.963 kN due to local and distortional buckling (Figure 4.40). From the overall observation, the warping occurred at the bottom was obviously showed the failures of the specimen (Figure 4.41).

For the load vs vertical displacement graph (Figure 4.42), the ultimate axial load applied was 103.96 kN with 1.355 mm displacement. This sample has a maximum axial load of 103.96 kN and a maximum displacement of 11.252 mm that happen at CH 2 at the end of the test. As seen from Figure 4.43, the graph intersects several times of the test. Results shows displacement moving towards positive displacement for the two transducers. From the figure specimen shows distortional buckling at the bottom and warping at the top after the end of experiment.

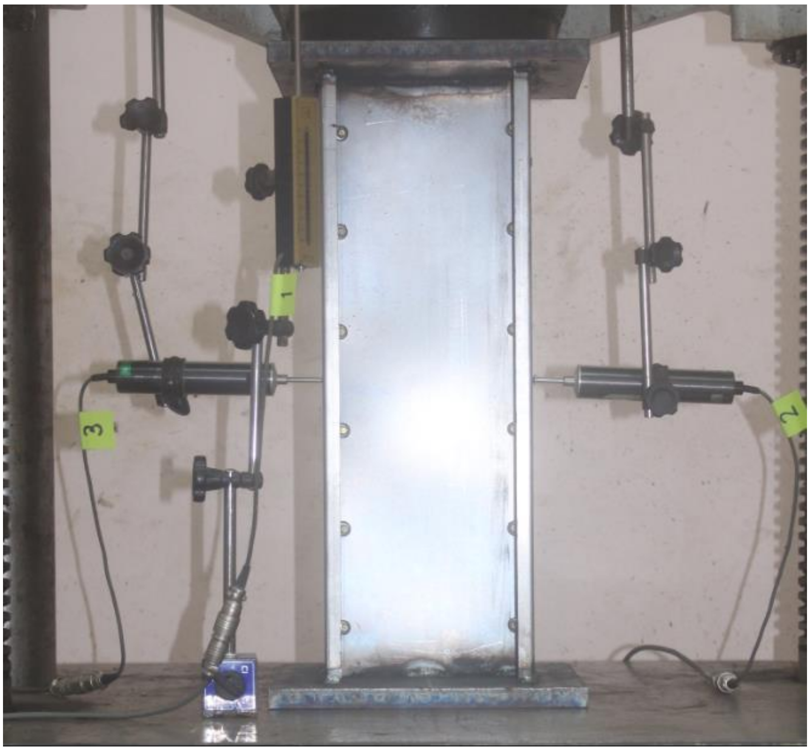


Figure 4.38 At Zero Loading

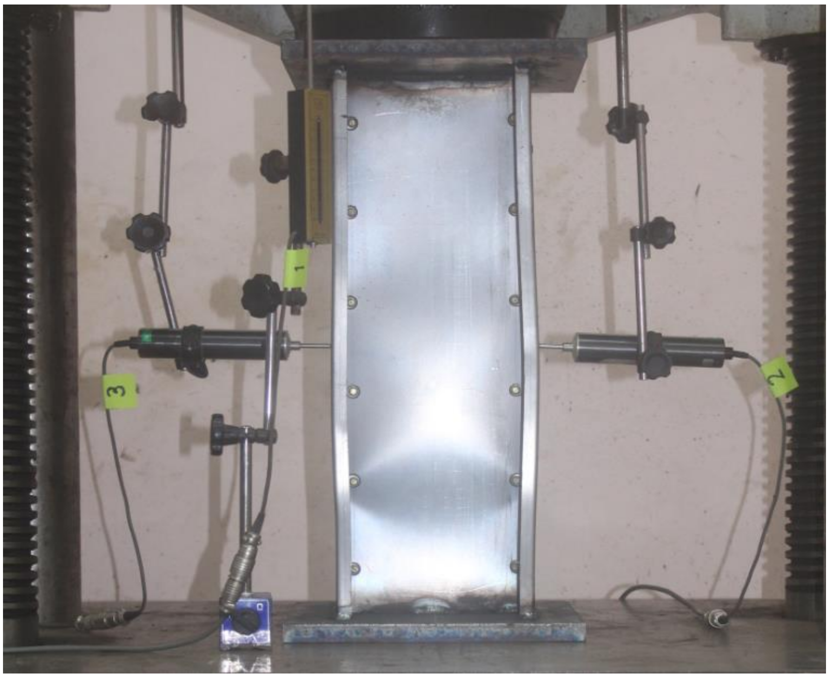


Figure 4.39 Initial Buckling

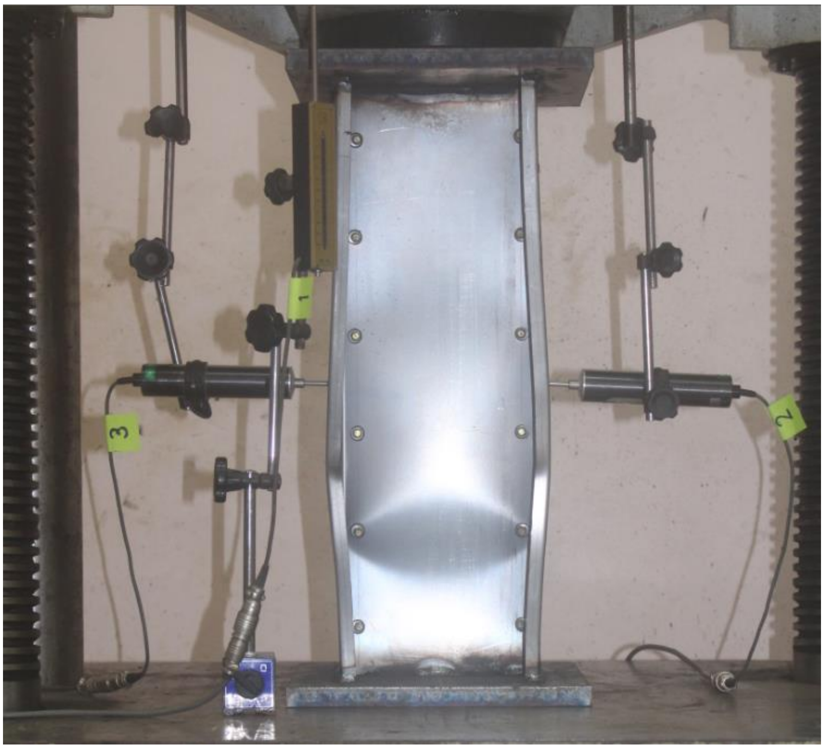


Figure 4.40 Peak Load

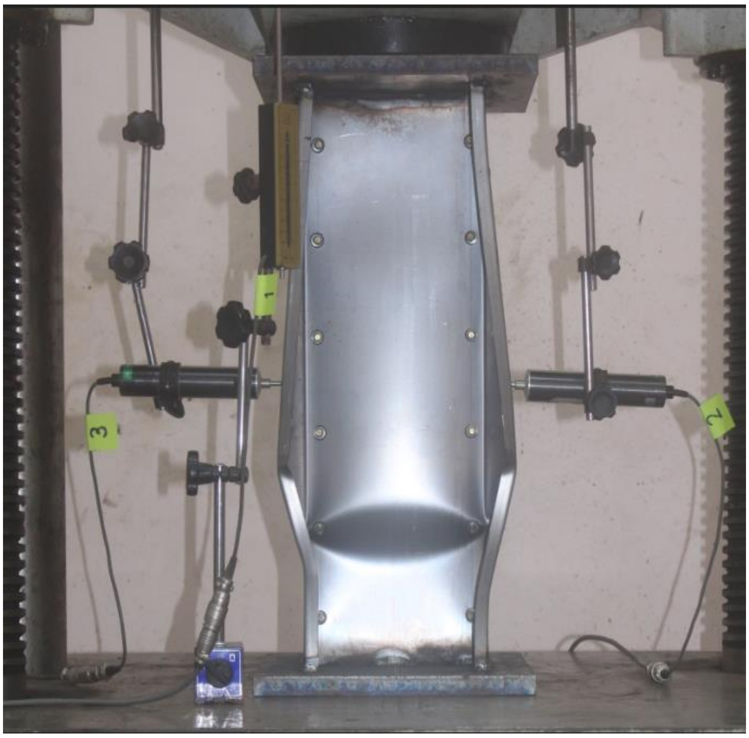


Figure 4.41 Final Post-Buckling

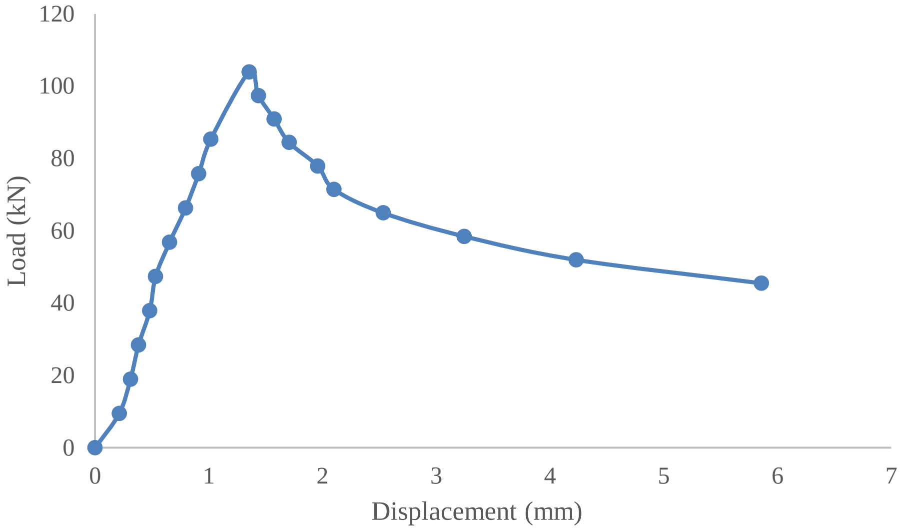


Figure 4.42 Load vs Vertical Displacement Graph

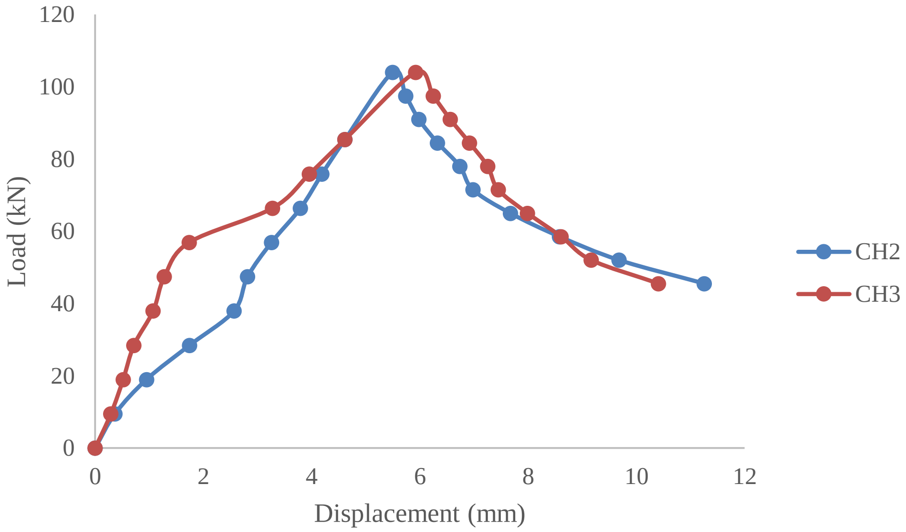


Figure 4.43 Load vs Horizontal Displacements Graph

4.3.4 Compressed on 203 – A2 – BC

The result for this specimen was as an expected. At the initial stage where the loading was applied, the initial load was 84.22 kN and the observation at specimen occurred local buckling at the top of the specimen (Figure 4.45). The specimen failure was at 96.89 kN due to local and distortional buckling (Figure 4.46). From the overall observation, the distortional buckling occurred at the top was obviously showed the failures of the specimen (Figure 4.47).

For the load vs vertical displacement graph (Figure 4.48), the ultimate axial load applied was 96.89 kN with 0.96 mm displacement. Figure 4.49 shows result of 203-A2-BC which maximum load at 96.89 kN and the maximum displacement at -5.797 mm that occurs at both CH2 and CH 3. The sample move into negative displacement for CH2 and CH3 transducers until it reach the failure. It shows that the displacement is slowly moving towards negative after the maximum load. 203-A2-BC occur distortional at the bottom of the specimen at the end of the test.

Figure 4.44 At Zero Loading

Figure 4.45 Initial Buckling

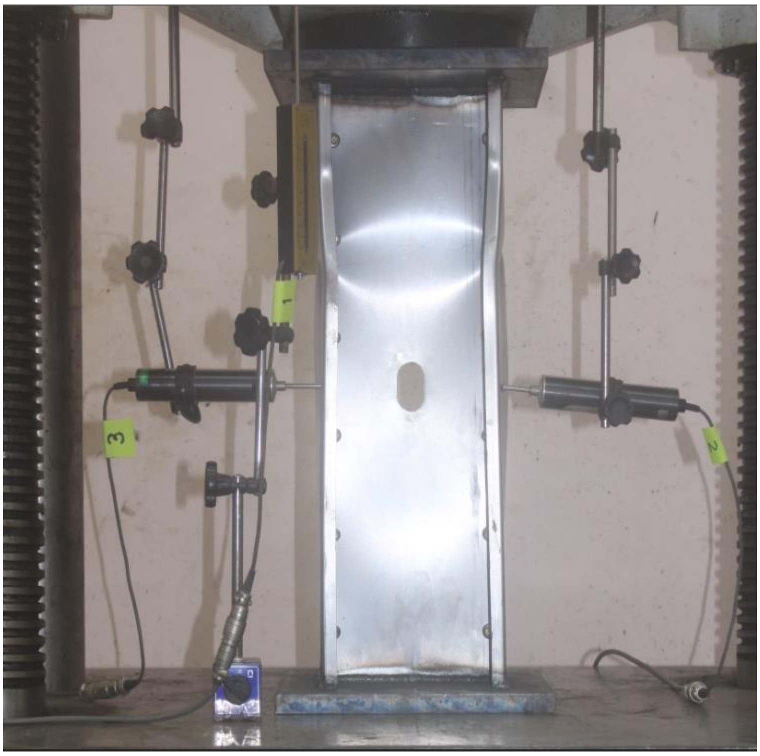


Figure 4.46 Peak Load

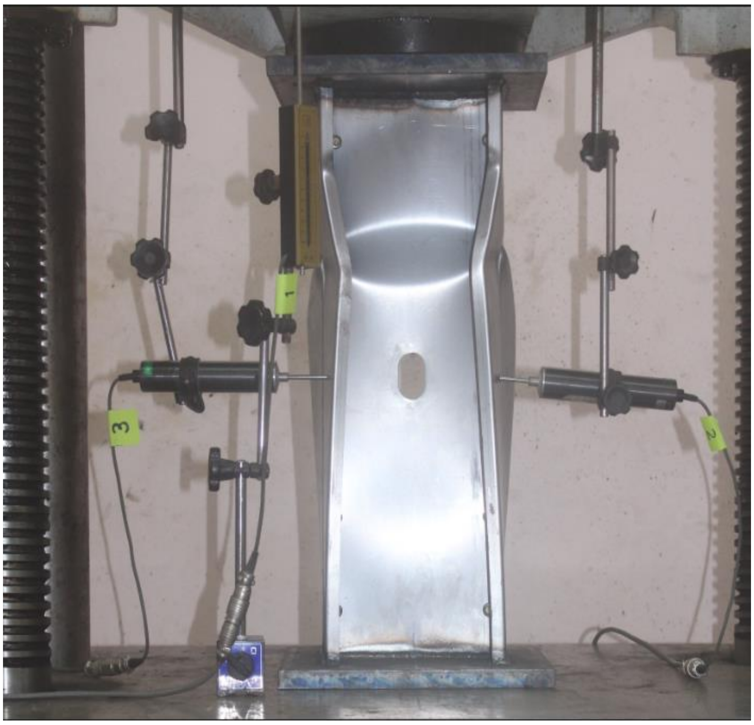


Figure 4.47 Final Post-Buckling

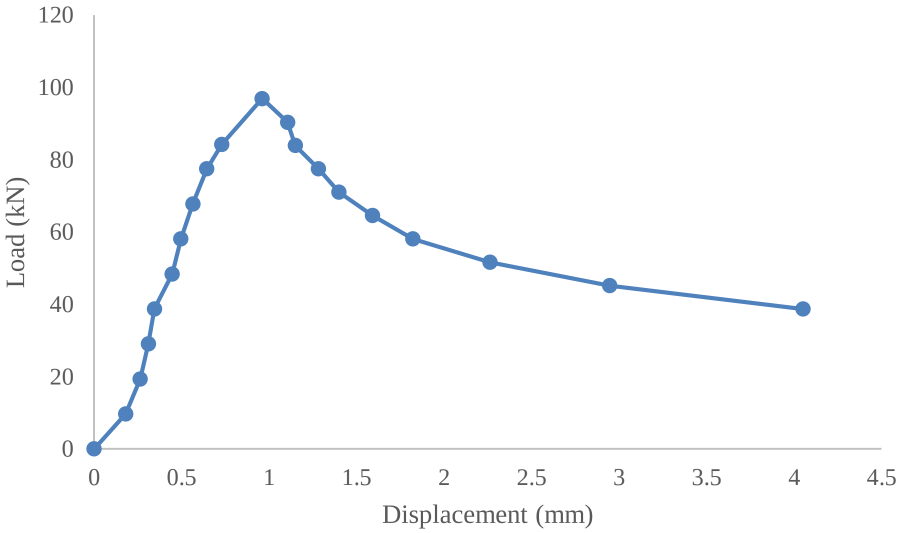


Figure 4.48 Load vs Vertical Displacement Graph

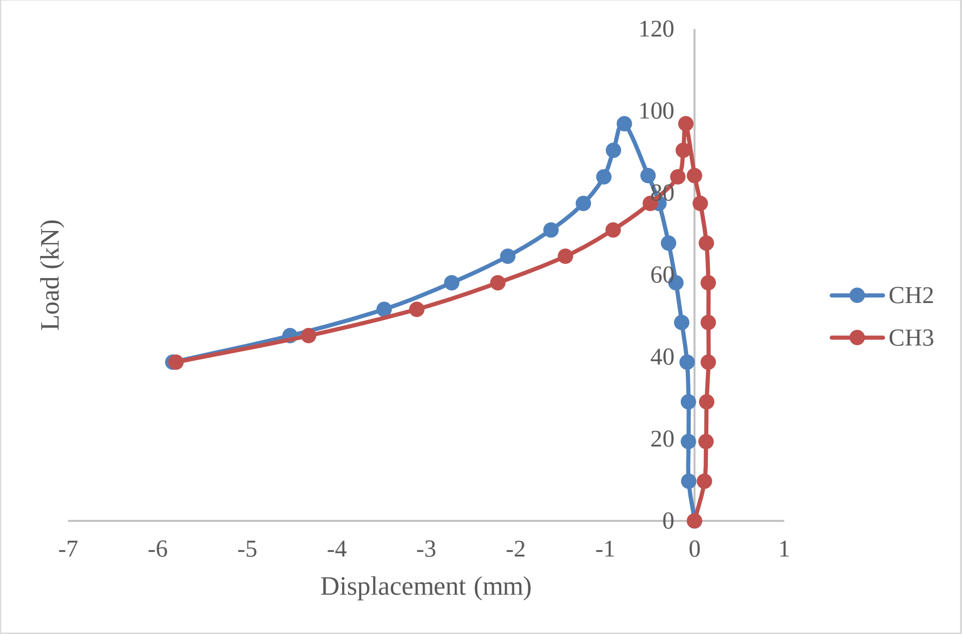


Figure 4.49 Load vs Horizontal Displacements Graph

CHAPTER 5

CONCLUSION

5.1 Conclusion

From the overall result obtained, we can conclude that most of the section failed due to distortional buckling either its flanges buckle inward or outward. It is because that as width to thickness ratio increases, local buckling and distortional buckling capacity decreases. From the mode of failures, we can observed that few parameters play an important role for a cold formed steel to fail under this mode. Among the parameters are the size of specimens, presence of the opening, and the type of section.

For ultimate loads, the size of the specimen which is 203 mm have higher strength compared to the specimen with 103 mm's size. Presence of the opening also effects to ultimate load as we can see the lowest ultimate load obtained from the specimen with hole. According to physics, the presence of the opening make the strength of the specimen decreases because it has a relatively low sensitivity of the specimen. In addition, the built-up section have more strength which is ultimate loads compared to single section due to point of gravity are more stable. The data collected for this experimental study is approved to be applied in construction industry.

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

I. Any initial physical changes (buckling).

II. Transducer are very sensitive equipment and easy to changes the data although small movement on the specimens.

5.2 Recommendations

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

II. To prevent local buckling, D/t ratio shall below 100.

III. Increase rotational stiffness of section to prevent distortional buckling. By limiting the B/D ratio to 0.3 where distortional buckling stress is the highest.

IV. Longer lipped (L) will enhance the distortional buckling strength. The highest distortional buckling strength can be achieved when flange width is equal to lipped length.

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

REFERENCES

Al-Jallad, S. & Al-Thairy, H., 2016. Effect of web opening on the axial load capacity of steel columns with cold-formed thin walled section (CFS). *Kufa Journal of Engineering, 7(3), pp.13-26.*

Crisan, A., Ungureanu, V. & Dubina, D., 2012. Behaviour of cold-formed steel perforated sections in compression. Part 1—Experimental investigations. *Thin-Walled Structures. www.elsevier.com/locate/tws.*

Crisan, A., Ungureanu, V. & Dubina, D., 2012. Behaviour ofcold-formed steel perforated sections in compression: Part 2—numerical investigations and design considerations. *Thin-Walled Structures.*

Dinis, P. B., Batista, E. M. & Camotim, D., 2012. Local–distortional–global interaction in lipped channel columns: experimental results, numerical simulations and design considerations. *Thin-Walled Struct. 61 (6) (2012) 2–13..*

Georgievaa, I., Schueremansa, L., Vandewallea, L. & Pyla, L., 2012. Design of built-up cold-formed steel columns according to the direct strength method. *Steel Structures and Bridges 2012.*

Georgieva, I., Schueremans, L. & Pyla, L., 2012. Composed columns from cold-formed steel Z-profiles: Experiments and code-based predictions of the overall compression capacity. *Engineering Structures 37 (2012) 125–134.*

Jakab, G., 2009. Analysis and Design of Cold-Formed C-Section Members and Structures. *Budapest University of Technology and Economics.*

Jakab, G. & Dunai, L., 2008. Resistance of C-profile cold-formed compression members: Test and standard. *Journal of Constructional Steel Research 64 (2008) 802–807..*

Kalavagunta, S., Naganathan, S. & Mustapha, K. N. B., 2013. Experimental Study of Axially Compressed Cold Formed Steel Channel Columns. *Indian Journal of Science and Technology.*

Kulantunga, M. P. & MacDonald, M., 2013. Investigation of cold-formed steel structural members with perforations of different arrangements subjected to compression loading. *Thin-Walled Structures67(2013)78–87.*

Landesmann, A., 2013. On theDirect Strength Method (DSM) design of cold-formed steel columns against distortional failure. *Thin-Walled Structures67(2013)168–187.*

Lu, Y., Zhou, T., Li, W. & Wu, H., 2017. Experimental investigation and a novel direct strength method for cold-formed built-up I-section columns. *Thin-Walled Structures 112 (2017) 125–139..*

MacDonald, M. & Kulatunga, M. P., 2013. Finite Element Analysis of Cold{Formed Steel Structural Members with Performations Subjected to Compression Loading. *Mechanics and Mechanical Engineering.Vol. 17, No. 2 (2013) 127–139. Lodz University of Technology*.

Mahmood, M. T., 2007. Performance of Local Produced Cold-Formed Steel Sections for Roof Truss System. *Public Works Department Malaysia 42, pp. 11–27..*

Meiyalagan, M., 2010. Investigation on Cold formed. *International Journal of Applied Engineering Research, Dindigul.*

Moen, C. D., 2008. Direct Strength Design of Cold-Formed Steel Members with Perforations. *Johns Hopkins University.*

Moen, C. D. & Schafer, B. W., 2008. Experiments on cold-formed steel columns with holes. *Thin-Walled Structures 46 (2008) 1164–1182.*

Moen, C. D. & Shafer, B. W., 2009. Elastic Elastic buckling of thin plates with holes in compression or bending. *Thin-WalledStructures47(2009)1597–1607.*

S.Vijayanand & Anbarasu, M., 2017. Effect of Spacers on Ultimate Strength and Behavior of Cold-Formed Steel Built-up Columns. *Procedia Engineering.*

Santos, E. S., Batista, E. M. & Camotim, D., 2012. , Experimental investigation concerning lipped channel columns undergoing local–distortional–global buckling mode interaction. *Thin-Walled Struct. 54 (2) (2012) 19–34..*

Schafer, B., 2008. Review: The Direct Strength Method of cold-formed steel member design. *Journal of Constructional Steel Research 64 (2008) 766–778.*

Seong, T. H., 2008. Behaviour of Cold Formed Steel Under Axial Compression Force. *University Technology of Malaysia.*

Vardakoulias, I., 2015. Structural Behaviuor of Light Gauge Cold-Formed Steel Frame Walls under Fire Conditions. *National Technical University of Athens.*

Whittle, J. & Ramseyer, C., 2009. Bucklingcapacitiesofaxiallyloaded,cold-formed,built-upC-channels. *Thin-WalledStructures.*

Yao, Z., Kim, J. & Rasmussen, R., 2012. Inelastic local buckling behaviour of perforated plates and sections under compression. *Thin-Walled Structures61(2012)49–70.*

Yu, W. & Laboube, R., 2010. *Cold-formed steel design..*

Yu, W. W., 2000. Cold-Formed Steel Design. *John Wiley & Sons.*

Zhou, 2017. Distortional buckling of cold-formed lipped channel columns subjected to axial compression. *Steel and Composite Structures, 23(3), pp.331-338..*