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Impact of Shear Connector Spacing in Composite Construction Incorporating Cold-Formed Steel Channel Lipped Section

Anis Saggaff[1] --- Mustapha Muhammad Lawan[2] --- Mahmood Md. Tahir[3] --- Jahangir Mirza[4]

[1]Civil Engineering Department, Faculty of Engineering, Sriwijaya University, Indonesia
[2,3,4]UTM Construction Research Centre, Institute for Smart Infrastructure and Innovative Construction, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia

Abstract

Composite construction with traditional Hot Rolled Steel (HRS) sections has been known to perform much better than with Cold-Formed Steel (CFS) sections for decades; as observed by extensive rules and requirements for their design as prescribed in current design codes. There is, however, limited technical information available about the use of composite systems that incorporates the use of light gauge steel sections, despite the potentials of the system in residential and light industrial constructions. However, the composite action of CFS with an in-situ concrete, especially Self-Compacting Concrete (SCC) using bolted shear connector has not yet established. Therefore, this study attempted to investigate the behaviour of bolted shear connector used with SCC and CFS to form a composite beam system at designated longitudinal spacing. Push-out and full-scale test specimens of longitudinal spacing of 250 mm and 300 mm with bolted shear connector of grade 8.8 installed with single nut and washer on the CFS flange and beneath it were fabricated, cast and tested till failure occurred. The experimental test results shows that the bolted shear connector possessed good ultimate strength and ultimate moment capacities with an increase in the longitudinal spacing of the bolted shear connector from 250 mm and to 300 mm respectively. It was therefore concluded that, longitudinal spacing between bolted shear connectors had significantly influenced the shear connector strength capacities.

Keywords: Cold-formed steel, Composite construction, Bolted shear connector, Push-out test, Longitudinal spacing.

1. Introduction

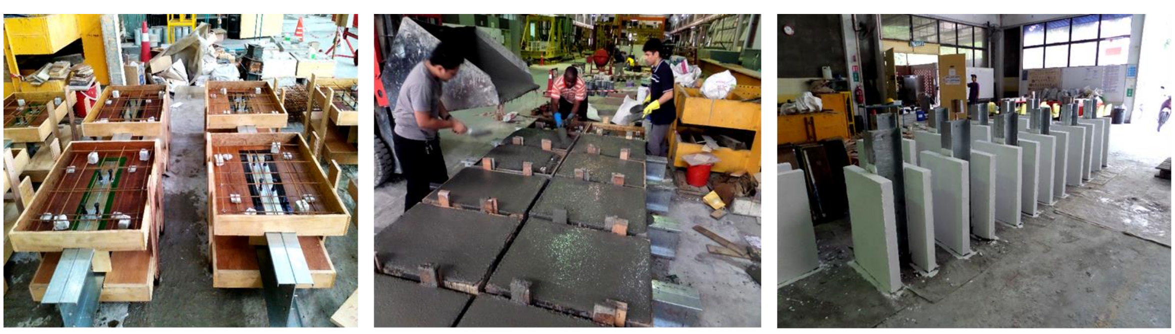
Construction practices and philosophies in the present time have become more enormous in which players in the construction industries played an important role (Keyvanfar *et al.*, 2014). In construction, the main constituents' materials are concrete and steel. Corrosion in steel could be resisted by using corrosion inhibitors (Asipita *et al.*, 2014). Corrosion in the reinforcing steel could cause concrete to crack, leading to crushing of the whole concrete mass in the structure (Ismail *et al.*, 2010; Noruzman *et al.*, 2012). Therefore, to prevent the cracking in concrete structures, self-healing agents are incorporated in the mixing of concrete prior to its application in the construction process (Talaiekhozani *et al.*, 2014). But, in light-weight composite construction the Cold-Formed Steel (CFS) section used is prevented from corrosion by coating. CFS sections are lightweight materials that are produced by bending of a flat steel sheet at a room temperature (Hancock *et al.*, 2001) into a desired shape that can withstand more load than the flat sheet itself; and are suitable for building construction owing to their high structural performance (Yu and LaBoube, 2010). The most common sections of CFS are channel lipped C and Z sections, and the typical thickness ranged from 1.2 to 6.4 mm with a depth range of 51 mm to 305 mm (Yu, 2000). In steel and construction industry, Hot-Rolled Steel (HRS) and CFS are two distinguished known steel sections that are used. But, among the two steel sections, HRS is the most familiar among the building contractors and engineers. Some studies reported on the potentials of using CFS sections in composite construction and significant improvements in terms of strength were demonstrated.

For instance, an extensive study was conducted by Hanaor (2000) on the use of CFS section as a composite beam in cast-in situ and precast concrete slabs. Tests conducted consisted of push-out and full-scale flexural tests. Varied in the push-out test using the in situ concrete were the shear enhancements consisted of screwed channel (CS), welded channel (CW) and screwed deck (DS) connectors of the same CFS section embedded in the concrete slab. For the precast specimens, screwed bolt connections and through bolted connections were used. The results showed that the connection methods were effective for attaining the desired capacity and the CFS composite slabs responses were ductile. Lakkavalli and Liu (2006) investigated on the strength capacity of different types of shear transfer enhancement which consisted of pre-drilled holes, pre-fabricated bent-up tabs created on the flange surface of the CFS section, self-drilling screws and surface bond between the CFS section and the concrete. The results showed that reduced deflection and significant increase in strength capacity were notably observed in specimens with shear transfer enhancements when compared with the specimens relying only on the surface bonding between the steel and the concrete to provide the shear resistance. In this paper, the use of CFS channel lipped section is reported with bolted shear connector used at a designated longitudinal interval of 250 mm and 300 mm and spaced laterally at 75 mm to possibly establish the influence longitudinal spacing could have on the shear connector ultimate strength capacity. The shear connection system is suggested as welding of stud on the thin flanges of CFS is not practically feasible, and could offer better means of shear enhancement in composite construction in which reliance on using headed studs shear connectors with HRS section in the construction of small and medium size buildings can be eliminated. This study aimed at addressing the concept of using CFS section in composite construction, although very few technical information is available on composite system that incorporates the use of light gauge steel sections (i.e. CFS section), despite the demonstrated advantages for the system in residential and small scale industrial constructions. Therefore, this study contributes in the existing literature by demonstrating the use of CFS section with bolted shear connector embedded in Self-compacting concrete (SCC).

2. Experimental Program

2.1. Push-Out Test Specimens

Four push-out test specimens comprised of M12 bolted shear connector of grade 8.8, longitudinally spaced at 250 mm and 300 mm and laterally at 75 mm were fabricated, cast and tested until failure. An I-section beam was formed by placing the CFS back-to-back using a self-drilling screws of 5.8 mm diameter. Bolt holes of 13 mm diameter were drilled on the top flanges of the CFS I-section beam and M12 bolted shear connectors were installed with single nut and washer at top and beneath the CFS flange through the bolt hole with height of the shear connector kept at 60 mm above the upper flanges of the CFS beam section. The push-out test specimens were 800 mm x 600 mm x 75 mm. Fig. 1 shows the test specimen preparation.



(a) (b) (c)

Figure-1. Preparation of push-out test specimens [(a) samples formwork, (b) samples casting, (c) finished samples]

2.2. Full-Scale Composite Beam Specimens

The composite beam specimens were 4500 mm length, effectively spanned at 4200 mm between supports. The effective width of the slab was 1500 mm with a depth of 75 mm. The fabrication and installation process are the same as in the push-out test program. Fig. 2 shows the preparation of the test specimens.

(a) (b) (c)

Figure-2. Preparation of full-scale test specimens [(a) samples formwork, (b) samples casting, (c) finished samples]

2.3. Test Set-Up and Procedure

The push-out test set-up is shown in Fig. 3, and all specimens were tested in the same manner. Each specimen was placed on 3mm thick plywood and on a steel section (800mm x 800mm x 50mm thick) to properly lay the concrete slabs. A restrain of an angle steel iron was provided to hinge the movement of the test sample of 2000mm length and 10mm thick when the load was applied from the Jack machine. The capacity of the Jack machine load cell was 2000 kN and it was applied on the upper vertical side of the CFS beam section. Each specimen was equipped with two linear variable displacement transducers (LVDT's) on the sides of the CFS beam section to monitor the vertical slip between the concrete and the CFS section. The load cell and the LVDT's were connected to a data logger for data collection and subsequent analysis. The load was applied at a constant rate of 0.2 kN/s up to 40% of the predicted failure load. The loading was cycled three times (loading and unloading) between 5% and 40% of the expected failure load. After the cyclic loading, the load was then applied until failure. The loading was stopped when a drop of 20% from the maximum load of the specimen occurred or the specimen failed to resist any additional load as stated in Eurocode 4.

All the composite beam specimens were tested in the same manner using DARTEC jack machine with a load cell capacity of 2000 kN. Test specimen was subjected to four point bending test, where the load from the jack machine was applied at 1050 mm (shear span) from the supports. The specimen was placed as simply supported beam as shown in Fig. 4. Deflections of the specimens were monitored at the mid-span and at the quarter spans underneath the bottom flanges of the CFS section using linear variable displacement transducers (LVDT's). Strains in the specimens were monitored on the concrete slab and under the bottom flanges of the CFS section using strain gauges. All LVDT's and strain gauges were connected to the data logger. Due to high concentration of stresses at the supports, premature failure of the CFS may occur; therefore it was prevented by fitting the supports with a CFS section of dimensions 150 mm x 65 mm x18 mm of thickness 2.3 mm (see Fig. 4). Load from the jack machine was applied on the specimen at a constant rate of 0.2 kN/s through the distribution beam which transfers it to the concrete slab through the line load beams. The line load beams were rested on a steel spreader plates of 200 mm x 150 mm x 12 mm thick, to spread the load as a point load on the concrete slab. The specimen was loaded up to 15% of its predicted failure capacity and then zeroed. This was to ensure that the instrumentation process was okay and that the specimen was in equilibrium state prior to the proper testing. The specimen was loaded again this time not to 15% of its predicted capacity. Load was further increased until failure of the specimen occurred. The failure of the specimen was considered when there was a significant drop in the applied load or when a large deformation of the test specimen was observed. Lateral restrains were provided during the test, this was to prevent the specimen from having lateral torsional buckling failure prematurely.

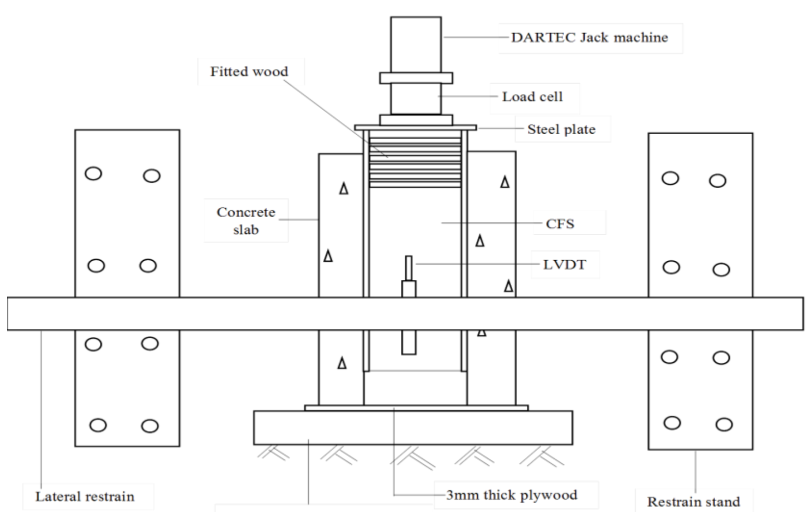


Figure-3. Push-out test set up

Figure-4. Full-scale test arrangement

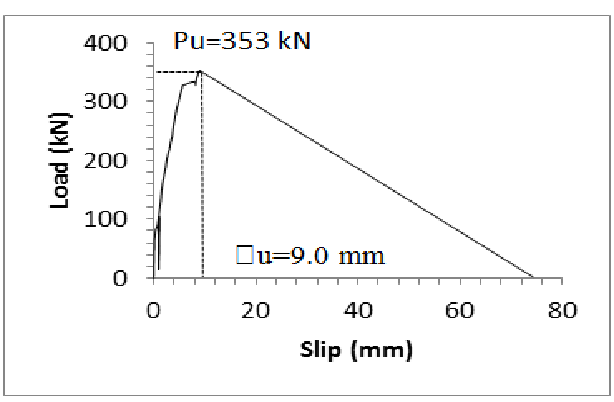
3. Results and Discussions

The push-out test result is presented in Table 1. Fig. 5 shows the load-slip relationships of tested specimens. The failure mode experienced by the tested specimen can be categorized as connector sheared-off. The failure modes of the test specimens were similar to each other which failed due to sheared-off as shown in Fig. 6. The experimental test result of the composite beam specimens is presented in Table 2. Fig. 7 shows the load against mid-span deflections of the composite beam specimens. From Table 2 and Fig. 7, the ultimate loads ($P_{u,\ exp.}$) attained for specimens FS250-12 and FS300-12 were 438.5 kN and 466.1 kN with an initial crack observed at loads level of 185 kN and 200 kN respectively. Mid-span deflections at ultimate loads level were recorded as 49.6 mm and 56.9 mm for FS250-12 and FS300-12 specimens respectively. The specimens exhibited the same failure modes by flexure which initiated by longitudinal cracks along the line of shear connector on the slab surface, transverse cracks underneath the concrete slab as well as shear connector pull-out from the slab. The shear connector pull-out from the concrete slab could be attributed to the smaller head diameter of the shear connector. The specimens failed as a result of torsional buckling of the CFS section when the ultimate was reached. From the results, specimen with bolt connector at 300 mm attained an ultimate moment capacity of 6.3% higher than that at 250 mm longitudinal spacing. However, this shows that, the moment carrying capacity between the specimens does not differ much. This finding indicates that the specimens could provide the required composite action by considering the load resisted by the specimens (see Table 2). It can be clearly observed that, as the shear connector longitudinal spacing was increased from 250 mm to 300 mm, the ultimate moment capacity attained also increased. This shows that, the shear connector longitudinal spacing influenced the load and moment carrying capacity of the specimens. The influence of the longitudinal spacing of the shear connector on the ultimate moment capacity agrees well with investigation carried out by Lakkavalli and Liu (2006). Fig. 8 (a-c) shows the failure modes of the test specimens and the shear connector condition after the test.

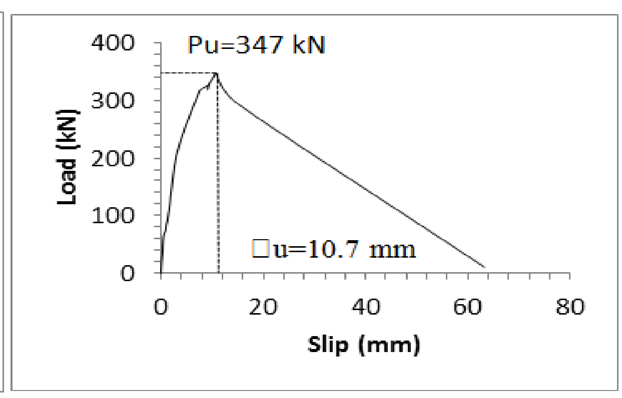
Table-1. Push-out test result

Specimen ID	P_u per connector (kN)	$P_{u\ pre.}$ per connector (kN)	$P_{u\ exp}/P_{u\ pre}$	δ_u (mm)	δ_{uk} (mm)	Average δ_{uk} (mm)	Failure mode
PS250-12-1	44.13	38.26	1.15	9.0	8.1	8.4	Connector sheared-off
PS250-12-2	43.38	38.26	1.13	10.7	9.6		
PS300-12-1	47.38	37.59	1.26	11.4	10.3		
PS300-12-2	44.06	37.59	1.17	6.3	5.7		
Mean Standard deviation			1.18 0.06				

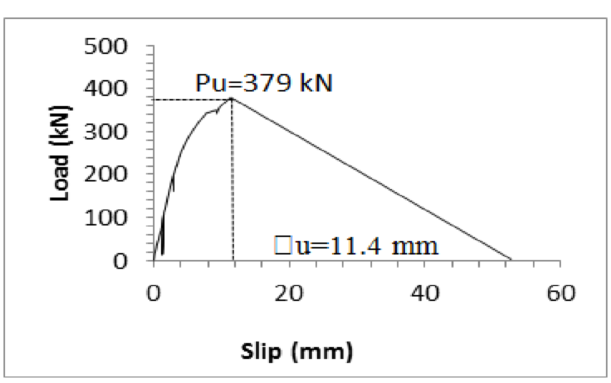
PS300: push specimen@300 mm spacing; P_u: ultimate load; $P_{u\ pre}$: predicted load; δ_u: slip at ultimate load; δ_{uk}: characteristic slip capacity



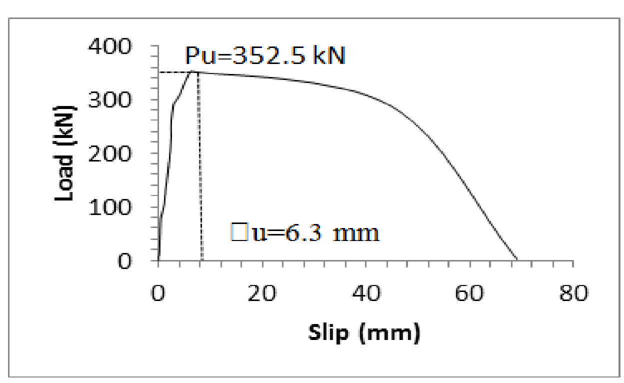
(a) PS250-12-1



(b) PS250-12-2

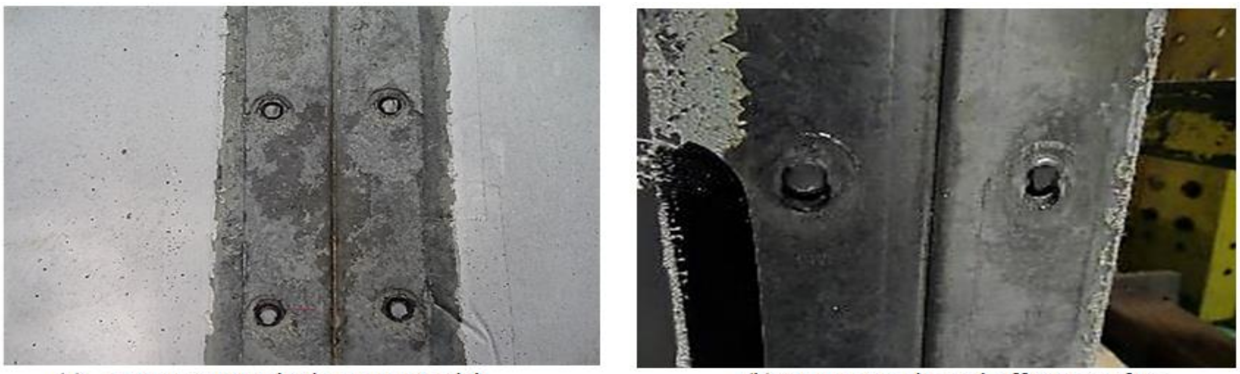


(c) PS300-12-1



(d) PS300-12-2

Figure-5. Load-slip responses of push-out specimens



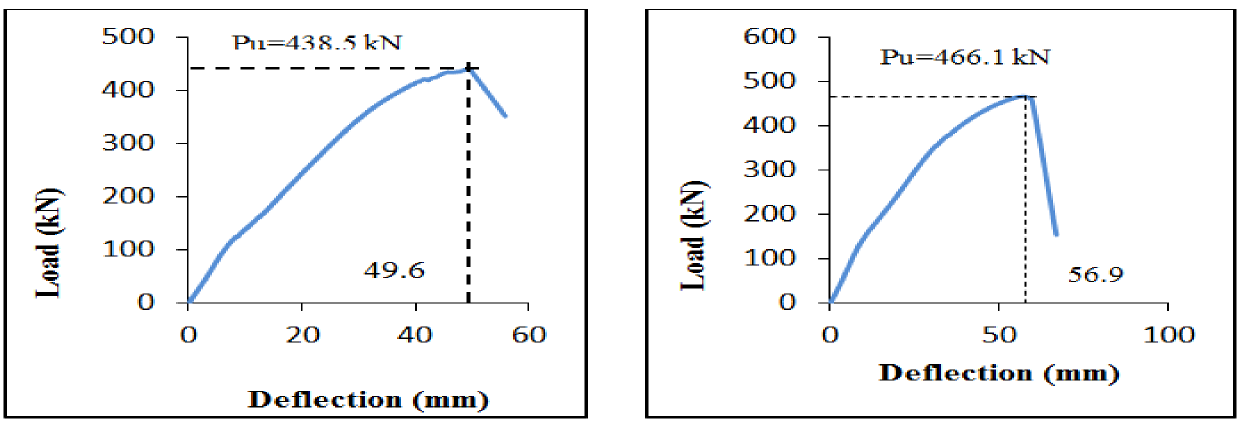
(a) Connector inside the concrete slab (b) Connector sheared-off CFS surface

Figure-6. Failure mode of specimens with M12 bolted shear connector

Table-2. Flexural test result of composite beam specimens

Specimen ID	fck at test day (N/mm^2)	Ultimate load, Pu, exp. (kN)	Deflection at Pu, exp. δu, exp. (mm)	Ultimate moment, Mu, exp. (kNm)
FS250-12	32.6	438.5	49.6	230.3
FS300-12	35.3	466.1	56.9	244.8

FS250-12: Full-specimen @ 250 mm spacing with M12 bolt diameter



(a) FS250-12 (b) FS300-12

Figure-7. Load-mid-span deflection of composite beam specimens

(a) (b) (c)

Figure-8. Failure modes of composite beam specimens: [(a) Concrete cracks on slab surface, (b) Transverse cracks beneath the slab, (c) Non-deformed shear connector]

3.1. Comparison of Experimental and Theoretical Results

The experimental results were compared with theoretical results. The theoretical calculation was based on the well-known plastic analysis approach. From the results of the analysis, it can clearly be seen that, the experimental results values agrees well with the theoretical values. The result of the comparison is presented in Table 3. Referring to Table 3, it can be observed that, the ratio of experimental shears to that of theoretical ranges from 1.03 to 1.13 with mean and standard deviation values of 1.08 and 0.07 respectively. Moreover, in terms of ultimate moment capacity, the ratios range from 1.06 to 1.16 with mean and standard deviation values of 1.11 and 0.07 respectively. This shows that, close agreement between the compared results is well achieved.

Table-3. Results of comparison between experimental and theoretical values

Specimen ID	Experimental results		Theoretical results Interpolation method			
	Vexp. (kN)	Mexp. (kNm)	Vtheory (kN)	Vexp./Vtheory	Mtheory (kNm)	Mexp./ Mtheory
FS250-12	219.3	230.3	213.1	1.03	217.2	1.06
FS300-12	233.1	244.8	207.2	1.13	211.3	1.16
Mean				1.08		1.11
Std. deviation				0.07		0.07

4. Conclusion

From the results of the experimental tests, the following conclusions can be drawn.

1. The shear connector used could be classified as ductile connector as it achieved an average characteristic slip capacity of 8.4 mm more than 6 mm as recommended by Eurocode 4.
2. Close agreement is observed between experimental and theoretical shears of the push-out specimens with a standard deviation value of 0.06.
3. The shear connector used demonstrated a good strength capacity and ductility.
4. Experimental shear and moment capacities of the full-scale specimens are in good agreement with the theoretical values with standard deviation of 0.07.
5. Strength capacity of the composite beam specimens increases with an increase in the spacing of the shear connector.
6. The shear connector showed to have the capacity of providing good composite action between concrete slab and the steel section as no deformation is observed on the shear connector.
7. The results compared proved that the plastic analysis approach for determining ultimate moment capacity of the composite beams can be estimated efficiently by using the constitutive laws as prescribed by Eurocodes and British standards.

5. Acknowledgement

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