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Structural Performance of Bolted Moment Connections among Single Cold-Formed Channel Sections

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ABSTRACT

This paper presents an experimental investigation on bolted moment connections between single cold-formed channels connected back-to-back at the joints. A total of ten column-base connection tests and beam-column sub frame tests with different connection configurations were conducted to investigate the performance of the connections in term of strength and stiffness. Two modes of failure were identified from the tests; 1) Mode BFcsw: Bearing failure in section web around bolt hole. 2) Mode FFcs: Flexural failure of connected section. Among all the tests, the moment resistance of bolted moment connections with four bolts per member ranged 70 - 90 % of the moment capacities of the connected members. Consequently, it can be concluded that the use of cold-formed steel sections connected back-to-back at the joints allows simple and effective connection to be formed among cold-formed steel sections leading to improved build ability.

Keywords: *cold-formed steel; bolted moment connections; laboratory tests*

1. INTRODUCTION

One of the most exciting developments in structural steelwork during recent years has been the widespread and increasing use of cold-formed members as main structure in the construction of steel framing. Their strength, light weight, versatility, non-combustibility, and ease of production have encouraged architects, engineers, and contractors to use cold-formed steel products which can improve structural function and building performance, and provide aesthetic appeal at lower cost. Common shapes of cold formed steel sections used in structural framing are channels(C-sections), Z-sections, angles, hat sections as shown in Figure 1. In general, the depth of cold-formed individual framing members ranges from 51-305 mm, and thickness of material ranges from 1.2 to about 6.4 mm (Yu, 2000).

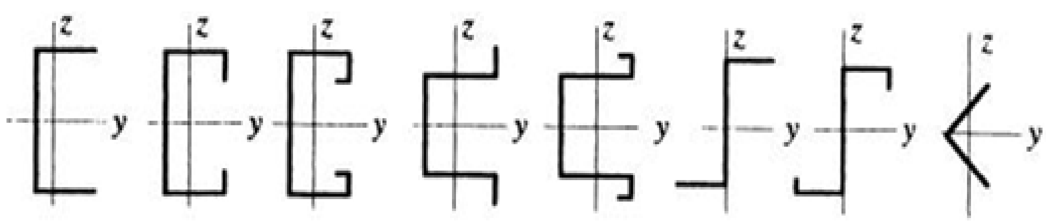

Figure 1: Typical cross-section types of CFS members

Both steel with yield strengths of 280 and 350 N/mm^2 are commonly used. Recently, steel with high yield strength of 450 N/mm^2 is also used while steel with yield strength of 550 N/mm^2 can be found in new cladding product.

The structural response of a steel frame is closely related to the behavior of its beam to column connections (Hancock, et al. 2001). The realistic modeling of a steel frame, therefore, requires the use of realistic connection modeling if an accurate response of the frame is to be obtained. Recently, bolted moment connections between cold-formed steel sections with different connection configurations suitable for general application were studied by Professor Chung K.F. and his team of Hong Kong Polytechnic University (1999, 2002 & 2005).The research was performed to quantify maximum moment resistances of the connection which may be mobilized safety in practical connection configuration. The strength, the stiffness and the deformation capacity of the bolted moment connections were examined in details.

Lim and Nethercot (2003 & 2004) studied experimentally and numerically on simple bolted moment-connections for eaves and apex joints of portal frame to investigate ultimate strength of the connections.
The latest study of cold-formed steel structures was made by McDonald et al (2008). He highlighted the development of more complex cold-formed steel sections in recent application, mainly for beam and column design. He concluded the needs to involve numerical approaches in the determination of design specification, such as in the recent analysis methods namely direct strength method, finite element method, and finite strip method and generalized beam theory.

The objective of the present paper is to study the connection behavior of lightweight, cold-formed section to be used in frame structure for small span building construction. The test series consisted of isolated column-base and beam-column connection tests. The beam and column members are formed from single channel sections which are bolted back-to-back at the joint. It is expected that the proposed structure will offer efficient and economic connecting system and further insight on behavior of single channel sections. There are a number of codes of practice on the design of cold-formed steel structures together with complementary design guides and worked examples to assist practicing engineers. This study will base on the requirements of British Standard BS 5950: Part 5:1998 with assistance from complementary design guides and worked examples (Chung, 1987).

2. SECTION GEOMETRICAL PROPERTIES

The beam and column members are formed from single cold-formed lipped channel sections. The flange width, web and lip depth of the cold-formed section are 50,100 and 14 mm, respectively, and the thickness of each section is either 1.6 or 2 mm. The section properties are given in Table 1. The member capacity was calculated according to the British Standard BS 5950: Part 5: 1998.

Table 1: Section Properties

Specimen	Depth (mm)	Thickness (mm)	Area (mm^2)	Ix (cm^4)	Zx (cm^3)	Zxr (cm^3)	Mcx (kNm)
C10016	100	1.6	335	55.8	11.2	9.65	4.24
C10020	100	2	414	67.9	13.6	12.6	5.5

3. MATERIAL PROPERTIES

The structural steel grade of the cold-formed steel section is G450. In order to obtain the actual yield strength, tensile tests were carried out in accordance to the British Standard BS EN 10002-Part 1 2000, tensile test of metallic materials with the nominal width of 25 mm. The average measured yield strengths were found to be 490 and 500 N/mm^2 for 1.6 and 2 mm thick sections respectively. The test results showed that actual resistance of cold-formed steel was higher than the design strength as in accordance with the code BS 5950: Part 5: 1998. The tests concluded that the proposed steel sections gave good yield strength value compared to the design strength.

The fasteners used in the study were bolt grade 8.8 of 12 mm diameter with two washers. The bolt holes were standardized to 12.5 mm so as to prevent abrupt deformation due to wide hole-spaces between the steel members (Tahir & Tan, 2008).

4. CONNECTION TESTS

4.1 Scope of Investigation

The connection test specimens consisted of column-base and beam-column sub frame tests formed by single cold-formed channels C10016 or C10020 with a member thickness of 1.6 and 2 mm respectively. For all specimens, bolts grade 8.8 of 12 mm diameter were used.

A total of eight column-base connections were investigated to examine the effect of bolt arrangement on structural performance of the connections for two different member thicknesses. The test specimens referred as CB02, CB03, CB04, where a column member is connected to a typical fabricated steel base plate with two, three and four bolts respectively. A typical connection detailing is given in Figure 2.

Another two isolated beam-column connection tests were carried out under lateral load to asses the strength and stiffness of the connections with different member thickness designated as BC-T1.6 and BC-T2. Channel sections were connected back to back at the joint as simple and effective means to connect beam to columns in steel constructions as indicated in Figure 3. The applied loads at the loaded points, rotations and deflections of the test specimens were recorded during the tests.

4.2 Testing Set-Up and Boundary Conditions

The type of test arrangement employed for the isolated tests in this study was the cantilever arrangement of which bending in the beam was produced by the load applied at the end of the cantilever. The line of force application passed close to the centre of gravity of the section as it is closer to actual condition loading case in steel structure.

As the load did not pass through the shear center of the section, the section will twist and torsional stresses will be induced on to the connection. In all tests, rotational restraint to the section was provided by using a lateral restrained bar. The load was applied using hydraulic jack and recorded by a 100 kN load cell. An inclinometer was placed near the connection at the centre of web depth to record member rotation. Displacement transducers (LVDT) were placed close to the centre of gravity of the column and beam sections. Two of them were placed closed to the connections to check the rotation of the respected structural members and one LVDT was placed at the load application position to record member end deflection. For the beam-column connection test, an external joint of sub frame was tested but it is applicable to internal joint and gable joint as well. All testing set up are shown in Figures 2, 3 and 4.

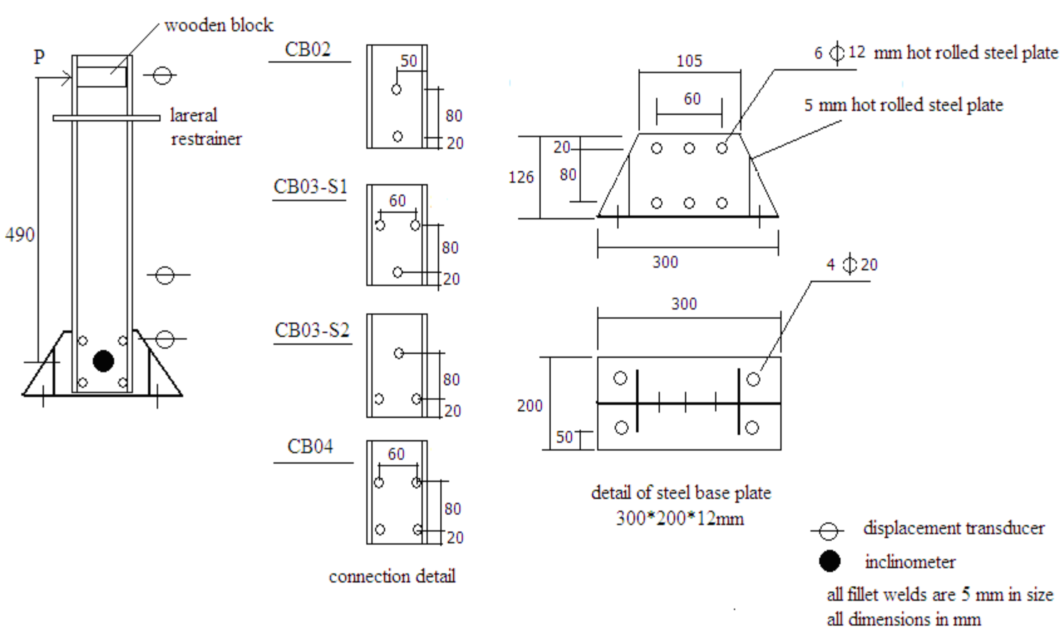

Figure 2: General set-up and instrumentation of column-base connection tests

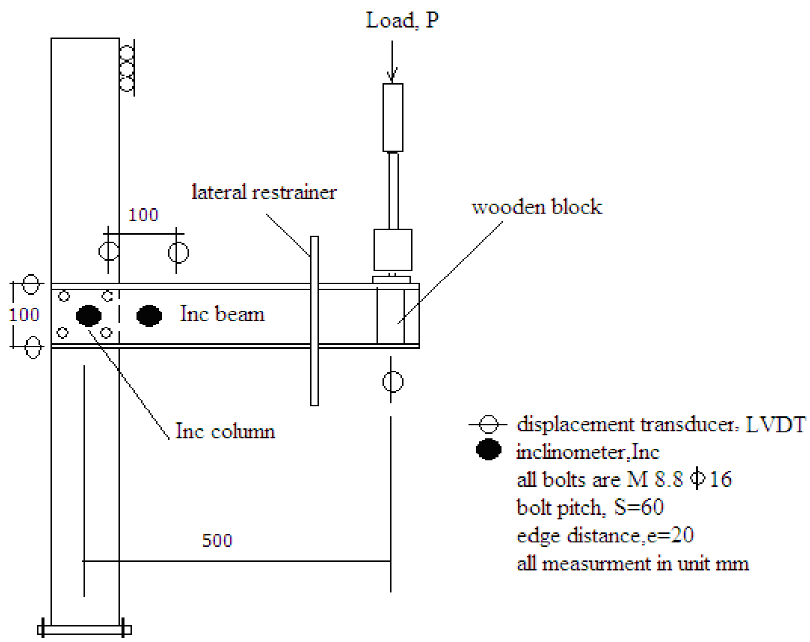

Figure 3: Set-up and instrumentation for beam-column connection tests

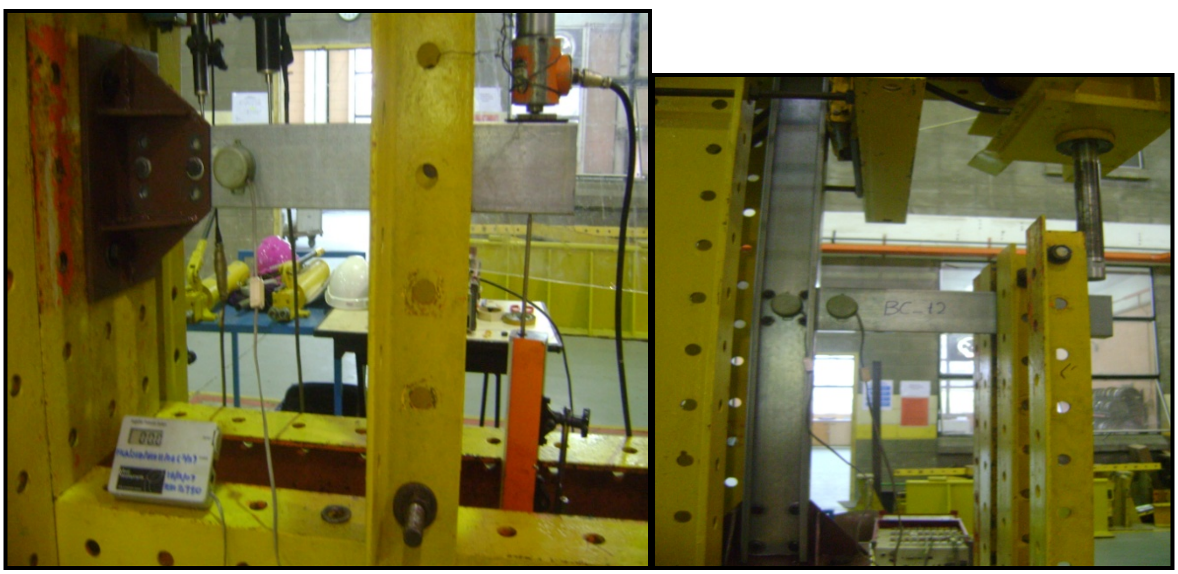

Figure 4: Actual specimen layout for column-base connection (left) and beam-column connections (right)

4.3 Connection Test Procedures

Due to the presence of the clearance in the bolt holes of the tested specimens, tightening the bolts was essential prior to any testing. The load application was applied with the increments controlled by the load. This loading application was continued until the specimen had reached its failure condition. The applied loads of the loaded points, rotations and deflections of the test specimens were recorded during the tests.

4.4 Connection Test Results

The recorded experimental data from the isolated joint tests are given and explained in this section. The first part of the data is the test results of column-base connections. The second part is related to the beam-column connection tests. The test results are discussed under the headings of strength and stiffness. For each test, member rotations and end deflections were recorded. Member rotation were taken from inclinometer readings and converted from the unit of degree to unit of radian. Alternatively, it can be obtained as the relative displacements divided by the separation between the transducer. Member end deflection was measured by using the displacement transducer. The moments were taken as the applied loading times the liver arm measured from the load point to the fastener centroid and normalized with the ratio of design yield strength and actual yield strength of the test specimens. For test specimens with excessive deformation under loading, the moment resistances of the connections are restricted to be the applied moment at a connection rotation of 0.05 rad (Chung, 1999).

In order to assess the effectiveness of the bolted moment connections, a moment resistance ratio is calculated as the ratio of the measured moment resistance of a connection to the calculated moment capacity of connected section. For connections with moment resistance ratios approaching unity, the connections are regarded to be effective in transmitting moment across. The rotational stiffness of the connections is measured from the slope of the moment rotation curves on elastic range. The experimental and theoretical collapse loads of all the connections investigated. Joint test results showed good agreement to the analytical predicted in accordance to British Standards BS 5950: Part 5: 1998. The actual capacities of all proposed connection are higher than the design values. This is good because the design capacity should be lower than the actual capacity for a safe engineering design. Comparisons were made among all the proposed connections and the findings are presented in Table 2.

In all the tests, two different modes of failure were identified as follows:

Mode **BFcsw**: Bearing failure in section web around bolt hole, as shown in Figure 5(a).

Mode **FFcs**: Flexural failure of connected section, as shown in Figure 5(b).

In some of the specimens there is a combination of both modes of failure shown in Figure 5(c).

Table 2: Summary of Test Specimens and Test Results of Column-Base and Beam-Column Test Specimens

Test Refrences	Applied load (kN)	Predicted Load BS5950 (kN)	Applied/ Predicted load	Failure mode	rotational stiffness kNm/rad	*Measured moment resistance (kNm)	Normalized Moment resistance (kNm)	Moment resistance ratio
CB02-T1.6	4.5	3.3	1.4	BF_{CSW}	25	1.28	1.17	0.28
CB03-S1-T1.6	7.4	4.8	1.5	BF_{CSW}/FF_{CS}	49	2.06	1.89	0.44
CB03-S2-T1.6	7.5	4.8	1.5	BF_{CSW}/FF_{CS}	55	2.42	2.22	0.52
CB04-T1.6	8.1	8	1.0	BF_{CSW}/FF_{CS}	90	4.18	3.83	0.90
BC-T1.6	7.8	6.6	1.2	BF_{CSW}/FF_{CS}	54	3.94	3.61	0.85
CB02-T2	4.5	4.3	1.0	BF_{CSW}	30	1.36	1.22	0.22

CB03-S1-T2	8.7	5.8	1.5	BF_{CSW}	54	2.5	2.25	0.41
CB03-S2-T2	8.7	5.8	1.5	BF_{CSW}	55	2.69	2.42	0.44
CB04-T2	10.4	10.4	1.0	BF_{CSW}	92	4.96	4.46	0.81
BC-T2	8.7	8.6	1.0	BF_{CSW}/FF_{CS}	56	4.2	3.78	0.70

CB: denotes a column-base connection; BC: denotes a beam-column connection in members connected back to back; T1.6 and T2: denote the thickness of cold-formed steel member 1.6 and 2 mm respectively; S1and S2: denote different bolt arrangement for column base with three bolts.

* for both thickness, the measured moment resistances for CB02 and CB03 were restricted to rotation of 0.05radian to avoid the tested specimens to be excessively deformed.

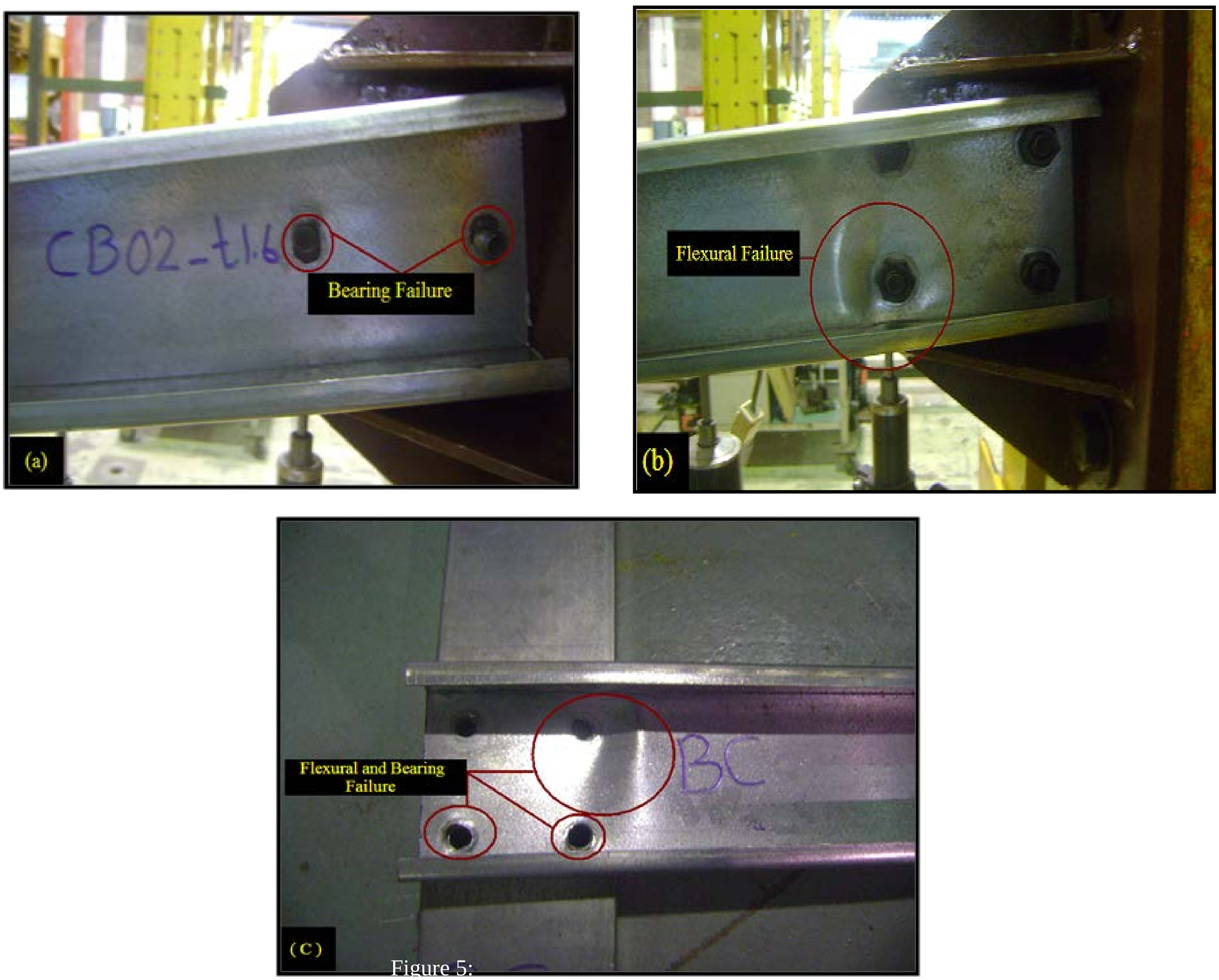

Figure 5: Modes of failure of the specimens

4.4.1 Column-Base Connections

In order to allow direct comparison among the column base test specimens, the moment rotation curves for all column-base connections and load-displacement relations obtained are presented in Figure 6 and 7 respectively. The load versus deflection graph explains the physical behaviour of the joint specimens along the test progress and it can be seen that the connection overall stiffness increases when stiffer connections are used.

(a) Column with 1.6 mm thickness: it is shown that for tests CB02, CB03-S1 and CB03-S2, no maximum moments was recorded. The tests were terminated when rotation reached 0.15radian approximately at the column bases. Due to excessive deformation, the maximum moment resistance of the tests was restricted to be 1.28, 2.06, and 2.42 kNm respectively at rotation 0.05radian. On the contrary, in the test CB04, the column base connection attained its maximum moment resistance of 4.18 kNm at a rotation of 0.068 radian. The initial rotational stiffness of the column base connections of tests CB02, CB03-S1, CB03-S2 and CB04 estimated to be 25, 49, 55 and 90 kNm/rad respectively. All tests show sufficient rotation more than 0.03 radian. After testing, the column members were disassembled from the fabricated section for inspection. It was found that in CB02, CB03-S1 and CB03-S2 the steel around bolt holes of the section webs failed in bearing, and the bolt holes were distorted significantly. For column base with three bolts, flexural failure also combined with the bearing failure. While, CB04 failed in flexural failure near the column base connection and there was little evidence of bearing failure in the bolt holes.

(b) Column with 2 mm thickness: For tests CB02, CB03-S1, CB3-S2 and CB04, no maximum moments was recorded. The tests were terminated due to excessive deformation. The maximum moment resistance of the tests CB02, CB03-S1 and CB03-S2 were restricted to be 1.36, 2.5, 2.69 kNm respectively at rotation 0.05radian. Moment resistance of specimen CB04-T2 was 4.96 kNm. All tests show sufficient rotation more than 0.03 radian. The column base connections of specimens CB02, CB03-S1, CB3-S2 and CB04 had rotational stiffness of 30, 54, 55 and 92kNm/rad respectively. After testing and disassembling the column member from fabricated base, there was little evidence of bearing failure in the steel around bolt holes, which indicates that all specimens had not yet attended the maximum moment situation due to limited rotational capacity at column base specimens

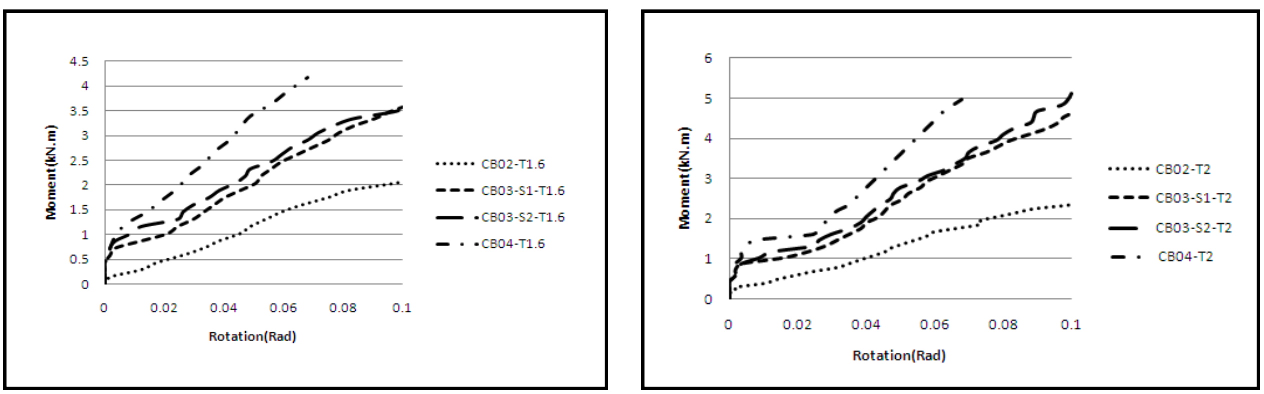

Figure 6: Moment-rotation curves of column-base connections, T1.6 and T2

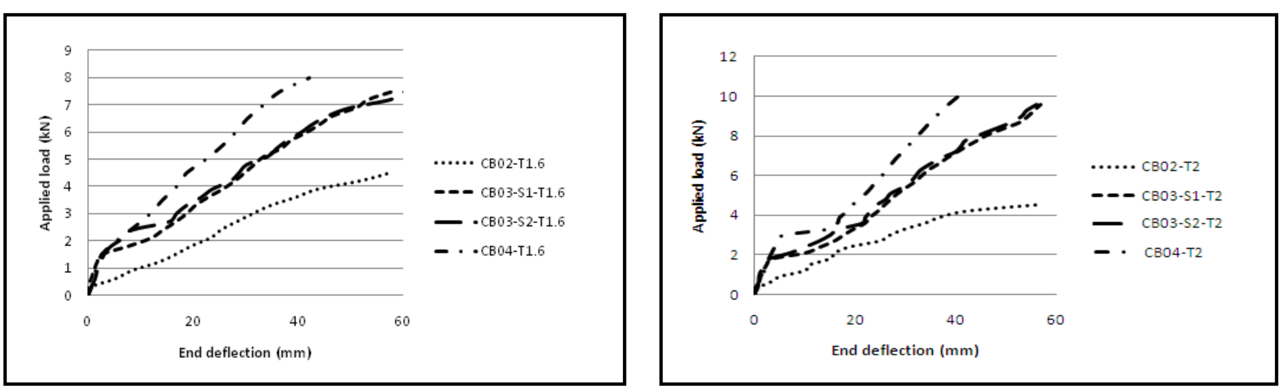

Figure7. Load-deflection curves of column-base connections

4.4.2 Beam-Column Connections

For easy comparison among the test specimens, the moment rotation curves for both beam-column connections and load-displacement relations obtained are presented in Figure 8 and 9 respectively.

BC04-T1.6 attained its maximum moment resistance of 3.94 kNm at a rotation of 0.10 radian. The initial rotational stiffness of the test specimen estimated to be 54kNm/rad. The failure was found to be flexural failure and little evidence of bearing failure in the steel around bolt holes.

BC04-T2 attained moment resistance of 4.2 kNm at a rotation of 0.10 radian. The initial rotational stiffness of the test specimen estimated to be 56kNm/rad. The specimen fail due to flexural failure and little evidence of bearing failure in the steel around bolt holes.

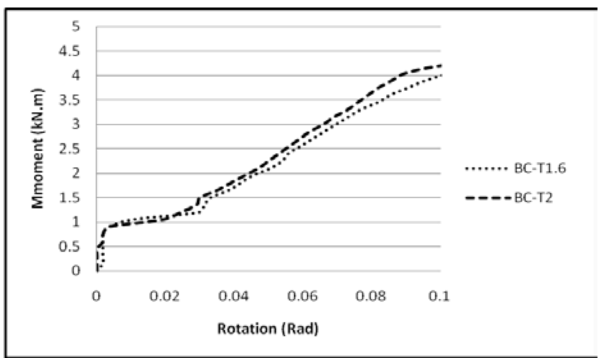

Figure 8: Moment-rotation curves of beam-column connections

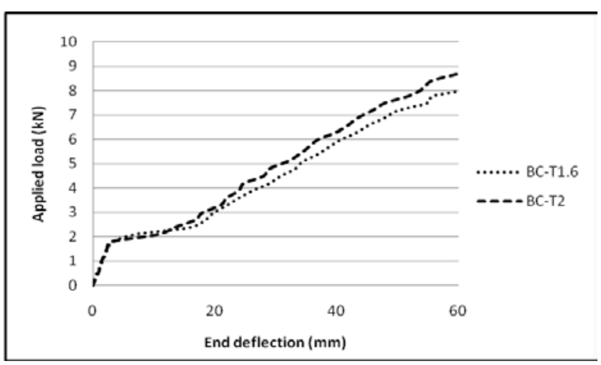

Figure 9: Load-deflection curves of beam-column connections

4.5 Findings of column-base and beam-column tests

a) Column base with four bolts is able to form stiff and strong moment connection with a rotational stiffness about 90 kNm/rad and a moment resistance over 80% of the connected members.

b) In beam-column connection test specimens, the moment capacity of joint compared to the moment capacity of beam section were 0.85 and 0.70 with rotational stiffness estimated 54 and 56 kNm/rad for 1.6 and 2 mm thick sections respectively. Consequently, simple, practical and effective joints are achieved to be used among cold-formed structural framing.

c) The initial rotational stiffness of the connections in the tests was proportional to the distance of bolt in the connections, and the number of bolts used at the connections. The longer distance of bolt and higher number of bolts in the connection provide higher rotational stiffness in the connection. These show agreement to Professor Chung's findings (1999, 2002).

d) It can be observed that all the predictions are lower than the experimental results for maximum loads. The ratios of different were between 1.0 and 1.5.

e) All specimens developed high ductility performance, no catastrophe failure happened. The beam developed large deflection and the rotation of joints were more than 30 mRad.

5. CONCLUSIONS

An experimental study was conducted to investigate the structural performance of bolted moment connections among cold-formed steel sections in term of strength and stiffness. Channel section was connected back to back at the joint as simple and effective means to connect beam to columns in steel constructions. Among all the tests on column base and beam column connection tests it was demonstrated that practical, strong and stiff moment connections may be formed with bolts through rational design. The maximum measured moment resistance is found to be 90 % of the moment capacity of the connected sections. Two different modes of failure were observed in the tests, bearing failure in section web around bolt hole and flexural failure of connected section. It is shown that bearing failure is ductile mode with large deformation capacity while flexural failure may cause sudden collapse. Combined failure modes also indicated in some tests. Due to large deformation of the test specimens in some tests, the moment resistance is restricted to the applied moment at a connection rotation of 0.05rad in order to avoid excessive deformation. Consequently, it is demonstrated that bolted moment connections among cold-formed steel section are readily achieved with the proposed connection configuration with four bolts. The bolted moment connection are shown to be effective in transmitting moment between the connected sections, enabling

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effective moment framing among cold formed steel structure. In addition, connection formed by connecting single channels connected back to back is also simple to fabricate and suitable for general application.

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