Laboratory Investigation of Bolted Angle Joints for Cold-formed Steel Double Channel Sections

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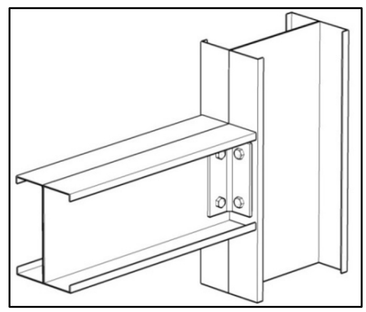
***Abstract*— The application of cold-formed steel in light steel framing design can serve as an alternative for Industrialized Building System, by extending steelwork construction into residential housing. There is a lack of in-depth study on the joints behaviour for cold-formed steel frames, particularly the beam-to-column connection. This paper presents the isolated joint test on three types of joints using bolts and steel angles, namely web-cleats, top-seat flange-cleats and combined flange-web-cleats connections. Six specimens with different joint configuration and thickness of angle were tested. The experimental setup, procedures and failure modes of the joints are discussed in detail. From the comparison, it is observed that by increasing the thickness of angle from 2 mm to 6 mm, the strength in term of joint's moment resistance increases in the range of 1.80 to 2.28. The ratio of difference for rotational stiffness increases in the range of 1.27 to 2.06.**

Keywords-cold-formed steel; double channel section; bolted joints; angle connection; partial strength; stiffness

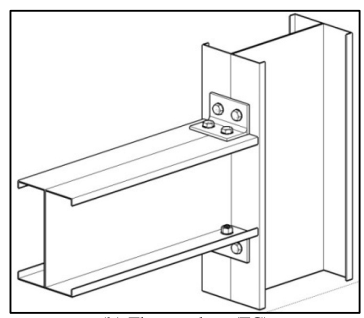
I. INTRODUCTION

Industrialized Building System (IBS) that being promoted diligently by CIDB Malaysia [1] is one of the prefabricated building technologies. By transferring building manufacturing works into factory, IBS aims to reduce dependency on mass unskilled foreign labor, produce higher quality control of building, increase productivity and at the same time reduce construction time and material wastage, leaving the construction site a cleaner environment. The application of cold-formed steel in light steel framing design can become one of the Industrialized Building System that optimizes economical and sustainable construction.

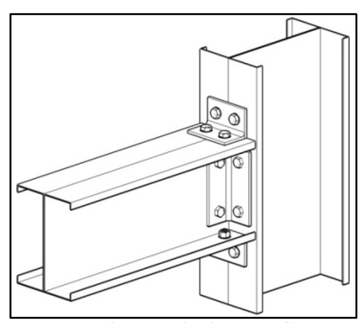
In production of joints for steel structures, the use of bolts and angles can eliminate the dependent on welding works. The bolted connection can be formed into three types, namely web-cleat connection (WC), flange-cleat connection (FC) and combined flange-web-cleat connection (FWC) as shown in Fig. 1. Researches have been carried out [2,3] to study the strength and stiffness behaviour of angle connection for hot-rolled steel structures. Little works have been done on angle connection for cold-formed steel structures. Chung and Lawson [4] studied the shear strength of single web-cleats (WC) for cold-formed steel channel sections. Tan et al. [5-7] reported on experimental tests on various joint configurations for cold-formed steel beam-to-column connections. This paper reports on the investigation of bolted angle joints for cold-formed steel frames built with 250 mm double channel sections.



(a) Web-cleat (WC)



(b) Flange-cleat (FC)



(c) Flange-web-cleat (FWC)

Fig. 1. Bolted angle joints for cold-formed steel frame

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Best practice to obtain the most realistic information on physical behaviour of steelwork joints are experimental tests performed on full-scaled structural frames [8]. This is due to the facts that the connections strongly affect the overall response of a frame and likewise, the frame behaviour may influence the mechanical properties of the connections. However, the incurred cost in performing tests on whole frame is very expensive, and the tests may demand huge and specific testing facilities. So, tests on isolated joints could be carried out with limited scope as mentioned. The experiment design employed for the isolated tests in this study are cantilever arrangement, of which the moment resistance of the joints are developed by the load applied at the end of the cantilever beam. Representing the external joints of a steel frame, the cantilever arrangement was relatively sufficient in producing expected results especially the moment-rotation characteristics. Many researchers have resorted to this type of arrangement in their studies, e.g. Bose and Hughes [9], Mottram and Zheng [2] and Prinz et al. [10]. For cold-formed steel connections, Markazi et al.[11], Chung and Lau [12] and Wong and Chung [13] also conducted series of isolated joint tests to determine the moment-rotation behaviour of their proposed connection methods.

II. METHODOLODY

Cold-formed steel lipped channel sections manufactured by Kemuning Structures S/B are used as the beam and column members of steel frame. The grade of steel is 350 N/mm2 and the thickness of each channel section is 2 mm. The depth of the sections is 250 mm. All specimens were cut into desired length and bundled up to transport to the structural laboratory of Universiti Teknologi Malaysia. Two lipped channel sections were placed back-to-back to form an I-section, with intermediate fasteners at 500 mm for beam sections of 1.5-meter length, and 1000 mm for column sections of 3-meter length. These beam and column are named as Double Channel sections, i.e. DC250.

Fasteners used in the study are non-preloaded bolts M12 Grade 8.8 with two washers. The bolt holes were standardized to 13 mm in prevention of abrupt deformation due to wide hole-spaces between the steel members [14]. The connections were formed by using 2 mm and 6 mm angles. The experimental test specimens are summarized in Table 1. Tensile test of steel-coupon cut from the specimens were tested and recorded [15] to validate that the actual yield strength of steel are satisfying the designed yield strength.

A total of six tests were carried out in the Magnus Frame as shown in Fig. 2. The out-of plane movement of the test specimens was restrained by bracing system. The load was applied using hydraulic jack and recorded by 100 kN load cell. Six displacement transducers (DT) namely DT1 to DT6, were placed at the beam and column members to record deformation. One inclinometer was placed at the centre of each column and beam sections, closed to the connection to record the rotation of the respected structural members. The data acquisition layout is given in Fig. 2. The data from load cell and LVDT were directly recorded into computer via data logger, while the reading from inclinometers was manually recorded by hand throughout the test program.

The loading was applied with an increment of 0.2 kN. By inspection, when it reached to an estimated 25% of the analytical designed load, the specimens were unloaded and then re-loaded after the reading was initialized to zero. This procedure was taken so as to enable the specimens set up in an equilibrium stage. The specimen was further loaded until there was a significantly large deflection of the beam observed. At this stage the increments of applied load was controlled by the deflection instead of the load. A deflection of 5 mm was adopted as a suitable increment of this stage. This procedure was continued until the specimen had reached its failure condition. The 'failure' condition was deemed to have been reached when any of the following situations mentioned below occurred:

i. An abrupt and significantly large reduction in the applied load being attained.

ii. An abrupt and significantly large increment in the deflection of the beam being attained with significant deformation of the connections.

iii. Excessive deflection of the beam, which is over 150 mm or reaching the DT's limit.

It is estimated that more than one failure modes may occurred before the joint reaching to its limit. Thus the failure mode was being carefully observed along the test program, so that the sequence of the failure modes is systematically recorded down and is to be compared to the obtained data.

Table 1. Details of laboratory specimens

Test No	**Size of beam and column**	**Size of web cleat[2]**	**Size of flange cleat[2]**	**No of Bolts[3]**
1	DC200[1] Depth, D= 250 mm Breadth, B= 77 mm Thickness, t = 2.0 mm Root radius, r = 2.5 mm	200×60×2-S350		6
2			100×60×2-S350	8
3		200×60×2-S350	100×60×2-S350	14
4		200×60×6-S275		6
5			100×60×6-S275	8
6		200×60×6-S275	100×60×6-S275	14

Note:
1. The dimension of beam and column are to manufacturer's specification. Design steel grade = 350 N/mm^2.
2. Flange cleat and web cleat size label: length × width × thickness – design strength.
3. All bolts M12 Grade 8.8 with two washers. Bolt size d_b = 12 mm; Diameter of bolt hole $d_h = d_b + 1$ mm = 13 mm.

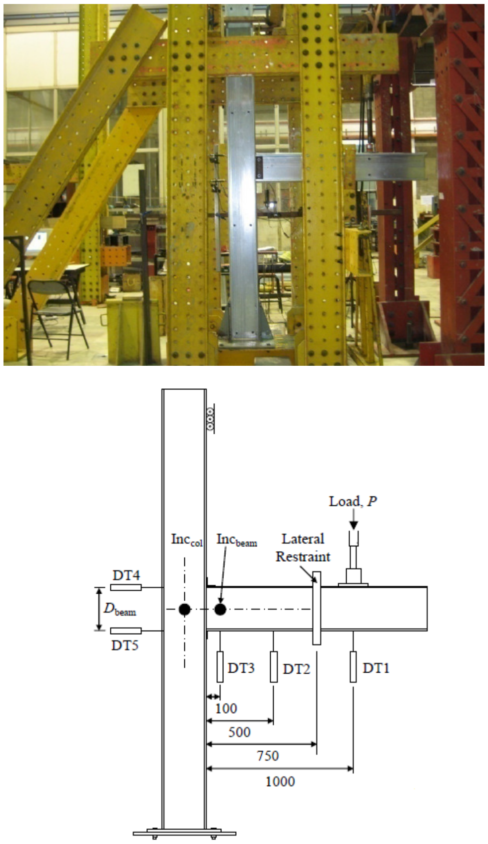


Fig. 2. Full-scale isolated joint test and data aquicition system

III. RESULTS AND DISCUSSION

All the isolated joint tests were conducted until failure, which occurred for a variety of reasons: yielding of angle-cleats, yielding of column flange around the bolts and bending of column flange. All tests were stopped due to excessive deflection of beam over 150 mm. The modes of failure are explained in detail, assisted by the pictures.

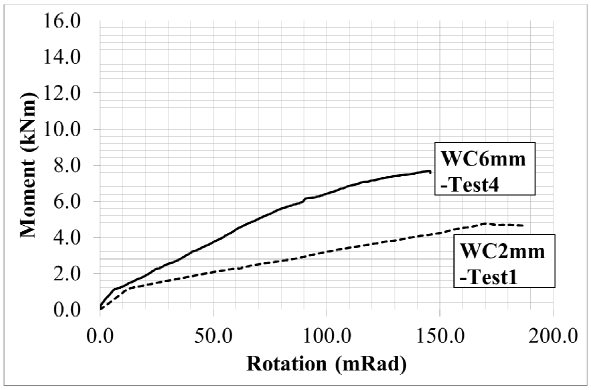
The 2 mm cold-formed bracket double angle web-cleats (WC) in test 1 serve as pin connection [4]. At early stage of the test progress, visible bending already occurred at the top part of the web-cleats. The web-cleats continue to tear-buckled widely. The bending of web-cleats caused large deflection to the connected beam. The test was stopped when DT1 record exceeded 150 mm. There was no visible defect on the bolts, beam and column section. For test 2, the top-seat flange-cleat (FC) started to tear out when the loading reached about 1 kN. When the top-flange yielded until the bolted part, it caused large deformation and reduced the strength. The bended flange-cleat started to pull the bolts at the column flange, caused a slight increment of load capacity, but did not reduce the deflection. The tests have to be stopped due to excessive deflection. Combined flange-web-cleat (FWC) in test 3 increased the stiffness and strength of the connection compared to WC and FC. The combination of top-flange and double web-cleats minimized the bending of these brackets, which lead to the reduction of deflection of beam. However when the flange-cleat developed large yielding, flange-cleat and web-cleats started to pull the flange of the column, caused a slight increment of load capacity.

The 6 mm web-cleats in test 4 were designed as pin connection as well. But these thick web-cleats were stiffer than the column flange, caused the column flange to bend. The web-cleats continued to pull the column flange while developing excessive deflection to the connected beam. The tests were stopped when deflection at DT1 recorded over 150 mm. The web-cleat was not buckled and had no visible defect. Top-seat flange-cleat (FC) in test 5 also pulled the relatively thin, 2 mm column flange and beam flange. Compared to cold-formed bracket, the top angle-cleat did not yield. The yielding happened at the connected flanges of beam and column. The FC connection developed large deformation, and failed when the bottom flange-cleat compressed the column flange and caused crushing of column. Combined flange-web-cleat (test 6) has resulted the highest strength and rotational stiffness as compared to test 1 to test 5. The stiff top flange-cleat and web-cleats pulled the column flange, while bottom flange-cleat pushed into the column flange, caused bending of the column flange. The critical failure mode was at compression zone of column flange. High concentrate force from the bottom flange of beam push at the column flange, until the column web part buckled. The buckling of column web marked the highest load applied, and loading started to decrease before the deflection at DT1 reached 150 mm.

Comparison on the effect of increasing the thickness of angle-cleats from 2 mm to 6 mm was done for three types of cleat connection, as depicted in Fig. 3. The quantify comparison is listed in Table 2. For comparison purpose, the moment of joints ($M_{J\text{-}50}$) is taken at the rotation of 50 mRad [12-13], and the stiffness ($S_{J,ini}$) are measured at the initial stage. It is observed that by increasing the angle-cleat size from 2 mm to 6 mm, the moment resistance would increase for in the range of 1.80 to 2.28. The ratio of difference for rotational stiffness increases in the range of 1.27 to 2.06.

Table 2. Strength and stiffness between 2 mm cleats and 6 mm bolted angle joints

No	**Connection type**	**Comparison of $M_{J\text{-}50}$ (kNm)**		
		2 mm cleat	**6 mm cleat**	**Ratio of Diff.**
1	WC (Test 4 to Test 1)	2.08	3.74	1.80
2	FC (Test 5 to Test 2)	2.53	5.78	2.28
3	FWC (Test 6 to Test 3)	4.30	7.92	1.84
		Comparison of $S_{J,ini}$ (kNm/rad)		
		2 mm cleat	**6 mm cleat**	**Ratio of Diff.**
4	WC (Test 4 to Test 1)	91	179	1.97
5	FC (Test 5 to Test 2)	153	195	1.27
6	FWC (Test 6 to Test 3)	186	383	2.06



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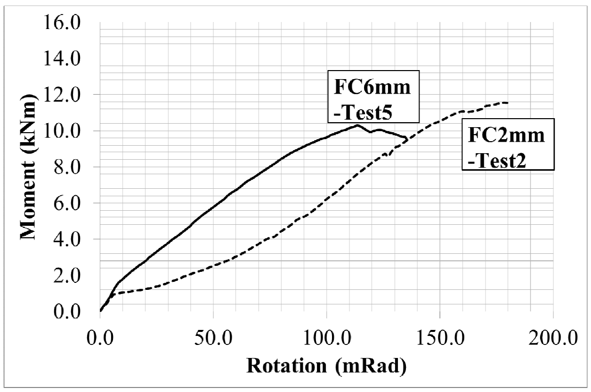

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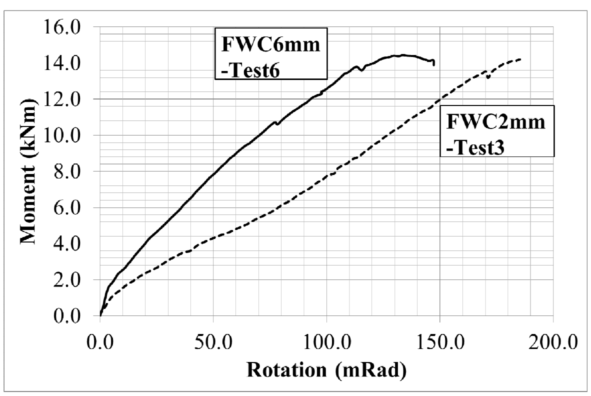

c)

Fig. 3. Moment rotation behavior of the tested joints

IV. CONCLUSION

Laboratory investigations on full-scaled isolated joint with three bolted angle configurations have been successfully carried out. All specimens were failed due to loss of joint strength and stiffness, leading to excessive deflection of beam. By increasing the angle-cleat size from 2 mm to 6 mm, the moment resistance would increase for in the range of 1.80 to 2.28. The ratio of difference for rotational stiffness increases in the range of 1.27 to 2.06. This work is limited by the number of test and joint configurations. It is recommended that numerical investigation can be carried out to study the joints behavior of wider range of bolted angle joints for cold-formed steel frames.

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