

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

**TAN CHER SIANG**

**UNIVERSITI TEKNOLOGI MALAYSIA**

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

TAN CHER SIANG

A thesis submitted in fulfilment of the  
requirements for the award of the degree of  
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering  
Universiti Teknologi Malaysia

DECEMBER 2009

## **ACKNOWLEDGEMENT**

The author would like to express his utmost gratitude to his supervisor, Professor Ir. Dr. MAHMOOD MD TAHIR for his guidance and assistance throughout the study. The author would also like to acknowledge his colleagues especially Mr. SHEK POI NGIAN, Mr. WONG KAH LEONG and the structural laboratory staff team headed by YM RAJA EZAR ISHAMUDDIN ABD LATIF and Mr. RAZALE BIN MOHAMAD, and all the staff of Faculty of Civil Engineering for their supports. Special Thanks also goes to Dr. ARIZU BIN SULAIMAN, Dr. AIRIL YASREEN BIN MOHD YASSIN and SELLYNA ABDUL SHUKOR from the Steel Technology Centre, Faculty of Civil Engineering for their contributions towards this research. Last but not least, deepest appreciation to the author's parents and friends for their encouragements and full moral supports throughout the progress of this doctorate study.

## 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-assembly 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 'Industrialized 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 keupayaan 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.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	<b>DECLARATION STATEMENT</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGEMENTS</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENTS</b>	vii
	<b>LIST OF TABLES</b>	xi
	<b>LIST OF FIGURES</b>	xiv
	<b>LIST OF SYMBOLS AND ABBREVIATIONS</b>	xix
	<b>LIST OF APPENDICES</b>	xxiv
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 General	1
	1.2 Background and Rational	4
	1.3 Problems Statements	7
	1.4 Objectives of Research	7
	1.5 Scope of Work	8
	1.6 Significant of Study	9
	1.7 Structures of Thesis	9
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>11</b>
	2.1 General	11
	2.2 Cold-formed Steel Structures	11
	2.3 Development of Research in Cold- formed Steel Structures	14

2.4	Partial Strength Semi-rigid Joints in Steelwork	17
2.5	Research on Joints for Cold-formed Steel	22
2.6	Critical Remarks from Literature Review	34
<b>3</b>	<b>ANALYTICAL STUDY</b>	<b>35</b>
3.1	General	35
3.2	Section Properties of Cold-formed Double Channel Sections	36
3.2.1	Gross Cross Section Area	37
3.2.2	Effective Section	39
3.3	Member Capacities of Cold-formed Double Channel (DC) Sections	41
3.3.1	Web Crushing Resistance	42
3.3.2	Shear Resistance in Web	43
3.3.3	Bending Moment Resistance	43
3.3.4	Buckling Resistance Moment	44
3.4	Design Procedures for Pin and Partial Strength Connection	46
3.4.1	Web-cleat Connection (J1-WC)	54
3.4.2	Flange-cleat Connection (J2-FC)	62
3.4.3	Flange-web-cleat Connection (J3-FWC)	69
3.4.4	Gusset Plate Connection (J4-HG)	75
3.4.5	Combined Gusset Plate and Flange-cleat Connection (J5-HGFC)	81
3.5	Stiffness Capacity of Connection	87
3.6	Analytical Results and Discussion	98
3.6.1	Section Properties and Member Capacities of Cold-formed DC Section	98

	3.6.2	Strength and Stiffness of Connections	103
	3.7	Concluding Remarks	105
<b>4</b>		<b>EXPERIMENTAL STUDY: FULL-SCALE ISOLATED JOINT TESTS</b>	<b>107</b>
	4.1	General	107
	4.2	Preparation of the Test Specimens	108
	4.2.1	Tensile Test of Specimens	109
	4.2.2	Cold-formed Steel Bracket Connections (Test T01 to T09)	113
	4.2.3	Hot-rolled Steel Angle Connections (Test T11 to T19)	118
	4.2.4	Hot-rolled Steel Gusset Plate and Angle Connections (Test T21 to T26)	120
	4.3	Testing Set-up and Boundary Conditions	123
	4.4	Experimental Programs and Procedures	127
	4.5	Modes of Failure	127
	4.5.1	Cold-formed Brackets Connection	128
	4.5.2	Hot-rolled Angle Connection	130
	4.5.3	Hot-rolled Gusset Plate and Angle Connection	132
	4.6	Results and Discussion	135
	4.6.1	Load versus Deflection	135
	4.6.2	Moment versus Rotation	139
	4.6.2.1	Comparison between Test Results and Analytical Results	139
	4.6.2.2	Comparison of the Types of the Connections	157



	4.6.2.3	Effects of Increasing the Size of Beam	161
	4.6.2.4	Effects of Increasing the Thickness of Angle-cleats	164
	4.6.2.5	Comparison between J2-FC and J3-FWC Connections to Pucinotti's Study	167
	4.6.2.6	Comparison of Gusset Plate Connection to Chung's Study	168
	4.7	Concluding Remarks	172
<b>5</b>		<b>EXPERIMENTAL STUDY: FULL-SCALE SUB-ASSEMBLAGE FRAME TESTS</b>	<b>174</b>
	5.1	General	174
	5.2	Experimental Specimens	175
	5.3	Testing Set-up and Boundary Conditions	180
	5.4	Experimental Programs and Procedures	183
	5.5	Results	184
	5.5.1	Modes of Failure	184
	5.5.2	Load versus Deflection	187
	5.5.3	Load versus Rotation	193
	5.5.4	Determination of Moments in Sub-assembly Frame Tests	201
	5.6	Discussion	207
	5.6.1	Load and Deflection Capacity	207
	5.6.2	Comparison of the Moment Capacity	208
	5.6.3	Comparison of the Rotational Stiffness of the Connections	212
	5.7	Concluding Remarks	215

<b>6</b>	<b>CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORKS</b>	<b>216</b>
6.1	Summary of Research Works	216
6.2	Conclusions	217
6.2.1	Analytical Investigation	218
6.2.2	Experimental Investigation in Full-scale Isolated Joint Test	218
6.2.3	Experimental Investigation in Full-scale Sub-assembly Frame Test	219
6.3	Suggestion for Future Works	220
	<b>REFERENCES</b>	<b>223</b>
	<b>APPENDICES A - D</b>	<b>230 – 289</b>

## LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Types of connections for cold-formed steel structures	22
2.2	Proposed practical detailing for fasteners in cold-formed steel web cleats by Chung & Lawson (2000)	25
2.3	Summary of test data by Yu <i>et al.</i> (2005)	27
2.4	Test results by Chung <i>et al.</i> (2005)	28
2.5	Summary of research on joints for cold-formed steel structures	29
3.1	Generic sections for cold-formed lipped channel	37
3.2	Comparison of $A_m / A_g$ for generic cold-formed channel sections	39
3.3	Gross section properties of Double Channel (DC) sections	41
3.4	Reduced section properties of Double Channel (DC) sections ( $p_y = 350\text{N/mm}^2$ )	41
3.5	Shear resistance in web for Double Channel (DC) sections	43
3.6	Bending moment resistance for DC sections	44
3.7	Member Capacities (Design yield strength, $Y_s = 350\text{N/mm}^2$ )	45
3.8	Bolt capacities of M12 Grade 8.8 to BS5950-1 (2000)	48
3.9	Equivalent T-stubs (adopted from SCI & BCSA , 1995)	50
3.10	Check list for connection design based on component method	51
3.11	Standard detailing of the web-cleat (J1-WC) connection	55
3.12	Example 1- Design strength of J1-WC connection	55
3.13	Standard detailing of the flange-cleat (J2-FC) connection	63
3.14	Example 2- Strength design of J2-FC connection	63
3.15	Standard detailing of the flange-web-cleat (J3-FWC) connection	70

3.16	Example 3- Strength design of J3-FWC connection	70
3.17	Standard detailing of the Gusset Plate (J4-HG) connection	75
3.18	Example 4- Strength design of J4-HG connection	76
3.19	Standard detailing of the Combined Gusset Plate Flange-cleat (J5-HGFC) connection	82
3.20	Example 5- Strength design of J5-HGFC connection	83
3.21	Stiffness coefficients $k_i$ for the five proposed connections	87
3.22	Stiffness coefficients for components at joint (Adopted from BS EN 1993-1-8 (2005))	88
3.23	Example 6- Stiffness design of J2-FC connection	91
3.24	Example 7- Stiffness design of J3-FWC connection	94
3.25	Member Capacities (Design yield strength, $Y_s = 350\text{N/mm}^2$ )	99
3.26	Connections capacities and rotational stiffness	99
3.27	Comparison of the section capacities with data from Lawson <i>et al.</i> (2002)	102
4.1	Coupon tensile test results	112
4.2	Summary of test specimen T01 to T09	117
4.3	Summary of test specimen T11 to T19	119
4.4	Summary of test specimens T21 to T26	122
4.5	Summary of modes of failure for isolated joint test	134
4.6	Summary of load-deflection results for isolated joint tests	138
4.7	Summary of moment-rotation results for isolated joint tests	141
4.8	Comparison of strength of different types of connection	157
4.9	Comparison of the effect of increasing the size of beam	161
4.10	Comparison of the effect of 2 mm cleat to 6 mm cleat connections	165
4.11	Comparison between J3-FWC and J2-FC connections	168
4.12	Comparison between FSIJ experimental results and Chung & Lau (1999)	169
4.13	Comparison between FSIJ experimental results and Yu <i>et al.</i> (2005)	170
5.1	Summary of specimens in full-scale sub-assembly frame tests	176
5.2	Summary of material tensile test results	177

5.3	Detailing of test specimen T31 to T43	178
5.4	Detailing of test specimens T51 to 56	179
5.5	List of data acquisition instruments used in the FSSAF tests	183
5.6	Summary of load-deflection results for FSSAF tests	193
5.7	Summary of moment-rotation results for FSSAF test	206
5.8	Comparison of the load capacity results in FSSAF tests	208
5.9	Comparison of the moments results in FSSAF tests	211
5.10	Comparison of rotational stiffness ( $S_{j,ini}$ ) to EC3-1-8 (2005)	213
5.11	Classification of connections in FSSAF tests	214

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Cold-rolling process of strip steel coil to form cold-formed steel channel section	2
1.2	Common shapes for cold-formed channel sections	3
1.3	Cold-formed light steel framing for residential house (adopted from Lawson <i>et al.</i> , 2002)	3
2.1	The stress-strain curve of cold-formed steel strip	13
2.2	Moment-rotation relationship of a partial-strength semi-rigid connection	19
2.3	Types of partial strength semi-rigid connections	21
2.4	Joints for cold-formed steel structures	32
3.1	Mid-line method for calculation of cold-formed steel section properties	38
3.2	Effective section of a lipped channel section subjected to axial compression and bending	41
3.3	Web crushing at the beam and at the connection	42
3.4	Buckling resistance moment, $M_b$ of DC section	45
3.5	Proposed cold-formed beam-to-column connections	47
3.6	Component design checks	49
3.7	Web-Cleat (J1-WC) connection	54
3.8	Equivalent T-stub for WC	56
3.9	Column web crushing and buckling	58
3.10	Bolt under shear and torsion	60
3.11	Flange-Cleat (J2-FC) connection	62
3.12	Column bearing length	66
3.13	Bolt subjected to shear and tension	67
3.14	Flange-Web-Cleat (J3-FWC) connection	69

3.15	Gusset plate (J4-HG) connection	76
3.16	Buckling moment of the gusset plate	77
3.17	Bearing force of the bolt group	78
3.18	Shear force of the bolt group	79
3.19	Bolt subjected to shear and torsion	79
3.20	Combined gusset plate and flange-cleat (J5-HGFC) connection	81
4.1	Full-scale isolated joint (FSIJ) test	108
4.2	Coupon sample for the tensile test	110
4.3	Bone-shape and strip steel samples for tensile tests	111
4.4	Typical stress-strain curve for tensile test result	111
4.5	Cold-formed steel brackets	113
4.6	Detailing of joints	114
4.7	Fabricated specimens for cold-formed bracket joints	116
4.8	Hot-rolled angle joints for test T11 to T19	118
4.9	Typical detailing of joints in T21 to T26	120
4.10	Hot-rolled steel gusset plate and angle connection for test T21 to T26	121
4.11	Magnus Test Frame (left) with test specimen inside (right)	123
4.12	(a) Hydraulic jack, (b) portable pump and (c) 100 kN load cell	124
4.13	Boundary: (a) lateral restraints; (b) base plate for T01-T19; and (c) base plate for T21-T26	124
4.14	Linear Variable Displacement Transducers (a)DT1-200mm, (b)DT2-100mm, (c)DT3-50mm; (d) DT4 (top) and DT5 (bottom)-25mm	125
4.15	Inclinometers (left) and readers (right)	125
4.16	The layout of FSIJ test and data acquisition system	126
4.17	Failure mode of cold-formed bracket double angle web-cleat, J1-CWC	129
4.18	Failure mode of cold-formed bracket top-seat flange-cleat, J2-CFC	129
4.19	Failure mode of cold-formed bracket combined flange-web-cleat, J3-CFWC	129

4.20	Failure mode of hot-rolled double angle web-cleat, J4-HWC	131
4.21	Failure mode of hot-rolled angle top-seat flange-cleat, J2-HFC	131
4.22	Failure mode of hot-rolled angle combined flange-web-cleat, J3-HFWC	132
4.23	Failure mode of hot-rolled gusset plate (J4-HG) and combined gusset plate and flange-cleat (J5-HGFC) connections	133
4.24	Typical load-deflection graph for FSII test	136
4.25	Moment-rotation graphs for test T01 (DC150 J1-CWC)	143
4.26	Moment-rotation graphs for test T02 (DC150 J2-CFC)	143
4.27	Moment-rotation graphs for test T03 (DC150 J3-CFWC)	144
4.28	Moment-rotation graphs for test T04 (DC200 J1-CWC)	144
4.29	Moment-rotation graphs for test T05 (DC200 J2-CFC)	145
4.30	Moment-rotation graphs for test T06 (DC200 J3-CFWC)	145
4.31	Moment-rotation graphs for test T07 (DC250 J1-CWC)	146
4.32	Moment-rotation graphs for test T08 (DC250 J2-CFC)	146
4.33	Moment-rotation graphs for test T09 (DC250 J3-CFWC)	147
4.34	Moment-rotation graphs for test T11 (DC150 J1-HWC)	148
4.35	Moment-rotation graphs for test T12 (DC150 J2-HFC)	149
4.36	Moment-rotation graphs for test T13 (DC150 J3-HFWC)	149
4.37	Moment-rotation graphs for test T14 (DC200 J1-HWC)	150
4.38	Moment-rotation graphs for test T15 (DC200 J2-HFC)	150
4.39	Moment-rotation graphs for test T16 (DC200 J3-HFWC)	151
4.40	Moment-rotation graphs for test T17 (DC250 J1-HWC)	151
4.41	Moment-rotation graphs for test T18 (DC250 J2-HFC)	152
4.42	Moment-rotation graphs for test T19 (DC250 J3-HFWC)	152
4.43	Moment-rotation graphs for test T21 (DC150 J4-HG)	153
4.44	Moment-rotation graphs for test T22 (DC150 J5-HGFC)	154
4.45	Moment-rotation graphs for test T23 (DC200 J4-HG)	154
4.46	Moment-rotation graphs for test T24 (DC200 J5-HGFC)	155
4.47	Moment-rotation graphs for test T25 (DC250 J4-HG)	155
4.48	Moment-rotation graphs for test T26 (DC250 J5-HGFC)	156



4.49	Comparison of $M-\phi$ curves for different types of connections	158
4.50	Comparison of $M-\phi$ curves for the increment of beam size	162
4.51	Comparison of $M-\phi$ curves for the 2 mm cleats to 6 mm cleats	166
4.52	Gusset plate connections by Chung and Lau (1999) and Yu <i>et al.</i> (2005)	171
5.1	Full-scale sub-assembly frame (FSSAF) test	175
5.2	Types of connections investigated in FSSAF tests	177
5.3	Schematic diagram of the FSSAF test frames and boundary conditions	181
5.4	Location of equipments for FSSAF tests	182
5.5	Schematic diagrams of the data acquisition system	182
5.6	Failure sequence (i): development of ‘wave’ pattern on the top flange of the beam section	185
5.7	Failure sequence (ii): crushing of the top flange of the beam section	185
5.8	Failure sequence (iii): lateral torsional buckling	186
5.9	Buckling of beam web near the connection	186
5.10	Typical load deflection curves for FSSAF test (Data form test T32)	187
5.11	Load-deflection graph for test T31 (DC150 J1-CWC)	188
5.12	Load-deflection graph for test T32 (DC200 J1-CWC)	188
5.13	Load-deflection graph for test T33 (DC250 J1-CWC)	189
5.14	Load-deflection graph for test T41 (DC150 J3-HFWC)	190
5.15	Load-deflection graph for test T42 (DC200 J3-HFWC)	190
5.16	Load-deflection graph for test T43 (DC250 J3-HFWC)	190
5.17	Load-deflection graph for test T51 (DC150 J4-HG)	191
5.18	Load-deflection graph for test T52 (DC150 J5-HGFC)	191
5.19	Load-deflection graph for test T53 (DC200 J4-HG)	192
5.20	Load-deflection graph for test T54 (DC200 J5-HGFC)	192
5.21	Load-deflection graph for test T55 (DC250 J4-HG)	192
5.22	Load-deflection graph for test T56 (DC250 J5-HGFC)	193
5.23	Load-rotation graph for test T31 (DC150 J1-CWC)	194

5.24	Load-rotation graph for test T32 (DC200 J1-CWC)	195
5.25	Load-rotation graph for test T33 (DC250 J1-CWC)	195
5.26	Load-rotation graph for test T41 (DC150 J3-HFWC)	196
5.27	Load -rotation graph for test T42 (DC200 J3-HFWC)	196
5.28	Load -rotation graph for test T43 (DC250 J3-HFWC)	197
5.29	Load -rotation graph for test T51 (DC150 J4-HG)	197
5.30	Load -rotation graph for test T52 (DC150 J5-HGFC)	198
5.31	Load -rotation graph for test T53 (DC200 J4-HG)	198
5.32	Load -rotation graph for test T54 (DC200 J5-HGFC)	199
5.33	Load -rotation graph for test T55 (DC250 J4-HG)	199
5.34	Load -rotation graph for test T56 (DC250 J5-HGFC)	200
5.35	Moment-rotation graphs (J1-CWC) for T31 to T33	201
5.36	Moment-rotation graphs (J3-HFWC) for T41 to T43	202
5.37	Moment-rotation graphs (J4-HG) for T51, T53 and T55	202
5.38	Moment-rotation graphs (J5-HGFC) for T52, T54 and T56	203
5.39	Shear force diagram and bending moment diagram at beam	204
5.40	Bending moment diagram for FSSAF tests	209
5.41	Classification of joints to EC3-1-8 (2005)	213

## LIST OF SYMBOLS AND ABBREVIATIONS

### SYMBOLS:

$\lambda$	-	Slenderness ratio
$\gamma$	-	Correction factor in mid-line method
$\delta$	-	Deflection
$\phi$	-	Rotation of a connection
$\lambda_{LT}$	-	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
$b_{f,eff}$	-	Effective flat width of flange element
$b_{w,eff}$	-	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 <sup>2</sup> )
$e, e_1, e_2$	-	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
$M_{J-50,exp}$	-	Experimental moment resistance of joint at 50 mRad rotation.
$M_{J-C,the}$	-	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

$S_{J,exp}$	-	Experimental initial rotational stiffness of a connection
$S_{J,ini}$	-	Initial rotational stiffness of a connection
$S_{J,the}$	-	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
$Z_{x,g}$	-	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
$\beta$	-	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-assembly 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

## LIST OF APPENDICES

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Calculation of Section Properties & Member Capacities	230
B	Calculation of Connection Design	245
C	Experimental Data of Full-scale Isolated Joint Tests (Test Label T01 to T26)	279
D	Experimental Data of Full-scale Sub-assembly Frame Tests (Test Label T31 to T56)	286



## CHAPTER 1

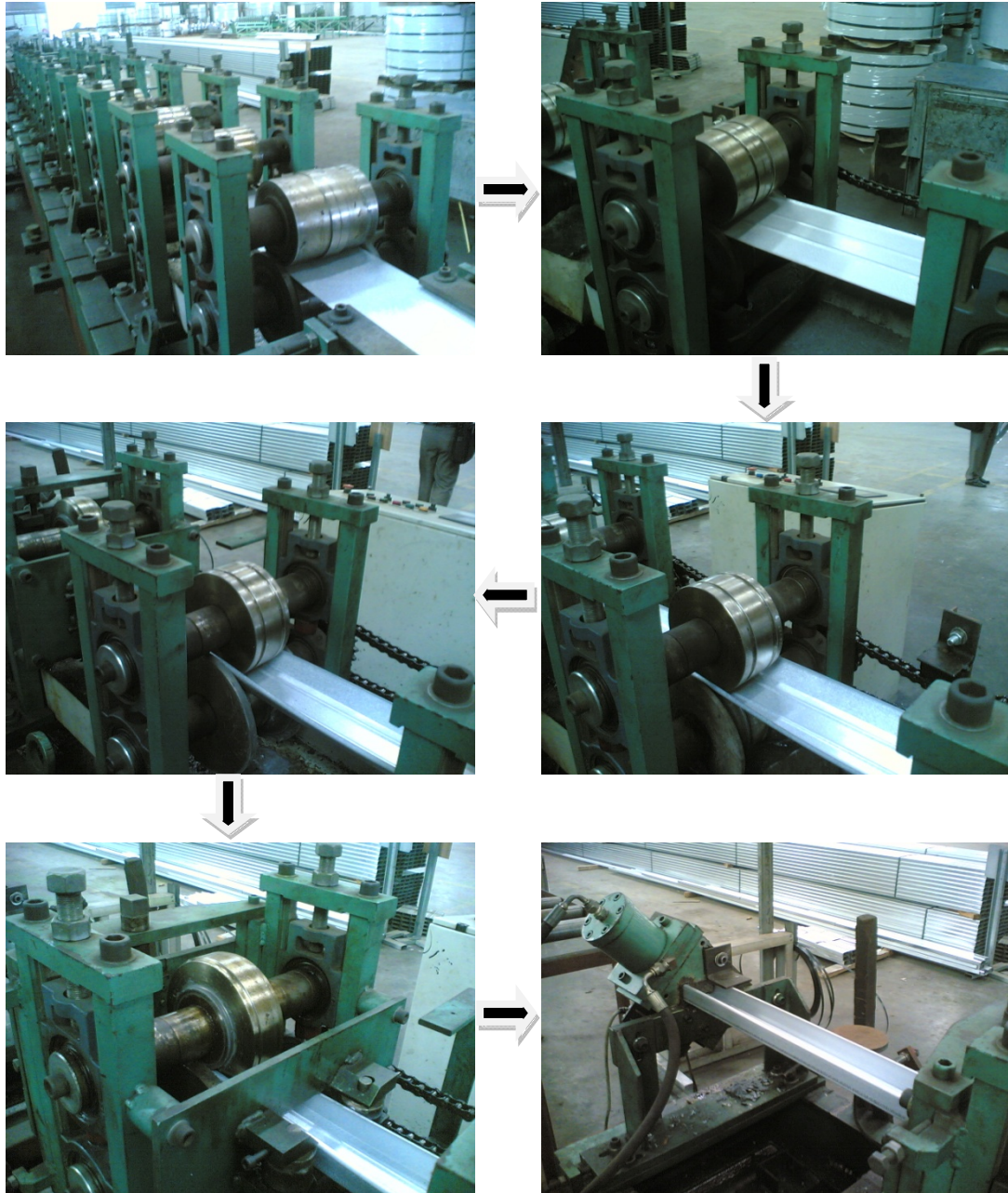
### INTRODUCTION

#### 1.1 General

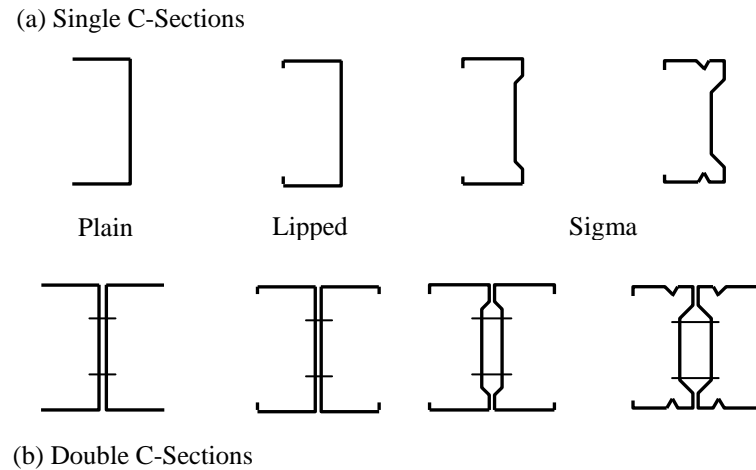
Industrialized Building System (IBS) has been promoted diligently by CIDB in Malaysia since Year 2000 (Sumadi *et al.*, 2001; Mohamed, 2003). Besides reduced dependency on foreign labour, the simplified construction solutions offer better control of quality, increase productivity, reduce construction 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<sup>2</sup>, 450 N/mm<sup>2</sup> and even 550 N/mm<sup>2</sup> (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-assembly 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-assembly 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-assembly 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.