Flexural behavior of continuous beams consisting of normal concrete and SIFCON under static and repeated loads

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Abstract. In this paper Slurry Infiltrated Fiber Concrete (SIFCON) has been used at plastic hinge locations to fix the ductility problem of continuous reinforced concrete beams. The use of SIFCON in compression parts of plastic hinge zones for continuous beam has been experimentally studied under both static and repeated loads. Six continuous beams with full scale have been tested; two with normal concrete totally and four with SIFCON at compression parts of plastic hinge locations. Three fraction volumes of fibers (Vf) % have been considered, 7%, 9% and 11%. Also, the influence of using SIFCON parts on redistribution of bending moment for continuous beams is investigated. It was noticed that, in all the reinforcement concrete beams, the using of SIFCON increased the capacity and ductility of the samples at same time. The improvement in the flexural capacity, the toughness and the moment redistribution for continuous beams could reach as high as 20%, 20% and 104% respectively. In addition, it was found that the reduction in flexural strength of composite continuous beam when it exposures to repeated loads was about 0.6% in comparison with that under static loads.

Keywords: SIFCON, continuous beam, repeated load, yielding compression, moment redistribution.

1. Introduction
As it is known, the relatively high moments can be considered as the main problem for simply supported beams with long spans. This large moments led to large deflection and wide cracking because there is no internal moment redistribution. In order to resolve this problem, continuous RC beams can be used[1]. For continuous beams, as the service load increases and the span of beam be longer, then concrete with higher strength is required at compression zones to hold the relatively large bending moments.

So as to develop the moment redistribution effect, it is necessary to enhance the ductility of the continuous beam. The moment redistribution is mainly depended on the ductility because, if a structure has adequate ductility then stress and moment redistribution will occur in the flexural members through the development of plastic hinges at critical sections[1], [2]. Ductility becomes an extremely important consideration in seismic structures or structures subjected to impact loading such as bridge beams. The methods of increasing ductility is one of the most active areas in the study of concrete structures[3]. To overcome this problems, it must use a high strength material which has good ductility at plastic hinge regions. SIFCON can be consider as one of the best solutions, in which the material could enhance the strength, ductility and stiffness of the member.

Slurry Infiltrated Fiber Concrete (SIFCON) represents an exceptional steel fiber reinforced concrete with high fiber content by about 3-20% of fibers by volume, whereas normally FRC contains 0.5-2% fibers. SIFCON is a pioneering construction material possessing superior durability, toughness, impact and abrasion resistance and energy absorption capacity [4], [5]. Since the fiber content in SIFCON is high about (5 to 20) %, the cost of fibers can be very significant in the fabrication of SIFCON structural
members. So, (RC) elements with SIFCON in the entire section considered uneconomical. Each of high strength and economy can be carried out if SIFCON used in chosen locations of conventional RC beam[6].

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[7]. 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. The influence of layer technology on bending moment redistribution and as a result on the behavior of the beam was studied. In addition, the interaction of the concrete layers was observed to demonstrate the ability of using such beams for real structures. The results obtained proper interaction between the layers because that cracks was not noted between beam layers up to the ultimate limit state of the tested beam[1]. 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[6].

2. Concept of compression yielding

In a structural member, the ductile deformation comes from the plastic deformation or yielding of the materials. Plastic hinge zone can be defined as a small area with a limited length in which large plastic deformation is mainly concentrated [8]. In conventional RC members, the plastic rotation mainly comes from the plastic yielding of the tensile reinforcement. If yielding or elongation of the reinforcement on the tension side of plastic hinge cannot achieve the large rotation at that zone, then it can be achieved through shortening or yielding on the opposite compression side. This can do by replacing the concrete in the compression zone of the plastic hinge with a material has both high strength and ductility[9]. Compression yielding (CY) can be consider as a new concept that achieves the desirable ductile behavior of reinforced concrete flexural members[3], [10], [11].

The mechanism for CY can be encased into a protective material and composed a precast block. After that, this precast block can cast into the beam to form a ductile compression zone. Good bond must ensure at interface parts between the ductile block and the concrete through roughened these parts[9].

In 2007 thirteen blocks of SIFCON with various designs were tested to find their effectiveness for use as a compression yielding material for simply supported beams[12]. The ductility behavior of compression- yielding (CY) for FRP-reinforced composite beams has examined through using both numerical and analytical approaches by Zhou[13]. Also, Wu et al. tested the using of Perforated SIFCON blocks as an extraordinarily ductile material ideal in compression yielding simply supported beam[14].

3. Research significance

Based on the review of literatures above, it can be noticed that although there are several studies deal with composite beams behavior, most of them were used layers and there is limited studies have been achieved on the composite action of SIFCON (at plastic hinge locations only) in the continuous RC beam. The present study is aimed to investigate the experimental response of a continuous, full-scale, composite beam under the effect of static and repeated loads. This composite beam has high strength and ductility. The parameters like load carrying capacity, cracks patterns, ductility, energy absorption capacity, and effect fraction volumes of fibers in SIFCON are investigated.

Also in this work, the theory of compression yielding is applied by casting SIFCON in compression plastic zones in the same time of casting of the beam. This will increase the bond between different concrete parts, and there is no need to addition reinforcement at interaction points. 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.
4. Experimental program
The experimental tests consist of the following specimens:
- Twelve cylinders (three for each concrete type) to get the compressive strength;
- Twelve cylinders (three for each concrete type) to get the splitting tensile strength;
- A full-scale six continuous beams (two of NSC and the others were composite from NSC and SIFCON).

4.1. Test Samples
Six beams of reinforced concrete were tested in flexure. They are of 3.0 m length and have a T-section of dimensions explained in figure 1. Each beam consists of two equal spans of 1450 mm for each span. Steel bars of $\phi 10$ mm were applied as longitudinal reinforcement. While for shear reinforcement steel bars of $\phi 8$ mm were used with 100 mm spacing. Also, $\phi 6$ mm bars were used to reinforced the flange at spacing of 150 mm as shown in figure 1.

![Figure 1. Details of tested beams (all dimensions in mm).](image)

The details for all samples are explained in table 1. Beams N-S-1 and N-S-2 were cast from normal concrete, while C7%-S-1, C9%-S-1, C11%-S-1 and C7%-S-2 were composite of normal concrete and SIFCON. According to compression yielding mechanism[9]–[11] SIFCON was used at compression part of plastic hinge zones (see figure 2). The length of the plastic hinge is taken as 300 mm in this study. There is no adequate limitation for the length of plastic hinge of concrete structural elements. Zhao et al. summarized several empirical equations can be used for the prediction of the plastic hinge length $L_p$ [15]. The length of plastic hinge was calculated approximately depending on the effective depth of beam and the distance from critical section to the point of contaflexure (for more information, see reference [15]). So, the depth of SIFCON part was 50 mm at positive moment zones and 60 mm on negative moment zone depending on the location of neutral axis at elastic stage. Both N-S-2 and C7%-S-2 tested under repeated loading (20 cycles of gradually loading and unloading up to 70% of ultimate load for similar beam under static loading condition after that the beam was loaded up to failure). In other hand, the other beams were tested under static loading.

![Figure 2. Locations of SIFCON at half of the composite beams(front view).](image)

Table 1. Details for samples.
According to elastic analysis, maximum moment over the middle support is 0.188Pℓ and it is equal to 0.156Pℓ at the mid of each span. The reference beam N-S-1 was designed based on 20% redistribution of negative moment into positive moment at mid span. Thus, the design of flexure reinforcement was considered the moment redistribution through provided flexural strength at middle support smaller than mid-span[16].

4.2. Material Properties

In this study the materials below were used for the production of the concrete mixes:

- Portland cement (Ordinary Type), commercially known (KARASTA)
- Natural sand, was used to provide the mix for normal concrete. While, very fine sand (from the same type) with maximum size 600μm was used in SIFCON. In SIFCON slurry, the important requirement of sand used is its size, it has to be small enough to ensure complete infiltration through the dense steel fiber without clogging[17].
- For normal concrete, crushed gravel, with maximum size of 14mm was used.
- SikaViscocrete-5930L was used in this work as high water reducing agent HWRA to product SIFCON. It is conformed with types G and F, ASTM-C-494[18]. HWRA was needed to satisfy the required workability (flowability) of the slurry. Wherever, the slurry must have enough flowability to flow through the dense fiber bed without leaving honeycombs[17].
- for providing SIFCON, Hooked ends steel fibers with a nominal length of (30 mm) and diameter of (0.56mm), manufactured by Jingjiang Hangtu steel fiber Factory in China. According to the manufacturer Company its ultimate tensile strength is 1185MPa.

Table 2 explains the composition of the SIFCON slurry and normal concrete mixtures which are used in this study. The NC mix was designed according to ASTM 211.1 while SIFCON was selected from research NO.[17]. Three fraction volumes of fibers (Vf) % have been considered, 7%, 9% and 11% for SIFCON. Normal ductile steel bars with diameters 10, 8 and 6 mm were applied for reinforced the beams. The properties for reinforced bars can be noticed in table 3. The details for beam reinforcement scheme can show in figure 1.

| Group No. | Samples name | Type of concrete | Type of loading | Fraction of fibers for SIFCON part |
|-----------|--------------|------------------|----------------|-----------------------------------|
| Group 1   | N-S-1        | Normal           | Static         | ---------------                  |
|           | C7%-S-1      | Composite        | Static         | 7%                  |
|           | C9%-S-1      | Composite        | Static         | 9%                  |
|           | C11%-S-1     | Composite        | Static         | 11%                 |
| Group 2   | N-S-2        | Normal           | Repeated       | ---------------                  |
|           | C7%-S-2      | Composite        | Repeated       | 7%                  |

Table 2. Mix proportion used for NC and SIFCON slurry.

| Concrete type | Cement (Kg/ m3) | Gravel (Kg/ m3) | Sand (Kg/ m3) | Superplasticizer (Kg/ m3) | Water (Kg/ m3) |
|---------------|-----------------|-----------------|---------------|---------------------------|----------------|
| Normal        | 388             | 1164            | 582           | -----                      | 155.2          |
| SIFCON        | 885             | --------        | 885           | 10.6                      | 265.5          |

Table 3. The properties of reinforced bars.
4.3. Compressive and tensile strength for concrete types
The compressive and the splitting tensile strengths were measured on twenty four cylinders. Where:

- Twelve cylinders (three for each concrete type) are tested to get the compressive strength;
- Twelve cylinders (three for each concrete type) are used to get the splitting tensile strength;

Each cylinder was of a 20 cm height and a diameter of 10 cm. The results for these specimens at the age 28 days are presented in table 4.

| Concrete type     | Compressive strength (MPa) | Splitting tensile strength (MPa) |
|-------------------|-----------------------------|----------------------------------|
| Normal concrete   | 32                          | 3.2                              |
| SIFCON(7%)        | 84.06                       | 14.8                             |
| SIFCON(9%)        | 100.52                      | 22.5                             |
| SIFCON(11%)       | 98.73                       | 20.1                             |

4.4. Testing of specimens
The two spans beams are supported on three supports, middle hinged support and roller support at each end beam. Two concentrated load was utilized at the center of each span by using a hydraulic compression machine with capacity of 1000 kN as shown in figure 3(a). The mid support reaction was measured using a 500 kN load cell. While, linear variable differential transformers (LVDTs) are utilized at the bottom face of the center for each span to measure the deflection. Data acquisition system monitored by a computer was used to record data electronically during the test. (figure 3(b)).

The beams N-S-1,C7%-S-1,C9%-S-1 and C11%-S-1 were tested under monotonic loads up to failure. In other hand, 20 cycles of repeated loads applied to samples N-S-2 and C7%-S-2. At every cycle the beam was loaded gradually until 70% of its ultimate static load and then unloading is followed. Finally, the sample was loaded gradually up to failure.
5. Discussions of results

5.1. Modes of Failure and Crack Pattern

- Group 1: During the testing of beams under static loading, it was observed that the first crack for NC beam was located up the central beam support section as a vertical flexural crack which followed by similar cracks at mid-spans. Then, new cracks formed and propagated vertically toward the compression zone at higher loading stages. Finally, the beam failed in yielding where the beam continued in deformation without increasing in loads. The failure mode of composite beams was similar to NC but the only difference was that the first crack appeared at mid span. However, at all beams the wider crack was above the middle support.

- Group 2: For repeated loading specimens and at first cycle, similar cracks that occurred in static test were observed. For next cycles, the same cracks which were observed during loading phase at the first cycle were gradually widened and propagated. After 20 cycles, beams loaded up to failure. The failure mode for both NC and composite beams was same to failure mode for specimens in group 1.

The failure patterns of all beams are presented in figures (4a-4f). No vertical or horizontal cracks at interaction lines between normal concrete and SIFCON were observed even at the failure state, and this can be a good indication to success the casting method which is used in the present study. So, it can say that this casting technology is more convenient for composite beam production in real construction conditions.

5.2. Load-deflection relationship

The relation between the deflections at the center of each span and the applied load presents in figure 5 for beams under static loads and figures 6-7 for beams under repeated loads.

- Group 1: The load deflection curve for beam N-S-1 demonstrated linear behavior before cracking (up to 60 kN where first crack appeared). Upon cracking, stiffness was reduced. It can also be noticed that composite beams demonstrated higher deflections compared to N-S-1 on first stage form zero load up to approximately 220 kN for C7%-S-1 and C11%-S-1 and to about 180 kN for C9%-S-1. This is because of the using of SIFCON in composite beams which give them more ductility and more strength in the same time. The cracks still grow toward compression zones in normal concrete beam, so the deflection increase rapidly in this stage. In other side, these cracks cannot be go on at that same fast in SIFCON at compression parts of composite beams, this is why the deflection be less for composite beams comparing with N-S-1 for the same load after first stage. In addition, it can be indicated that there is improvement for the ultimate load of composite beams comparing with the beam which is cast of normal concrete only. From the results in table 5, it is clear that there is an average of (15,20,16) % increase on flexural capacity for composite beams (C7%-S-1, C9%-S-1 and C11%-S-1) respectively compared with the normal concrete beam. The increase in inclusion of steel fiber in SIFCON for composite beam from 7% to 9% and 11% leads to rise ultimate load by approximately (5 %and 1%) for fibers fraction volumes 9% and 11% respectively with respect to C7%-S-1. It’s clear that the fraction volume 9% improved the flexure capacity more than 11%. This may due to the lack of matrix in between the fibers for fraction volume 11% which decreasing the bond strength for SIFCON. However, the development in flexural strength through increasing the volume fraction of fiber may be true only up to a certain limit[19].

- Group 2: Experimental results explained that the ultimate flexural strength for both NC and composite beams which are tested under repeated loads are reduced comparing with the strength of same beams under static loading. During the repeating of the loading and unloading process, new cracks formed and the existed cracks extended, and that led to decrease the
Figure 4. Failure crack patterns of beams.
stiffness of beam gradually. The strength decreased by about (4%, 0.6%) for NC and composite beam respectively. At the same time, the maximum deflection raise by about 8% and 11% for NC and the composite beam respectively comparing with the deflection of the same beam under static loads. So, it can be showed that the using of SIFCON at compression parts on plastic hinge locations makes the reduction in flexure strength be less than NC through increasing the compressive strength and the ductility on critical sections. The details for maximum deflection and ultimate load for group 2 can be seen in table 6.

Table 5. Ultimate load and maximum deflection for group 1.

| Beam     | Flexure capacity (kN) | Max. deflection (mm) |
|----------|-----------------------|----------------------|
| N-S-1    | 289.1                 | 24.05                |
| C7%-S-1  | 332.41                | 23.37                |
| C9%-S-1  | 345.62                | 24.00                |
| C11%S-1  | 335.8                 | 25.03                |

Figure 5. Load-deflection response of group1

Table 6. Ultimate load and maximum deflection for group 2.

| Beam     | Flexure capacity (KN) | Max. deflection (mm) |
|----------|-----------------------|----------------------|
| N-S-2    | 276.61                | 26.06                |
| C7%-S-2  | 330.3                 | 25.9                 |
5.3. Load and moment redistribution

Figures 8 and 9 present the variation of total applied load versus the mid support reaction for all beams. Also, the mid support elastic reaction \( R = \frac{22P}{32} \) was plotted to compare it with the experimental results and to show the redistribution in load values. The beams consider as statically indeterminate so, the mid support reaction which measured by the load cell was used to calculate the actual internal forces at any section along the beam. For beams with NC, hints of redistribution for load from the section of negative moment to the positive moment sections were observed through the decreasing of the actual mid support reaction comparing with its elastic value at the same load by about 2% and 4% under static and repeated loads respectively. This might due to the higher reinforcement ratio at mid-spans confront with the middle support section and that could lead to difference in stiffness between these sections. Composite beams had the same behavior, but redistribution for the reactions load was higher and continued for higher values of the applied load. Where, the reduction in mid support reaction was 4%,
5%, 3% and 5% for beams C7%-S-1, C9%-S-1, C11%-S-1 and C7%-S-2 comparing with elastic values for that reaction. In spite of that the composite beams have the same reinforcement ratio for normal concrete beams, the failure load and the redistribution load between reactions of the beam was higher. This is due to the higher strength and higher ductility which is provided by SIFCON at the compression parts for plastic hinge regions.

Table 7 summarizes the ultimate moments and the ratio of moment redistribution (β) which calculated using Eq. (1) for the hogging and sagging bending moments at the middle support and center of span, respectively:

\[ \beta = \frac{M_e - M_f}{M_e} \times 100 \]  

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

The results show that the NC beam under static loads had a moment redistribution ratio of -8.86 at the negative moment and +5.32 at positive moment. Moreover, the composite beams with static loading condition show significantly growing in moment redistribution as the steel fiber in SIFCON increased. C7%-S-1, C9%-S-1 and C11%-S-1 had moment redistribution ratios of -14.39, -18.08 and -12.49 at the middle support and +8.64, +10.85 and +7.49 at midspan, respectively. However, it is clear that there is an improvement in moment redistribution reach to 62%, 104% and 41% when SIFCON applied with steel fiber volumetric ratio 7%, 9% and 11% respectively. Yet, by comparing the results for beams under repeated loads with respect to beams under static loads, it was observed that there is clear increased in the moment redistribution ratio. Whereas the ratio for moment redistribution for N-S-2 and C7%-S-2 increased by about 23% and 36% comparing with similar beams under static loading condition. Figure 10 presents comparison between the experimental and elastic moments at center of beams. In other hand, figure 11 explain the moments at center for beams under static and repeated loads. So, from results above it can be observed that there is obvious enhancement in the moment redistribution for continuous concrete beams when SIFCON utilized in compression parts of plastic hinge zones according to compression yielding theory, especially for beams exhibition to repeated loads.

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**Figure 8.** Total load-mid supported reaction curves for group 1  
**Figure 9.** Total load-mid supported reaction curves for group 2
Table 7. Moment redistribution for beams.

| Group No. | Beam   | Pu (kN) | Ultimate reaction of mid support (kN) | At mid support(M-) | At mid span(M+) |
|-----------|--------|--------|--------------------------------------|--------------------|-----------------|
|           |        |        |                                      | Experimental failure moment (elastic analysis) (kN.m) | β | Experimental failure moment (elastic analysis) (kN.m) | β |
| 1         | N-S-1  | 289.10 | 193.95                               | 35.82              | -8.86           | 34.49           | -32.75          | 5.32 |
|           | C7%-S-1| 332.41 | 219.56                               | 38.68              | -14.39          | 40.91           | 37.66           | 8.64 |
|           | C9%-S-1| 345.62 | 225.90                               | 38.49              | -18.08          | 43.40           | 39.15           | 10.85 |
|           | C11%-S-1| 335.80 | 223.00                               | 39.95              | -12.49          | 40.89           | 38.04           | 7.49 |
| 2         | N-S-2  | 276.61 | 184.50                               | 33.49              | -10.93          | 33.39           | 31.33           | 6.56 |
|           | C7%-S-2| 300.30 | 215.00                               | 36.14              | -19.51          | 41.80           | 37.42           | 11.70 |

Figure 10. Experimental and elastic moments at center of beams.

Figure 11. Moments at center for beams under static and repeated loads.
5.4. Toughness
The toughness of a material ($U_t$) is known as the ability of a material to absorb energy. However, it is related to combination of strength and ductility. Ductility and energy absorption capacity are important for continuous beams and other statically indeterminate structures, especially for structures under cyclic or repeated loads because it improves the ability of moment redistribution through plastic hinges rotation. “Flexure toughness can define as the calculated area under the load deflection curve”[4], [20].

Table 8 shows the toughness values for samples of group 1. It can be seen that increasing the volumetric ratio of steel fiber for SIFCON led to increasing the toughness by about 10%,20% and 17.8% for C7%-S-1, C9%-S-1 and C11%-S-1 respectively comparing with N-S-1. This behavior can explain through the fact that, the capability of the fibers to bridge the micro and macro cracks which led to transfer the emerging loads and as reason the maximum load and the area of load deflection curve increased[21].

Table 8. Flexure toughness for group 1

| Beam      | Toughness (N.m) | %Increase over NC beam |
|-----------|-----------------|------------------------|
| N-S-1     | 5769.90         | 0                      |
| C7%-S-1   | 6342.87         | 10                     |
| C9%-S-1   | 6929.99         | 20                     |
| C11%-S-1  | 6798.51         | 17.8                   |

Figure 12. Flexure toughness for group 1

The increasing in the toughness might be as a result to the growing of load and enhancement in the stiffness beyond yielding. Hence, it can be concluded that the use of SIFCON as compression yielding material in composite beams provide an improvement of energy absorption and the ductility for the specimens. From figure 12 it can be seen the composite beam with SIFCON of 9% steel fiber ratio shows a higher increase in energy absorption.

6. Conclusion
Through the experimental results of this study, it can be concluded that:
1. Using SIFCON as compression yielding material in plastic hinge zones is improvement the flexure capacity and toughness of composite continuous beams and this improvement could reach as high as 20% for each one of these properties.

2. The development in the moment redistribution for composite beams was approximately 41%, 62% and 104% when SIFCON used with volumetric ratio 11%, 7% and 9% respectively.

3. No vertical or horizontal cracks at interaction lines between normal concrete and SIFCON in composite beams were observed even at the failure state, and this can be good indication to success the casting method which is used in the present study. So, it can say that this casting technology is more convenient for composite beam production in real construction conditions.

4. The reduction in flexural strength of composite continuous beam when it exposures to repeated loads was about 0.6% in comparison with that under static loads. While, this reduction was increased to 4% for NC. This is due to the improvement in the compressive strength and the ductility on critical sections provided by SIFCON in composite beam.

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