BEHAVIOUR OF PIN AND PARTIAL STRENGTH BEAM-TO-COLUMN CONNECTIONS WITH DOUBLE CHANNEL COLD-FORMED STEEL SECTIONS

TAN CHER SIANG

UNIVERSITI TEKNOLOGI MALAYSIA

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TAN CHER SIANG

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ABSTRACT

The application of cold-formed steel in light steel framing design can become a popular choice of Industrialized Building System (IBS), by extending the steelwork design into residential housing. However there is a lack of in-depth study on the joints behaviour for primary structures, particularly the beam-to-column connection. The objectives of this research are to develop the design procedures of bolted beam-to-column connections for double channel cold-formed steel sections, to study the pin and partial strength behaviour of the developed connections based on their strength and stiffness performance, and to validate the performance of the proposed connection configurations by comparing the analytical calculation to experimental results. Analytical study was carried out to develop design procedures for five types of joint methods, namely double angle web-cleats (J1-WC), top-seat flange-cleats (J2-FC), combined flange-web-cleats (J3-FWC), gusset plates (J4-HG) and combined gusset plate flange-cleats (J5-HGFC) to form bolted connections to accommodate members in practical orientations. A series of full scale experimental investigation comprised of twenty-four isolated joint tests and twelve sub-assemblage frame tests have been carried out to understand the connections' strength and stiffness behaviour. The experimental results showed good agreement compared to theoretical prediction. From the experimental and analytical results, J1-WC, J2-FC and J3-FWC connections were classified as pin joints, with the strength less than 25% of beam capacity; while J4-HG and J5-HGFC connections were classified as partial strength joints with moment resistance of joint in the range of 46% to 96% to the moment resistance of the connected beam. It was concluded that among the five types of proposed connections, J1-WC, J2-FC and J3-FWC connections were designed as pin joint, J4-HG and J5-HGFC connections were validated to be used as partial strength joints.

ABSTRAK

Penggunaan keluli tergelek sejuk dalam rekabentuk kerangka keluli ringan boleh menjadi satu pilihan yang popular bagi ’Industralized Building System’ (IBS) dengan memperluaskan rekabentuk struktur keluli kepada industri perumahan. Walau bagaimanapun terdapat kekurangan dalam kaji-selidik lanjutan terhadap kelakuan penyambungan bagi struktur utama, khususnya sambungan rasuk-tiang. Objektif penyelidikan ini adalah untuk menghasilkan prosidur rekabentuk untuk sambungan bolt rasuk-tiang bagi keratan keluli tergelek sejuk ‘channel berkembar’, mengkaji kelakuan pin dan separa kekuatan bagi sambungan yang dibangun berdasarkan prestasi kekuatan dan ketegaran, dan membuktikan prestasi sambungan dan keratan yang dicadangkan dengan membandingkan keputusan ujikaji kepada keputusan analitikal. Kajian analitikal dijalankan untuk menghasilkan kaedah rekabentuk bagi lima jenis sambungan, iaitu ‘double angle web-cleats’ (J1-WC), ‘top-seat flange-cleats’ (J2-FC), ‘combined flange-web-cleats’ (J3-FWC), ‘gusset plates’ (J4-HG) dan ‘combined gusset plate flange-cleats’ (J5-HGFC) yang membentuk sambungan bolt bagi anggota-anggota dalam kedudukan yang praktikal. Satu siri kajian eksperimen skala penuh yang melibatkan dua puluh empat ujian sambungan secara berasingan dan dua belas ujian kerangka subpasangan telah dijalankan untuk memahami kelakuan kekuatan dan ketegaran sambungan-sambungan. Keputusan eksperimen adalah memuaskan apabila dibandingkan dengan ramalan teori. Daripada keputusan eksperimen dan analitikal, sambungan J1-WC, J2-FC dan J3-FWC diklasifikasikan sebagai sambungan pin, dengan kekuatan kurang daripada 25% keupayaan anggota rasuk yang disambung; manakala sambungan J4-HG dan J5-HGFC diklasifikasikan sebagai sambungan separa-kekuatan dengan keupayan momen sambungan adalah antara 46% hingga 96% daripada keupayaan momen bagi anggota rasuk yang disambung. Kesimpulannya, daripada lima sambungan yang dicadang, J1-WC, J2-FC dan J3-FWC sesuai untuk direkabentuk sebagai sambungan pin, J4-HG dan J5-HGFC dapat digunakan sebagai sambungan separa kekuatan.

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SYMBOLS:

λ	-	Slenderness ratio
γ	-	Correction factor in mid-line method
δ	-	Deflection
ϕ	-	Rotation of a connection
λ_{LT}	-	Slenderness ratio for lateral buckling
A_{g}	-	Gross cross-sectional area of member
A_{m}	-	Area calculated with mid-line method
A_{t}	-	Tensile stress area of bolt
b	-	Flat width of an element
b_{eff}	-	Effective flat width of an element
b_{eu}	-	Effective flat width of lip element
$b_{\mathrm{f,eff}}$	-	Effective flat width of flange element
$b_{\mathrm{w,eff}}$	-	Effective flat width of web element
B	-	Width of section
B_{beam}	-	Width of beam section
B_{col}	-	Width of column section
B_{fc}	-	Width of flange-cleat
B_{g}	-	Width of gusset plate
B_{m}		Width of section calculated with mid-line method
B_{wc}	-	Width of web-cleat
C_4, C_5	-	Factors for calculation of web crushing resistance
C_{b}	-	Factor for calculation of buckling moment resistance
D	-	Depth of section
D_{beam}	-	Depth of beam section
D_{col}	-	Depth of column section

d	-	Depth of web between fillet welds or diameter of a bolt
d_b	-	Diameter of bolt
d_h	-	Diameter of bolt hole
D_m	-	Depth of section calculated with mid-line method
D_w	-	Depth of web for effective section calculation
E	-	Young's modulus (205000 N/mm^2)
e, e_1, e_2	-	End distance to bolt holes
e_p, e_{p1}, e_{p2}	-	Distance between fasteners
f_c	-	Compression stress of a cold-formed steel element
F_c	-	Compression resistance
F_t	-	Tension resistance
F_v	-	Shear resistance
F_w	-	Web crushing resistance
h, h_1, h_2, h_3	-	Lever arm from compression zone to tension bolt row
I_{xr}	-	Reduced second moment of area about the major axis
I_{xx}	-	Second moment of area about the major axis
I_{yy}	-	Second moment of area about the minor axis
K	-	Local buckling coefficient
k_i	-	Stiffness coefficient
L	-	Distance between levels at which both axes of the column section are restrained or, alternatively, the beam span
L_c	-	Compressive length of web
L_{eff}, L_E	-	Effective length
L_{fc}	-	Length of flange-cleat
L_g	-	Length of gusset plate
L_i	-	Length of lip of lipped channel section
L_{im}	-	Length of lip of lipped channel section calculated with mid-line method
L_t	-	Tensile length of web
L_{wc}	-	Length of web-cleat
m	-	Distance from bolt to 20% into root radius
M	-	Moment
M_b	-	Buckling moment resistance of beam.
M_{beam}	-	Moment at beam
M_{cx}	-	Bending moment resistance of beam

M_E	-	Elastic lateral buckling moment resistance
$M_{J,Ed}$	-	Elastic moment resistance of joint
$M_{J,Rd}$	-	Ultimate moment resistance of joint
$M_{J,exp}$	-	Experimental moment resistance of joint
$M_{J,the}$	-	Theoretical moment resistance of joint
$M_{J\text{-}50,exp}$	-	Experimental moment resistance of joint at 50 mRad rotation.
$M_{J\text{-}C,the}$	-	Theoretical moment resistance of joint based on compressive resistance.
M_Y	-	Elastic moment resistance
n	-	Number of bolts
N	-	Length of load bearing area
p_b	-	Buckling stress
p_{bb}	-	Bearing strength of bolt
P_{bb}, P_{bs}	-	Bearing capacity of bolt
p_{bs}	-	Bearing strength of connected part
p_c	-	Compressive stress
p_o	-	Limiting design yield stress
p_s	-	Shear strength of connected part
p_t	-	Tensile strength of connected part
p_v	-	Shear yield stress
p_y	-	Design yield strength
P	-	Concentrated point load
P_{cr}	-	Local buckling stress of an element
P_{nom}	-	Nominal tension capacity of bolt
P_s	-	Shear capacity of bolt
P_t	-	Tension capacity of bolt
q_{cr}	-	Shear buckling stress
r	-	Root radius of section
r_{fc}	-	Root radius of flange-cleat
r_m	-	Root radius of section calculated with mid-line method
r_{wc}	-	Root radius of web-cleat
r_{xx}	-	Radius of gyration about the major axis
r_{yy}	-	Radius of gyration about the minor axis

$S_{\mathrm{J,exp}}$	-	Experimental initial rotational stiffness of a connection
$S_{\mathrm{J,ini}}$	-	Initial rotational stiffness of a connection
$S_{\mathrm{J,the}}$	-	Theoretical initial rotational stiffness of a connection
T_{beam}	-	Thickness of beam flange
t_{beam}	-	Thickness of beam web
t_{col}	-	Thickness of column web
t_{fc}	-	Thickness of flange-cleat
t_{g}	-	Thickness of gusset plate
t_{wc}	-	Thickness of web-cleat
V	-	Shear force
$Z_{\mathrm{x,g}}$	-	Elastic section modulus for gusset plate
Z_{xr}	-	Reduced elastic section modulus about the major axis
Z_{xx}	-	Elastic section modulus about the major axis
Z_{yy}	-	Elastic section modulus about the minor axis
β	-	Ratio of smaller end moment to larger end moment

ABBREVIATIONS:

AISI	-	American Iron and Steel Institution
AS	-	Australian Standards
ASD	-	Allowable Stress Design
BCSA	-	British Constructional Steel Association
BS 5950-1	-	British Standard 5950 Part 1: 2000
BS 5950-5	-	British Standard 5950 Part 5: 1998
BSI	-	British Standard Institution
CIDB	-	Construction Industry Development Board, Malaysia
DC	-	Double channel section
DSM	-	Direct Strength Method
EC0		Eurocode 0 (BS EN 1990: 2002)
EC1		Eurocode 1 (BS EN 1991: 2002)
EC3-1-1	-	Eurocode 3 Part 1.1 (BS EN 1993-1-1: 2005)
EC3-1-8		Eurocode 3 Part 1.8 (BS EN 1993-1-8: 2005)
FC	-	Top-seat flange-cleats connection

FSIJ	-	Full-scale isolated joint test
FSSAF	-	Full-scale sub-assemblage frame test
FWC	-	Flange-web-cleat connection
GBT	-	Generalized Beam Theory
HG	-	Slip-in gusset plate connection
HGFC	-	Combined flange-cleats and gusset plate connection
IBS	-	Industrialised Building System
Inc	-	Inclinometer
LRFD	-	Limit State Format Design
LVDT, DT	-	Linear variable displacement transducer
NZS	-	New Zealand Standards
SCI	-	Steel Construction Institute
UB	-	Universal Beam section
UC	-	Universal Column section
WC	-	Double angle web-cleats connection

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CHAPTER 1

INTRODUCTION

1.1 General

Industrialized Building System (IBS) has been promoted diligently by CIDB in Malaysia since Year 2000 (Sumadi *et al.*, 2001; Mohamed, 2003). Besides reduced dependency on foreign labour, the simplified construction solutions offer better control of quality, increase productivity, reduce construction time, less wastage and cleaner environment. Through industrialization of construction, huge amount of work has been shifted to the factory and leaving the construction sites tidier and safer. In support of the ongoing process of implementation of IBS in the construction industry, the research and development have been identified to focus in the area of open-building, lightweight materials, joints and services. The application of cold-formed steel in light steel framing design can be one of the popular choices of IBS in small to medium size building construction.

Light steel framing design is generally based on the use of standard C or Z shaped steel sections produced by cold rolling from strip steel coil as shown in Figure 1.1 and Figure 1.2. Cold-formed sections are generically different from hot rolled steel sections, such as Universal Beams, which are used in fabricated steelwork. The steel used in cold-formed sections is relatively thin, typically 0.5 to 2.5 mm, and is galvanized for corrosion protection. The steel strength is higher than of hot-rolled steel, where the typical design strength is 350 N/mm^2, 450 N/mm^2 and even 550 N/mm^2 (Hancock, 1998). Besides traditional application as purlin or roof truss, cold-formed steel sections can be widely used in many sectors of construction, including industrial buildings, commercial buildings and hotels. It is gaining greater acceptance in the residential sector in United Kingdom and Australia (Davies, 2000; Lawson *et al.*, 2002). Modular construction of light steel framing for single-storey houses as shown in Figure 1.3 is one of the examples of IBS implementation.

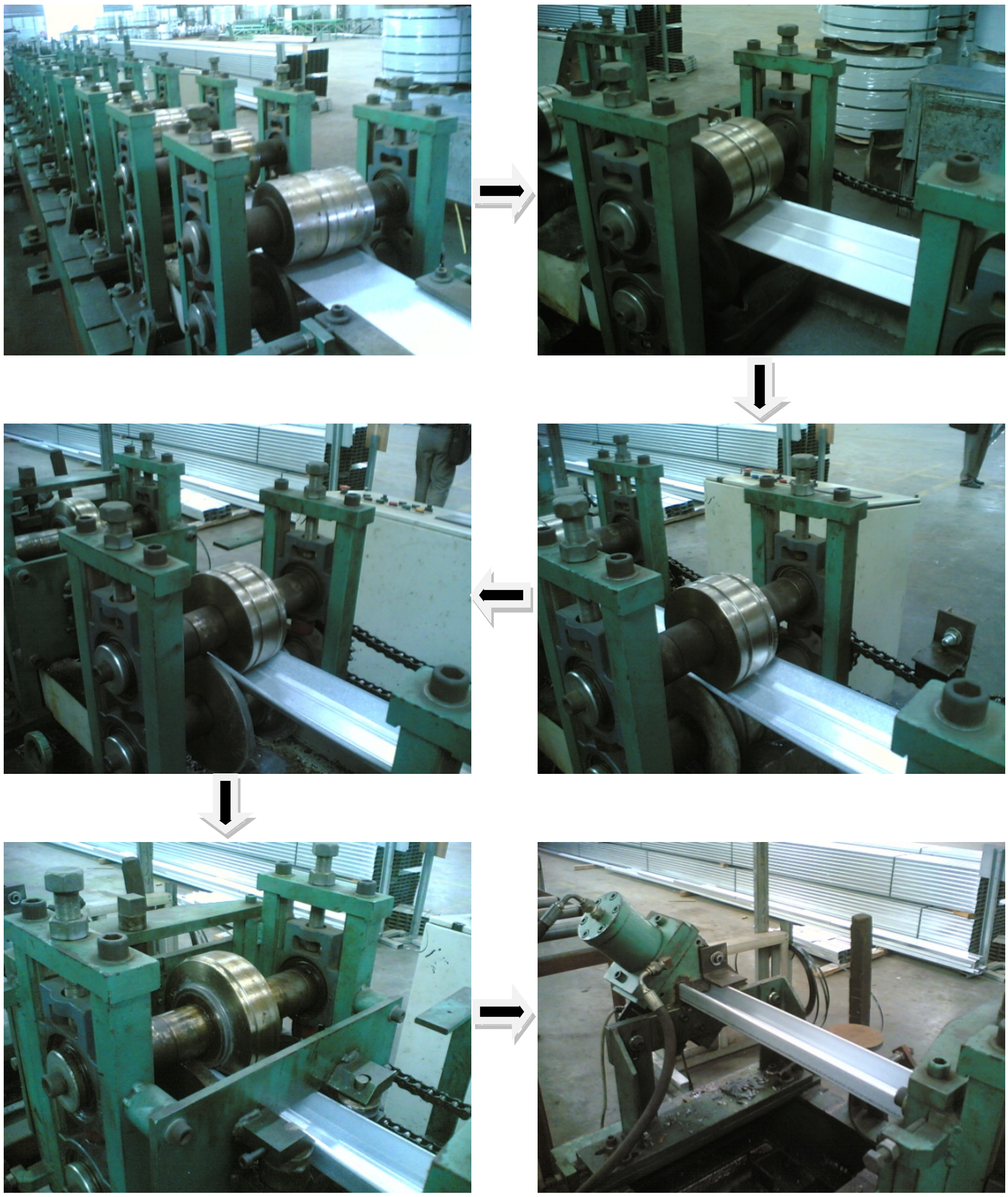

Figure 1.1: Cold-rolling process of strip steel coil to form cold-formed steel channel section

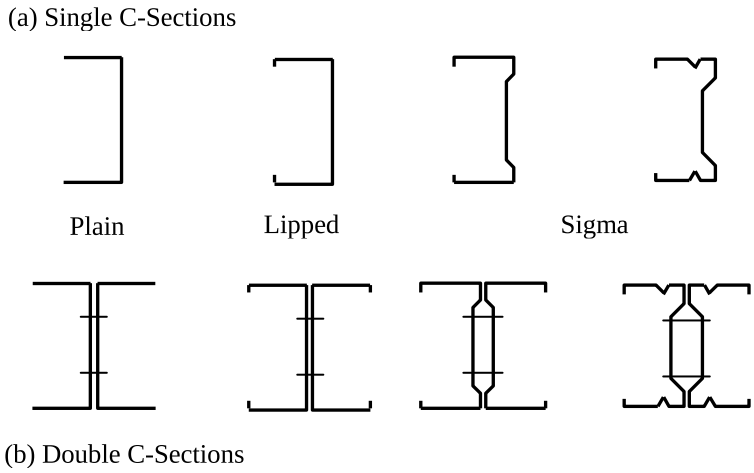

Figure 1.2: Common shapes for cold-formed channel sections

Figure 1.3: Cold-formed light steel framing for residential house (adopted from Lawson *et al*., 2002)

Most structures, especially the conventional steel buildings are still using the methods of simple design (simple construction) and rigid design (continuous construction). Simple design results in a more conservative approach but utilising heavier sections whereas the continuous design requires more rigorous, non-economical connection to ensure enough moment resistance. An alternative method of design known as semi-continuous construction, usually associated with partial strength connection, is more suitable which can be chosen to produce the most economic balance between the primary benefits associated with the two conventional designs. Moreover, the introduction of partial-strength connections in this semi-rigid design slightly increase the complexity compared to the simple design but yet able to produce significant reduction in beam depths and weight.

This research studies on the behaviour of pin and partial strength joints for cold-formed steel beam-to-column connection. The beam and column member are formed by using two lipped channel sections, clenched back-to-back, into an **I**-section as shown in Figure 1.2(b). The joint configuration aims to utilise the use of bolts, angle brackets and gusset plates to connect the beam to column, without the needs for welding work. A comprehensive analytical study on the design procedures for such joint configurations will be made, to understand the reaction behaviour of the connections. Since the use of partial strength joints for light steel framing has not been established yet, in depth experimental investigations on the isolated connection and sub-assemblage frames have to be conducted. The aspects of strength, stiffness, ductility and overall frame behaviour are compared between theoretical and experimental approaches to validate the standardized connection design procedures.

1.2 Background and Rational

Connections and frame responses in semi-continuous construction have received much attention of which researchers are aiming to improve the economical, practical and behavioural aspects. The Steel Construction Institute (SCI) and the British Constructional Steelwork Association (BCSA) have jointly developed a comprehensive guidance (SCI & BCSA, 1995) to design semi-rigid moment connections for steel construction. Bose and Hughes (1995) verified the performance of standard connections for semi-continuous steel frames with a series of experimental tests on flush end-plate and extended end-plate connections. The joint method was applied into design guides, where Couchman (1997) wrote the design of semi-continuous braced frames, Salter *et al.* (1999) presented wind-moment design for low rise frames, and Hensman and Way (2000) published a design guide to composite connection design for unbraced frames. The development of standardized flush end-plate and extended end-plates connections were later extended in Malaysia by Sulaiman (2007) and Saggaff (2007), into partial strength joints and composite joints for locally produced Trapezoidal Web Profiled (TWP) steel girder.

End-plate connections require both bolting and welding in their fabrication works. Mottram and Zheng (1999a and 1999b), Pucinotti (2001, 2006) and Danesh *et al*. (2007) studied semi-rigid moment joints using top-seat flange-cleat and double angle web-cleats. The joint configurations formed fully bolted beam-to-column connection, without the need of welding work. The flange-cleat and web-cleat were made from angle sections. Pucinotti confirmed such connection configuration were able to develop desired rotational stiffness. The moment resistance of the connection was higher than the design strength as predicted by Eurocode 3.

The use of cold-formed steel sections in building construction began in the 1850s, in both the United States and Great Britain (Yu, 2000). However, such construction methods were not widely used until 1940. Builders noticed that the design specifications for cold-formed steel construction cannot be covered completely by the design features of heavy hot-rolled steel. The development of thin walled cold-formed steel construction in United States is therefore accelerated by American Iron and Steel Institute (AISI), who sponsored research projects at Cornell University. They came out with the first design specification in Year 1942 (Hancock *et al*., 2001). The investigations resulted in new development of design, concerning the effective width for stiffened compression elements, reduced working stresses for un-stiffened elements, web crippling et cetera. Since then researches on light-steel construction using cold-formed members were carried out in various countries. Developments in cold-formed steel technology trend to manufacture high strength steel, more complex section shapes, better corrosion resistance and improved rolling and forming technology (Davies, 2000). The cold-formed steel researches in Year 1999 to 2001 can be categorized into eleven major areas (Hancock, 2003), such as compression members with distortional and element buckling, corrugated and curved panels, connections and fasteners, and mechanical properties of cold-formed steel.

Researches on connections and fasteners for cold-formed steel developed from 1997 to 2005 mainly fall in two categories. One focus on the pin connection that able to produce faster, lighter and economical joints. Self-tapping screws, clinching and riveting are among the developed methods of typical connection used. Makelainen and Kesti (1999) and Kaitila *et al*. (2001) describe a new type of joint called ‘Rosette’, which is particularly useful for connections in roof truss. The second category of research studies on the moment connections applied in storage racks, latticed beam and portal frames. Markazi *et al*. (1997) studied on the semi-rigid behaviour of boltless connection for cold-formed steel storage racks. Dubina and Zaharia (1997) and Dubina (2008) investigated the bolted joints for cold-formed steel truss, latticed beam and portal frames. Wilkinson (1999), Wilkinson and Hancock (2000) carried out tests on welded joints for portal frame apex and eaves, while Lim and Nethercot (2003, 2004, 2005) developed bolted joints for cold-formed steel portal frames. For beam-to-column connection, Chung and team (Chung & Lau, 1999; Wong & Chung 2002; Chung *et al.*, 2005) reported experimental and analytical testing on bolted moment connection for cold-formed double channel sections, utilising slip-in gusset plates.

At present as to the author knowledge, there is no study to extend the application of partial strength connections as in hot-rolled steel research, into light steel framing using cold-formed steel section. The use of web-cleat for pin connection design in cold-formed steel structures has been carried out by Chung and Lawson (2000), but the top-seat flange-cleats and combined flange-web-cleats for cold-formed steel beam-to-column connection have not been studied. The British Standard BS5950 Part 5 (BSI, 1998) and Eurocode BS EN 1993 Part 1.3 (BSI, 2006) give the permission to design cold-formed steel frame as semi-continuous construction, where the moment and rotation capacity of joint should be based on experimental evidence. The detailed design method and requirements, especially for partial strength connections in cold-formed steel construction has not been concluded.

1.3 Problem Statements

In Malaysia, the structural use of cold-formed steel section were limited to the roof truss and purlin structures. The thickness of the most available cold-formed steel sections are less than 1.2 mm. The use of thicker cold-formed steel sections, ranging from 1.2 mm to 2.5 mm, and the application of cold-formed steel section as beam and column structural members are yet to be studied.

In common practice, the cold-formed steel section were formed into truss system e.g. roof truss, lattice beam or wall panel in modular construction. The vertical and horizontal steel members were braced with unsupported length less than 2 m, to form robust truss and panel system. The behaviour of cold-formed beam section for longer clear span (say 4 meters) has to be further studied.

To date, partial strength connections in steelwork design were focused on application for hot-rolled steel section, no noticeable researches have been carried out for cold-formed steel framing. Current researches on connection for cold-formed steel were mostly study on pin joints and some in rigid moment connections. The design method for partial strength connections in cold-formed steel section has not been concluded. There is a need to carry out an in depth study for the performance of partial strength connection to cold-formed steel structures.

1.4 Objectives of Research

In order to answer the above problem statements, the objectives of research are summarized as follow:

1. To develop the design procedures of bolted beam-to-column connections for cold-formed steel double channel sections, based on the validated procedures applied to hot-rolled steel sections.
2. To study the behaviour of the developed beam-to-column connections in their strength and stiffness performance.

3. To validate the performance of the proposed connection configurations by comparing the analytical calculation to experimental results.

1.5 Scope of Work

The scope in this research covers on the behaviour of pin and partial strength connections in cold-formed lipped Double Channel (DC) section with thickness of 2 mm. Brackets, angle and gusset plate connections were chosen to ensure that the connections studied in this research fell under the partial strength category and so suitable to be used in the semi-continuous construction. All connections were formed using bolts, where no welding work is required.

Analytical investigations were carried to understand the section properties and member capacities of the cold-formed DC sections. Detailed studies on the connection design were made in a step by step calculation, to obtain the resistance capacities of each component of the joint configuration. Comparisons were made between the increment of beam depth, increment of cleat thickness and changes of different types of connection configuration. Substantial time was allocated in conducting the experimental investigations so that the actual behaviour and characteristics of the proposed connections could be acquired. Beam-to-column connection set up as cantilever to obtain the moment resistance of joints, and beam with connections at both ends and with the span of 4 m, set up as sub-assemblage frames to study the effects of proposed joint types to the light steel frames. Comparisons between the experimental and analytical investigations lead to a conclusive design of the proposed connections.

The details of the works involved were divided into several tasks of which, subsequently, were organised into relevant chapters as described in the Section 1.7 below.

1.6 Significant of Study

Partial strength connection would provide economical design by reducing steel weight and increasing the structure robustness, compared to conventional pin connection (Bose & Hughes, 1995; Sulaiman, 2007). Therefore, a study on the subject is necessary in order to obtain a new understanding on the behaviour of pin and partial strength semi-rigid moment connections in light steel framing built up by using cold-formed steel sections. The study can provide further justification, modification or even addition to the design guides in the current code of practices.

This research pioneers the study on partial strength joints for semi-continuous construction in cold-formed steel structures. It expands the validated result of researches on hot-rolled steel beam-to-column partial strength joints done internationally or locally in Malaysia, as well as satisfying design requirements as coded in British Standard BS5950 and Eurocode EC3 into the design of light steel framing.

1.7 Structures of Thesis

The general information of the research subject including basic information about the study to be conducted, objectives and scope of work are mentioned in Chapter 1. Chapter 2 consists of detailed background of the research, design standards and works that have been carried out by other researchers. It discusses on the background information about the investigations to the behaviour of semi-rigid connections, previous work on cold-formed steel connections and design standard requirements. Previous testing arrangements and connection configurations are also reviewed so as to device a standard and rational arrangement for the reliability and accuracy of the data. It is followed by the discussion of analytical works involved in generating design formula and calculations for partial strength connections utilizing cold-formed steel channel sections in Chapter 3. The next task, which is the most important task in the study, contains the detail descriptions of the experimental investigations carried out, covered in Chapter 4 for full-scale isolated joint tests and

Chapter 5 for full-scale sub-assemblage frame tests. Full-scale isolated joint refer to individual connections which were tested to determine the moment capacities, stiffness and ductility of the designed joint. The preparation of test specimen, data acquisition tools and test procedures were discussed in detail. Results acquired from the isolated tests were used to predict the moment resistance of the connections. In Chapter 5, the actual responses of pin and partial strength behaviour of connections over a long beam span is observed and details of calculations to predict the moment resistance of the beam are addressed. Checking procedures employed are in accordance with the British Standard and Eurocode 3. Finally the research works is summarized and concluded in Chapter 6, together with the recommendation for future works.