Using 2D digital image correlation to investigate the flexural behavior of continuous composite beams

S Z Abeer 1*, M B Dawood2, and M H Ghalib3

1 Roads and Transport Department, College of Engineering, University of Al-Qadisiyah, Al Diwaniyah, Iraq, abeer.alkraway@qu.edu.iq
2 Civil Engineering Department, College of Engineering, University of Babylon, Babylon, Iraq, dawoodcivileng@yahoo.com
3 Civil Engineering Department, College of Engineering, University of Babylon, Babylon, Iraq, habeebghalib@yahoo.com
*Corresponding author, email: abeer.alkraway@qu.edu.iq

Abstract. This paper aims at studying the flexural behavior of continuous composite beams casting from normal concrete and Slurry Infiltrated Fiber Concrete (SIFCON) by using DIC (Digital Image Correlation) technique. The DIC results are compared with the standard methods measurement. DIC is a new non-contacting and non-destructive optical technique based on digital photographs for the tested area to compare them at different stages of loading. Tests were performed on three full-scale T-section continuous beam specimens subjected to two-point loads. In this paper, the effect of using SIFCON at compression or tension parts of plastic hinge locations on the flexural capacity, moment redistribution and crack width are investigated experimentally. The results indicate that the DIC technique gives very good correspondence comparing with the results recorded by standard methods measurement. In addition, it was found that the enhancement in moment redistribution ratio for the beam with SIFCON at compression parts of plastic hinge zones was significantly higher by about 38% comparing with the beam with SIFCON at tension parts of plastic hinge zones.

1. Introduction

Due to the relatively large bending moments for continuous beams specially when the beam span be longer and the service load increases, it is common to use high strength and high ductility concrete to enhancement the moment redistribution effect. SIFCON can be used as one of the best concrete types to resolve this problem, in which the material could enhance the strength, ductility and stiffness of the member. Slurry Infiltrated Fiber Concrete (SIFCON) is a pioneering construction material with better mechanical properties, such as durability, toughness, impact and abrasion resistance and energy absorption capacity [1,2]. Also, SIFCON has high tensile strength, so it can be used at tension parts of the members to carry the tensile stresses and limited the crack development and crack propagation. Because of high fiber content about 5-20% in SIFCON, the fiber cost is very important parameter in the structures members that fabrication of SIFCON. In order that using of SIFCON in the entire section for the (RC) members may be uneconomical. So as to carry out both of economy and high strength, SIFCON must be used in limited locations of the (RC) conventional beam [3].
The flexural behavior of SIFCON composite and integrated beams plain have investigated by Lin et al, the results showed that SIFCON composite beams exhibits significantly enhancement in flexural strength and energy absorption capacity compared to conventional RC beams [4]. An experimental investigation have conducted to test the behavior of a continuous RC beam consists of two-layer with two-span by Iskhakov et al [5]. The influence of layer technology on bending moment redistribution and as a result on the behavior of the beam was studied. Balaji and Thirugnanam have studied the effect of using SIFCON with conventional Reinforced Concrete as a composite material in rectangular (RC) beams. SIFCON was used as layers at various locations in the beam to investigate the behavior of RC beams under two point cyclic loading. The effect of load carrying capacity, the reduction in stiffness, energy absorption capacity and ductility are investigated [3].

In the field of experimental analysis for the reinforced concrete specimens, several measurement techniques have been developed to study the parameters like displacements, strains, crack width. One of them is the technique of Digital Image Correlation (DIC), which is based on a comparative analysis of the structural member's digital images captured at various deformation states. DIC can be considered as an alternative or a supplement technique which might use instead of the normal measuring methods to determine displacement and strain in 2D or 3D mode because of its simple in use in addition to the cost effective [6]. It is a new non-contacting and non-destructive optical technique based on digital photographs for the tested area to compare them at different stages of loading. At (2009), Pan et al. considered that the DIC technique is presently one of the most promising visual measurement methods with wide application possibilities [7]. DIC method is provided several advantages in the measurement of the deflection, strains, crack pattern and crack width. The significant advantage for this method is its ability to measure the deflection, strain or any other required information at any points on the tested area. When the conventional methods used, there is problems in the cost of experiment and the sensors cable management. Also, sensors can often separate from the tested sample or destroy at higher displacements and strains because its limited measurement range. These problems can be avoided with DIC which might measure the strains and crack widths even at large deflections. The DIC test needs a digital camera, a personal computer and a free photo processing program (in this study GOM Correlate) only so, it’s very cheap comparing with sensors and data acquisition system prices [6]. DIC has demonstrated extensive potential for the measurement of crack width in concrete, as it allows continuous monitoring of crack width, especially during the opening phase when cracks are not yet visible by the technique of naked eye investigation, dye penetration or microscope [8]. All measurement values which obtained through the using of 2dimensions DIC, represent the relative relationship between the initial state of the examined points and that points state at any loading stage. In order that, it is very important that the location of the camera does not change from the start moment of the test until to the end of the test. How to use DIC on large structures such as bridges to measure crack width in situ, and horizontal and vertical displacement is shown in paper [9]. Frančić Smrkić et al. [6] studied the deflection and crack width values for three reinforced concrete slabs by means of the LVDT sensors and 2D digital image correlation so as to validate the DIC results. The searchers concluded that the results of DIC crack width vary by up to 7% compared to the results of LVDT sensors, but the deviations may reach up to 15% at lower load levels. Destrebecq et al. [10] used DIC technique to determine the actual mechanical behavior for reinforced concrete beam with full scale after 25 years of service in an extremely difficult industrial environment.

2. Research significance
From the review of literature, it found that there is very limited studies for the subject of using SIFCON at different locations in the RC conventional beam and most of them used SIFCON as layers along the total beam length. Therefore, an attempt has been carried out in the present study to investigate the effect of using SIFCON at compression or tension parts of plastic hinge zones only for continuous beams on the flexural behavior of the beam. Several parameters were studied like flexural capacity, load-deflection
relations, moment redistribution and crack width. DIC will be used in this research for the analysis of reinforced concrete continuous beams.

3. Experimental work

Three reinforced concrete continuous beams were tested experimentally in this study. Each beam consists of two equal spans with similar T-section dimensions and loading arrangements. The three beams were tested under two-point static loads and designed to fail in flexure. Steel deformed bars of \( \phi 10 \) mm were utilized as flexural reinforcement. While \( \phi 8 \) mm steel bars were used with 100 mm spacing for shear-reinforcement. Furthermore, \( \phi 6 \) mm bars were used to strengthen the flange at 150 mm. The flexural reinforcement design was considered at the redistribution of moment by providing flexural strength at middle support lower than mid-span [11]. Figure 1 lists the dimensions of the beam and details of its reinforcement.

![Figure 1. Beams details (dimensions in mm).](image)

Normal concrete was used to cast the beam N-S-1 (which was used as a reference beam), while C7%-S-1 and T7%-S-1 beams were consist of normal concrete and SIFCON. For the beam C7%-S-1, SIFCON was used at compression part of plastic hinge zones (see figure 2a) based on the mechanism of compression yielding (yielding on compression side of plastic hinge to achieve the large rotation at plastic hinge zone) [12–14]. While, for the beam T7%-S-1 SIFCON applied at tension parts of plastic hinge zones (as explain in figure 2b) considering that SIFCON has high tensile strength. The information for all specimens are described out in table 1.

Based on the beam effective depth and the distance from critical section to the point of contaflexure, the length of plastic hinge was approximately chosen to be 300 mm (see reference [15], for more information) because that the plastic hinge length of concrete structural elements has no adequate limitation. However, SIFCON was used with depth of 50 mm and 60 mm at positive and negative moment zones respectively for composite beam C7%-S-1 and with depth of 175 mm and 165 mm at positive and negative moment zones respectively for composite beam T7%-S-1 depending on the location of neutral axis at elastic stage.

Steel molds were used to fabricate the specimens. In order to increase the bond between concrete parts for composite beams, SIFCON was casting in its locations at the same time of casting of the beam. Where, barriers of steel plates of 2 mm thickness were used during casting to limited the boundaries of SIFCON parts. As well, in order to increase the bond between parts and let them behave as one part, the vibrator was used on the boundary lines between parts after removing the barrier. So, additional reinforcement at the interaction points is not required.
3.1 Materials properties

Specimens were made of two types of concrete which are normal concrete and SIFCON. Crushed gravel, with maximum grain size of 14mm, natural sand (gravel and sand conformed to IOS No.45 [16]) and Ordinary Type Portland cement which is conformed to EN 197-1 [17] were used for fabrication of normal concrete. While, the same type of cement, very fine sand with maximum size 600μm, high water reducing agent HWRA (SikaViscocrete-5930L) conforms to type G and type F, ASTM-C-494 [18] and 30 mm length hooked ends steel fibers with a diameter of 0.56mm were used for providing SIFCON. The ultimate tensile strength for steel fiber is 1185MPa based on manufacturer company information. There are several limitations that must be taken into account when selecting materials for SIFCON production:

- The important requirement of the sand used in SIFCON slurry is its size, it must be small enough to ensure complete penetration through the dense steel fiber without clogging [19].
- To satisfy the slurry's required workability (flow ability) HWRA is required. Wherever the slurry must have adequate flow ability to flow through the dense fiber bed without leaving honeycombs [19].

The NC mix was designed in accordance with ASTM 211.1, while the research No. [19] was used to select SIFCON slurry composition. Table 2 describes the normal concrete mix and SIFCON slurry composition that used in the present study. During concrete mixing, six cylinders with dimensions (100*200mm) were used for each concrete type, three for compressive strength testing and three for splitting tensile test. Table 3 lists the results for these cylinders tests at age 28 days.

For reinforcing the beams, standard ductile steel bars with diameters of 10, 8 and 6 mm were applied. Table 4 indicates the properties for the reinforced bars.
Table 2. NC and SIFCON slurry mix proportion.

| Concrete type | Cement (Kg/ m³) | Sand (Kg/ m³) | Gravel (Kg/ m³) | Water (Kg/ m³) | Super-plasticizer (Kg/ m³) | Fiber fraction volume (Vf) % |
|---------------|-----------------|---------------|-----------------|----------------|---------------------------|-----------------------------|
| Normal        | 388             | 582           | 1164            | 155.2          | -----                     | -----                       |
| SIFCON        | 885             | 885           | 265.5           | 10.6           | 7                         |                             |

Table 3. Results of splitting tensile and compressive tests.

| Concrete type                              | Normal concrete | SIFCON |
|--------------------------------------------|-----------------|--------|
| Compressive strength (MPa)                 | 32              | 84.06  |
| Splitting tensile strength (MPa)           | 3.2             | 14.8   |

Table 4. Reinforced bars details.

| Bar Diameter (mm) | Yield Strength (MPa) | Ultimate Tensile Strength (MPa) | Yield Strain |
|-------------------|----------------------|---------------------------------|--------------|
| 10                | 522                  | 611                             | 0.0190       |
| 8                 | 567                  | 634                             | 0.0166       |
| 6                 | 395                  | 461                             | 0.0165       |

3.2. Testing of specimens

Three supports are used to support the continuous beam which are two rollers at each end and one hinged support at the middle of the beam. 1000 kN capacity hydraulic compression machine was used to apply the load. While, load cell of 500 kN was used to determine the mid support reaction. Also, the deflections at the middle of each span were utilized by linear variable differential transformers (LVDTs) as shown in figure 3. The load was applied in an increment of 5 kN approximately up to the first crack and then the load increment was increased to about 10 kN.

3.3. DIC experimental setup

A digital recording camera type (Nikon) was used to establish the deformations depending on the technique of Digital Image Correlation (DIC). For the processing of digital images, a free version of the commercial software package 2018 of GOM Correlate was used. The camera was located in front of the tested beam as explained in figure 4. The selected parts of the tested continuous beams, which used in the imaging process, were coated with a white paint and pattern spots of black color was created. All results which obtained by the 2D -DIC represent the relative relationship between points on the tested specimen during the test with respect to the initial state. So, the reference photograph must be taken at the starting of the test and it is very important that the camera position ,from the first moment of the test until the end of the test, does not change[6]. For this reason, the camera was located in place that there is no movement, airflow or vibration close to the location of the camera that would led to move or shake it.
4. Discussions of results

4.1. Load-deflection relationship
So as to validate of the DIC methodology and check the accuracy for the results which got from GOM program, load-deflection curves at mid-span for all specimens that examined with DIC method will compare with values that recorded by LVDTs. The camera was used to record the digital photographs for one span only. GOM program can be utilized to obtain the deformation in any direction for any points within the imaging area of the specimen and for any stage of loading. But, in the present study, the vertical deflection during the loading stages for one point only (the nearest point to the LVDT location) was studied and compared with LVDT measuring values.

Figures 5 to 7 plotted the load-deflection relations of LVDT alongside that of GOM program for all tested continuous beams. According to the results, there is very good correspondence between the two method (LVDT and DIC technique) with maximum difference less than 8%.

Accordingly, it can be said that the DIC technique, which is used in this work, can be considered as appropriate method for measuring the deformation of concrete specimens and can give reliable results for tested parameters like growth of cracks and strain distribution for different loading stages.
Load-deflection behavior for three beams N-S-1, C7%-S-1 and T7%-S-1 is illustrated in figure 8. It is generally shown that using SIFCON in composite beams has a positive effect on the ultimate capacity of the tested continuous beams. However, the enhancement in flexural capacity is reach to 15% and 18% for the beams C7%-S-1 and T7%-S-1 respectively with respect to the reference normal concrete beam. There is an increasing in the beam stiffness when SIFCON is used in tension zones of plastic hinge locations T7%-S-1 as compared to the two other beams. Maximum mid-span deflections of composite beam with SIFCON in tension parts is 16.70mm as shown in table 5 and that is lower than of the other two beams, because of its high stiffness. While, maximum deflection of composite beam C7%-S-1 was 23.37mm which is higher than that of T7%-S-1 because that the beam with SIFCON in compression locations of P.H zones allowed to withstand higher energy absorption (large deflections).

Table 5. Ultimate load and maximum deflection for all tested beams.

| Beam     | Flexure capacity (kN) | Max. deflection (mm) |
|----------|-----------------------|----------------------|
| N-S-1    | 289.1                 | 24.05                |
| C7%-S-1  | 332.41                | 23.37                |
| T7%-S-1  | 340.86                | 16.70                |
4.2. Crack width development

Crack width was measured in this study by using two methods which are crack-meter and DIC technology. Crack width for each stage of loading found through 2D digital image correlation, which is provided by GOM software. For the tested beam with SIFCON at tension locations, cracks of two types were observed; the shear cracks, which appear first, were found at the regions beside the maximum moments zones where combined moment and shear effects found. These cracks were found as a result of the inclined tensile stresses. After that flexural cracks which is resulted from flexural tensile stresses at maximum moment regions were formed. However, the high tensile strength of SIFCON limited the cracks growth at the critical positive and negative moments locations and transformed the deformation to the other parts of the beam which is casting from normal concrete.

The first crack does not give the maximum crack width for the composite beam with SIFCON at compression parts of plastic hinge locations, where the first crack appears at mid spans and maximum crack happens up the middle support while, the first crack was the wider for the reference beam which appeared up the middle support. In order that, the crack width development with loads was recorded for first crack at mid span and for the maximum crack width up the support as shown in figures 9 to 11. These figures show good agreement between the results of the crack-meter and DIC method. So, it can say that DIC method may be used instead of crack meter to study the growth of crack width during the test and this can led to reduce the test time and give the values for the width of any crack and at any stage of loading.

![Figure 8. Load-deflection response.](image)

![Figure 9. Crack width development for beam N-S-1.](image)
Figure 10. Crack width development for beam C7%-S-1

(a) crack width by GOM Program

(b) crack width development

Figure 11. Crack width development for beam T7%-S-1

(a) crack width by GOM Program

(b) crack width development

4.3. Load and moment redistribution

Figure 12 presents the load redistribution for central support when SIFCON parts used at compression or tension sides of plastic hinge locations. While, table 7 summarizes the ultimate moments and the ratio of moment redistribution ($\beta$) which calculated using Eq. (1) for the hogging and sagging bending moments at the middle support and center of span, respectively:

$$\beta = \frac{M_e - M_E}{M_e} \times 100$$ (1)

Where: $M_e$ is the value of the elastic bending moment at failure moment and $M_E$ is the experimental bending moment value which evaluated according to equilibrium consideration by using the actual reaction of mid support and the total load.

In general, the results in table 7 and figure 13 indicated that the addition of SIFCON either in compression or in tension regions increases the ultimate flexural capacity for the composite continuous beams and enhancement the redistribution load and moment comparing with the reference beam N-S-1. But, it is clear that the enhancement in moment redistribution ratio for the beam C7%-S-1 was significantly higher than T7%-S-1 beam (higher by about 38% comparing with T7%-S-1) in spite of the little increase in ultimate load for T7%-S-1 beam (about 2.5%) comparing with C7%-S-1. This behavior can be explain through the high stiffness for the beam T7%-S-1 that led to carry addition load, in other hand beam C7%-S-1 show high ductility as a result to use SIFCON as a compression yielding material at compression sides of plastic hinge zones. So, it can concluded that using SIFCON at compression sides of plastic hinge is more suitable for practical application where the used volume of SIFCON is less than that for tension parts. Furthermore, utilized SIFCON as compression yielding material increases the ductility for the continuous beam and prevent the brittle failure which is not preferred. However, the
strength of tension for the beam can improve through the enhancement for the reinforcement resistance instead of using SIFCON at tension sides of the plastic hinges locations.

| Beam    | Pu (kN) | Ultimate reaction of mid support (kN) | At mid support (M-) | At mid span (M+) |
|---------|---------|---------------------------------------|---------------------|------------------|
|         | Failure moment (elastic analysis) (kN.m) | Experimental failure moment (kN.m) | β                   | Failure moment (elastic analysis) (kN.m) | Experimental failure moment (kN.m) | β |
| N-S-1   | 289.10  | 193.95                                | 39.30               | 35.82            | -8.86                          | 32.75                          | 34.49 | 5.32 |
| C7%-S-1 | 332.41  | 219.56                                | 45.19               | 38.68            | -14.39                        | 37.66                          | 40.91 | 8.64 |
| T7%-S-1 | 340.86  | 227.66                                | 46.34               | 41.49            | -10.46                        | 38.61                          | 41.04 | 6.27 |

5. Conclusion

It can be concluded from the experimental results of this study that:

1. DIC technique can be considered as appropriate method for measuring the deformation of concrete specimens with maximum difference less than 8% comparing with LVDT results.
2. DIC method can be used instead of crack meter to study the growth of crack width during the test and this can lead to reduce the test time and give the values for the width of any crack and at any stage of loading.
3. In generally, using SIFCON in composite beams has a positive effect on the ultimate capacity of the tested continuous beams. Where, the enhancement in flexural capacity is reach to 15% and 18% for the composite beams with SIFCON at compression and tension parts of plastic hinge zones respectively with respect to the reference beam.
4. The enhancement in moment redistribution ratio for the beam with SIFCON at compression parts of plastic hinge zones was significantly higher by about 38% comparing with the beam with SIFCON at tension parts of plastic hinge zones.
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