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# Structural Performance of Cold-Formed Steel Section in Composite Structures: A Review

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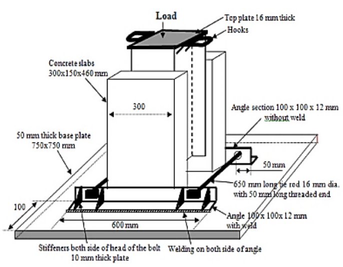
**Graphical abstract**




**Abstract**

Cold-formed steel (CFS) sections are lightweight materials where their high structural performance is very suitable for building construction. Conventionally, they are used as purlins and side rails in the building envelopes of the industrial buildings. Recent research development on cold-formed steel has shown that the usage is expanding in the present era of building constructions and infrastructural applications. However, the study on cold-formed steel as composite structures is yet to be explored in the literature. Therefore, this review paper has presented research works done which investigate the structural improvement of cold-formed steel as composite structures. The use of cold-formed steel with self-compacting concrete (CFS-SCC) which can be considered as a unique composite entity is also presented. The significance of using the CFS-SCC as composite is also highlighted. The results of various researchers indicated that the robustness of the product (cold-formed steel-concrete) was significantly improved for both the shear resistance and the flexural resistance. The investigation on the behaviour of CFS-SCC designed as composite is a key issue where the innovative construction method and significant advantages are highlighted in this paper. The review papers have proven that the use of cold-formed steel as composite has enhanced the application of the cold-formed steel as competitive material for construction.

*Keywords*: Cold-formed steel; self-compacting concrete; composite beam; structural performance



## 1.0 INTRODUCTION

Cold-formed steel (CFS) sections are lightweight materials where their high structural performance, is very suitable for building construction. Conventionally, they are used as purlins and side rails in the building envelopes of the industrial buildings. The most common cold-formed steel sections are the lipped C, and the Z sections. The thicknesses of these sections are typically varied from 0.9 mm to 3.2 mm [1]. The yield strength of these sections are generally between 280 to 450 N/mm2 [2].

CFS and hot-rolled steel (HRS) sections are two common types of steel sections that are largely used in steel construction industry. The HRS type is very well known among designers as its can accommodate heavier load than the CFS. However, the use and importance of the CFS is expanding in the present building constructions due to its advantages of lightness and cost effective. The CFS sections have also been recognised as an important contribution to environmental friendly and to sustainable 'green' construction material for low rise residential and medium rise commercial buildings [3]. The popularity of using CFS as construction materials has enhanced more research to be conducted as composite structures.

Composite structures exist when various components (i.e. steel and concrete) are connected to act as a single unit. The composite structure has higher stiffness and load bearing capacity as a result of the composite action when compared with their non-composite counterparts [3-6]. For the composite action to take place, a shear transfer mechanism should be incorporated by using enhanced shear connectors such as headed studs shear connectors [6]. Thus, the steel-concrete composite is stiffer and stronger than the steel and the concrete slab alone [7-11].

## 2.0 REVIEW OF PREVIOUS STUDIES

This comprehensive review study explored the composite behaviour of cold-formed steel- concrete (CFS-Concrete). Various studies were performed on the CFS sections and concrete as composite elements and also on the applications of ferrocement with concrete as composite entities. Some of the studies are hereby presented.

## 2.1 Push-out Tests

### *2.1.1 Shear Stud Connectors*

Smith and Couchman [12] investigated on the strength and ductility of headed stud shear connectors in the profiled steel sheeting. They performed a series of push test on 27 specimens by using a newly developed push rig. Various parameters such as mesh position, transverse spacing of shear connectors, number of shear connectors per trough, and the depth of the slab were changed through the experiment. They observed that the mesh located at the nominal cover below the slab top and directly on the profile steel sheeting top resulted in higher ductility and strength (about 30%) of the shear connectors. Moreover, transverse spacing of the shear connectors was found to have little effect on the shear resistance. However, adding the third shear connector has no effect rather than using the shear connectors in pairs. Smith and Couchman also found that by increasing the slab depth, the resistance of the shear connectors was also increased.

Pallares and Hajjar [13] reviewed a comprehensive compilation of experimental studies on headed studs shear connectors performed by push-out test. They conducted 391 monotonic and cyclic tests on the headed studs shear connectors to investigate the composite beam-column (typically concrete-encased steel shapes or concrete-filled steel tubes). From their findings comparisons were made with the provisions in the ACI 318-08 Building code, and Eurocode 4 to propose formulas which were within the context of AISC 2005 Specifications. They concluded that for steel and concrete failures, the provision in the Eurocode 4 presented conservative formulae.

Prakash *et al.* [14] modified push-out tests to determine the shear strength and stiffness of high strength steel (HSS) stud shear connectors. Four specimens S1, S2, S3, and S4 (Figure 1) were tested until failure. Their experimental results were validated and compared with the recommendations by Eurocode 4, and they concluded that the shear strength of HSS studs were within the provisions of Eurocode 4 for conventional headed studs shear connectors.

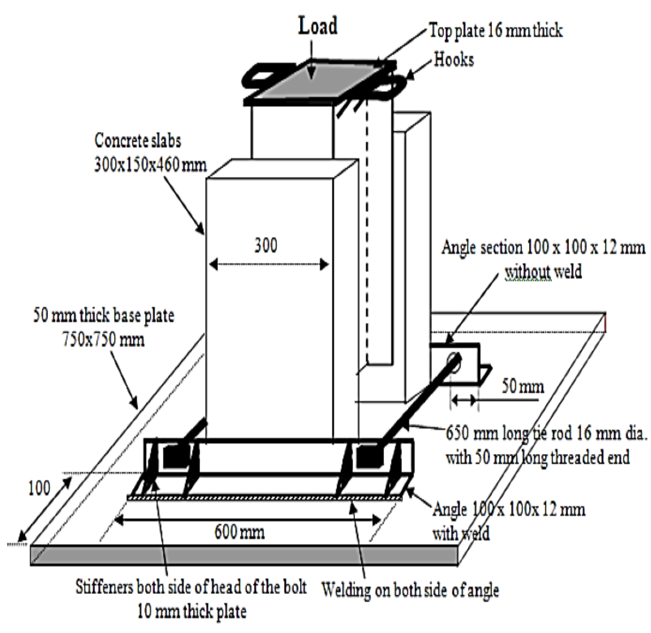



**Figure 1** Modified push-out test arrangement [14]

Xu *et al.* [15], studied on the static analysis of headed shear studs group with typical push-out tests. Two groups of specimens suggested by the authors called DT, and QT were designed and tested namely, DT1, DT2 and DT3 as well as QT1, QT2 and QT3. From the result, the studs group that has larger shank diameter (19mm and 22mm), their mechanical behaviour had less effect from the biaxial action. Also the initial bending-induced concrete cracks seemed unfavourable to the stud shear stiffness. Xu et al., also verified the results obtained from the shear stiffness, and shear capacity of the studs group using Finite element modelling (FEM) and a good agreement was achieved.

Xu and Suguira [16] studied the parametric push-out analysis for a group of headed studs shear connectors under the effect of bending-induced concrete cracks. The results indicated that, the bending-induced concrete cracks caused the stud stiffness reduction. This resulted since the shear load transferred from the stud to the concrete during the pushed-out process had been unfavourably affected by the cracks. A comparison of the stud strength resistance was made with the FEM results and a good agreement was attained.

The strength of headed studs shear connectors in composite steel beams with precast hollow core slabs were also investigated by Lam [17]. Lam proposed a new push-out test procedure consist of a composite beam made of precast hollow core slabs. Seven push-out specimens were tested on the headed studs shear connectors in solid Reinforced Concrete (RC) slabs accordingly. After established push test with the solid slabs, 72 full scale push-out specimens were tested using the hollow core slabs. The experimental results were validated with the standard codes of practice (i.e. BS5950 and Eurocode 4) adopted for solid RC slabs and a close agreement was achieved. The summary of the studied literatures is presented in Table 1.

**Table 1** Summary of the researches with headed studs shear connectors

| Author | Methodology | | Shear Connector | | Conclusions |
|---|---|---|---|---|---|
| | Experiment | FEM | Type | Size(mm) | |
| Smith & Couchman[8] | √ | - | HS | 19x100 | Ductility and strength increased |
| Pallares & HAjjar[9] | √ | - | HS | - | Results compared with Eurocode 4 formulae, good agreement was achieved |
| Parakash *et al.* [10] | √ | - | HSS | 20x100 | Shear strength of HSS lied within Eurocode 4 provisions |
| Xu *et al.* [11] | √ | √ | HS | 13x80; 16x80; 19x80; 19x100; 22x80; 22x100 | Good agreement was achieved between experimental and FEM results |
| Xu & Suguira [12] | √ | √ | HS | 13x80; 16x80; 19x80; 19x100; 22x100 | Good agreement achieved |
| Lam [13] | √ | - | HS | 19x100; 19x125; 22x100; 22x125 | Close agreement was achieved when validated with BS5950 and Eurocode 4 |

Description: HS= Headed Stud; HSS= High Strength Steel; FEM= finite element modeling

### *2.1.2 Bolted Connectors*

The behaviour of bolted shear connectors and stud connectors in push-out tests were investigated by Pavlović *et al.* [18]. To gain a better understanding of the failure modes for the shear connectors, different types of shear connectors (bolts and studs) were used (Figure 2). Push-out tests were performed according to EN1994-1-1 using 4 No M16-grade 8.8 bolts with a single embedded nut in the concrete. The shear resistance, stiffness, ductility, and failure modes were investigated in the study. It was concluded that the bolted shear connector with single embedded nut could achieve up to 95% of the shear resistance, for the static loads that were applied in comparison with the conventional arc welded headed shear studs shear connectors. Finite Element Modelling for both shear connectors was simulated and the results were compared with the experimental test results. It was found that the comparison was well agreed.

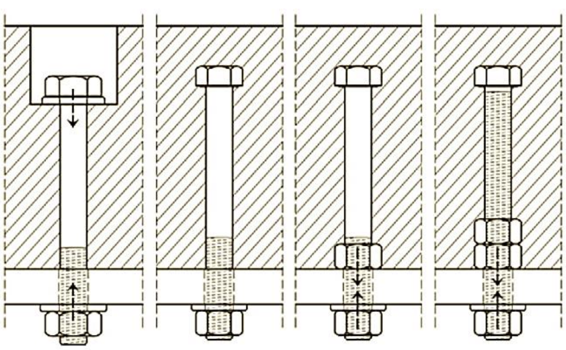



**Figure 2** Shear connectors [18]

Post-installed shear connectors behaviour under static and fatigue loading was investigated by Kwon *et al*. [19]. They investigated three types of 22 mm diameter (bolt) post-installed shear connectors namely; Double Nut Bolt (DBLNB), High-Tension Friction-Grip Bolt (HTFGB), and Adhesive Anchor (HASAA) (Figure 3). The results were then compared with the previous findings obtained from other studies by Hungerford, Schaap and Kayir, where 19mm diameter (bolt) post-installed shear connectors and conventional headed shear connectors were used. It was concluded that the post-installed shear connectors showed significantly higher fatigue strength than conventional headed studs shear connectors. Furthermore, the fatigue strength of the post-installed shear connectors enhanced the strengthening of bridge girders using fewer shear connectors in comparison with conventional headed shear studs connectors.

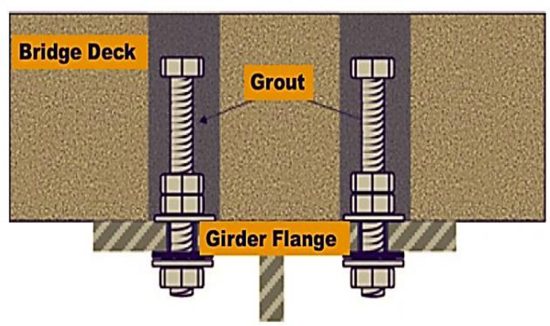



Figure 1(a)

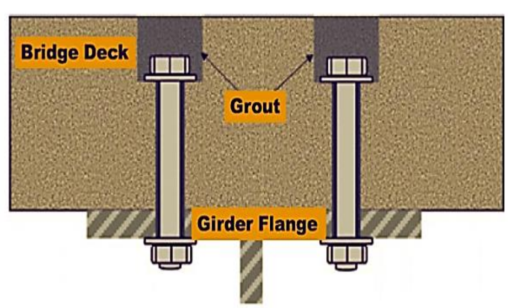



Figure 1(b)

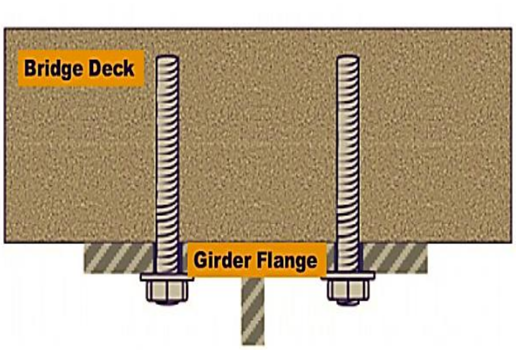



Figure 1(c)

**Figure 3** Post-installed shear connectors (a) double nut bolt (b) high-tension friction-grip bolt (c) adhesive anchor [19]

The summary of the studies are presented in Table 2.

**Table 2** Summary of the researches studied

| **Author** | **Methodology** | | **Shear Connector** | | **Conclusions** |
|---|---|---|---|---|---|
| | **Experimental** | **FEM** | **Type** | **Size(mm)** | |
| Pavlovic *et al.* [14] | √ | √ | Bolted | 16x140 | Experimental results were well agreed with FEM validation |
| Kwon *et al.* [15] | √ | - | Bolted | 22x127 | Strength increased In comparison with conventional headed studs shear connectors |

### *2.1.3 Perfobond Shear Connectors*

Innovative shear connectors for composite beams were studied by Bamaga and Tahir, [20]. They used a CFS section and profiled concrete slab with the proposed innovative shear connectors (Figure 4). The ductility and the strength capacities of the proposed shear connectors were investigated using push-out tests. The results of the proposed shear connectors showed large deformation, strength capacities and proved that it can be used for lightweight composite beams.

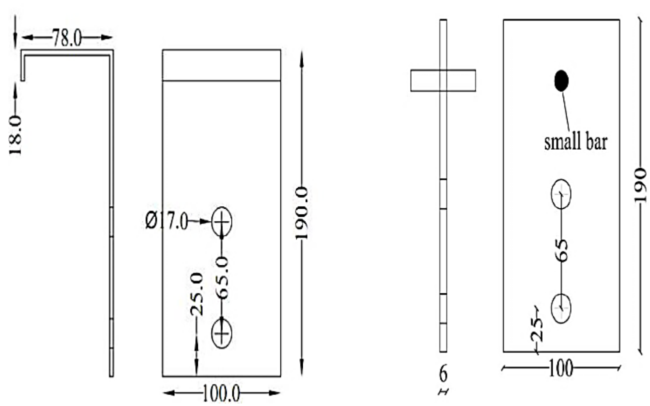



**Figure 4** proposed shear connectors [20]

Yan *et al.* [21] studied the performance of J-hook shear connectors in steel-concrete-steel sandwich structure (Figure 5). Accordingly they performed one hundred and two push-out tests. The strength behaviour of the J-hook shear connectors embedded in the ultra-lightweight cement composite core was compared with those in the normal concrete. The shear interaction area, concrete bearing area and shear resistance were increased. Then a new design guide was proposed to predict the shear strength and load-slip behaviour of the J-hook shear connectors. The experimental results were then compared with the new proposed design guide; available methods in the literature and also with standard codes which were developed for headed studs shear connectors.

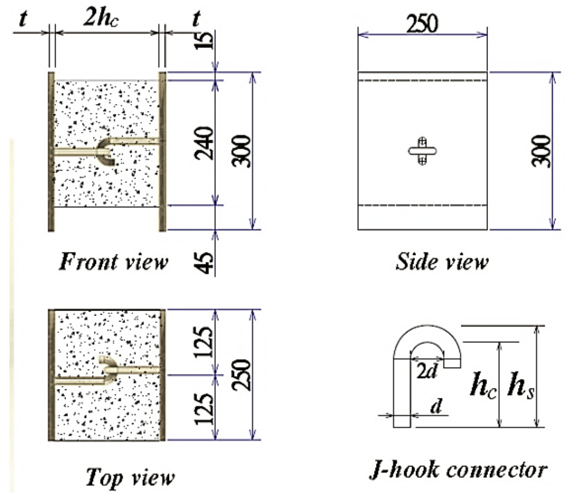



**Figure 5** Typical J-hook connector used by Yan *et al.* [21]

A study on composite girders under monotonic loading using perforated shear connectors was investigated by Costa-Neves *et al.* [22]. They performed sixteen push-out tests which focused on the shear capacity, ductility, and failure modes of the shear connectors. The influence of the shear connector geometry (Figure 6) and the provision of transverse reinforcement within a shear connector's holes were evaluated through the experiments. Two types of the shear connectors were used in this study namely, I-perfobond, and 2T-perforbond. Costa-Neves *et al.,* observed that, the shear connectors with the flanges (i.e. I and 2T perforbonds) lead to a greater resistance enhancement (approximately 200% and 300% with single and double flanges, respectively) when no reinforcement bars were provided. However, in the specimen with reinforced connection through the connector hole, the resistance was 150% and 200%. They concluded that, the inclusion of the reinforcement bars within the hole of the connectors, the connection resistance increased in all the geometries. But it has more effect on the perfobond shear connectors than the flanged shear connectors.

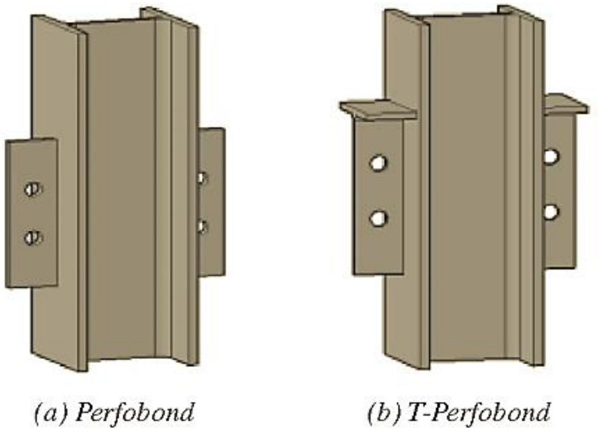



Figure 6 (a)

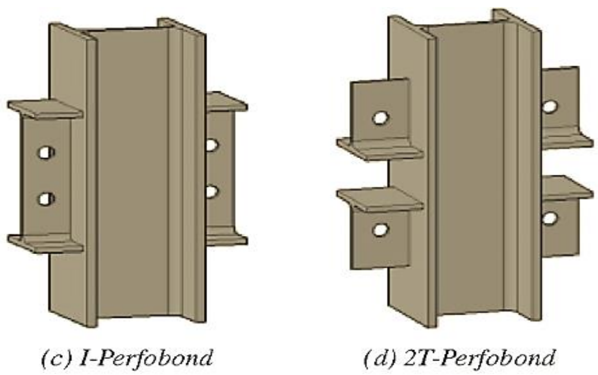



Figure 6 (b)

**Figure 6** Shear connector types [22]

Shariati *et al.* [23] investigated on the behaviour of C-shaped shear connectors with the height of 75 mm, and 100 mm under monotonic and fully reversed cyclic loading. Eight push-out tests were carried out to assess the resistance, strength degradation, ductility, and failure modes of the C-shaped angle shear connectors. Fracture failure was observed in the C-shaped angle connectors, and particularly more cracks were monitored in slabs with larger angles connectors. They concluded that, the C-shaped angle shear connectors showed a proper behaviour in terms of ultimate shear capacity However, the ductility criteria was not satisfied as stated in Eurocode 4.

Rodrigues and Laim [24] have investigated the behaviour of perforbond shear connectors at high temperatures. Accordingly 32 push-out tests were conducted where 8 of the specimens were tested at room temperature and 24 of the specimens were tested at the high temperatures. The specimens were heated at temperatures in the range of 840oC, 950oC, and 1005oC and then loaded up to failure point. Thereby, the shear connectors' resistance and its ductility were assessed in both at room temperature and high temperature. The study parameters were number of holes in the perforbond shear connectors (P2h; means perforbond 2-holes see Figure 7), transverse reinforcement bars passing through the holes, and two connectors placed side by side at high temperature. The results of the modified push-out test at the room temperature and at high temperatures were compared. It was concluded that the load capacity of the shear connectors at high temperatures was lower than those at room temperatures within the limit of the experiment.

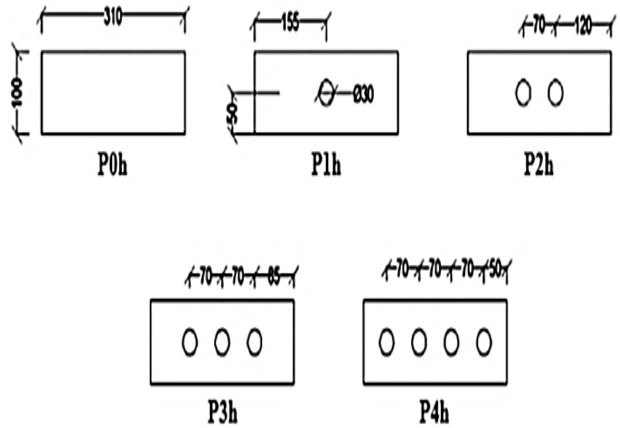



**Figure 7** Geometry of the perforbond connectors [24]

Candido-Martins *et al.* [25] studied on experimental evaluation of the structural response of perforbond shear connectors. Eight push-out tests were conducted which focused on the resistance, ductility, and the failure modes of the shear connectors. The number of holes within the connector, the reinforcing bar through the connectors' holes, and the performance of two perforbond connectors side by side were varied through the experiments. It was observed that the ductility requirement of 6mm minimum set by Eurocode 4 for the slip capacity could be attained, except for the side by side configuration. However, for the large load carrying capacity of the perforbond connector, the ductility significantly increased.

Ahn *et al.* [26], investigated on shear resistance of the perforbond-rib shear connector based on concrete strength and the rib arrangement. Push-out tests on different kinds of perforbond shear connectors' arrangement were conducted and results were compared with established shear capacity equation for perforbond shear connectors from literature by Oguejiofor and Hosain. It was concluded that the perforbond rib could be used as a shear connector in composite structures since it showed sufficient ductility and high shear capacity.

An experimental and analytical study on channel shear connectors in reinforced and fiber-reinforced concretes was investigated by Maleki and Mahoutian [27]. A series of the push-out tests were performed to assess the capacity of the channel shear connector embedded in the fiber concrete (Figure 8). The FEM for the push-out specimens was also used to predict the shear capacity of the channel shear connectors in the fiber concrete (polypropylene concrete). It was concluded that based on the FEM, the shear capacity of the channels shear connector in PP concrete were 26% lower than that embedded in normal RC concrete as also predicted by using Canadian code.

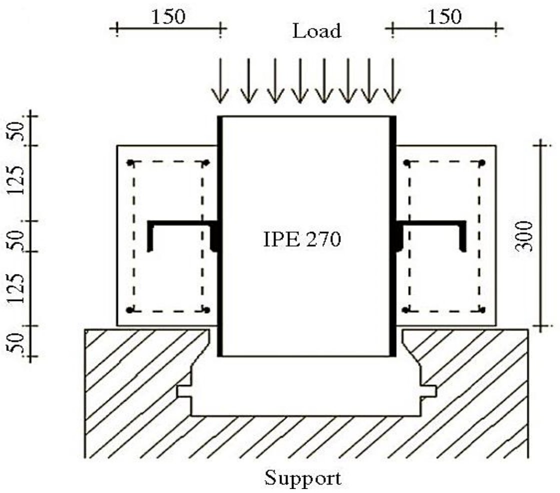



**Figure 8** Push-out specimens [27]

Maleki and Bagheri [28], investigated the behaviour of channel shear connectors embedded in solid concrete slab. They conducted a total of sixteen push-out experiments. The specimens were consisted of channel shear connectors embedded in plain, reinforced, fiber concretes, and engineered cementitious composites. The observed failure modes were the channel fracture and the concrete crushing. From the test results however, the engineered cementitious composites specimens showed a considerable increase in the ultimate strength and ductility of the channel shear connector.

## 2.2 Concrete-Cold-Formed Steel Composite Beam

Investigation on composite beams with cold-formed sections was carried out by Hanaor [29]. The study presented several methods of embedded and dry shear connections involving cold-formed sections in the composite construction. They used self-drilling screwed cold-formed shear connectors, and built-up sections bolted to precast concrete planks (Figure 9). Extensive number of push-out tests for the numerous types of connectors and a series of full-scale composite element tests were carried out. The findings indicated that design of shear connectors can in most cases be conservatively based on available codes of practice for the design of cold-formed connections. Also, the full-scale tests revealed high ductility and capacity of the tested shear connectors.

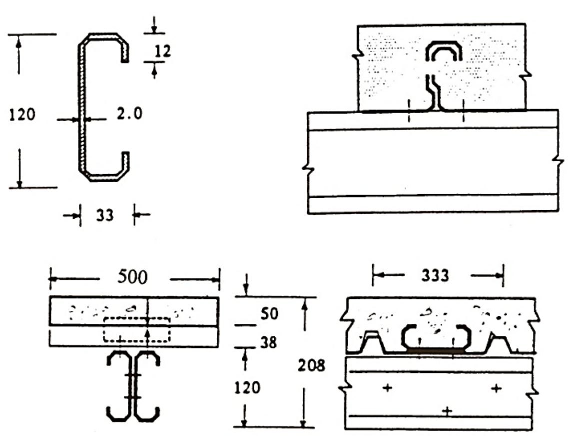



**Figure 9** shear connectors employed by Hanaor [29]

Bending behaviour of composite girders with cold formed steel U- section was investigated by Nakamura [30]. Nakamura proposed three girder models U1, U2 and U3 (Figure 10). The steel U girder is used composite with reinforced concrete slab at the span centre, whereas concrete is poured into the steel U section and pre-stressed at the intermediate supports of the continuous bridge. Bending tests were carried out to investigate the static bending behaviour of the girder models. The girder model at the span centre (U1) behaved as a composite beam. The girder model at the intermediate supports (U2) behaved as a pre-stressed beam and the filled concrete restricted the local buckling of steel plates in compression. The study revealed that the new composite girder system has sufficient bending strength, deformation, and rotation capacity. The bridge system is also practically feasible and it is economical.

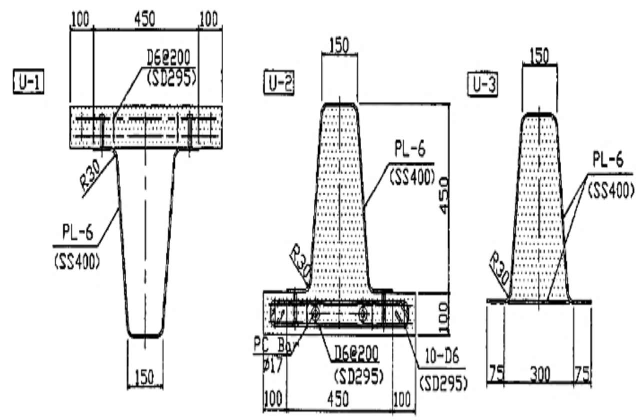



**Figure 10** Test Specimens configuration by Nakamura [30]

An experimental study by Lakkavalli and Liu [4] on composite cold- formed steel C- section floor joists was investigated. Twelve large-scale slab specimens accompany with the twenty-two push-out specimens were tested to investigate on the behaviour and strength capacity of composite slab joists consisting of cold-formed steel C-sections and concrete. Four shear transfer mechanisms including surface bond, pre-fabricated ben-up tabs, pre-drilled holes, and self-driven screws were employed on the surface of the flange embedded in the concrete to provide shear transfer ability (Figure 11). Results indicated that the specimens that were employed with shear transfer enhancement showed a marked increase in strength and reduced deflection in comparison with those relying on a natural bond between steel and concrete to resist shear. Among the four shear transfer enhancements investigated the bent-up tabs provided the best performance at both of the strength and serviceability limit states, followed by drilled holes in the embedded flanges. Furthermore, the use of self-driven screws resulted in the lowest strength increase. Drilled holes were recommended to be industrially viable due to its simplicity of fabrication, effectiveness and economy.

Figure 11(a)

Figure 11(b)

Figure 11 (c)

**Figure 11** Shear transfer enhancements (a) pre-drilled holes (b) pre-fabricated bent-up tabs (c) self-drilling screws by Lakkavalli and Liu [4]

Shear transfer enhancement in the precast cold-formed steel-concrete composite beams was investigated by Irwan *et al*. [31]. Ten companion push-out specimens were tested in order to investigate on the strength and behaviour of a bent-up taps shear transfer enhancement (Figure 12). The bent-up triangular tab shear transfer (BTTST) and angles bent-up tabs were studied in this research. As a result, the shear capacities of the specimens employed with the shear transfer enhancement increased in comparison with those relying only on a natural bond between cold- formed steel and concrete. After comparing the shear transfer enhancements they have concluded that the BTTST provided a better performance in terms of strength resistance as compared with the bent-up tab shear enhancement.

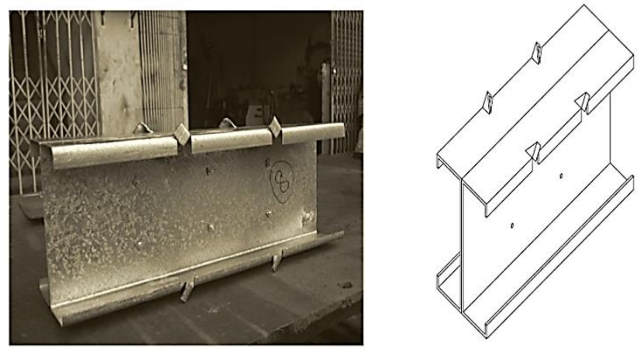


Figure 12 (a)

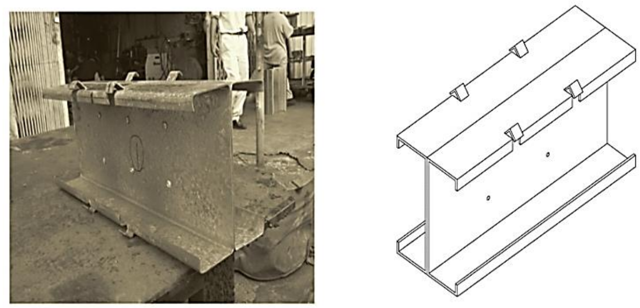


Figure 12 (b)

**Figure 12** Shear transfer enhancement by Irwan *et al*. [31]; (a) BTTST (b) Bent-up tab

Irwan *et al.* [3] have investigated large-scale test of symmetric cold-formed steel-concrete composite beams with BTTST enhancement (Figure 13). In this study a symmetric CFS-concrete composite beam was subjected to a static bending test based on BTTST. The results proved that the predicted values of the calculated flexural capacities using the Equation (1) for the shear capacity of BTTST agrees reasonably well with the experimental values. It was also revealed that specimens with shear transfer enhancement could largely reduce the deflection and increased the shear strength as compared with those without the shear enhancement. However, for all the specimens, the moment capacities (Mu, exp) were all above (Mu, theory) and showed an agreement with the calculated ratio of (≥1.00). They concluded that in terms of strength factors, the developed equation (1) had under predicted the actual strength of the CFS-Concrete composite beams when used to calculate the ultimate moment capacity.

$$Ptab = 0.01LfLsSin\theta (\sqrt{fcuE}) +0.5Lftfy \quad \text{Eq. (1)}$$

where,

Lf is collar length of BTTST in (mm), Ls is span length of BTTST in (mm), θ is angle of BTTST (in degrees), t is the thickness of CFS (in mm).

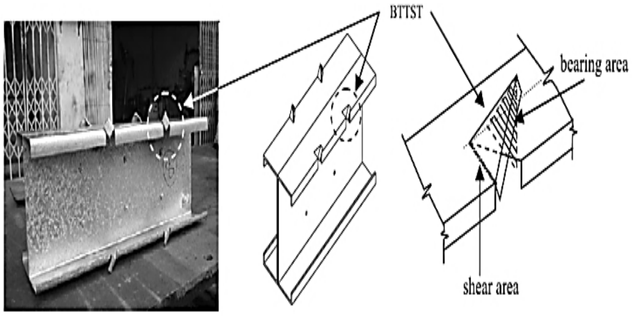



**Figure 13** BTTST employed by Irwan *et al*. [3]

Development of concrete and cold-formed steel composite flexural members was investigated by Wehbe *et al.* [32]. The research involved both experimental and analytical studies to assess the structural performance and failure modes of concrete and CFS track composite beams and also to develop optimum beam configurations for use in light-gauge steel (LGS) construction. The specimens are grouped as (Group 1 to Group 5 as shown in Figure 14). The flexural and shear strengths, flexural stiffness, and interface shear transfer were investigated in this research. The results indicated that concrete and CFS track composite beams can be designed for ductile flexural failure. Furthermore, the composite action was dependent upon the stand-off screws intensity rather than its configuration.

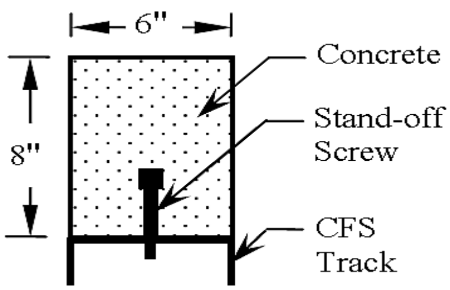



Figure 14(a)

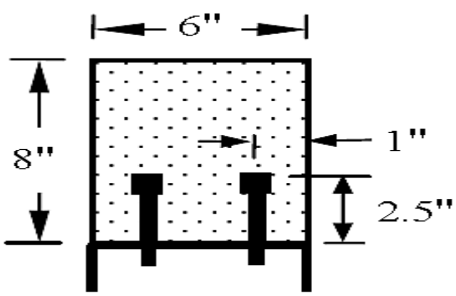



Figure 14(b)

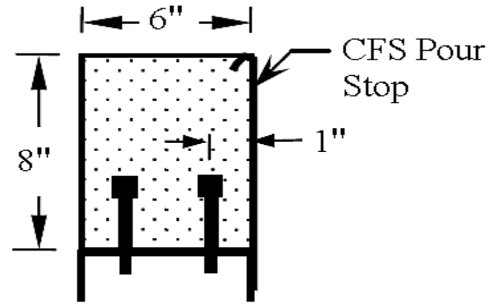



Figure 14(c)

**Figure 14** Cross sectional details of the test specimens (a) group 1(b) groups 2, 3, 4 (c) group 5[32]

Lee *et al.* [5] investigated on the effective steel area of fully embedded cold-formed steel frame in composite slab system under pure bending. They investigated four types of cold-formed steel frame profiles that were embedded in the concrete to form a new type of composite slab system (Figure 15). From the arrangement of tested specimens, it was concluded that S3-DV was predicted to have higher bending resistance in comparison with other three types of configuration.

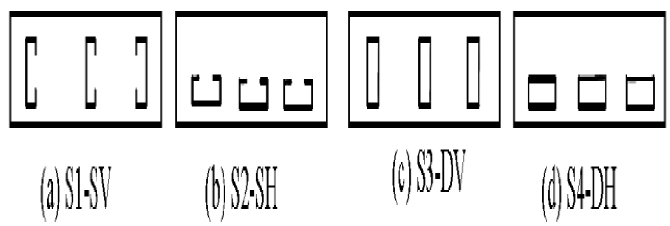



**Figure 15** Typical cross sectional view of the four types of slab configuration [5]

Bending behaviour, deformability, and strength analysis of prefabricated cage reinforced concrete (PCRC) beams were investigated by Rethnasamy *et al.* [33]. Comprehensive data and their interpretation on strength, deformation characteristics, ductility and mode of failure of beams in terms of effects of thickness of sheet, concrete strength and amount of tension reinforcement were presented. Accordingly, eighteen PCRC beams specimens and three rebar reinforced cement concrete (RRCC) were tested as shown in (Figure 16). Nine beams were created with cold-formed steel sheet with average yield strength of 260 N/mm2 and the rest of the beams were made with average yield strength of 400 N/mm2. The result showed that the confinement offered by prefabricated cage prolonged the initiation and propagation of cracks when compared to reinforced cement concrete (RCC) beams specimens and the beams exhibited well defined post peak behaviour. It was observed that the PCRC beams improved ductility and energy absorption capacity making it suitable for seismic resistant structure

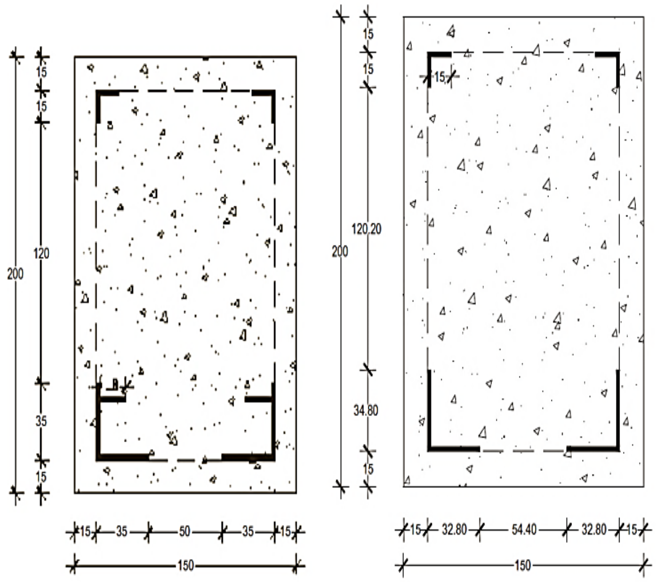
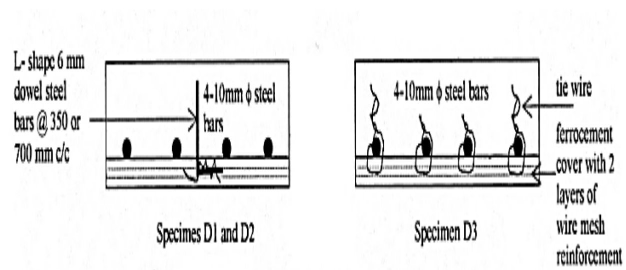



**Figure 16** Typical cross sectional details of beams specimens [33]



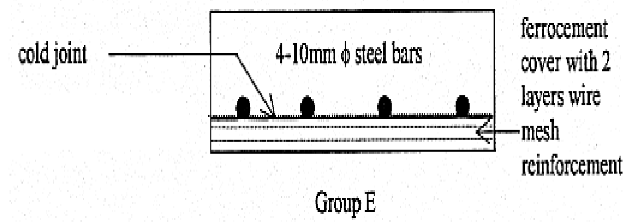




Figure 17 (c)

**Figure 17** Test specimen details [34].

## 2.3 Concrete-Ferrocement Composite Beam

Flexural behaviour of reinforced concrete slabs with ferrocement tension zone cover was investigated by Al-kubaisy and Jumaat [34]. The specimens were grouped A to E (Figure 17) in which A1-A3 labelled as for the control specimen, B1-B3; C1-C2; D1-D3 and E labelled for the test specimens. Effect of wire mesh reinforcement in the ferrocement cover layer, thickness of the ferrocement layer, and the type of connection between the ferrocement layer and the reinforced concrete slab on the flexural load, and first crack load were examined. The results indicated that the use of ferrocement cover slightly increases the ultimate flexural load and increases the first crack load.

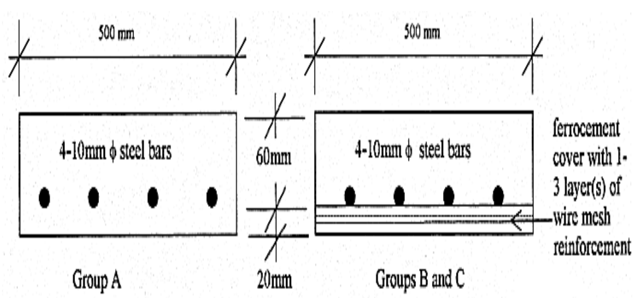



Figure 17 (a)

Nassif and Najm [35], investigated on the ferrocement-concrete composite beams from both of the experimental and analytical viewpoints. They explored methods of shear transfer between composite layers grouped as B1 and B2. Besides, beam specimens with various mesh types (hexagonal and square) grouped as A1 and A2 were also tested under two-point loading system up to their failure points (Figure 18). It was found that the group B2 consisting a shear connectors with hooks showed a better pre-cracking stiffness and strength than those in group B1 with L-shaped connectors. Also, group A1 with the square mesh exhibited better cracking capacity than group A2 with the hexagonal mesh. Thereby, the proposed composite beam showed a good ductility, cracking strength, ultimate capacity, and feasibility for field application.

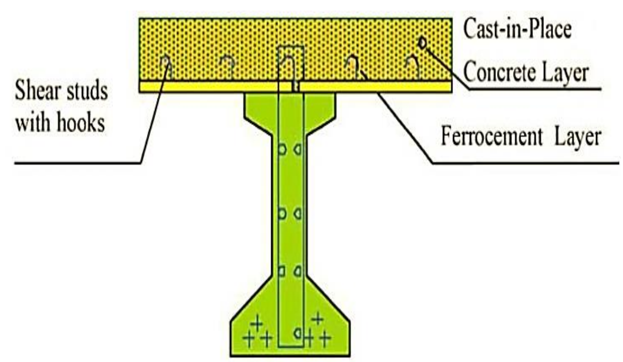



**Figure 18** shear connectors type used by Nassif and Najm [35]

Haddad *et al*. [36] investigated on various repair techniques to restore the structural capacity of heat-damaged high- strength reinforced concrete shallow beams using advanced composites. A series of sixteen under-reinforced concrete hidden beams were cast (Figure 19), heated at 600ºC for 3 hours, repaired, and then tested under four point-loading. The used composites include the high strength fiber reinforced concrete jackets;

ferrocement laminates; and high-strength fiber glass sheets. The repaired beams with steel and high performance polypropylene fiber reinforced concrete jackets regained up to 108 and 99% of the control beams' ultimate load capacity, respectively. Accordingly, their stiffness's were also increased up to 104 %, and 98% respectively. Furthermore, the repaired beams with the fiber glass sheets and ferrocement meshes regained up to 126 % and 99% of the control beams' ultimate load capacity, with a corresponding increase in stiffness of up to 160 and 156%, respectively. Most of the repaired beams showed a typical flexural failure with very fine and well- distributed hairline cracks in the constant moment region.

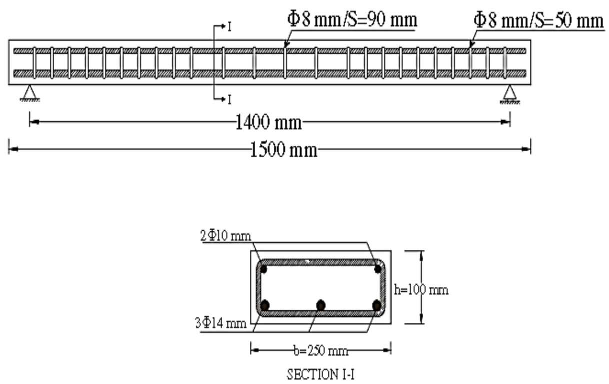



**Figure 19** Details of beams reinforcement presented by Haddad *et al*. [36]

An experimental investigation on flexural behaviour of reinforced concrete beams strengthened with high-performance ferrocement was studied by Liao and Fang [37]. Three RC beams strengthened with high-performance ferrocement and two control specimens without strengthened with the ferrocement were investigated when the RC beams were of low compressive strength. Flexural behaviours of strengthened RC beams with high-performance ferrocement were then evaluated and compared with the normal RC beams. The flexural capacity, deflection, and crack width of RC flexural beams were measured. The test results indicated that ferrocement contributed greatly to the increase on the flexural capacity and raised crack-resisting capacity.

Sandesh *et al.* [38] investigated on the performance of chicken wire mesh on the strength enhancement of retrofitted beams with ferrocement jackets (Figure 20). The RC beams were initially stressed to a prefixed percentage of the safe load. Then, in order to increase the strength of beam in both shear and flexure stiffness, the RC beams and were retrofitted using ferrocement jackets. The chicken wire mesh was placed along the longitudinal axis of the beam. It was concluded that the load carrying capacity of the retrofitted RC beams was significantly increased with chicken wire mesh used as reinforcement for the retrofitted ferrocement.

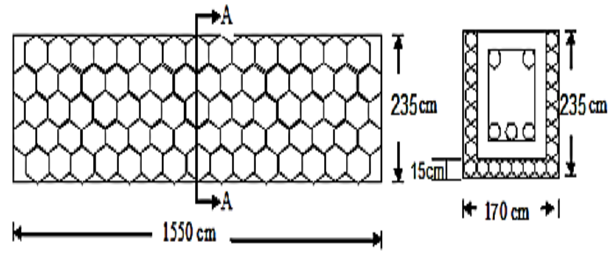



**Figure 20** Retrofitted beam specimen by Sandesh *et al*. [38]

The use of permanent ferrocement forms for concrete beam construction was also investigated by Tawab *et al*. [39]. They examined the feasibility and effectiveness of using precast U-shaped ferrocement laminates as permanent forms for construction of reinforced concrete beams (Fig. 21). The experimental program comprised of casting and testing of three control reinforced concrete beams of dimensions 300x150x2000 mm. A total of eighteen beams with the dimensions of 300x150x2000 mm consisting of a reinforced concrete core cast in a precast U-shaped permanent ferrocement form and thickness 25mm were created. The performance of the test beams in terms of strength, stiffness, cracking behaviour and energy absorption were investigated. The results showed that high serviceability and ultimate loads, crack resistance control, and good energy absorption properties were achieved by ferrocement forms.

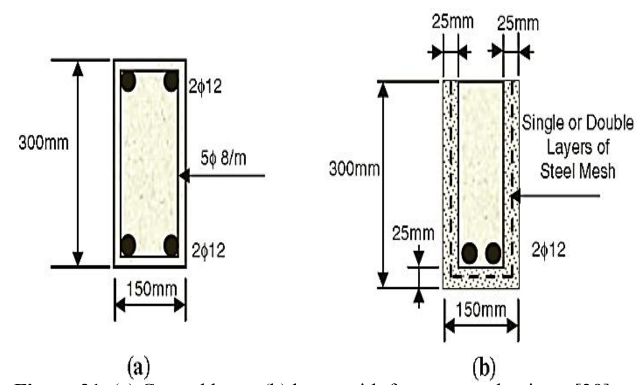



**Figure 21** (a) Control beam (b) beam with ferrocement laminate [39]

## 3.0 CONCLUSIONS

This review study revealed the composite characteristics of both the CFS-Concrete and Concrete-Ferrocement as composite elements. Accordingly, various structural composite elements were studied, which they were made up of CFS-Concrete as composites. After reviewing numerous literatures, it is observed that the RC beams created with the ferrocement as an encasement of concrete proved to be more satisfactory on improving the structural element's performances. In addition, the ferrocement RC beams also enhanced both the shear resistance and flexural strength significantly. Considering the researches presented in this study, composite performance between CFS-SCC is yet to be established. Therefore, study on composite behaviour between CFS-SCC is a key research that needs to be investigated.

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