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Behaviour of rebar shear connector in a push test for composite beam with cold-formed steel section

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Abstract. Cold-Formed Steel (CFS) has been widely used for residential, commercial and light industries due to lightweight and ease to install. Development of suitable shear connector for composite beam systems with CFS is proposed in this research. This paper presents the performance of the proposed shear connector using rebar in CFS composite beam systems. A new method is introduced to install the proposed shear in composite beam system encased in Self-Compacting Concrete (SCC). Three specimens are tested until failure for the rebar of a shear connector with different configurations with a dimension of 12 mm and 16 mm and interval distance longitudinally 200 mm and 330 mm for the standard push-out test. The shear capacity, ductility and failure modes are recorded from the test specimens. The experimental results are compared with Eurocode 4 to establish the relationship between theoretical value and experimental value. It can be concluded that the increased in dimension size and the reduced in intervals longitudinal distance of rebar contributed to an increase in the shear capacity.

1. Introduction

Development of a suitable shear connector for composite beam systems using Cold-Formed Steel (CFS) to replace Hot-Rolled Steel (HRS) needs extensive research before actual construction can become reality. The selection of CFS as construction materials which is known to be lighter in weight and ease to install as compared with HRS has contributed to significant advantages to CFS. However, for composite beam system in CFS to be established, a full scale for push-out tests should be done in order to investigate shear capacity, ductility and failure modes of the proposed shear connectors using re-bar with different configurations.



Headed welded studs as shear connectors are most commonly used in composite beams, but not suitable for CFS due to thin behavior of its section. Alternative materials that are rarely used are bolt and nut as shear connector by drilling holes in top flange. Pavlović et al., [1] had studied material behavior by standard push-out test to gain better understanding of the failure modes of the bolted and welded headed studs shear connectors for M16 grade 8.8 bolt as shear connectors and headed studs of same dimensions. Experimental data provides good agreement by comparing with finite element models. Ataei et al., [2] conducted three push-out tests to determine the load-slip behavior of bolted shear connectors using M16 and M20 grade 8.8 which results showed that these connectors provide reliable and adequate shear connection to composite beams and connections with precast concrete slabs. Saggaff et al., [3, 4], Lawan et al., [5] and Tahir et al., [6] were investigated on the application of different types of shear connector using bolt and nuts which test results that the shear connector showed good strength capacity and good composite action between concrete slab and CFS beam and the ductility of the shear connector was very good.

CFS generally has relatively thin section properties that are susceptible to local buckling under small applied load even though the condition is still elastic (not reaching yield stress). This research was conducted to obtain better understanding on structural performance on the behaviour of CFS composite beams encased in Self-Compacting Concrete (SCC). Kvočáka and Drab [7] found that composite steel beams with slender cross-section embedded in partially-encased concrete has showed better performance in providing buckling resistance. Kamal [8] studied the capacity and ductility of upper steel section of beam flange totally encased in concrete slab loaded by concentrated load acting at mid-span. It was concluded that the ductility of the encased beam was very high and more ductile. The existence of the upper steel flange near the compression zone delayed the initiation of concrete crushing and cracking. Samer Ahmed et al., [9] investigated partially-encased composite steel beams with and without web openings. It was found that the specimens with web openings provided better performance and also the partially-encased steel beams were effective in enhancing the flexural capacity and the energy absorption.

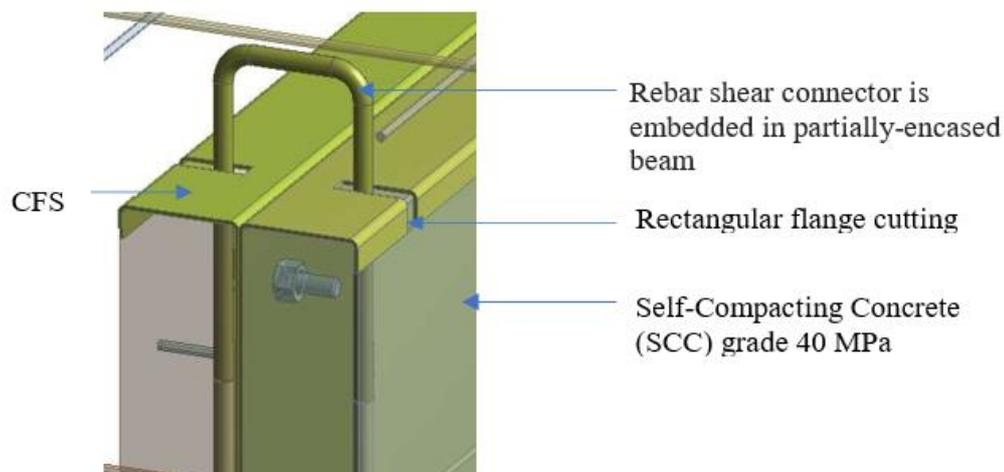


Figure 1. Proposed shear joint mechanism using rebar between beam and slab

A new method to provide shear using rebar is proposed to the composite beam system encased in double lipped C-channel assembled back-to-back and formed into double boxed section is shown in

Figure 1, embedded in SCC about half the depth of the beam. For easy installation of rebars, CFS profiles are cutting square on the flange.

2. Materials and Methods

2.1. Materials

All tests were designed and conducted in accordance with Eurocode 4 (EC4) [10], and configuration of push-out specimens are summarized in Table 1. Details of push-out specimens are also presented in Figure 2. The CFS profile to be used in this research use a C profiled with a minimum yield strength of 450 N/mm² by the manufacturer with 250 mm in web depth, 75 mm in flange width, 20 mm lipped depth and a thickness of 2.4 mm is used for the proposed encased composite beam. The CFS beam material will be formed into I-profile (back to back) linked with a bolt M12 grade 8.8 mm with 45 mm of length and a tensile strength of 800 N/mm² by the manufacturer, using 2 washers and 1 nut, which is on the web of CFS associated with the bolt is perforated with a diameter of 13 mm. The proposed shear connector using deformed rebar with steel graded S460 is diameter of 12 mm and diameter of 16 mm, the shear connector is embedded in the SCC through a CFS flange that has been cut-off at half the height of the CFS beam. BRC Wiremesh A142 fabrication with spacing of 200 mm x 200 mm in both directions is used to prevent shrinkage, creep and surface cracking of concrete slabs. The concrete to be used in this study is a ready-made SCC supplied and designed to have a compressive strength of 40 N/mm².

Table 1. Detail of push-out test specimens

| Specimen ID | CFS Beam (mm) | | Shear connector (mm) | | | Number of connectors |
|--------------|---------------|-----------|----------------------|--------|--------------------|----------------------|
| | Depth | Thickness | Diameter | Height | Longitudinal space | |
| PS250-12-200 | 250 | 2.4 | D12 | 75 | 200 | 8 |
| PS250-12-330 | 250 | 2.4 | D12 | 75 | 330 | 8 |
| PS250-16-330 | 250 | 2.4 | D16 | 75 | 330 | 8 |

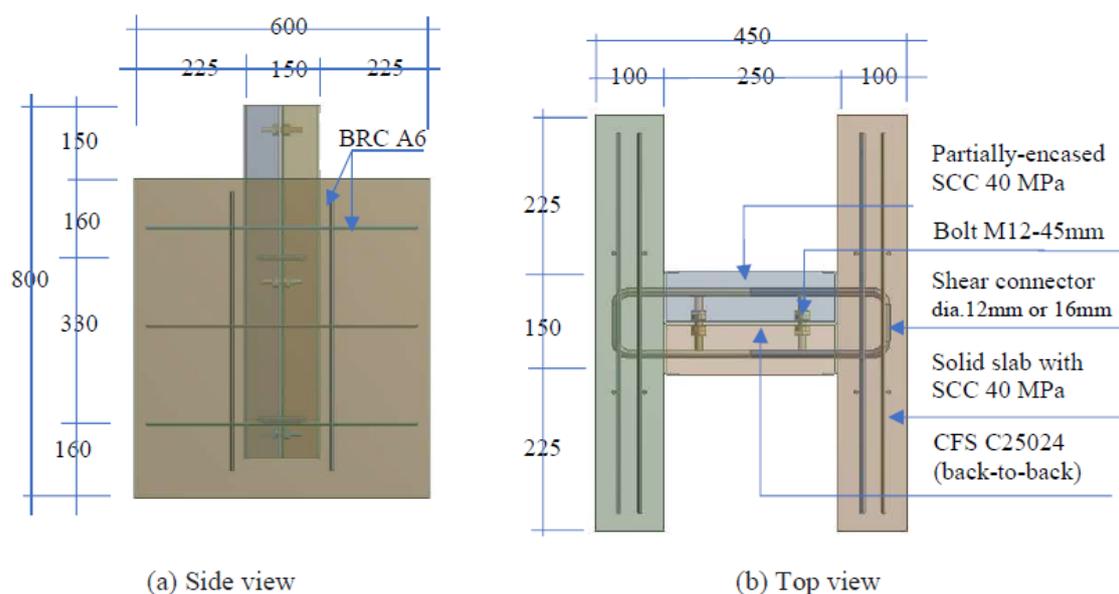


Figure 2. Details of push out test specimens

Cutting rectangular measuring 47 mm x 14 mm for rebar with diameter of 12 mm and 47 mm x 18 mm for rebar with diameter of 16 mm on the flange of the CFS section to install the shear connectors. The proposed shear connectors of D12 x 75 mm, and D16 x 75 mm were installed and embedded in encased composite beam on the lower part and embedded in composite slab on the upper part with longitudinally at 200 mm and 330 mm centers and 75 mm for lateral space.

2.2. Material properties

To obtain material properties such that the yield and ultimate stresses from the CFS section as showed in Table 2, it was established by tensile tests by making several sample coupons taken from pieces of the web and flange from the CFS section. The manufacturing and testing procedure based on BS EN10002-1 [11], where the equipment used is INSTRON 600DX with a capacity of up to 600 kN.

Table 2. CFS coupon tensile test results

| Properties (N/mm ²) | Thickness (mm) | Web | | Flange | | Average | f_u/f_y |
|------------------------------------|-------------------|--------|--------|--------|--------|---------|-----------|
| | | Wb1 | Wb2 | Fln1 | Fln2 | | |
| Yield stress (f_y) | | 570 | 571 | 546 | 555 | 560.50 | 1.14 |
| Ultimate stress (f_u) | 2.4 | 639 | 649 | 623 | 636 | 636.75 | |
| Elasticity modulus (E_s) | | 188000 | 187000 | 176000 | 177000 | 182000 | |

In this study, the deformed rebar with a size of 12 mm and 16 mm was used as a shear connector. Tensile test procedure to get material properties from the rebar based on BS 4449 [12] and in Table 3 is presented the results of testing of the proposes shear connectors obtained from the test results using INSTRON 8801 with a capacity of up to 100 kN.

Table 3. Results of rebar tensile test

| Rebar size | Yield stress | Average yield stress | Ultimate stress | Average ultimate stress | f_u/f_y | Elasticity modulus | Average Elasticity modulus |
|------------|---------------------------|---------------------------|---------------------------|---------------------------|-----------|---------------------------|----------------------------|
| d, mm | f_y , N/mm ² | f_y , N/mm ² | f_u , N/mm ² | f_u , N/mm ² | | E_s , N/mm ² | E_s , N/mm ² |
| SC12-1 | 665 | | 752 | | | 211000 | |
| SC12-2 | 660 | 657 | 742 | 747 | 1.14 | 189000 | 213333 |
| SC12-3 | 645 | | 746 | | | 240000 | |
| SC16-1 | 514 | | 598 | | | 210000 | |
| SC16-2 | 523 | 525 | 601 | 599 | 1.14 | 240000 | 218333 |
| SC16-3 | 538 | | 598 | | | 205000 | |

In Table 4, the test results of the fresh properties of the SCC are presented based on the standard [13, 14], where to get hardened properties accordance with BS EN12390-3 [15] for cube compression and BS1881-121 [16] to obtain the elastic modulus from the cylinder test.

Table 4. SCC fresh and hardened properties results

| Fresh property | | | | |
|--|-------|-------|-----|---------|
| | | | | Average |
| Slump flow (mm) | 630 | 673 | 674 | 659 |
| T ₅₀₀ (sec) | 1.9 | 2.0 | 1.8 | 1.9 |
| J-ring slump flow (mm) | 580 | 640 | 660 | 626.7 |
| T _{500j} (sec) | 3.7 | 5.3 | 4.8 | 4.6 |
| V-funnel (sec) | 7.1 | 6.1 | 5.6 | 6.3 |
| Hardened property | | | | |
| | | | | Average |
| Cube compressive strength, f_{cu} (N/mm ²) | 53.69 | 55.81 | | 54.75 |
| Cylinder compressive strength, f_{ck} (N/mm ²) | 42.95 | 44.65 | | 43.80 |
| Modulus of Elasticity E_c (N/mm ²) | 35856 | 36211 | | 36034 |

2.3. Testing method

In this study, to determine the ultimate shear capacity and ductility of the proposed shear connector; the failure modes for the shear connection of the composite beam system and load-slip is supposed to be determined by a push-out test based on EC4 [10]. From the push-out test, load-slip curves of the shear enhancement are obtained; strength, stiffness and ductility of the rebar shear connectors are then evaluated. Experimental setup for push-out is shown below in Figure 3.

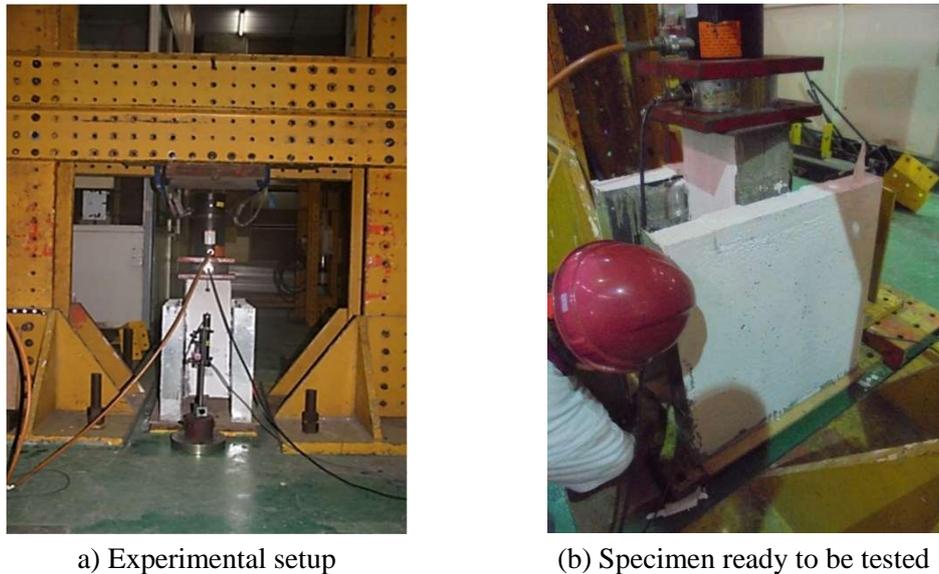


Figure 3. Experimental setup photograph for push-out test specimens

2.4. Prediction of shear capacity

According to EC4 [10], to predict the shear connector capacity is given as in Eq. 1 (stud failure) and Eq. 2 (concrete crushing failure). In this research, the predicted of the rebar shear capacity is determined using two equations is considered as the strength capacity of the rebar shear connector.

$$P_{Rd}^{(1)} = \frac{0.8 f_u \frac{\pi d^2}{4}}{\gamma_v} \quad (1)$$

$$P_{Rd}^{(2)} = \frac{0.29 \alpha d^2 \sqrt{f_{ck} E_{cm}}}{\gamma_v} \quad (2)$$

Hicks [17] propose for limiting the applicability the design Eq. 2 to $\frac{h_{sc}}{d} > 4$, the resistance of headed studs could be harmonized with EC4 [10] by substitution of $\frac{\sqrt{f_{ck}}}{\gamma_v}$ with $\sqrt{f_{ed}}$ to give:

$$P_{Rd}^{(2)} = 0.25 d^2 \sqrt{f_{cd} E_{cm}} \quad (3)$$

In order to justify a uniform value for the partial factor, and in the interests of harmonizing the design equation for steel failure of the studs with EC4 [10], a conversion factor for the stud diameter η could be introduced, to give:

$$P_{Rd}^{(1)} = \eta \frac{0.94 f_u \frac{\pi d^2}{4}}{\gamma_{M2}} \quad (4)$$

3. Results and discussions

The results of experimental test are presented in Table 5. The load-slip curves relationships of the specimen that has been tested, PS250-12-200, PS250-12-330 and PS250-16-330 respectively as shown in Figure 4. The average failure loads recorded from the push-out test were 474.1 kN, 489.6 kN and 740.6 kN for specimens and the early cracks were observed at load levels of 440 kN, 296.6 kN and 731.6 kN for PS250-12-200, PS250-12-330 and PS250-16-330 specimens respectively.

The failure modes for PS250-12-200 and PS250-12-330 specimens demonstrated a remarkable shear resistance from the applied load. However, the general failure mode of specimens in this category could all be attributed to the sheared-off of the shear connectors within the concrete slabs at the ultimate load level. Maximum average failure loads resisted by the test specimens per shear connector were recorded to be 59.3 kN for specimen PS250-12-200 and 61.2 kN for specimen PS250-12-330 respectively.

Table 5. The result of experimental test

| Specimen ID | Connector size (mm) | Experimental results | | EC4 [10] | | Hicks [17] | |
|--------------|---------------------|----------------------|--------------------------------|-------------------|--------------------|-------------------|--------------------|
| | | $P_{u,exp}$ (kN) | $P_{u,exp}$ per connector (kN) | Stud failure (kN) | Conc. failure (kN) | Stud failure (kN) | Conc. failure (kN) |
| PS250-12-200 | 12 | 474.1 | 59.3 | 47.6 | 41.97 | 63.8 | 36.9 |
| PS250-12-330 | 12 | 489.6 | 61.2 | 47.6 | 41.97 | 63.8 | 36.9 |
| PS250-16-330 | 16 | 740.6 | 92.6 | 67.6 | 74.6 | 87.9 | 65.6 |

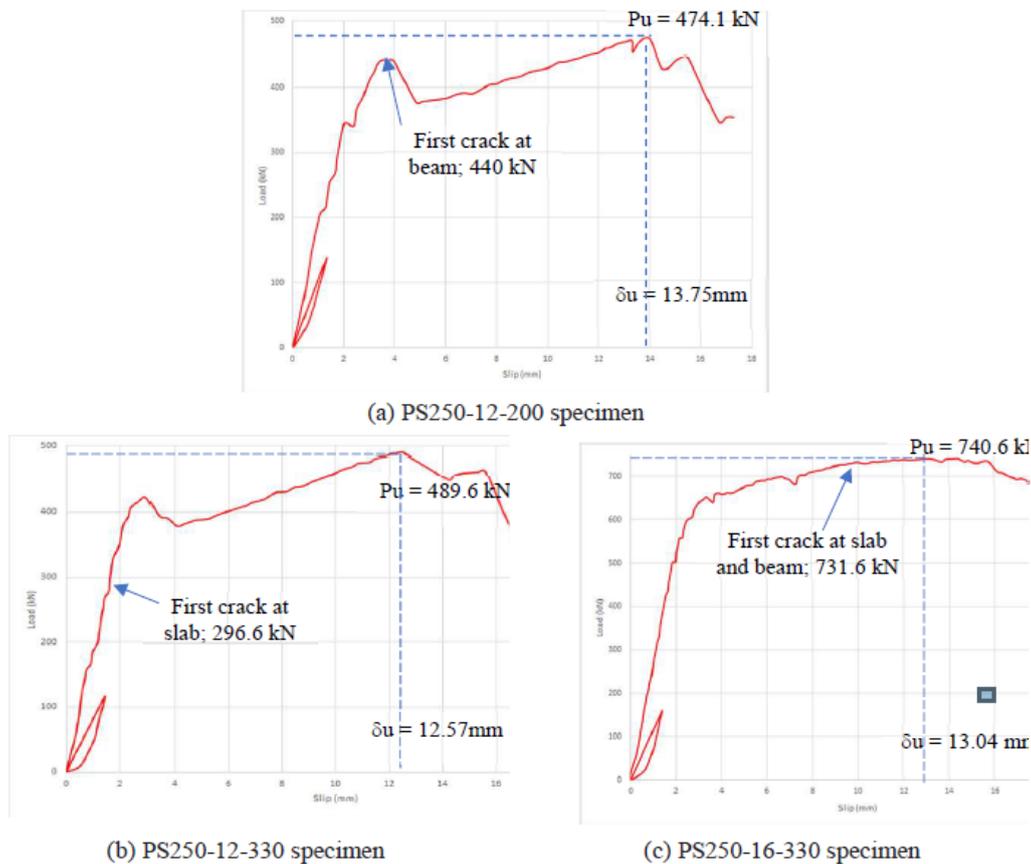
The failure modes for PS250-16-330 specimen could be attributed to the cracks developed on the solid slabs and concrete beam. The cracks became moderately large at the underneath of concrete beam as the applied load was increased which resulted to the crushing of concrete. However, as the ultimate load was reached, due to high strength of concrete, CFS beam experienced a failure at underneath of concrete slab. Maximum average failure loads resisted by the test specimens per shear connector were recorded as 92.6 kN for specimen PS250-16-330. Figure 5 shows the failure modes that occurs on the tested specimens. PS250-12-330 experienced shear-off of the re-bars and transverse cracks at slabs. However, for PS 250-6-330 specimen, transverse shear and deformation of the CFS beam are clearly seen as the failure mode.

From Table 6 and Figure 5, it can be observed that the rebar shear connectors with size of 12 mm and 16 mm developed a ductile behaviour with an average characteristic slip capacity of 13.75 mm, 12.57 mm and 13.04 mm which is higher than 6 mm recommended by EC4 [10]. A major challenge for a wider use of rebar shear connectors in composite structures is lack of design rules. Further investigation of the ductility and influence of initial slip to the overall behaviour of composite beam would be necessary to promote the use of the proposed shear connector in composite construction.

It is noted that the type of failure that occurs in the specimens as compared to EC4 [10], showed that there was an increased in shear strength capacity of 1.25 and 1.29 higher than that of the theoretical values for specimen with size of 12 mm that had 250 mm and 330 mm spacing. An increased in shear strength of 1.24 was also manifested between experimental and the theoretical results for specimen with size of 16 mm that had 330 mm spacing. Adjust to Hicks [17], that there was a decreased in shear strength capacity of 0.93 and 0.96 for specimen with size of 12 mm but for size of 16 mm there was an increase 1.41 higher than theoretical values.

Table 6. Comparison between experimental results and theoretical results

| Specimen ID | Conn ector size (mm) | Experimental | | EC4 (10) | | Hicks (17) | | Failure mode |
|--------------|-------------------------------|--------------------------------------|--------------------------------|---------------------|-----------------------------|---------------------|-----------------------------|-------------------------|
| | | $P_{u,exp}$ per connector (kN) | Slip (δu) (mm) | $P_{u,pre}$ (kN) | $P_{u,exp}/$ $P_{u,pre}$ | $P_{u,pre}$ (kN) | $P_{u,exp}/$ $P_{u,pre}$ | |
| PS250-12-200 | 12 | 59.3 | 13.75 | 47.6 | 1.25 | 63.8 | 0.93 | Shear off |
| PS250-12-330 | 12 | 61.2 | 12.57 | 47.6 | 1.29 | 63.8 | 0.96 | Shear off |
| PS250-16-330 | 16 | 92.6 | 13.04 | 74.6 | 1.24 | 65.6 | 1.41 | Slab + beam crushing |

**Figure 4.** Load-slip curves of push-out test specimens

Tahir et al., [6] have carried out experimental test on the uses of M12 and M16 bolts of Grade 8.8 with spacing of 250 mm and 300 mm longitudinally as shown in Table 7. Experimental results using rebar provide better shear strength and more ductile if compared using the same size bolts.

Table 7. Comparison between experimental results and other researches

| Studies comparison | shear connector | | Description of beam | Experimental results | |
|--------------------|------------------|--------------------|---|-----------------------------|--------------------------|
| | Description | Long. Spacing (mm) | | $P_{u, exp.}$ per stud (kN) | Slip (δ_u) (mm) |
| Present study | Rebar, D = 12 mm | 200 | CFS with thickness of 2.4 mm encased with SCC | 59.3 | 13.75 |
| | H = 75 mm | 330 | | 61.2 | 12.57 |
| | Rebar, D = 16 mm | 330 | | 92.6 | 13.04 |
| Tahir et al., (6) | Bolt, D = 12 mm | 250 | CFS with thickness of 2.3 mm | 43.38 | 6.3 |
| | H = 75 mm | 300 | | 44.06 | 10.7 |
| | Bolt, D = 16 mm | 250 | | 62.06 | 10.2 |
| | H = 75 mm | 300 | | 62.14 | 7.9 |



The rebar shear connector shear-off



Transverse cracks at slabs

(a) PS250-12-330 specimen



Transverse cracks at slabs



beam experienced a failure at underneath

(b) PS250-16-330 specimen

Figure 5. Failure modes of tested specimens

The effect of concrete slab quality and thickness on the result of the push-out test is presented by Saggaff et al., [3] using ferrocement of 35 N/mm² and 50 mm slab thickness, the result of total shear capacity of 12 mm bolt with wire-mesh 2 layers and spacing of 75 mm was 299.5 kN. It showed the failure of concrete in compression around the stud and the mode failure in ferrocement slab. Current research for SCC slab of 40 N/mm² and thickness of 100 mm with spacing of 200 mm was 474.1 kN where the rebar shear-off. This shows that the quality and thickness of concrete affect shear strength of the proposed shear connectors. However, further research is required with full-scale bending beam testing to investigate and to fully understand the behavior of the composite beam system with the proposed shear connector on SCC.

4. Conclusion

The main purpose of this research work is to investigate the structural performance of CFS encased with SCC as a composite beam system, by means of shear connection mechanism of proposed using rebar of 12 mm and 16 mm diameter. The conclusions of the proposal from this research work can be listed as:

- The proposed shear connector using rebar provides reasonable results that can be applied in composite beam systems and when compared to the use of bolts in previous studies. Test results for rebar with dimensions of 12 mm in the standard push-out test, the general failure mode of specimens in this category could all be attributed to the sheared-off of the shear connectors within the concrete slabs at the ultimate load of 474.1 kN and 489.6 kN for the PS250-12-200 specimen and PS250-12-330 specimens respectively. Other results for rebar with dimensions of 16 mm, the type of failure was due to cracks developed on the concrete slabs and concrete beam at the ultimate load of 740.6 kN for the PS250-16-330 specimens respectively
- The comparison between experimental results with that of theoretical values based on EC4 showed that there was an increased in shear strength capacity of 1.25 and 1.29 higher than that of the theoretical values for specimen with size of 12 mm. An increased in shear strength of 1.24 for specimen with size of 16 mm.

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