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Experimental Investigation of Tensile Test on Connection of Cold-formed Cut-curved Steel Section

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Abstract. Cold-formed steel (CFS) is widely used as structural and non-structural components such as roof trusses and purlin. A CFS channel section with double intermediate web stiffener and lipped is chosen based on the broader usage in roof truss construction. CFS section is cut to form cold-formed pre-cut-curved steel section and lastly strengthened by several types of method or likely known as connection to establish the cold-formed cut-curved steel (CFCCS) section. CFCCS is proposed to be used as a top chord section in the roof truss system. The CFCCS is to resist the buckling phenomena of the roof truss structure and reduced the compression effect on the top chord. The tensile test connection of CFCCS section, especially at the flange element with eight types of connection by welding, plate with self-drilling screw and combination is investigated. The flange element is the weakest part that must be solved first other than the web element because they are being cut totally, 100% of their length for curving process. The testing is done using a universal testing machine for a tensile load. From the experiment, specimen with full welding has shown as a good result with an ultimate load of 13.37 kN and reported having 35.41% when compared with normal specimen without any of connection methods. Furthermore, the experimental result is distinguished by using Eurocode 3. The failure of a full welding specimen is due to breaking at the welding location. Additionally, all specimens with either full weld or spot weld or combination failed due to breaking on weld connection, but specimen with flange plate and self-drilling screw failed due to tilting and bearing. Finally, the full welding specimen is chosen as a good connection to perform the strengthening method of CFCCS section.

1. Introduction

Cold-formed steel (CFS) sections become popular and broadly utilised as structural components and also non-structural component, particularly in civil and mechanical engineering areas. There are two major types of CFS products, structural shapes and panels with varieties of shapes produced such as open, closed and built-up sections. Examples of CFS sections are channel, zee, double channel built-up, I beams, hat sections with and without intermediate stiffeners, U sections and many others. The manufacturing process of CFS section involves forming by press-braking or cold-roll forming to attain the required shape and generally produced from steel plate, strip or sheet. CFS sections are normally thinner than hot-rolled steel (HRS) sections and created from different process as mentioned before. The HRS sections are manufactured at elevated temperatures while the CFS sections are produced at room temperature. Consequently the buckling, failure and material behaviour can be relatively different. In addition, lower total energy is required due to the thermal energy to heat the material. CFS section properties are also affected by temperatures as well as yield strength decreases when the working temperature is raised. As CFS sections are thinner than HRS sections, the unit weight of CFS section is much smaller compared to the HRS section. When the unit weight is high, it will increase the cost of the material, equipment of lifting and also transportation. A CFS section with low weight also influences to the deduction of the construction period and leads to quick installation in construction activity. The CFS also can be cut and erected with very light machine. The use of CFS also eliminates the formwork and curing time of concrete. The construction speed becomes fast because it reduces the delays due to weather.

In building construction, CFS can serve as the roof substructure in the appearance of roof trusses or purlins. Shape of Z and channel section of roof purlins is usually utilised to support the roof structure to become stable and another role is to transfer the wind load to the primary structure. CFS truss offers the same capability of the span and flexibility of design when compared with timber trusses, far lighter and dimensionally stable. Furthermore, the lightweight CFS roof truss allows for ease of handling and transporting to the construction site in larger capacities. The CFS roof truss is also simple, easy and fast to erect because they no need of cutting or drilling work on-site, just need a fastener such as bolts or screw for jointing the truss member. So, it is greatly reduced labour costs, material, and the project duration. CFS is also non-combustible material and it has lower costs of fire protection. Variety of connection and jointing method such as bolting, welding, riveting and screwing that are recognised in CFS sections and roof truss system.

CFS connection is one of the most crucial problems and most frequent failures in the structure. Normally, the connection fails first in cases where there is an unpredicted or unexpected force on the structures. The ultimate load carrying capacity of a CFS connection was controlled or dominated by one of the many possible modes of failure such as bearing, tilting, end pull-out, bolt shear, net section fracture, block shear rupture and etc. Lee et al [1] have discussed that the connection is the one of the imperative elements for CFS to facilitate achievement its structural stability and performance. Anwar et al [2] have reported that the CFS connection normally utilise broadly self-drilling screw as a fastener because ease of installation and offer a rapid joint. Neto et al [3] have studied and reported the stiffness and flexural strength behaviour of CFS purlins with sleeved and overlapped bolted connection testing. The lateral forces are introduced after the member is prone to distortional buckling and proven to reduce in strength of the purlin arrangement [3].

Cai and Young [4] has conducted a series of shear tests on a CFS stainless steel single and double bolted connections. The CFS stainless steel is jointed with a different bolt diameter and arrangement of connection. The single shear connection specimen is joined by bolts with two plates together, classified as one shear plane, whereas the double shear connection specimen is joined by bolts with three plates together, recognised as two shear planes as shown in figure 1. From the observation of CFS stainless steel connection tests, the bearing failure and the combination failure by bearing and net section tension of the bolted connection are studied and analysed in-depth. The nominal strengths of CFS stainless steel from the experiment are determined and verified by using the American Specification, European codes and Australian Standard.

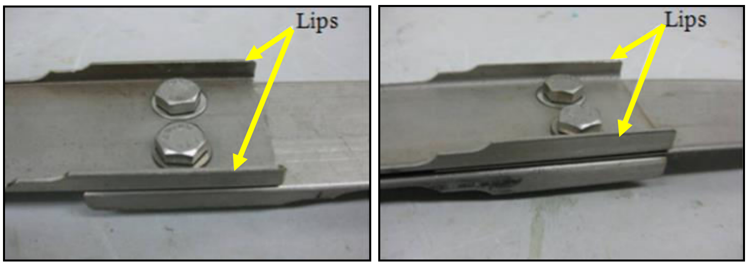


Figure 1. Example of test specimen of CFS stainless steel bolted connection (a) Single shear and (b) double shear [4]

Talja and Torkar [5] have continued their efforts to carry out experimental studies on bolted and screwed connections with a variety of configurations in order to establish a design guideline for ferritic stainless steels in BS EN 1993-1-4. Normally, the bolted connections are covered a single and double shear testing through a material thickness and bolt diameter of 0.8-4.5 mm and 12 mm, respectively. While, the screwed connection is deal with the self-drilling stainless steel screws with a diameter of 5.5 mm and class of corrosion, A2. Lastly, the failure mode due to bearing, block tearing and net section is reported. Stefan et al [6] have investigated the shear test of spot weld for utilising in the built-up CFS beam specimen and verified by Eurocode 3 [7].

Teh and Uz [8] have studied on block shear failure planes by using bolted connections. Five specimens are joined through the webs with wide flange sections and another ten specimens are situated in one leg of an angle section by using bolt connection. In the other case, Nguyen et al [9] have studied the shear connections between Fiber-Reinforced Polymer I-shape girder and Ultra-High Performance Fiber-Reinforced Concrete slabs, and also the effect of the arrangement of bolt connector. Fourteen of push-out tests are carried out to assess the load-slip performance and also the ultimate resistance of the bolt [9]. Additionally, Wang and Wang [10] have studied the design procedure of self tapping screw as a connector that jointed the steel plate and non-steel plate with verifying by Chinese Technical CFS code. Recently, Ye et al [11] have carried out a test on monotonic and cyclic loading on different sheathing-to-stud connections with four different types of sheathing. From the observation and testing, the failure modes shape and load-deformation graph of the connections are observed and determined. As conclusion, there are several factors that must be considered in the testing and design such as screw diameter, edge distance, stud thickness, and sheathing material and orientation. Yang and Liu [12] have reported the natural characteristic of the sleeve connection is affected by the structural behaviour of the overall purlin system. The failure modes of the sleeve connections are observed and recognised as the local buckling near the web purlin system, tension fracture and the local buckling on the compression section of flange element. Liu et al [13] has noted the sleeve connection is a popular ways to join a roof construction of purlin with the shape of sigma because of their advantages for instance ease of installation and sufficient structural efficiency. Yu and Panyanouvong [14] have stated that the CFS is normally assembled for trusses, racking and scaffolding systems by using bolt connection. Based on the experimental work, the conclusion of the study is represented with a new bearing factor and modification factor for the truss connections.

There is a lot of the innovative connectors or fastener that used in CFS structure such as Howick Rivet Connector (HRC) [15] [16], self-piercing rivet, Rosette tube joint. Normally, HRC is initiated to cater the low proportionality limit problem due to tilting, slipping or bearing and also restricted post peak strength [15]. In the study, Ahmadi et al [15] have mentioned a minimum end distance of HRC of 1.5 times the HRC diameter is adequate to avoid the failure. From the study of literature review, it does not provide a fully or partially preparation or prefabrication procedure of the connection of cold-formed cut-curved steel section (CFCCS) for roof truss construction. Besides, there is no relevance and appropriate codes or standard with sufficient design information for establishing the CFCCS. So, previous study of screw, sleeve and weld connections are referred and selected in forming the CFCCS as a top chord section in the roof truss system.

The objective of the study is to determine the ultimate load of connection test by a tensile load for CFCCS section. CFCCS section is established as an innovative top chord in a roof truss system which could be a buckling resistance. Besides, the experimental program is utilised to observe the failure behaviour of the flange element of the CFCCS. This is because the flange element of the CFCCS is the critical part that normally failed first due to buckling compared with another element. Lastly, an excellent connection with higher ultimate loads and appropriate in the strengthening of a flange element of CFCCS is selected.

2. Preparation and experimental method

Cold-formed steel (CFS) channel section with lipped and double intermediate web stiffener was selected in the experimental program. The cross-section, dimension and section properties of the CFS channel section are shown in figure 2 and table 1. Generally, this CFS section was used in the roof truss construction. The CFS channel section was cut from the bottom flange until upper intermediate web stiffener for proposing the pre-cut-curved section. The cut breadth, depth and spacing were noted and approximately 3 mm, 60 mm and 100 mm, respectively. After CFS channel section was cut, the section was curved by using bender tool and strengthened by using several of method. The method chosen depends on factors such as ease to erection and easy to find equipment to form CFCCS section. Strengthening method in the study is prepared along the cut section, especially at flange and web element. The fully strengthen method of curved section is located on the flange element that situated at the bottom of the curved section. Thus, the flange element with strengthening method is the important location of the connection of the curved section when compared to the web element. The web element has only cut about 80% of the total length, but the flange element is cut for overall length.

Figure 3 (a) illustrated the schematic diagram of a dimension of flange element section for connection testing. Two types of connection have been introduced in the study, plate with self-drilling screw and welding. The plate used for a CFS channel section taken from flange until lipped element is shown in figure 3 (b). A method of strengthening with description as connector is tabulated in table 2. The tensile test was carried out utilising the Universal Testing Machine with 100 kN capacity and pace rate of 1 mm/min. The ultimate load of tensile test and failure mode of the experiments was observed and compared with the predicted design by using [16].

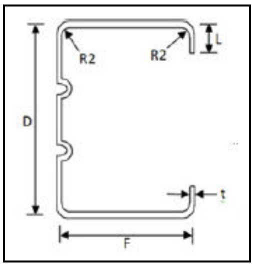
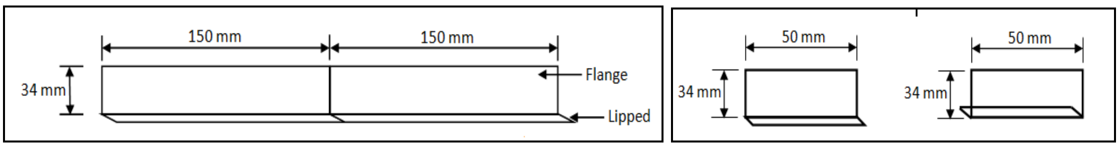


Figure 2. The cross-section and dimension of cold-formed steel channel section

Table 1. The section properties of cold-formed steel channel section

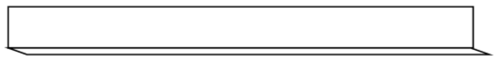
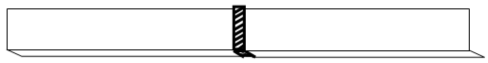
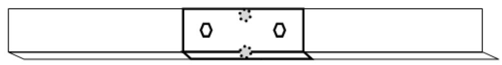
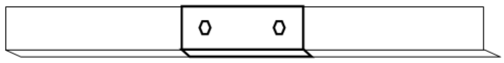
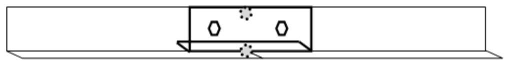
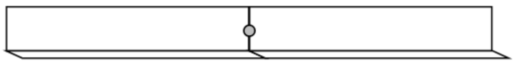
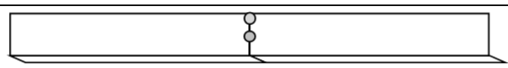
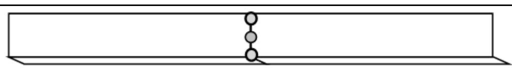
Web, D (mm)	Flange, F (mm)	Lipped, L (mm)	Thickness, t (mm)	Area, A (mm^2)	Yield Strength, γs (MPa)	Dimensional Ratio			
						D/t	F/t	D/F	L/t
75.00	34.00	8.00	1.00	148.00	550.00	75.0	34.0	2.21	8.0



(a) (b)

Figure 3. Schematic diagram and dimension of (a) flange element and (b) cold-formed steel plate for lipped down and up section

Table 2. Specimen label and method of connection of cold-formed cut-curved steel section

Specimen Label	Method of Connection	Arrangement of Connection
NSSC	Normal Section without connection	
FWSC	Full welding	
LDWSC	Lipped down two spots weld (flange & lipped corner)	
LDSC	Lipped down without spot weld	
LUWSC	Lipped up with two spots weld (flange & lipped corner)	
LUSC	Lipped up without spot weld	
SW1SC	One spot weld (mid)	
SW2SC	Two spots weld (mid + flange corner)	
SW3SC	Three spots weld (mid + flange corner + lipped corner)	

3. Result and discussion

Table 2 is the tabulated data and result of the tensile test of connection for CFCCS section. From the experiment, the method of full welding is estimated to be the highest ultimate load when compared with other methods. The percentage difference between the normal section and full welding is about 35.41%. The methods with spot weld or add spot weld in the method of connection the CFCCS section influenced the result of ultimate load. The number of spot welds with the appropriate location gave the higher result of ultimate load and 53.28% when compared with normal section. Whilst as, the percentage difference between the number of spot weld and normal section is reduced by reducing the number of spot weld roughly 82.94% and 85.46% for two and one number of spot weld, respectively. Furthermore, the percentage of ultimate load has increased roughly 27.67% when three numbers of spots weld are extended to become full weld. The percentage difference of 14.87% and 68.88% is recorded when compared one spot weld with two spots weld and three spots weld, respectively. With added spot weld at the corner of the flange, the ultimate load of the section became more stiffen. Additionally, when another spot weld is added at the other end of the section is reported to have about 63.45% when compared with two spot weld. Three spots weld placed on the middle and both ends of the section gave the section more stable and strong. The percentage difference between the full welding and section with consist three spot weld is noted more or less 27.67%. Finally, the flange with full welding used in strengthening the CFCCS section was found to be the best solution to joint up the one part of the cut section with another part of cut section.

Lipped down and lipped up connection sample is classified that the position of the flange plate with lipped facing upward or downward on the flange element as shown in table 2. Lipped down means the flange plate with lipped is placed to link up to origin section and established double of lipped. Whereas, lipped up flange plate is located in the upper side and facing upward or opposite direction of a flange element that as shown in table 2. From the result, the position or location of flange element plate has obtained the appropriate of the ultimate load value was noted and to have a 19.27% and 6.69% of the percentage difference between lipped down and lipped up with or without spot weld, respectively. The percentage difference between the lipped down and lipped up with two spots weld method is about 12.72% and 29.47% is recorded when compared with three spots weld without any flange element plate. Subsequently, the flange element plate with self drilling screw at the middle of flange element section can't be compared and matched directly with spot weld at the middle of a flange element section. In addition, the flange plate weather placed in downward or upward of lipped position brought a reasonable value of ultimate load. This can be proven by the percentage of difference between the sections with plate and without plate is reported having about 58.14% for lipped down and 48.15% for lipped up. Lastly, with the two numbers of spots weld on flange element and added with flange plate can't be distributed or gave the higher of the ultimate load for the cut-curved section. Three number of spot weld with located on the corner of the flange element provided the stability and stiffened by spot weld at the middle part of the section.

Table 3. Data and result of the ultimate load of tensile test of the CFCCS section

Specimen	Ultimate Load by experiment (kN)	Ultimate Load by Eurocode 3 [17] (kN)	P_{exp}/P_{euro3}	Failure Mode
NSSC	20.70	18.48	1.12	Break at middle of the section
FWSC	13.37	34.54	0.39	Break at the weld
LDWSC	8.44	5.88	1.43	Bearing and tilting failure & break at the both spots weld
LDSC	5.12	3.85	1.32	Tilting failure
LUWSC	6.82	5.88	1.15	Bearing and tilting failure & break at the both spots weld
LUSC	4.78	3.85	1.24	Tilting failure
SW1SC	3.01	1.02	2.96	Break at the weld
SW2SC	3.53	2.03	1.74	Break at the weld
SW3SC	9.67	3.05	3.17	Break at the weld

The ultimate load of the experiment is compared with the predicted value by using Eurocode 3 [17] and is tabulated in table 3. There is significant result and showed the lowest and the highest ratio of the experiment and Eurocode 3 [17] recorded in normal section and one number spot weld, respectively. This is because the method with one spot weld proposes the fluctuation and non-uniform distribution of load on beginning. The failure mode shape of the all method is also tabulated in the table 3.

The failure of the specimen is observed and reviewed. The welding connection either by full welds or spot weld failed due to breaking on the weld part. However, the connection method by a flange element plate with self-drilling screw failed due to tilting of self-drilling screw and bearing failure on the CFCCS surface. This proved that the flange element plate with the self-drilling screw is easier to fail due to bearing and tilting of the self-drilling screw which fail first when compared with connection method by spot weld. Whereas figure 4 (a) and figure 4 (b) are illustrated the failure of the spot weld for specimen LDWSC and SW1SC, respectively. Rounded circle on the figure presented the location of the failure in the specimen. In addition, figure 5 is shown the failure of spot weld for SW3SC specimen on front and back view. The failure of the connection between the plates added with two self-drilling screw as LUWSC specimen is represented in figure 6. From the observation, the failure of the self-drilling screw and plate occurred due to bearing and tilting.

(a) (b)

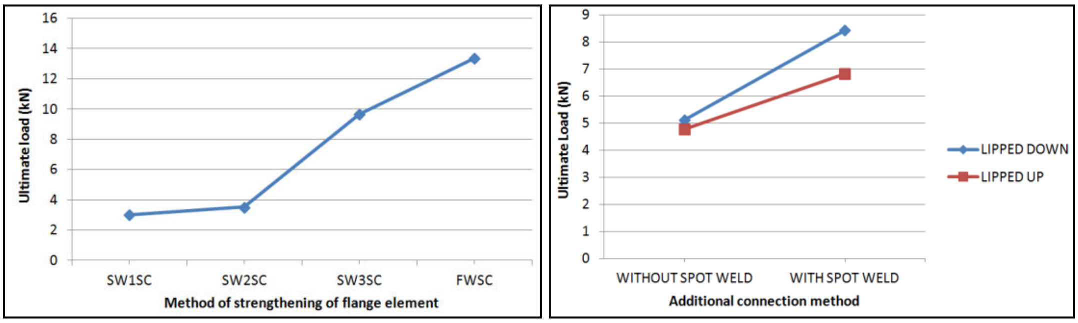
Figure 4. Example of the failure on spot weld for (a) LDWSC and (b) SW1SC specimen

(a) (b)

Figure 5. The failure on spot weld for SW3SC specimen (a) front view and (b) back view

Figure 6. The failure of the self-drilling screw of LUWSC specimen

From the result of the experiment, the relationship of the tensile connection test and strengthening method is established. The ultimate load of specimen versus the method of strengthening of flange element graph is shown figure 7 (a). The one spot weld specimen and two spots weld specimen presented the lowest of ultimate load dramatically when compared with three spots weld and full weld. Therefore, the location of the spot weld is more critical and must be studied properly. The spot weld at the middle of the specimen is not affected by the ultimate load of the specimen and added a spot weld at the corner of the flange. The location of spot weld at the corner of the flange made the specimen become not stable and tended to fail at the other free side or at another corner than without spot weld. With three spot weld placed on the middle of the specimen and at both ends of the specimens generally provided the stability condition and stiffeners to resist the applied load. Even as, the arrangement of the flange plate either in lipped down or up that partially react as a connector is reviewed detail in the figure 7 (b). Graph line of lipped down produced more stiffeners and stronger when compared with the lipped up specimen. This is because the lipped down specimen with the additional of lipped element formed a double resistance load on the location of lipped. So, the specimens are stronger and stiffen when compared with the lipped up specimen. The arrangement of the plate with lipped situated to upper side doesn't provide a stiff to the specimen and resistance to applied load. Specimen with additional spot weld is obtained the higher value of ultimate load when compared without additional spot weld.



(a) (b)

Figure 7. The relationship graph of ultimate load with (a) method of strengthening of flange element (b) arrangement of lipped for without and with spot weld

4. Conclusion

From the study, the experimental investigations have found one comprehensive guide to the discovery the appropriate method for the connection of CFCCS section and also known as a method of strengthening the cut-curved section. With several methods of connection and production process, FWSC is revealed and selected as a good practice in strengthening the CFCCS section on flange element. FWSC with deduction of 35% of ultimate load of a normal specimen without connection is determined. Although, the percentage difference between the sample of the connection by spot weld either one or until three spots weld with normal specimen is reported to have a range of 53%-82%. Additionally, the three spots weld recorded a higher ultimate load and obtained 27.67% when compared with full welding specimen. From experimental observation, the full welding and spot weld failed due to the breaking of the connection and specimen with flange plate and self-drilling screw failed due to bearing and tilting.

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