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# Push-out Tests of Innovative Shear Connectors Between Cold-formed Steel Section Integrated with Ferrocement Jacket

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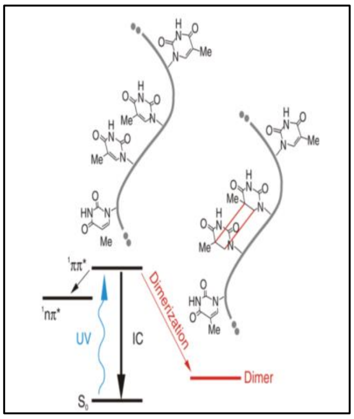
**Graphical abstract**




**Abstract**

Traditional construction materials such as steel and concrete exhibit signs of deterioration over the years. This can be attributed either to the inherent nature of the materials or their weak resistance to adverse the environmental conditions and natural disasters, such as, fires, earth quakes, etc. The use of ferrocement as an external jacket to cold-formed column is presented in this study to provide an alternative solution to existing construction materials. Ferrocement is a special form of reinforced concrete, which exhibits a behavior that differs much from conventional reinforced concrete in strength performance and other potential applications. The use of ferrocement with cold-formed steel as composite column is a new approach to enhance the axial load capacity of the later. Hence, the composite action between ferrocement and cold-formed steel section have to be established by means of understanding the behavior of the proposed shear connectors. In this study, push-out test set-up is proposed for eight specimens with various shear connectors' configuration. The utilization of high strength self-compacting ferrocement mortar in the design of cold-formed steel integrated with ferrocement jacket as composite column is proposed. It was observed that ferrocement jacket with 12 mm bolt shear connectors showed the best shear capacity when compared to other proposed shear connectors.

*Keywords:* Push out test; cold-formed column; ferrocement jacket; shear connector; bolts; wire mesh



## ■1.0 INTRODUCTION

Traditional construction materials for composite column such as hot-rolled steel and concrete are well-known for their long-term performance. This is due to the well-established advantages of composite columns, like increase in strength, increase in stiffness, good fire resistance and corrosion protection in encased columns [1, 2, 3, 4, 5, 6]. In composite construction process, bare steel section carries out the preliminary load during construction. Concrete is cast around the steel section in a later stage. Concrete and steel are combined together to form a composite column by proposed shear connectors. However, retrofitting or rejuvenation of structures composed of such materials requires the use of skilled labours, heavy equipment, excessive energy and time which results in the escalation of overall cost. Recent evaluation of the civil engineering infrastructure has demonstrated that most of it needs major repairs in the near future.

The maintenance of under-strength or deteriorated steel structures has been a subject of concern to structural engineers for decades. Major causes of distress or pre-mature deterioration pertaining to steel structures include improper design or its construction, changes in structural function, and modifications in load specification, corrosion of steel, and exposure to impact or fire, etc. When a structural member is a steel column, the use of concrete jacketing is a commonly used technique by encasing the existing steel section in a reinforced concrete jacket. Despite the wide application of concrete jacketing to strengthen the steel columns of existing structures, research on the jacketing of such cold-formed steel columns is still in the early stages. Since the last century, concrete jackets have been provided primarily to serve as protection against corrosion and fire [7], and were thus assumed not to resist structural loading. In modern steel–concrete composite construction techniques, stiffness and strength of the column can be increased by the use of concrete jacket.

This study investigated the use of proposed shear connectors in ferrocement as an external jacket to cold-formed column. Ferrocement is a special form of reinforced concrete, which exhibits a behavior differing much from conventional reinforced concrete in strength performance and potential application. Therefore, the uniform dispersion of reinforcement in the matrix offers in achieving improvement in many of the engineering properties of the material, such as tensile and flexural strength, toughness, fracture, crack control, fatigue resistance impact resistance and also providing advantages in fabrication [9]. In developing countries, raw materials for ferrocement construction are easily available and able to form into any complicated shape. The skill required is of low level and it has superior strength properties compared to conventional reinforced concrete [10, 11, 12, 14, 15]. Published data showed that jacketing with rounded corner give certain degrees of confinement by reducing stress concentration at corners [15, 16]. This justifies the development of innovative rehabilitation and strengthening method by ferrocement jacket for cold-formed steel structures. The development of innovative rehabilitation and strengthening technique is required to extend the life expectancy of many steel structures. Limited studies were reported for similar work in case of ferrocement strengthened with cold-formed column.

Stud (or bolt) connectors are subjected to flexural and axial forces in resisting the interface forces by means of dowel action. Force transfers in composite structures depend on the strength and stiffness of various components of the composite beam as well as the shear connectors. Therefore, it is necessary to determine the design parameters namely, shear strength and stiffness for stud connector prior to their use in construction. This task is mostly accomplished by conducting experiments on push-out specimens.

Several types of push-out specimens have been studied in the past decades and reported in some literatures. Behaviour of stud shear connectors in light weight and normal weight concrete was studied by Al-Salloum [17]. Investigation on the strength of push-out specimens have been carried out by Ollgaard *et al*. [18] Later, Hawkins [19] recommended various empirical equations to include the effect of variation in material strength as well as on the strength of shear connectors. Effect of transverse reinforcement on the shear strength of stud shear connectors have been investigated by Oehlers and Johnson [20] using push-out tests. It was reported that the shear strength is affected by stiffness of transverse reinforcement and not by its strength. Static push-out tests were conducted by Lloyd and Wright [20] as well as Shim *et al*. [21] to determine the ultimate slip and strength of large diameter stud shear connectors.

It is reported by BS EN 1994-1-1 [23] that transverse reinforcement provides confinement to the concrete in the vicinity of studs rather than contribution to the strength. Shear stiffness, ultimate slip capacity and shear strength of stud connectors have been determined. The behaviour of stud connectors in high strength and normal strength concrete has been studied by Oehlers and Park [20]. Studs in normal strength concrete reported to exhibit ductile behaviour as the descending branch was gradual and longer as compared with studs in high strength concrete. Research work by Li and Cederwall [24] and recently by Bro and Westberg [25] reported a comprehensive compilation of experimental studies on push-out specimens. It was reported that the equations given in Pallares and Hajjar [26] need modifications to comply with experimental trends. In this paper a new push-out test set-up is proposed with eight push-out specimens, designated as S1 to S8, and are tested under compression axial loading. The utilization of high strength self-compacting ferrocement mortar in the design of cold-formed steel / ferrocement jacket composite column was presented and discussed.

## ■2.0 PUSH OUT TEST

### 2.1 Material Properties and Mix Design

Considering the real situation on a building site where mechanical consolidation is not possible for conventional mortar to be distributed into the wire mesh of ferrocement, a self-compacting mortar (SCM) is used. The significant advantage of using SCM is its ability to flow easily as compared to the typical mortar. The free flow of the SCM has the ability to fill in a small holes in ferrocement developed in the column. The hydraulic cement matrix for ferrocement in this study was designed according to standard mix design procedures for mortar and concrete. It is well known that mixing procedures have a significant influence on fresh properties of SCM [27]. All materials in SCM including water were weighed prior to the mixing process. The sand and binder were mixed in an electrically operated mortar mixer at 275 ± 10 rpm for about 3-10 minutes to ensure uniform mixture as proposed by Jawahar *et al*. [28]. The details of properties of mortar mix are presented in Table 1.

Four trial mixes were prepared base on cement/dry sand weight ratio of 1:2, 1:1.5 and 1:2.25. All mixes were batched in a horizontal electrically operated mixer and each mix has six cubes specimens of size 100 mm×100 mm×100 mm for all specimens. The cubes were kept in water tank until the day of testing. Properties of the mortar, compressive strength, $f_{cu}$ was obtained through cube compression test. Three of the nine cubes were tested at age 3, 7 and 28 days for compressive strength of grade 35 N/mm$^2$. The mixture of cement/dry sand ratio (1:2) was chosen in this investigation because of its optimum strength and workability. Table 2 shows the details of properties of trial mixes.

**Table 1** Mix proportion of mortar

| **Binder : Sand** | **1:2** |
|---|---|
| OPC | 85 % of total binder by weight |
| Silica fume (SF) | 15 % of total binder by weight |
| Water-binder ratio | 0.35 |
| Sand | Passing through sieve size # 8 |
| Superplasticizer (S.P.) | 2 % of OPC by weight |

**Table 2** Properties of trial mixes of mortar by weight (kg/m$^3$)

| Mortar MIX | Cement (kg) | Sand (kg) | Silica Fume (kg) | Water (kg) | lime stone powder (kg) | S.P (kg) | C:S |
|---|---|---|---|---|---|---|---|
| **Mix1** | 600.0 | 1200.0 | 48.00 | 259.2 | 90 | 12.00 | 1:2 |
| **Mix2** | **621.0** | **1242.0** | **93.15** | **250.88** | --- | **12.42** | **1:2** |
| **Mix3** | 710.5 | 1065.7 | 106.57 | 284.2 | --- | 14.21 | 1:1.5 |
| **Mix4** | 583.0 | 1312.6 | 87.50 | 235.7 | --- | 11.66 | 1:2.25 |

## 2.2 Cold-Formed Steel (CFS)

All cold-formed steel (CFS) materials used in this study are un-galvanized steel of 4 mm thickness. This material produced by LYSAGHT has a yield strength of 300N/mm$^2$ (G300), which is prepared from the ALEXFORM steel manufacturing factory in Egypt. Properties of the steel sections were obtained through a series of coupon tests. The dimension of the test coupon and tensile test procedure were carried out according to ASTM 370-03a [29]. Three test coupons of 4 mm thick were conducted in order to determine the yield and ultimate stresses of the built-up steel tubes. The results from the tensile test are given in Table 3.

**Table 3** Tensile coupon test results

| Coupon specimen | Yield stress, fy (MPa) | Ultimate strength , fu (MPa) | Modulus of Elasticity, E (MPa) |
|---|---|---|---|
| **1** | 331.8 | 426.3 | 223106 |
| **2** | 325.5 | 439.1 | 215171 |
| **3** | 331.7 | 421.5 | 198026 |
| **Average** | **329.7** | **429.0** | **212101** |

## 2.3 Reinforcement and Skeleton Wire Mesh

Weld mesh was arranged in different layers in ferrocement jacket instead of reinforcement. The wire mesh used in this study was 20 BWG (British Standard Wire Gauge) with woven GI (Galvanized Iron) wire mesh of 20 mm square opening. Weld mesh of size 750 mm × 400 mm with grid size square opening of 20 mm × 20 mm and rod diameter 1.2 mm was used for casting ferrocement jacket. The number of wire mesh layers (2 and 6) was tied with binding wire on weld skeleton steel mesh and providing no spacing between them. The average ultimate stress and young's modulus of elasticity of wire mesh were 300 MPa and 2.1× 105 N/mm2, respectively.

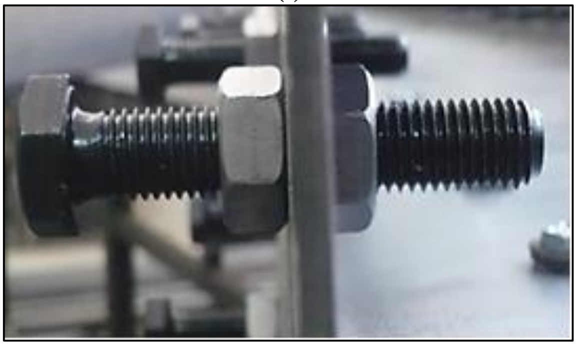
## 2.4 Shear Connectors

Various types and shapes of shear connectors, namely bolts (10 mm and 12 mm diameter), bar-angle (10 mm diameter) and self-drilling screw (6.3 mm diameter) were used (Figure 1a). In order to prevent the uplift shear force all of the shear studs were fastened between two nuts on the wall of CFS surface. All shear connector were embedded 40 mm inside the ferrocement jacket and tied by two nuts directly to the flange of cold-formed column (Figure 1b). The spacing distance between the upper shear connector and the lower part of the jacket was kept constant at 300 mm and the spacing between connectors was 85 mm, as suggested by Eurocode 4 [23].

## 2.5 Test Program

Experimental tests with ferrocement jacket were prepared for eight specimens using SCM. As shown in Figure 2, a push-out specimen consisted of full jacket ferrocement boxed around the short lipped C-channel of cold-formed steel section of size 300×75×25×4 mm by means of shear connectors. The assembly was subjected to a vertical load which produced shear load along the interface between the ferrocement jacket and the cold-formed steel column flange on both sides. The shear load was transferred to the ferrocement jacket through shear connectors. A recess of 50 mm was provided between the bottom of the jacket and the lower end of the lipped C-section cold-formed steel column to allow for slip at the cold-formed steel-ferrocement interface during testing. The task of this study is to investigate the strength behavior of varied shear connectors between ferrocement jacketed with cold-formed steel under compression axial load. Four of the test specimens were installed with bolts of sizes 10 and two specimens were installed for bolt with 12 mm diameter, two specimens of L-bar angle with 10mm diameter and two specimens of self-drilling screw of 6.3mm diameter. The ferrocement jacket which used to strengthen the cold-formed steel section has resulted in a uniform cross section of 400×250 mm$^2$ along the full length of the cold-formed column for all of the specimens. The overall thickness of the jacket for all specimens was 50 mm. All shear connector were embedded 40 mm inside the ferrocement jacket and tied by two nuts directly to the flange of cold-formed column.


(a)



(b)

**Figure 1** The shear connectors used, (a) Types of shear connection; (b) Method of nuts fastening

## 2.6 Fabrication of Ferrocement Jacket

The lipped C-section of cold-formed columns was jacketed with different number of wire mesh layer of ferrocement jacketing. Final section of jacketed specimens was 400×250 mm$^2$ including 50 mm thick ferrocement jacket woven GI

(Galvanized Iron) wire mesh of 20 mm square opening was used in this study. Wire mesh was kept at the middle of jacket with a clear cover of 2.0 mm. All composite columns, after completing jacketing, were cured in the water for 28 days from the date of casting.

The ferrocement jackets of all the push-out specimens were cast vertically to simulate the actual casting condition in a composite column. In conventional ferrocement jacket, a square jacket consists of only a single layer wire mesh. However, in this study, a single layer of wire mesh was change to two and six layers (see Figure 2).

**Figure 2** Preparation of CFS and wire mesh layers as column jacket

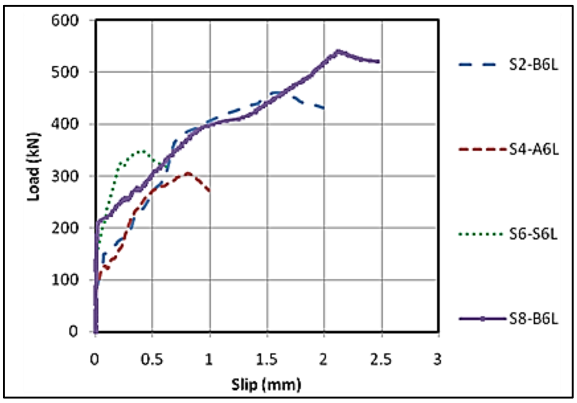
After curing, all columns were tested under monotonically increasing concentric load applied at the top with a hydraulic compression testing machine of capacity 1000kN until failure. Axial and lateral deflections were measured using three LVDT's within the accuracy of 0.00254 mm. Test set-up and LVDT's positions are shown in Figure 3.

**Figure 3** Push-out specimen under testing

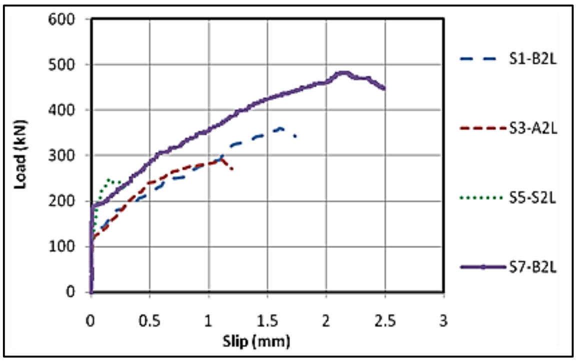
## 3.0 RESULT AND DISCUSSION

### 3.1 Test Results

During the experimental tests for specimens S1 to S6, it was observed that shear connectors, namely bolts (10 mm diameter), bar-angle (10 mm diameter) and self-drilling screw (6.3 mm diameter) have broken while the condition of ferrocement jacket still continued intact without any crushing. The failure mode was occurred in the head of the stud connectors (see Figure 5). Conversely, for bolt (12 mm diameter) in specimens S7 and S8, the failure was in the axial displacement on ferrocement jacket. The summary of experimental results is shown in Figure 4. Table 4 presents the slippage at ultimate load, the comparison of results and the failure mode.




(a)




(b)

**Figure 4** Load-slip curves for specimens with 2 and 6 wire mesh layers of ferrocement jacket, (a) 6 wire mesh layers of ferrocement jacket, (b) 2 wire mesh layers of ferrocement jacket

**Table 4** Summaries of tests specimens and results

| Designation | Diameter (mm) | Type of Shear connector | Number of layers | Ultimate Load (kN) | slip at ultimate load (mm) | Strength capacity (2&6 layers) (%) | Failure Mode |
|---|---|---|---|---|---|---|---|
| S1-B2L | 10 | Bolt | 2 | 360.62 | 1.609 | 27.58 | Bolt |
| S2-B6L | 10 | Bolt | 6 | 460.1 | 1.589 | | |
| S3-A2L | 10 | Bar-angle | 2 | 290.75 | 1.107 | 20.18 | Bar-angle |
| S4-A6L | 10 | Bar-angle | 6 | 349.42 | 0.806 | | |
| S5-S2L | 6.3 | Self Drilling Screw | 2 | 248.32 | 0.163 | 22.73 | Self Drilling Screw |
| S6-S6L | 6.3 | Self Drilling Screw | 6 | 304.76 | 0.161 | | |
| S7-B2L | 12 | Bolt | 2 | 481.53 | 2.121 | 12.16 | Ferrocement |
| S8-B6L | 12 | Bolt | 6 | 540.11 | 2.132 | | |

**Notes:** S1: Specimen number; B (bolt) A (bar-Angle), S (self-drilling screw): Type of shear connector; (2 or 6 L): Number of wire mesh layer.

## 3.2 Strength and Load Capacities

The test data revealed that the load slip responses of all specimens tend to exhibit a different pattern. It can be observed from these curves that the strength capacity of the ferrocement and load carrying capacity of the specimen increase up to 27.58% with an increase in the number of layer of wire mesh from 2 to 6 layers (see Figure 4). Each curve consists of a linear relationship up to about 80 to 90% of the failure load followed by a non-linear pattern before the failure point. Most of these specimens showed that the load was dropping off after reached to failure point. These specimens remained almost cohesive even after failure point until reaching to a total loss of bonding between the ferrocement jacket and the steel section as shown in Figure 6. It was also noted that a slight deformation in the flanges of specimens S7 and S8 was occurred.

## 3.3 Ferrocement Failure

Failure pattern of tested ferrocement jacket specimens are shown in Figure 6. Failure of ferrocement jacket in the specimens S7 and S8 started due to spalling of ferrocement at the corner of jacket. The ultimate strength load in specimen S8 with 6 layers of wire mesh showed the highest failure load value. In addition, depending on the direction of transmitted force from the connection, shear or tension type failures are observed. A relatively small displacement indicates that the ferrocement fails due to shear forces which lead to longitudinal shear crack. However, a relatively high observed displacement indicates that high shearing force developed in the screw has been transferred to the concrete jacket which leads to the crushing of ferrocement jacket. It developed a crack in the jacket with lower concrete strength at the level of the shear connector at approximately 350 kN. As the applied load was increased, splitting cracks were observed in the mid jacket. Then, after the removal of the damaged concrete jacket, it was observed that the shear connectors had undergone considerable deformations but remained attached to the steel wall with the wire mesh. As a consequence, the crushing of the ferrocement jacket was more observed in the specimens of 2 wire layers more than the specimens with 6 layers of wire mesh.

(a) Self drilling screw (b) Bar-angle (c) Bolt 10mm

**Figure 5** Failure modes of shear connectors

(a) Cracking Pattern (b) Bolt 12mm Shear Connector

**Figure 6** Crushing failure mode in ferrocement jacket

### 3.3 Discussion of Results

The shear capacity and the bond strength of push-out tests with the newly proposed connecting system between lipped C-channel of CFS and ferrocement jacket has been investigated in this study. Three types of shear connectors were used to form the composite action between steel column and ferrocement namely bolt, bar-angle and self-drilling screw shear connectors. From the push out test it was found that ferrocement jacket of all shear connectors except the connector (bolt 12 mm) had apparent failure modes. The following conclusions are drawn from this study.

- Increase in the number of wire mesh layer has negligible contribution to the shear strength of the connector.
- Shear connectors consisting of bolt with10 mm in diameter and self-drilling screw 6.3 mm in diameter were failed due to shear off failure. However, in 12 mm bolt, the failure was due to the cracking of ferrocement mortar.
- Specimens consists of two layers of ferrocement showed more cracks than specimens with six layers of ferrocement which indicate that the increase in the layers of mesh can decrease considerably the formation of cracks in the ferrocement jacket.
- The highest shear capacity (540.11 kN) in steel-ferrocement jacket interface was recorded for the proposed shear connector with 12 mm bolt diameter.
- The new shear connectors of 12mm bolt diameter was suitable to provide composite action between CFS column and ferrocement jacket as composite column structure as the strength and ductility of the connectors performed well during the tests.

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