



Flexural Performance of Mill Cut Steel Fiber Reinforced Concrete Beam Degraded by Mild Corrosion

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Abstract. Corrosion of steel occurred in the reinforced concrete structures is one of the most significant causes of deterioration and reduction of the loading capacity of the reinforced concrete structures. Applying fiber extended the initiation stage and postponed the crack propagation stage of corrosion process in RC structure. Therefore, this research aims to evaluate the effectiveness of utilizing steel fiber reinforced concrete (SFRC) for its application in a chloride environment. To investigate the flexural behavior of the corroded SFRC beam under static loads, the concrete with the water-to-cement ratio of 0.4 containing steel fibers of 0, 0.5%, 1.0%, and 1.5% were used. The impressed current method was applied to accelerate the corrosion of steel to reach 5% by applying the constant current of $250 \mu\text{A}/\text{cm}^2$ within 38 days. The flexural strength of eight beams having an identical section of 150×200 mm and a length of 1400 mm were examined under a four-point bending test. The experimental results showed that the presentation of mill cut steel fibers significantly influenced the flexural performance of the corroded SFRC beams. Corrosion of steel led to a more significant reduction of load capacity of the RC beams, whereas the beam containing the steel fiber remained the ultimate or yield load capacity. Fibers take account for compensating the flexural strength of the structure due to the loss of cross-section of the steel bar by corrosion effect and limit the propagation of the width crack.

Keywords: SFRC · Steel corrosion · Flexural behaviors · Load capacity · Deflection

1 Introduction

The reinforced concrete (RC) structure is one of the most used materials for various construction such as buildings, underground structures, highways, tunnels, harbors, dams, bridges... Nevertheless, corrosion of steel rebar in RC structures appears to be a critical

worldwide issue. It shortens the structure's service life and concerns the budget for repair, rehabilitation, or reconstruction. Concrete with high alkalinity is assumed to be an excellent material to protect steel reinforcement and prevent it from corrosion (Broomfield 2003). The alkaline condition leads to the form of a dense 'passive' layer; this impenetrable film entirely prevents further corrosion on the steel surface. However, the invasion of aggressive ions from exposing environment incorporating the reduction of alkalinity in concrete can induce the corrosion of steel reinforcement in reinforced concrete (Pour-saei 2016). The formation of corrosion products, which have a volume of about 2.5–5 times higher than the original steel, resulted in a reduction in cross-section and strength of corroded steel bar (Almusallam 2001; Ou et al. 2016), subsequently degrading the bonding strength between steel rebar and concrete (Fang et al. 2004, Tondolo 2015). In addition to decreasing the effective cross-section of steel bar, the corrosion products also degrade the performance of RC by making concrete crack due to high expansive stress. This deterioration leads to a change in the structure's performance, considerably increases the brittleness of the structure (Du et al. 2013; Yu et al. 2015; Zhang et al. 2018; Yalciner et al. 2020).

The economic loss and damage caused by steel corrosion in concrete make it arguably the enormous single infrastructure problem facing industrialized countries. Therefore, it is a potential market for those responsible for dealing with structures suffering from corrosion. In recent decades, several methods have been applied to reduce or prevent the corrosion of reinforcement, such as corrosion inhibitors, surface reinforcement bars treatment, or utilizing the alternative reinforced material with high corrosion resistance such as stainless steel or fiber-reinforced polymer (FRP) (Bicer et al. 2018; Marcos-Meson et al. 2018). However, the additional chemical compounds into the concrete mixture, coating epoxy on the steel bar surface, or using the alternative materials face drawbacks such as equipment requirement, loss of mechanical properties, and prohibitive cost. Recently, a method is preventing the mitigated corrosion effectively and provides a mechanism to improve the structural behaviors by using fiber-reinforced concrete since the degradation process of reinforced concrete is affected by the transport mechanism relative to the crack, which is regarded as potentially harmful to the corrosion process, as they provide preferential paths for external agents to penetrate the reinforced location (Berrocal et al. 2017; Berrocal et al. 2018; Hou et al. 2021).

Fiber-reinforced concrete (FRC) has been studied and applied for decades for various construction due to its advantage of providing the toughness and more ductile behavior that are commonly considered the disadvantages of plain concrete (Micelli et al. 2020). With appropriate volume content of steel, fiber can increase crack resistance, ductility (Şahin and Köksal 2011), cyclic loading capacity (Boulekbache et al. 2016), impact, and fatigue resistance for concrete (Yoo et al. 2015a). Fibers are more effective in improving the post-cracking behavior of concrete, thanks to fiber-bridging mechanisms across the crack surface, it inhibits cracking and limits the high brittleness of conventional concrete (Lee et al. 2017; Abbass et al. 2018; El-Sayed 2019; Nassani 2020). It consequently increases the ductility and capacity of absorbing energy and durability of concrete (Yoo et al. 2015b). Since the FRC could be applied in structures such as bridges, harbor piers due to its limit the crack, using FRC exposed to the chloride environment has become

a controversial issue. There is a lack of relation to the durability of SFRC structural elements exposed to chloride.

Thanks to these aforementioned problems, this research aims to investigate the correlation between the loading capacity of SFRC beams with the degree of corrosion. The mill cut steel fiber is utilized in this study due to its advantages, such as no fiber balling while mixing, non-subsidence, and non-outcrop. Three values of volume contents of fiber 0.5, 1.0, and 1.5 percent were used, and the level of corrosion was considered as 5 percent mass loss of the steel. The corrosion of steel reinforcement is accelerated by applying the impressed current method utilizing current densities of $250\mu\text{A}/\text{cm}^2$ (Caré and Raharinaivo 2007; Ahmad 2009).

2 Materials and Experimental Methods

2.1 Materials and Mixture Proportion

Materials were used in this study consisting of ordinary Portland cement type 1, fine aggregates as river sand, coarse aggregates with a maximum size of 20mm, chemical admixture as the superplasticizers (SP), and the addition vary volume fractions of steel fibers. The RC beam was reinforced by round and deformed bars with yield strengths were 240 MPa and 390 MPa, respectively. The hook-end steel fiber has a rough surface, twisted along the length, and tensile strength is more than 700 MPa. The physical property of mill cut steel fiber is illustrated in Fig. 1, and other properties are listed in Table 1.

Table 1. Properties of mill cut steel fibers

Average length (mm)	Diameter (mm)	Tensile strength (MPa)	Young modulus (GPa)	Density (kg/m^3)
32.0 ± 2.0	2.6 ± 1.2	≥ 700	200	7850



Fig. 1. The geometry of mill cut steel fibers

The concrete was designed to achieve a compressive strength of 40 MPa at 28 days having the water/cement ratio of 0.4 with a slump of 14 ± 2 cm, which was cast on both the plain and SFRC beams. The mixture proportion of materials is shown in Table 2. In total, 24 cylinders with 100 mm in diameter and 200 mm in height, six specimens for each mixture with three different volume fractions of 0.5%, 1.0%, and 1.5% of fiber equivalent to 39 kg, 78 kg, and 117 kg were cast for the compressive test at 7 and 28 days.

Table 2. Mixture proportions of RC beams

Mix design	Cement (kg)	Water (L)	Sand (kg)	Gravel (kg)
Plain	445	178	666	1126

2.2 Fabrication of the Beam Specimens

Eight beams including RC and SFRC were of identical dimensions with a rectangular section of 150×200 mm and a length of 1400 mm was cast to study the flexural behavior of corrosive SFRC beam. The beam was designated as C5F10, where C and F denote the degree of corrosion and fiber volume content, respectively. The configuration of the specimens was demonstrated in Fig. 2 with the same tensile reinforcement ratio. These specimens were reinforced with four longitudinal deformed steel bars diameter of 12 (two placed in the compression zone and two in the tensile zone) and transverse round steel bars with 6 mm diameter equally spaced 100 mm arranged within a span. To avoid local pitting corrosion causing the shear failure, known as the brittle failure, the stirrup, and the anchor bars was coated with epoxy to prevent the formation of corrosive products. All beams were cast into the steel molds. For steel fiber reinforced concrete, extra time was inquired to improve the higher volume fraction and well dispersion rheology. The specimens were demoulded after the first 24 h and cured under humidity conditions and temperature for 28 days by covering and watering 2–3 times daily.

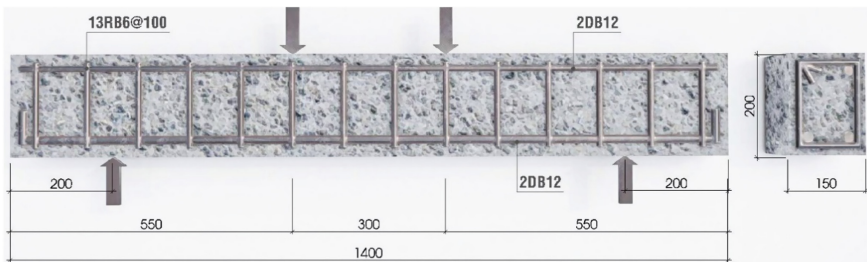


Fig. 2. Detail of the section of the beam’s elements

The impressed current technique was applied to accelerate corrosion of the primary reinforcement embedded in the SFRC beam within a short period. These beams were

submerged into the 3% sodium chloride environment with the solution depth were equivalent to concrete cover thickness to allow the entrance of both humidity and oxygen. After the first 24 h, these specimens were ensured in a saturated condition, and a constant direct density was applied. Figure 3 shows the detail of the impressed current technique; a water tank was built for the facility for the technique. The steel bars were connected to the positive terminal of the DC power source, while the negative terminal was connected to a stainless-steel plate placed along the length of the beam. In order to obtain the degree of corrosion of steel bar equal to 5 percent, a constant current density of $250 \mu\text{A}/\text{cm}^2$ was set for all specimens for approximately 38 days.

$$t = \frac{zF \Delta m}{MiS} \quad (1)$$

The corrosion times can be determined based on the Faraday laws where F is Faraday's constant ($96500 \text{ C}/\text{mol}$), z is the ionic charge number ($z = 2$) of iron, Δm is the mass loss of corroded reinforcement (g), M is the molar mass of iron ($56 \text{ g}/\text{mol}$), i is the corrosion current density (A/cm^2), and S is the superficial area of rebar within the corrosion region (cm^2).

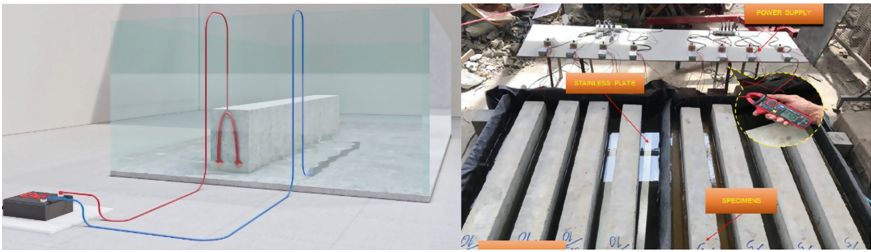


Fig. 3. Accelerated corrosion setup.

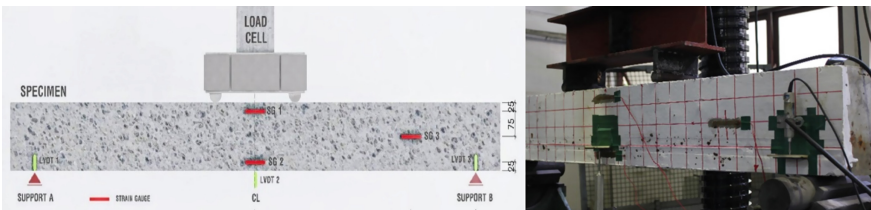


Fig. 4. Four-point bending test setup.

2.3 Test Method

Eight beams had been tested under four points bending up to failure. Figure 4 demonstrates the flexural strength test setup for the specimens with 1200 mm effective span and 400 mm shear span. A load cell with a maximum capacity of 200 kN was used as a

monitor with a rated load of 0.2 mm/min. Three linear variable differential transducers were attached at the mid-span and support to measure the vertical deflection corresponding to load capacity. Moreover, A strain gauge was attached to the surface concrete at the middle top of the beams to measure the strain at the compressive zone. Another two strain gauges were set in the tensile zone and shear zone. All of the measurements were connected to the data logger, transferred to the computer, recording all of the data during the test.

The original and damaged weight of steel rebars were recorded to measure the degree of corrosion. The corroded steel bars were extracted from concrete and immersed into a 3,5 g hexamethylenetetramine solution diluted in 500ml of hydrochloric acid and 500 ml of reagent water for at least ten minutes to remove the rust according to the procedures of ASTM G1-03. The bars were taken out of the solution, washed with clean water, and then measured the mass to determine the level of corrosion following the equation. Where ρ = percentage loss due to corrosion (%), W_i mass of reinforcing steel before corrosion (g), W_f mass of reinforcing steel under corrosion (g).

$$\rho_i = \left(\frac{w_i - w_f}{w_i} \right) \times 100 \quad (2)$$

3 Result and Discussion

3.1 Effect of Volume Content SF on the Flexural Strength of RC Beams

The load capacity of the SFRC beams under four-point loading is indicated in Table 3. The test result showed that the load capacity of the SFRC beams improved proportionally to the volume content fibers utilized. The addition of volume fraction steel fiber from 0.5% to 1.5% increased both the RC beam's yield and ultimate load capacity. The ultimate failure load of beam C0F0 is 120.85 kN, whereas the SFRC beams had higher failure loads ranging from 123.08 kN to 133.11 kN. After the yield strength was reached, the load capacity was strongly dependent on the volume fraction of steel fiber which transferred the load through the crack by the bridge mechanism. Furthermore, fiber presentation increases the steel cross-section area playing an essential role in resisting tensile stress. Nevertheless, this increase was insignificantly for plain RC beam since the improvement is only 10% or even a negligible effect for the case of lesser fiber content.

While the ultimate load capacity of SFRC beams was slightly enhanced compared to the RC beam, the load-deflection curve was noticeable, as shown in Fig. 5. The ascending part clearly showed that the deflection of SFRC beams was lower than the RC beam under the same load stage, particularly those containing a higher quantity of SF.

3.2 Effect of Corrosion on the Flexural Strength of RC Beams

The corrosion of steel is accelerated by the impressed current method was achieved. The average degree of corrosion determined by Eq. 2 is equal to 5.1% compared to the 5% theoretical evaluation. Despite the difference between natural corrosion and artificial corrosion, the technique still is reliable to generate corrosion considering a lost mass

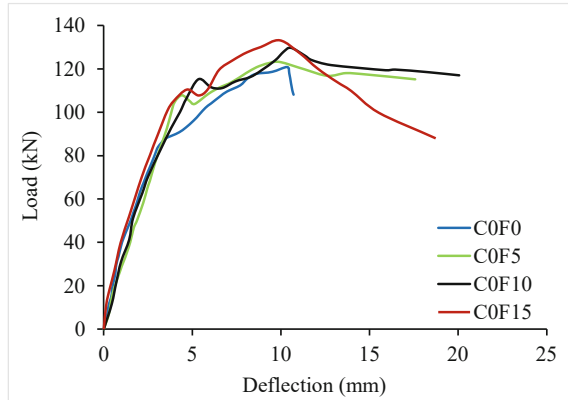


Fig. 5. Load deflection curve of SFRC beam

of steel. Figure 6 illustrates the correlation between the load capacity and deflection of the corroded RC beams under static load. The load-deflection curve exhibited the reduction load capacity of the corroded RC beam. Due to corrosion, the loss of cross-sectional tensile reinforcement, subsequently loss of mechanical properties of corroded steel bar degraded the performance of structural element contemporaneously. As a result, beam C5F0 experienced a decrease in ultimate load and yield load capacity by 21.3% and 24.6%, respectively. In addition, the ultimate deflection of the beam C5F0 is dramatically higher at 41% than the non-corrosive RC beams.

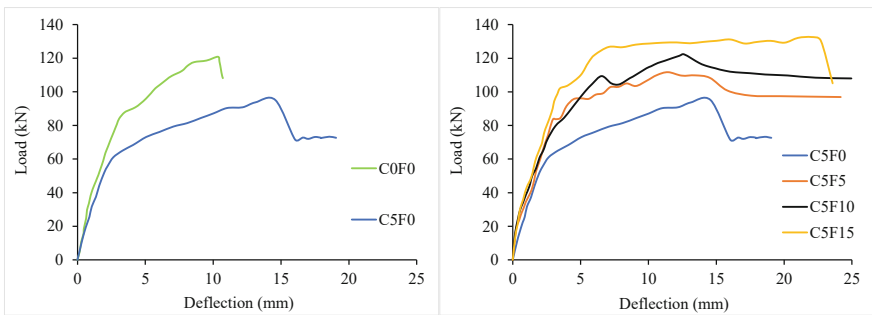


Fig. 6. Load-deflection curve of corroded RC and SFRC beams

3.3 Load-Deflection Curve of Corroded SFRC Beams

Figure 6 illustrates the relationship between the deflection and load capacity of the corroded SFRC concrete beams. Those corrosive SFRC beams were observed to have a tendency similar to non-corrosive SFRC beams; yield and ultimate load capacity improved linearly according to the volume contents of steel fiber. However, the corrosive RC beams experienced a more significant reduction of ultimate load capacity. Nevertheless,

the corroded SFRC beams showed considerably maintained load capacity; for instance, the ultimate failure load of beam C5F5 was reduced by 10% or even unchanged in the case of beam C5F10. In general, the corroded RC shows a loss of performance due to the loss of cross-section of the tensile bar. With sufficient volume fraction of steel fiber still maintains the performance of RC beams. Due to steel fiber serving as compensation for the loss of reinforced and rising the amount of reinforcing steel to the beam cross-section then, the flexural strength was improved better than the non-fiber corroded beams.

There was a growth ultimate deflection of the corroded SFRC beams. Figure 7 demonstrated that the rising both deflection and load capacity of corroded SFRC was more significant than the non-corrosive SFRC. The steel fiber not only compensated the load capacity of corrosive RC but also provide more deflection since beam C5F15 showed the ultimate deflection reached 22 m whereas this number was 14.58 mm for beam C5F0.

Table 3. Experimental program test result

Specimen	Yield Load f_y (kN)	Ultimate Load f_u (kN)	Deflection Δ_y (mm)	Deflection Δ_u (mm)
C0F0	80.88	120.85	2.91	10.34
C0F5	107.79	123.08	4.41	9.96
C0F10	115.27	129.73	5.36	10.56
C0F15	110.43	133.11	4.69	9.94
C5F0	60.98	95.05	2.64	14.58
C5F5	96.17	111.77	7.84	11.45
C5F10	109.38	122.28	6.55	12.64
C5F15	102.22	132.63	3.49	22.02

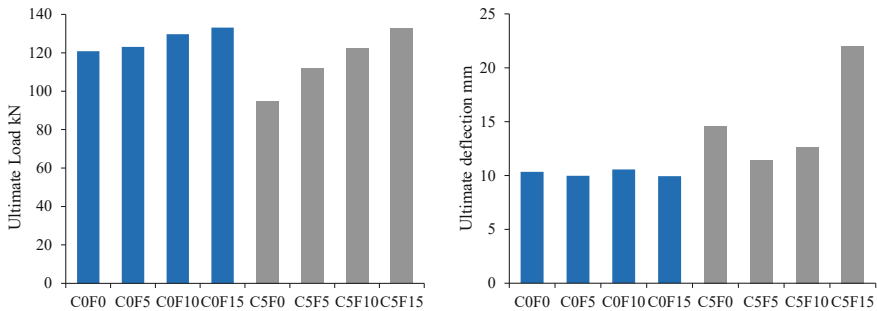


Fig. 7. Ultimate load capacity and deflection of the specimen

4 Conclusion

This study investigated the flexural strength of corroded SFRC beams containing different volume fractions of fiber. The load-bearing capacity of artificial corroded SFRC beams under static load was presented. Based on the result obtained from the experimental program, the following conclusion can be drawn:

1. Using mill cut steel fiber combined with the steel-reinforced slightly improved both yield and ultimate strength of the SFRC beams, nevertheless SF provides greater stiffness for RC beams to reach lower deflection under the same load stage.
2. The load capacity of corroded RC beams decreased dramatically with the corrosion of a couple of tensile bars. At corrosion ratios of about 5%, ultimate load capacity was reduced by 21.3% compared to the RC beams.
3. The sufficient amount of steel fiber perfectly enhanced some limits of the mechanical behavior of the corroded RC beam. The steel fiber maintained the load capacity by transferring the stress through the cracks such as the beam C5F15 reached the ultimate strength equally to C0F15.

Currently, there are few studies carried out on the durability of corroded SFRC, the controversial problem is still unclear. Therefore further experimental study or simulation work with various degrees of corrosion is still required for fully understanding the behavior of corroded SFRC elements.

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