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Behaviour of bolted apex connector in single-channel cold-formed steel portal frames- An experimental study

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Abstract

The present study is conducted to quantify the ultimate moment capacity and understand the behaviour of apex connector for single-channel Cold-Formed Steel rafters. The behaviour of apex connector is studied by varying the parameters such as thickness of connector (1.0 mm, 2.0 mm and 3.0 mm) and gauge of bolts (50 mm and 150 mm) and performing four-point bending tests on a total of 12 specimens. The results indicate that ultimate moment capacity is significantly affected by increasing the connector thickness compared to the gauge distance. Further, vertical bending and lateral bending of top flanges of apex connector are observed as the prominent failure modes for a gauge distance of 150 mm and 50 mm respectively along with an excessive deformation in the connector web. A generic load transfer mechanism of proposed apex connection is discussed.

1. Introduction

Cold-Formed Steel (CFS) portal frames are gaining popularity due to their versatility in providing high strength-to-weight ratio, ease of fabrication and installation compared to Pre-Engineered Building systems (PEBs). However, the design of joints for CFS portal frames is not straightforward. It is primarily due to influence of semi-rigid behaviour of the CFS connections on load carrying capacity of portal frame (Rinchen 2019). Although a significant amount of research is conducted on connectors like clip angles, combination of clip angle and flange cleat (Natesan 2019a, 2020, 2021, Mallepogu 2022, 2023a, 2023b), C- and L- shaped sleeves (Natesan 2019b, 2020) for beam-to-column and beam-to-beam joints, a few literatures is available on the apex joints in CFS portal frames. The previous studies on apex connection are focused on determining moment-rotation and load-displacement characteristics for industry specific apex connection types. However, the studies are not conducted either to provide a standard apex connector shape or behaviour of apex connection. Premature failure of members is observed due to an excessive bearing (Dundu 2006) by adopting a direct connection between the rafters. Hence, the present study adopts an additional connector between rafters for the apex joint. Mills and Laboube (2004) used a channel as apex connector screwed to rafters for single-channel CFS rafters. However, the

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failure of proposed connection type is governed by shear failure of screws due to higher shear strength of member compared to screws. Hence, it is not suitable to use screws for structural connections.

Component study conducted by Lim (2002) have observed a premature failure of apex CFS bracket for back-to-back bolted built-up CFS rafters. The main reason is selection of an apex bracket which provides a simple lip by cold bending the top edges of connector web on either side of apex point resulting in a discontinuity at apex point. This highlights the significance of the shape of apex connector. Recently, a study was conducted by Rinchen (2018, 2019, 2020) on three types of apex connection configurations for single channel CFS rafters. All the apex connections tested in the study are formed by bolting connector to rafters through web, top flanges and bottom lip. The study focused on determining the load carrying capacity of apex connection by changing different types of fasteners like tek screws, M8 bolts at bottom lip connection. The study has reported failure modes such as shear failure of screws or inelastic buckling of CFS rafters which are governed by the specimen configuration. Hence, the existing literature does not provide a standard apex connection type. Further, it does not give a generic understanding of the design of apex joint for single channel CFS portal frames due to lack of awareness about failure modes of apex connection.

2. Experimental Program

2.1 Material properties

The material properties of CFS connector are obtained based on tensile testing. The average material properties are obtained based on three coupons which are cut using the Electrical Discharge Machining (EDM) technique from CFS sheets with dimensions conformed to ASTM/E8M-13a, Huang and Young (2014). The coupon samples were tested under a displacement control rate of 0.5 mm/min in a Universal Testing Machine of 30kN capacity.

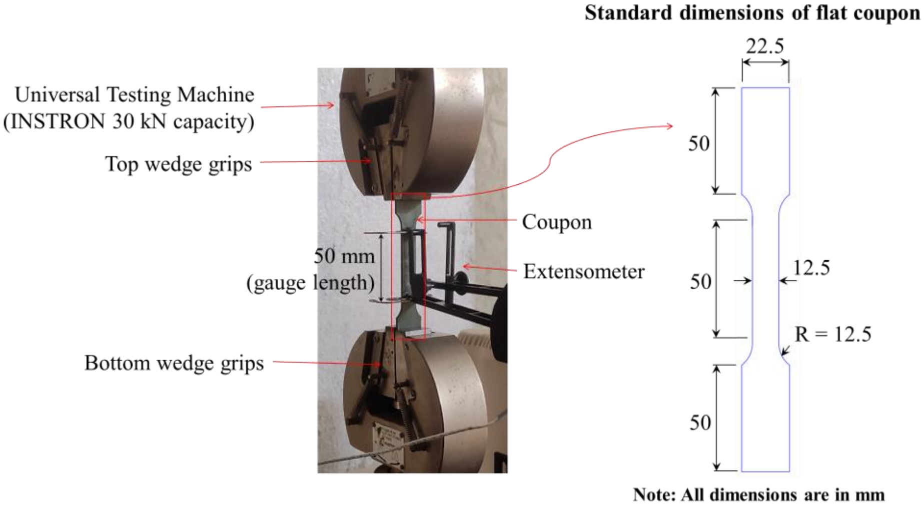

Figure 1: Details of coupon test

2.2 Geometry of proposed apex connection

This study proposes the use of an additional CFS apex connector instead of direct connection between rafters avoiding premature failure of rafters. The proposed apex connector is fabricated from a single CFS sheet by marking and bending along the fold lines in the development length as shown in Fig.2. The discontinuity between the flanges is strengthened using an additional CFS cover plate screwed to connector avoiding premature failure of connector. The apex connection is provided on the top flange and web to primarily resist the in-plane moment. In addition, the rafter and connector are connected through top flange and bottom lip to prevent the opening of the apex connector. A 2 x 2 bolt group configuration is adopted for the web connection in all the tests. Further, three types of thickness (1 mm, 2 mm, 3 mm) and two types of gauge distance, G (50 mm and 150 mm) are adopted to investigate the behaviour of the proposed apex connector under different magnitudes of moments in apex connection.

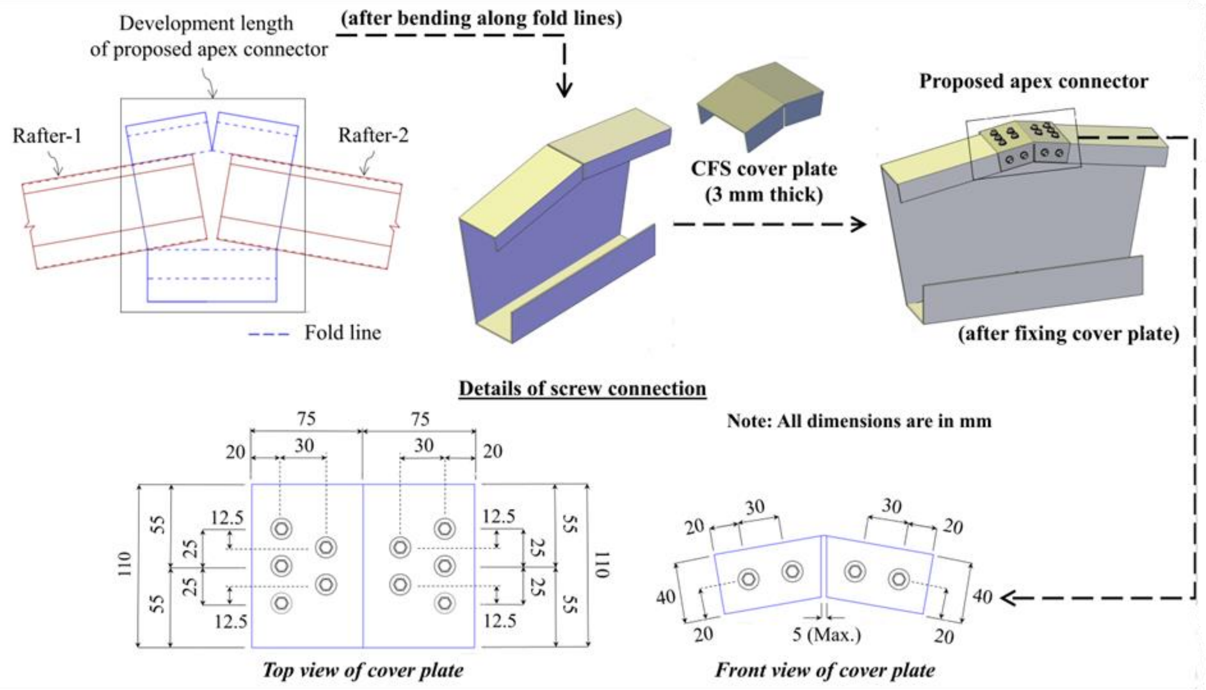

Figure 2: Details of Proposed apex connector

2.2.1 *Specimen labelling*

A total of 12 specimens are fabricated and tested by varying thickness of CFS connector and gauge of bolts. The labelling scheme adopted in this study is **TX_GY_NZ** where **TX** represents apex connector with a thickness of ‘X’, **GY** represents bolt group with a gauge length of ‘Y’ and **NZ** represents Z^{th} trial of specimen.

2.2.2 *Specimen fabrication*

The apex connection investigated in this study is formed by bolting the proposed CFS apex connector to the ends of HRS rafter. 10 mm thick Hot-Rolled Steel (HRS) rafters are adopted in this study to determine the actual connection capacity and its performance. Since, the apex connection is expected to transfer moment at apex joint through web and flanges, 10.9 grade bolts of 16 mm diameter were used for web bolts and flange bolts. However, the contribution of bottom lip bolts is unknown. Hence, 4.6 grade bolts of 12 mm diameter were used for bottom lip connection for all the specimens. This enables us to understand the contribution of bottom lip bolts in the load transfer at the apex joint.

2.2.3 *Experimental setup*

The proposed apex connection is tested under four-point bending with simple supported boundary conditions as shown in Fig.3. The test setup consisted of loading rollers and roller supports fitted with lateral restraint fixtures to prevent out-of-plane movements near the loading and support locations. A loading rate of 0.5 mm/min under displacement control method in a servo-hydraulic controlled actuator of 250 kN capacity is used.

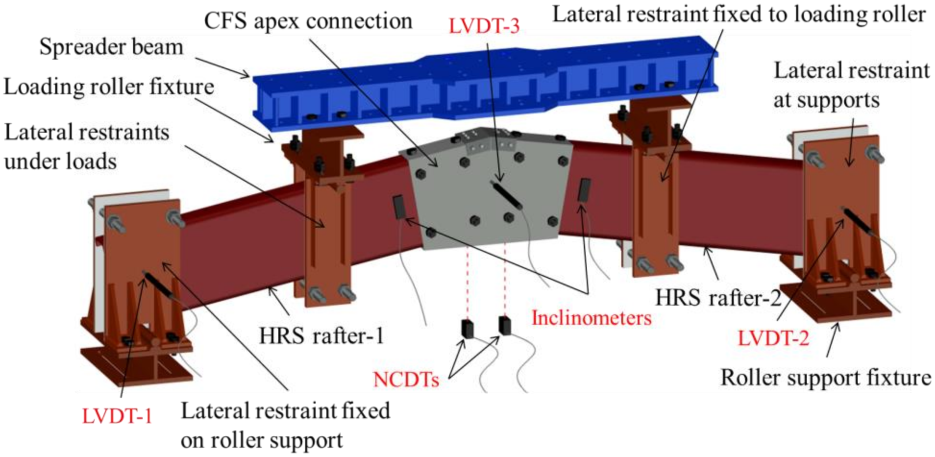

Figure 3: Test setup for proposed apex connection

3. Results and Discussion

The outcomes of the experimental investigation are tabulated in Table 1. The various failure modes from this investigation include (i) bending of top flange of connector, (ii) out-of-plane deformation in web of connector, (iii) inelastic buckling at the web-flange junction, (iv) shear failure of bolt and (v) shear failure of screws is observed by varying the thickness of connector and gauge of bolts.

Table 1: Experimental test results

Specimen	Ultimate moment capacity (kN-m)	Apex vertical displacement (mm)	Failure mode
T1_G50_N1	6.33	19.65	BF
T1_G50_N2	5.24	43.04	BF
T1_G150_N1	8.64	20.62	IB
T1_G150_N2	6.31	14.00	IB
T2_G50_N1	18.49	83.02	BF+SS
T2_G50_N2	16.99	59.49	BF+SS
T2_G150_N1	19.49	73.14	SS+BS
T2_G150_N2	19.53	66.65	SS+BS
T3_G50_N1	22.25	61.34	BF+SS
T3_G50_N2	21.17	80.03	BF+SS
T3_G150_N1	25.79	94.54	SS+BS
T3_G150_N2	24.69	84.15	SS+BS

Note: BF – Bolt Failure, IB – Inelastic buckling, SS – Screw shear, BS – Bolt shear

3.1 Ultimate moment versus thickness and gauge

A percentage increase of 174.2 % and 235.5 % is observed by changing thickness of connector from 1 mm to 2 mm and 1 mm to 3 mm respectively for a gauge of 50 mm. Similarly, a percentage increase of 171.8 % and 237.4 % is observed by changing thickness of connector from 1 mm to 2 mm and 1 mm to 3 mm respectively for a gauge of 150 mm. However, the percentage increase in ultimate moment capacity is reduced to 22.4 % and 24.1 % by increasing thickness of connector from 2 mm to 3 mm for gauge of 50 mm and 150 mm respectively. This increase can be considered as a result of a significant decrease in web slenderness of connector (i.e.; ratio of web depth of connector at apex point to thickness of connector) by increasing the thickness from 1 mm to 2 mm and 1 mm to 3 mm compared to 2 mm to 3 mm. However, shear failure of screws in cover plate is observed in this study by increasing the thickness of connector. This may be because of an increase in bending stiffness of top flange of connector as result of increase in thickness, thereby, resulting in the increase of relative movement between connector and cover plate. However, screw failure has not governed the ultimate load capacity in any of the specimens.

3.2 Ultimate moment versus thickness and gauge

Figure 4 shows an increase in ultimate moment capacity with an increase in thickness of apex connector with a relatively lesser increase with an increase in gauge of bolts. A stiffer response is observed for apex connection with 50 mm gauge compared to 150 mm upon increasing the connector thickness.

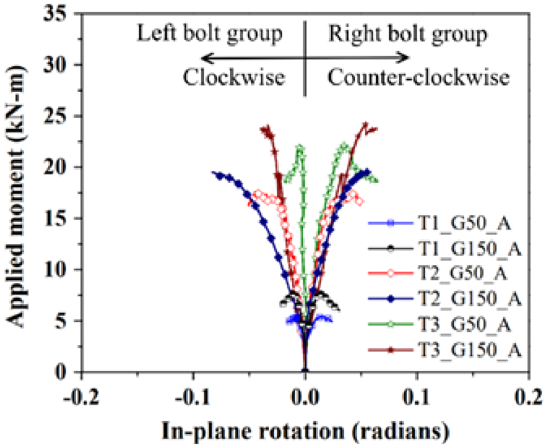

Figure 4: Moment-rotation plot of proposed apex connection

3.3 Behavior of proposed apex connection

Although an in-plane bending moment is applied to the apex connection, a combination of vertical and lateral bending deformations is observed in the proposed apex connector. From the parametric study, it is observed that the proportion of these vertical and lateral bending deformations depends on gauge distance while ultimate moment capacity depends on both connector thickness and gauge distance. Furthermore, the lateral bending of top flange is predominant for a gauge 50 mm while vertical bending is predominant for a gauge of 150 mm. In addition to bolt-hole elongation, the vertical bending is observed in the form of inelastic buckling of web-flange junction for 1 mm thick connector and shear failure of bolt between bottom stiffener of rafter and connector for 2 mm and 3 mm thick connectors. The shear failure of bolts is analogous to shear failure of screws observed in the previous study by Rinchen and Rasmussen (2018, 2019, 2020) which indicates that 4.6 grade of bolts are insufficient for 2 mm and 3 mm thick apex connectors. Since the ultimate moment capacity is governed by shear failure of screws but not premature failure of apex connector, the aforementioned method may be adopted to circumvent the problem. Hence, for the bolt grade and diameter, it can be observed that the moment resistance is majorly offered by lateral bending of top flange of connector for 50 mm gauge and by major axis bending of cross-section for 150 mm gauge.

4. Conclusions

Based on the outcomes of experiments, the following conclusions can be drawn:

a) The ultimate moment capacity of proposed apex connection is dependent upon thickness of connector and gauge distance. Further, it can be observed to significantly increase with an increase in connector thickness compared to gauge distance.
b) Combined vertical and lateral bending are evident from experimental investigation of proposed apex connection.
c) The failure load of specimens with a gauge of 50 mm is primarily dependent on lateral bending of top flange of connector while it is primarily dependent on vertical bending associated with shear failure of bolts in bottom-lip and bolt-hole elongation when gauge is 150 mm.

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