Experimental study on ferrocement slabs externally reinforced with CFRP strips

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Abstract. This study was conducted to investigate the effect of Carbon Fibre Reinforced Polymer (CFRP) on the stress responses of ferrocement slabs. For this purpose, a total of eight ferrocement slabs of size 500 x 500 x 18 mm were cast and tested. The major variables studied in this investigation included the number of CFRP strips and their configurations. Structural performance parameters used for comparisons included load–deflection curves, ultimate load and corresponding deflection at failure, failure modes, and crack patterns. That the inclusion of CFRP strips for strengthening ferrocement slabs can significantly improve their resistance may be concluded from these experiments. The increases ranged between 26 and 74% compared with the control specimen. Furthermore, an increase in the stiffness of the ferrocement slabs at all stages of loading, and a consequent reduction in the deflection at corresponding loads, was observed in specimens with CFRP compared to the control specimen. This decrease in maximum deflection was about 23.5 to 53.6% compared with the unstrengthened slab.

Keywords: ferrocement, CFRP, punching shear, slabs, wire mesh.

1. Introduction
Ferrocement is a special type of reinforced concrete that consists of multiple layers of closely spaced continuous small size wire mesh embedded in a hydraulic cement matrix to produce a thin element [1-2]. This construction makes the raw materials that used in construction of ferrocement more obtainable, and it can be fabricated in complex shapes with less skilled labour. Ferrocement exhibits a high tensile strength-to-weight ratio and magnate cracking behavior compared to conventional reinforced concrete, and as such, it can be utilised in a number of practical application such as agricultural applications [2], applications in water supply and sanitation [3], housing and rural energy [4-8], repair [9-12], and strengthening of other concrete structural members [13-16].

During the process of drilling ferrocement structural elements to connect them with other structural elements or when they are subjected to punching forces, the vicinity of the drilling regions is exposed to multiple small fractures which leads to weakness in the overall bearing resistance. The study conducted by Mansur et al. [17] indicated that punching shear failure occurs at the bolt locations in thin ferrocement panels subjected to bending moment. The use of short fibres or microfibres in the matrix of ferrocement has been seen to help in overcoming that problem. Researchers have proved that adding fibres to the matrix can help to significantly increase shear capacity, help with making neater drilled holes, improve impact resistance, reduce crack width and, spacing of cracks in ferrocement members [18-19].

The performance and ductility behaviour of ferrocement elements externally strengthened with FRP strips in their tension zones have also been investigated [20]. According to the information available from previous studies, however, work focusing solely on the strengthening of ferrocement slabs with CFRP are insufficient. Therefore, to uncover the most efficient use of CFRP strips to strengthen ferrocement slabs under punching shear is the main goal of the current study.
2. Experimental investigation

The experimental program consisted of testing eight specimens to explore the punching resistance of ferrocement slabs strengthened with CFRP strips. The major variables studied in this investigation included the number of CFRP strips and their configuration. The cast slabs dimensions were 500 × 500 ×18 mm. Specimen details and main study parameters are summarised in Table (1) and Figure 1. Load-deflection curves, crack patterns, and cracking at ultimate load and the corresponding deflections were observed throughout the study.

![Schematic drawings showing the CFRP layout](Image)

**Figure (1)**. Schematic drawings showing the CFRP layout
Table 1. Details of specimens.

| Slab No. | No. of wire mesh layers | Volume fraction (Vf %) | No. of CFRP strips | Location of CFRP strips                        |
|---------|-------------------------|-----------------------|-------------------|------------------------------------------------|
| S1      | 5                       | 3.5                   | 0                 | ---                                            |
| S2      | 5                       | 3.5                   | 4                 | Adjacent to the column face                     |
| S3      | 5                       | 3.5                   | 2                 | Perpendicular at the centre of slab             |
| S4      | 5                       | 3.5                   | 4                 | At a distance (1.5 d *) from column face at 45° |
| S5      | 5                       | 3.5                   | 4                 | Perpendicular and at the distance (1.5 d) from column face |
| S6      | 5                       | 3.5                   | 2                 | Perpendicular toward the diagonal               |
| S7      | 5                       | 3.5                   | 4                 | Adjacent to the column face at 45°              |
| S8      | 5                       | 3.5                   | 8                 | Perpendicular and at the face of column         |

* d = depth of the slab

2.1. Materials and mixing proportions

The mortar matrix consisted of locally available ordinary Portland cement and natural sand passed through sieve No. 30. In the mix, 10% by weight of cement was replaced with silica fume. The water and sand to binder ratios by weight were chosen as 0.33 and 1.0, respectively. A superplasticizer, Sika Viscocrete 5930, was used as a high-range water reducer, and the dose of superplasticizer used was 2.8% by total binder weight. Sika Viscocrete 5930 complies with BS 5075, 1982, and ASTM-C494, Type F specifications. Potable water was used in the experimental work for both mixing and curing.

Reinforcement of the ferrocement slabs was provided by steel welded square wire mesh with an average wire diameter of 1.0 mm and 12.5 mm spacing. The mesh was tested according to the design guide on the construction and repair of ferrocement published by ACI committee 549[1]. The yield strength of the wire mesh was determined to be 405 MPa, and the average ultimate strength of the wire mesh and modulus of elasticity were found to be 600 MPa and 95 GPa, respectively.

Sikawrap 300, a unidirectional woven carbon fibre fabric equipped with weft fibre of a thickness of 0.17 mm, was used to enhance the ferrocement slabs. Sikadur 330 structural impregnating resin epoxy adhesive was used to attach the strips; this is a solvent-free, two-component adhesive non-sag paste.

2.2. Fabrication of test specimens

The wooden mould used their dimensions were 500 x 500 x 18 mm. Five layers of wire with 3.5% volume fraction (Vf) per slab were tied together using fine steel wires and then placed inside the moulds after they were lubricated with oil. A fresh highly workable mortar mix was then poured into the wooden moulds. Along with the slabs, a total of six 50 x 50 x 50 mm mortar cubes and six 40 x 40 x 160 mm mortar prisms were moulded. The mortar specimens were used for determining the compressive and flexural strengths of samples. The matrix was characterised by average compressive and flexural strengths of 45 MPa and 3.24 MPa, respectively. The moulded specimens were cured in the mould for 24 hours and then removed from their moulds and immersed in the curing tank for 28 days. After that, the ferrocement slabs were grinded and cleaned. The two components of the adhesive (Sikadur-330) were mixed in appropriate 4:1 proportions with an electric mixer until a uniform grey colour was obtained. A thin layer of adhesive paste was then applied with a special tool to the bottom side of each ferrocement slab and to the CFRP strips, which were then adhered as shown in Figure 2. Before the testing day, each slab was painted with white paint on all surfaces to promote clear visibility of cracks during testing. Each slab was carefully placed on simple supports. Figure 2 shows details of the creation of specimens.

2.3. Specimens testing

The tested slabs were simply supported on all four sides with the corners free to lift, and each slab was free to rotate about its support axes. A single concentrated load was applied at the centre of the top slab.
surface of each slab via a rigid bearing steel plate with dimensions of 40 x 40 x 40 mm. The central deflection was measured using a dial gauge laid under the centre of the bottom surface of each slab. All specimens were tested under a centre-point loading method with an effective span of 400 mm for each side. The load was applied in increments, and at each load level, at the mid-span of the slab using a machine with a capacity of 5.0 Ton. Figure 3 shows the test setup of a specimen.

3. Results and discussions

3.1. Load-deflection relationships
The load versus central deflection curves for the slabs are presented in Figures 4 to 11. The curves in these Figures seem to approximately show the same trends. The progress of cracks and failure pattern of all tested specimens also developed in similar ways. At the first stage of loading, the load-deflection relationship was linear, and the initial stiffness of all strengthened slabs was higher than that of the control sample. After the development of cracks, a reduction in the stiffness of slabs with increases in the applied loads was seen. When approaching maximum load, the load-deflection response appeared
to respond to the reduction in stiffness of the tested slabs, and the tendency of the curve moved closer to the horizontal line.

To investigate the effect of CFRP on the behaviours of ferrocement slabs, the deflection of the strengthened specimens was compared with that of the reference specimen. As observed from the figures, the addition of CFRP strips to the soffit of ferrocement slabs created higher stiffness relative to the reference slab. Slabs S7 and S8, strengthened by the addition of CFRP strips, showed major decreases in total deflection relative to the reference slab S1. The increase in stiffness of strengthened specimens was related to the number of CFRP strips applied and their configuration. The same finding can be noted for other strengthened specimens. The average decrease of ultimate deflection of the strengthened ferrocement slabs compared to the control slab were 35.4, 28.8, 41.2, 23.5, 50.0, 52.9, and 53.6% for slabs S2, S3, S4, S5, S6, S7, and S8, respectively, as shown in Table 2. Based on this, it is obvious that the stiffness of strengthened slabs will increase with an increase in the number of CFRP strips.

Also, from Table 2, an increase in ultimate punching resistance of the strengthened ferrocement slabs compared to the control slab can be shown. The average increase in ultimate punching resistance was 58.9, 37.0, 29.4, 26.1, 37.8, 69.6, and 73.7% for the slabs S2, S3, S4, S5, S6, S7, and S8, respectively. From this, it can be clearly seen that the ultimate punching load is greatly influenced by presence of CFRP strips.

Further, Table (2) clearly shows that slab S7 has the best scheme of CFRP configuration. Slab S7 had four strips located with a skew of 45°at the face of the column, as shown in Figure1. When comparing S7 and S8, slab S8 has a slightly high ultimate load than S7; however, the number of CFRP strips used in S8 was twice that of S7, as the arrangement of the strips becomes approximately perpendicular to the punching shear cracks distributed in a radial direction to the edges of the slab. Based on this observation, it can be concluded that the distribution and configuration of CFRP has a superior effect in terms of improving the punching resistance capacity of strengthened specimens.

### Table 2. Test results.

| Slab No. | Ultimate load (kN) | Increasing in ultimate load (%) | Ultimate deflection (mm) | Decreasing in ultimate deflection (%) |
|----------|--------------------|---------------------------------|--------------------------|--------------------------------------|
| S1       | 7.08               | -                               | 17                       | -                                    |
| S2       | 11.25              | 58.9                            | 10.98                    | 35.4                                 |
| S3       | 9.70               | 37.0                            | 12.1                     | 28.8                                 |
| S4       | 9.16               | 29.4                            | 10.0                     | 41.2                                 |
| S5       | 8.93               | 26.1                            | 13.0                     | 23.5                                 |
| S6       | 9.76               | 37.8                            | 8.5                      | 50.0                                 |
| S7       | 12.01              | 69.6                            | 8.0                      | 52.9                                 |
| S8       | 12.3               | 73.7                            | 7.88                     | 53.6                                 |
Figure 4. Load versus central deflection for S1

Figure 5. Load versus central deflection for S2

Figure 6. Load versus central deflection for S3

Figure 7. Load versus central deflection for S4

Figure 8. Load versus central deflection for S5

Figure 9. Load versus central deflection for S6
3.2. Cracks patterns and failure modes

As mention, the propagation of cracks and the failure pattern for all tested specimens were similar, in that the progress of cracks and failure patterns for all tested specimens were visually similar. For control slab S1, the first visible crack (flexural crack) was recorded at the bottom face of the slab, sited directly below the loading plate. With an increase in the load, more new cracks developed in both directions, and the propagation of cracks that started from the centre spread toward the corners and the edges of the slab. Newly formed cracks created an almost semi-circular feature or elliptical shape located on the underside of the slab. When approaching the maximum load, the load-deflection response created a reduction in stiffness of the tested slab and the tendency of that curve was to move towards the horizontal line. Failure mechanisms occurred abruptly with a decrease in load capacity, when the load reached ultimate value and the slab failed against punching shear. Punching failure is characterised by a serious and rapid drop in the load. The upper face (compression face) of each slab did not show signs of any cracks, except for those seen around the region of loading at the failure stage, which were almost identical to the dimensions of the loading plate. The crack patterns in the tension side of the control slab are presented in Figure 12.

For slabs strengthened with CFRP strips, the failure mode was generally punching shear combined with debonding of the CFRP strips. Debonding of CFRP occurred due to the pulling out of the specimen at punching load, which led to the production of shear stresses between the CFRP strips and slabs. The debonding happened simultaneously with a yielding of the internal wire mesh reinforcement. During failure, parts of the slab cover were also removed along with the CFRP strips on strengthened slabs. This demonstrates that no epoxy bond failure occurred in these slabs. Figure 12 demonstrates the failure mode of strengthened slabs at ultimate load. In this figure, it can be seen that the failure mode of strengthened specimens is similar, and that most slabs with between 2 and 8 strips at the bottom face of strengthened slabs show no significant influence on the mode of failure of specimens. However, the effects of increasing the number of CFRP strips on crack pattern and distribution are more evident. When the number of external strips increases, the cracks appear finer and more closely spaced, and they are concentrated close to the loading area, as shown in Figure 12.

![Figure (10). Load versus central deflection for S7](image)

![Figure (11). Load versus central deflection for S8](image)
4. Conclusions
In this study, experimental testing was performed on ferrocement slabs externally strengthened with CFRP strips that were subjected to patch loads. Based on the results obtained from these experiments, the following conclusions may be drawn:

1. Externally strengthened ferrocement slabs with attached CFRP strips show a great increase in ultimate load and capacity; this increase is about 26 to 74% compared with the unstrengthened (control) slab.

2. External CFRP strips bonded to the tension faces of ferrocement slabs increase the stiffness of the slabs at all stages of loading, and thus reduce the deflection at corresponding loads; the decrease in maximum deflection is about 23.5 to 53.6% compared with the unstrengthened slab.

3. The presence of CFRP strips as external strengthening has a significant effect on crack pattern of the ferrocement slabs, in particular by delaying the appearance of first cracking.

4. It is clearly appeared that the existence of CFRP strips improves the structural behaviour of ferrocement slabs, and that this enhancement is largely influenced by the location, quantity, and configuration of CFRP strips provided for these slabs.

5. References
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