Flexural Behaviour of Hybrid Concrete Beam-Column Connections Under Static and Repeated Loads

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Abstract. The present study includes an experimental investigations for the behavior and the load carrying capacity of hybrid beam-column connections subjected to static and repeated loading condition. The goals were to evaluate the effect of using slurry infiltrated fiber concrete (SIFCON). Experimental program consists of testing six beam-column connections, two of them casted with normal concrete and the other using SIFCON in critical section in addition to normal concrete. Also, the program testing three of connection subjected to static load and the similar other subjected to repeated loads. Results show an improve in flexural behavior for specimens with SIFCON as compared with normal concrete under static and condition, on the other hand, the reduction in flexural strength when was exposed to repeated loads in comparison with that under static loads reach 2.6% at hybrid connection. While, the reduction was increased to 5.1% for the specimen without SIFCON.

1. Introduction

Connection define as that portion of the column inside the depth of beam which frame into column [1]. Connection with severe damage may lead to catastrophic failure during earthquake or blast. Since the 1960s, many studies on connection have been consider and several parameters have been studied. Lu [2] investigate using additional diagonal bars on beam-column intersection and found this addition show control of crack capacity and which improve the seismic performance. Maha [3] tested beam-column connection under static and repeated load, and find that using hybridisation technique at different region of joint enhanced the behaviour of connection. Raj and Jeen [4] studied the behaviour of beams containing normal concrete and ultrahigh performance concrete. They found that hybrid beams can resist high loads, while the deflections lower than that measured in reference beam.

On the other hand, SIFCON (Slurry Infiltrated Fiber Concrete) consider as a special type of FRC (Fiber Reinforced Concrete). There are two main differences between SIFCON and FRC which are fiber volume fraction and the production method. Volumetric fiber content in SIFCON is in range 3-20% comparing with 0.5-2% in FRC [5]. The method to produce SIFCON started with placing the fiber in the form and then the rich flow able slurry of cement and fine aggregate is poured or pumped into the forms, while in FRC, fibers add to mixture during mixing process. There is no coarse aggregate in SIFCON matrix because of the dense fiber which cannot allow to infiltrate coarse aggregate between the steel fibers. However, it may contain a high cementitious materials such as fine or coarse sand in addition to additives like slag or fly ash [6].
The first development for SIFCON was in Materials Laboratory at Columbus, Ohio, USA in 1979 by Lankard [7, 8]. After that it was developed by using the technique that depending on used cement based materials to infiltrate steel fibers layers and proving that increasing steel fibers percentage in the cement matrix led to provide a material with very high strength properties that christened as SIFCON[6, 7]. SIFCON has high strength in compression, tension, flexure and shear in addition to exceptional toughness values, SIFCON describes as a distinctive construction material [9].

The goal of the work is to investigated the flexural behaviour of the hybrid beam-column connections under static and repeated load.

2. Experimental Programme

2.1. Description of the Specimens

Six specimens were constructed. Two of them casted with normal concrete and set as reference specimens. The other connections using hybrid Concrete (SIFCON Slurry Infiltrated Fiber Concrete) at critical region of connection where maximum moment was located (top of beam-column intersection). The dimensions and details of beam and column explained in table 1 and figure 1 to 3.

| Specimen | Type of concrete | Size of SIFCON | Type of Loading |
|----------|------------------|----------------|-----------------|
| N-N-S    | NC               | -              | Static          |
| N-N-R    | NC               | -              | Repeated        |
| N-SIF1-S | NC+SIFCON        | 150×100×150    | Static          |
| N-SIF1-R | NC+SIFCON        | 150×100×150    | Repeated        |
| N-SIF2-S | NC+SIFCON        | 150×100×250    | Static          |
| N-SIF2-R | NC+SIFCON        | 150×100×250    | Repeated        |

2.2. Properties of Material

Normal concrete was utilized to pour various areas of specimens with compressive strength about (32) MPa and a suitable workability. It is designed according to (ACI-211.1R-91) [10]. A mixture by weight of cement, sand and gravel (1:1.45:2.86), and 0.4 water cement ratio are used. Ordinary

Figure 1. Details of N-N-S and N-N-R

Figure 2. Distribution Type of Concrete For Specimens with hybrid concrete.
Portland cement, natural sand with maximum size aggregate of 4.75 mm, and coarse aggregate with a maximum size of 9.5 mm are used. Compressive strength about (32) MPa and a suitable workability. For SIFCON mix ratio (1:1) (cement:Fine Aggregate) by weight was used which subject on literature review [11]. SIFCON concrete used the same type of sand in normal concrete as a fine aggregate, but its passing through 600mm sieves to ensure complete infiltration through steel fibers. The SIFCON mix contains 7% of steel fiber was used and which sufficient to give an adequate compressive strength about (90) MPa, figure 3 shows steel fiber used. Details of the selected mixtures and properties of using steel fibers are given in Table2 and Table3, respectively.

| Parameter                  | Normal concrete | SIFCON  |
|----------------------------|-----------------|---------|
| w/c ratio                  | 0.4             | 0.3     |
| w. (Kg/m³)                 | 160             | 265.5   |
| Cement. (Kg/m³)            | 400             | 885     |
| Fine Aggregate. (Kg/m³)    | 582             | 885     |
| Coarse Aggregate. (Kg/m³)  | 1145            | -       |
| Super plasticizer. (L/m³)  | 6.5             | 10.6    |

| Property Specifications   | Specifications |
|---------------------------|----------------|
| Appearance                | Appearance     |
| Bright and clean wire     | Bright and clean wire |
| Diameter                  | Diameter       |
| 0.51 mm                   | 0.51 mm        |
| Length                    | 30.2 mm        |
| Density (kg/m3)           | 7800 kg/m3     |
| Tensile strength (MPa)    | 1200           |
| Aspect ratio (L/d)        | 60             |

2.3 Casting specimens
Initially, the normal concrete will be poured in the specified places after the reinforcing steel bars is placed in the mold as shown in figure 4. The regions with SIFCON casted in its specified places and to
ensure there is no overlap between the two types of concrete, steel barriers (1.5mm thickness) are laid, as shown in figure 5. After 24 hours of casting, all specimens were extracted from the molds and subsequently the burlap sacks were set over them to remained moist to 28 days. After curing, all specimens were dried in air and ready to tested.

![Casting reference specimens by NC](image)

**Figure 4.** Casting reference specimens by NC

![Casting Specimens with SIFCON](image)

**Figure 5.** Casting Specimens with SIFCON

2.4 Control Samples
After 28 days of casting, the prism and cylinders tested with each beam-column joint specimen at the same time according to the standard specifications ASTM to obtain the compressive strengths, splitting tensile, and modules of rupture. Table 4 show the mechanical's properties of concrete that using in work as an average of three samples. Elasticity modulus for SIFCON was had slightly lower amount comparing with NC and this is in agreement with references. The modulus of elasticity was calculated through the slope of stress strain relationship between zero stress and (20 %) of the ultimate compressive capacity that shown in Figure 6 [11]. The decreasing in modulus of elasticity for SIFCON
comparing with the conventional concrete can be a result for the high cement contents and absence of the gravel in SIFCON mortar.

![Stress-strain curve for NC and SIFCON](image)

**Figure 6.** Stress-strain curve for NC and SIFCON [11]

| Type of concrete | $f'c$ (Mpa) | $f_r$ (Mpa) | $E_c$ (GPa) |
|------------------|------------|------------|-------------|
| NC               | 32.7       | 4.8        | 26.87       |
| SIFCON           | 90.3       | 38.1       | 15.15       |

**Table 4.** The Mechanical Properties for Control Samples.

3. **Test Procedure**
The connection was supported on the fixed supported at end of column. Two point load utilized at the free ends of the beam by hydraulic compression machine. Two linear variable differential transformers employed at each free end of connection to measure the vertical displacement as shown in figure 7. Three of specimens were tested under static loading, while the other tested under 20 cycles of repeated loads applied at every cycle loaded gradually until 70% of its ultimate static load then unloading is followed. Lastly, the connection loaded up to failure.

![Specimen under testing](image)

**Figure 7.** Specimen under testing.
4. Result Discussions

Table 5 show the experimental results of the test, including cracking loads (Pcr), ultimate load (Pu) and their growing percentage as compared with reference connections. N-N-S consider as reference connection for static condition while N-N-R for repeated condition.

| Specimen | Pcr (kN) | Pcr(i) – Pcr(r) ×100 | Pu (kN) | Pu(i) – Pu(r) ×100* | Reduction in Ultimate Loads under Repeated Loading |
|----------|----------|------------------------|--------|---------------------|-----------------------------------------------|
| N-N-S    | 25       | -                      | 117    | -                   | -                                             |
| N-N-R    | 25       | -                      | 111    | -                   | 5.1                                           |
| N-SIF1-S | 30       | 20                     | 131    | 11.9                | -                                             |
| N-SIF1-R | 30       | 20                     | 127    | 14.4                | 3.0                                           |
| N-SIF2-S | 35       | 40                     | 153    | 30.7                | -                                             |
| N-SIF2-R | 35       | 40                     | 149    | 34.2                | 2.6                                           |

*: Reference specimen, i: other specimens.

4.1. Cracking Loads

It is clear from test result, the specimens used SIFCON have an increase in the first cracking load reach to 40% as a compare with reference specimen which using NC only. For reference specimen at, the location of the first crack observed at critical section on beam-column intersection. For specimen having SIFCON in critical section area, the first crack happened outside critical section region (outside the SIFCON region) due to effect of steel fibers that improve flexural behavior.

4.2 Ultimate Loads

At static condition, the connections (NSIF1-S and N-SIF2-S) showed an increase in ultimate load reach to (11.9% and 30.7%) compared to (N-N-S) specimen, respectively, due to high strength of SIFCON in addition to fibers effect to bridge and collect the micro and macro cracks which improve stiffness and flexural strength. Under the effect of loading and unloading process, it has been observed a new visible cracks formed and the existed cracks extended. This phenomenon decreases the stiffness of connection gradually. As a result, the deflection increased slightly after each cycle where the beam does not return to the original shape when load at the end of each loading period decreased to zero level. When comparing the results of repeated and static loads for beam-column connections it was observed that there is a significant decreasing in ultimate strength. Whereas, the ultimate strength for N-N-R, N-SIF1-R and N-SIF2-R specimen decreased by about (5.1%,3% and 2.6%) respectively, but, simultaneously, the maximum deflection goes up by about (5.0%, 5.1 and 6.4%) respectively. Using SIFCON increases concrete compressive strength and ductility on critical section. As a result, the miniimization in concrete flexure strength becomes little than reference specimen N-N-R and this effect is increased by increasing the SIFCON region, as shown in figure from 8 to 12.

4.3 Cracking Pattern and Failure Mode

As shown in figure 13, the specimen having SIFCON in critical section area, notice that flexural failure at static load, happened outside critical section region (outside the SIFCON region) due to effect of steel fibers that improve flexural behavior. Higher SIFCON tensile strength limited the cracks development at the critical negative moments locations and transformed deformation to the other portions of the beam segment which is casting from normal concrete. At repeated load, First flexural crack was observed during the first cycle and located outside the beam-column intersection (out of SIFCON region). At the loading increase, addition cracks most of them in first cycles were appeared
but with less width, number, and length due to high tensile strength of SIFCON. After being subjected to 20 cycles of repeated loads, flexural failure occurred after the formation of several cracks in the beam region and follow by crushing in concrete.

Figure 8. Load-Deflection Curves of Specimens N-SIF1-S and N-N-S

Figure 9. Load-Deflection Curves of Specimen N-SIF2-S and N-N-S

Figure 10. The Load-Deflection Curve for N-SIF1-R Specimen

Figure 11. The Load-Deflection Curve of Specimens N-N-R

Figure 12. The Load-Deflection Curve of Specimen N-SIF2-R
4.4. Stiffness Criteria
It is the load needed for cause a one unit of deformation in a member. Stiffness criteria measured by drawn the slope of each cycle in the curve at loading 0.75 times of the maximum load of that cycle [12]. As shown in Table 6, the stiffness of beam-column connections under static loads was enhanced reach to 22.19% of reference specimen N-N-S, where using SIFCON offers an improvement in stiffness.

| Specimen   | 0.75 Pmax (kN) | Deflection at 0.75 Pmax (mm) | Stiffness,k (kN/mm) | \( \frac{k(i)-k(r)}{k(r)} \times 100^* \) |
|------------|----------------|-----------------------------|---------------------|------------------------------------------|
| N-N-S      | 87.75          | 5.83                        | 15.05               | -                                        |
| CF-ST1-S   | 98.25          | 5.34                        | 18.39               | 22.19                                    |
| CF-ST2-S   | 114.75         | 6.32                        | 18.15               | 20.64                                    |

*: Reference specimen N-N-S, i: other specimens.

5. Conclusion
Experimental results show the subsequent conclusions:
1. Using SIFCON in beam-column connections improved cracking load, ultimate load, and stiffness.
2. Using SIFCON in critical region can improve the flexure capacity, where its show an increase in ultimate load reach to 30.7% in static load and 34.2% for repeated load as compared with reference specimens.
3. First cracking load increased by about 40% as a compare with reference specimen.
4. The increased in stiffness of connection reach to 22.19% of reference specimen.
5. The minimum reduction in beam-column connection flexural strength when it exposures to repeated loads in comparison with that under static by about 2.6%. While, this reduction was increased to 5.1% for the specimen in reference group.

Figure 13. Failure and crack pattern of specimens.
6. SIFCON can improve the mechanism of crack.

6. Reference
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