On the influence of Steel fibers in RC beams under flexural fatigue loading

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Abstract

The present research brings the analysis of the influence of steel fibers on the mechanical degradation of reinforced concrete beams when under flexural fatigue loadings. Current experimental work aims to highlight the potential in diminishing the mechanical degradation of reinforced concrete beams due to fiber addition by effectively maintaining structure stiffness, rebar deformation and crack spacing along the fatigue life. The experimental campaign encompasses two beams with the same reinforcing ratio of 0.35%. While one beam was produced with 50 MPa self-consolidating plain concrete, the other one was fabricated with the addition of 40 kg/m³ of hooked-end steel fibers. The fatigue tests were load-controlled and a sinusoidal wave with a frequency of 6 Hz was applied for the test routine on the pre-cracked beam specimens. The tests were carried on under the same fatigue loading range in order to assess the fiber influence on the mechanical degradation along the cycles. The beams were subjected to fatigue loading until reaching 1,000,000 cycles (run-out) or failure. The use of steel fibers was especially effective in maintaining the structure stiffness under the fatigue cycles. While reinforced beams with steel fiber addition were able to maintain 19 kN/mm along the fatigue test, plain concrete beams presented around 10 kN/mm. The addition of steel fibers also contributes in mitigating the steel strain evolution throughout the time. Therefore, the addition of fibers showed major potential in enhancing the RC structures capacity to resist the fatigue degradation along the structure service life.

Keywords

Fiber reinforced concrete, structural beams, reinforced concrete, fatigue, mechanical degradation.

1 Introduction

The design of reinforced steel fiber reinforced (SFRC) structural members subjected to cyclic loading such as offshore structures (Holmen (1984)), concrete pavements (Belletti et al. (2008)) and wind towers (Aglan et al. (1993)) demand further analysis in terms of the fatigue deterioration. In general, the cited structures are subjected to millions of stress cycles along the proposed service life (Göransson et al (2011)), due to wind action, thermal oscillations and traffic loads. The continuous stress cycles along the years is responsible to lead to crack initiation and propagation, which eventually can lead to a significant stiffness decay (Subramaniam et al. (2000)).

To characterize the cementitious composite performance under fatigue loading, innumerous parameters should be analyzed, such as stress ratio, maximum stress level, loading frequency and loading sequence. While Carlesso et al. (2019) already brought the development of S-N curves for both steel and polypropylene fiber reinforced concretes, Baktheer et al. (2021) has successfully verified the influence of the loading sequence on damage evolution. When it comes to the study of the oscillation frequency, Medeiros et al. (2015) worked on novel equations to insert the frequency parameter on the failure probability Weibull distributions. More recently, Castillo et al. (2009) proposed Bayesian mathematical methods to determine the concrete fatigue life.

When it comes to the fatigue degradation of reinforced concrete structural members, a wide range of tests have been carried on to verify the structural deterioration along the fatigue life (Bishara et al. (1982)). The fatigue performance of reinforced concrete structures is associated to the constituent and interaction between steel bars and concrete (Papakonstantinou et al. (2001)). The main causes on the stiffness degradation subjected to fatigue loading is the damage accumulation on the rebars and concrete. While compressive stresses of concrete are redistributed along the fatigue cycles, the tensile reinforcement must sustain more stress in order to maintain equilibrium. In general, the fatigue damage on the rebar is accumulated, resulting in nucleation and propagation cracks along the beam section. In accordance with previous results the verified issues observed in fatigue tests, the addition of fibers in the concrete mix has vast potential to enhance the cementitious composite resistance in the traction zone.

However, there is still a major gap in the literature and in the present design codes and guidelines when it comes to the analysis of the fatigue degradation of fiber reinforced concrete structural members. Among the literature, the works by Gao et al. (2020) and Parvez et al. (2015) bring an overall study of the fiber influence on the mechanical deterioration in fatigue tests. The addition of 0.50% steel fibers could promote an increase of at least 38% in the fatigue life.

The present work, therefore, developed an experimental program with the aim to enhance knowledge about the use and influence of steel fibers in reinforced concrete structural members under flexural fatigue loading. The applied mixture presented a 50 MPa self-consolidating concrete with the addition of 40 kg/m³ of hooked-end steel fibers. The reinforced concrete beams were manufactured with 6.3 mm longitudinal rebars, resulting in an overall reinforcing ratio of 0.35%. The low reinforcing ratio was selected in order to study the maximum gain in terms mechanical properties under fatigue due to steel fiber addition on the mix. Both RC and R/FRC beams were subjected to approximately the same fatigue loading range in order to evaluate the use of fibers in a structural level. The mechanical deterioration under fatigue loading was analyzed in terms of rebar strain evolution and stiffness degradation along the cycles.

2 Experimental program

2.1 Mix composition and material characterization

The studied matrix composition was developed with Brazilian cement type CPII-F (ASTM Cement type IL – Portland-Limestone cement), fly ash and silica fume as the cementitious materials. Two classes of particle size of sand were used: sand S1 ranged from 0.15 mm to 4.8 mm and the second (S2) from 0.15 mm to 0.85 mm. Coarse aggregate of 9.5 mm maximum diameter, superplasticizer (MasterGlenium 51), viscosity modifying admixture and silica flour also composed the formulation in table 1. With a water/cement ratio of 0.50 resulted in a compressive strength of 50 MPa after 28 ± 2 days. The used steel fiber presents a length (L) of 35 mm, diameter (d) of 0.75 mm, aspect ratio of 45 (L/d) and tensile strength of 1225 MPa. A mass fraction of 40 kg/m³ was added to the R/SFRC structure. The beams were named accordingly with the mass fractions: C0SF and C40SF.

Table 1: Matrix mix composition

Constituent	Matrix
Coarse aggregate (kg/m³)	492
Sand (S1) (kg/m³)	827
Sand (S2) (kg/m³)	100
Silica mesh 325 (kg/m³)	70
Cement (kg/m³)	360
Fly ash (kg/m³)	168
Silica fume (kg/m³)	45
Water (kg/m³)	164
Superplasticizer (%)	5.5
Viscosity modifying admixture (%)	0.75

Sand (S2): Sand (S1) with diameter less than 0.85 mm

Fresh concrete properties were analyzed in accordance with ASTM C1611 (2005) standard with no evidence of bleeding or segregation of the matrix. The self-consolidating concrete spread was analyzed by the average of two mass diameters. The following spreads were observed for C0SF and C40SF: 710 mm and 690 mm.

The post-peak flexural strength of the SFRC composition was previously verified through EN 14651 (2005) three-point bending test standard by Monteiro et al. (2023). A total of 21 specimens were tested in previous study. As defined in the *fib* Model Code (2012), $f_{R,i}$ is the flexural residual stress with $i = 1,2,3$ *and* 4, respectively for crack mouth opening displacements (CMOD) values of 0.5, 1.5, 2.5 and 3.5 mm. Table 2 summarizes the mean post-peak results.

The beam reinforcement presented 6.3 mm diameter steel bar used in this research program. A nominal 500 MPa yield strength and a 210 GPa young modulus were reported by the manufacturer. The deformed steel bar has transverse ribs.

Table 2: Post-peak parameters for monotonic three-point bending tests. Standard deviation values in parentheses.

Mix	f_{lop} MPa	$f_{R,1}$ MPa	$f_{R,2}$ MPa	$f_{R,3}$ MPa	$f_{R,4}$ MPa
C40SF	6.38	7.07	6.01	3.78	2.75
	(0.56)	(1.00)	(0.82)	(0.33)	(0.22)

2.2 Fatigue test program

A short beam was produced for the structural fatigue tests with 120 mm height, 150 mm width and 1200 mm length. The beams were reinforced with two steel bars with 6.3 mm in diameter and 6.3 mm stirrups with 12.5 mm spacing. The total steel area in the cross section was of 0.35%. The complete beam geometry and reinforcement configuration can be analyzed in figures 1 and 2(a).

All structural tests were carried on a MTS servo-controlled hydraulic system with maximum capacity of 500 kN. The beam deflection was measured by three LVDTs, which were equally distributed along the loading span. The span between the loading rollers measured 370 mm and the support rollers presented a span of 1100 mm. The test illustration is displayed in figure 2(b) and in figure 1. The pair of longitudinal rebars were instrumented with two 6 mm and 120 Ω strain gauges. 50 mm length strain gauges were also positioned along the beam height of the specimen to measure the concrete strain. The complete gauge locations can be assessed in figure 2(a).

Figure 1: Structural test photo

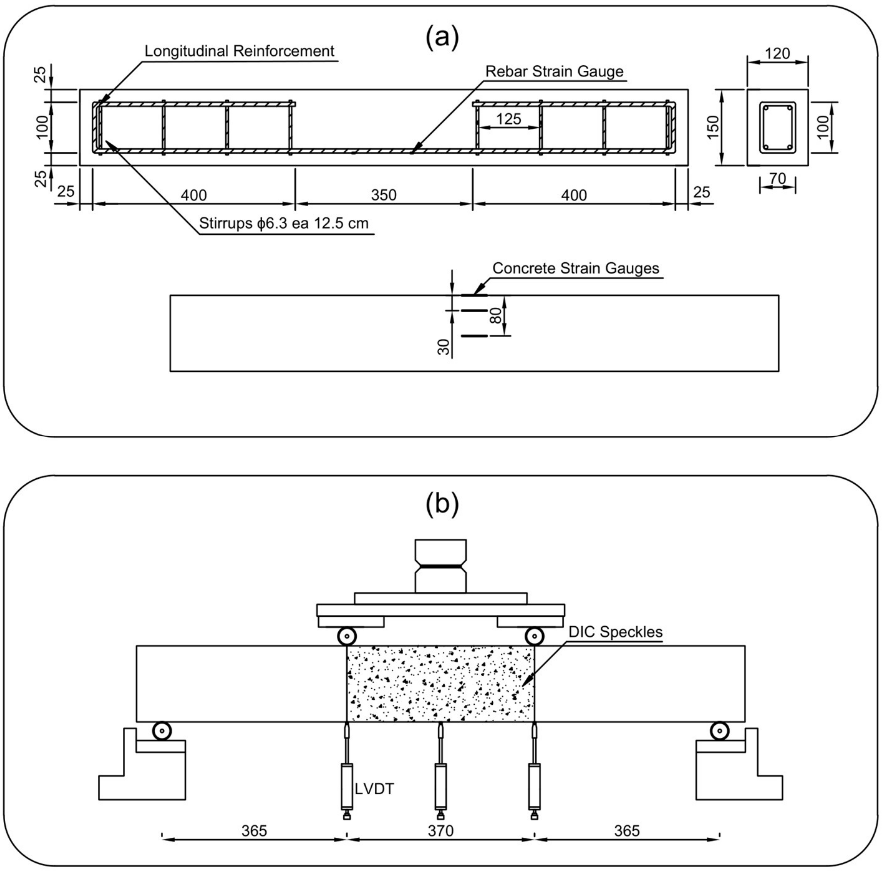

Figure 2: Setup illustration: (a) reinforcement configuration and gauge positions and (b) setup with LVDTs disposal. Dimensions in mm

The structural tests were performed in two distinct stages. First, the beams were pre-cracked until reaching the maximum fatigue load (P_{upp}). Thereafter, the beams cycled between the maximum (P_{upp}) and minimum (P_{low}) forces in a sinusoidal form. The minimum force was defined as 30% of P_{upp} ($P_{low} = 30\% x P_{upp}$). The two tested beams were loaded under the same maximum fatigue load of 15 kN. All tests were carried on at 6 Hz frequency along the time. The tests were terminated when the studied specimen either reached failure or 1,000,000 cycles (run-out). The complete test instrumentation was connected to a HBM data acquisition device, which stored the collected data at a 1024 points per second rate. The data was recorded in the system every 30 minutes of test time for 30 seconds straight. Figures 3(a) and 3(b) summarize the fatigue test procedure.

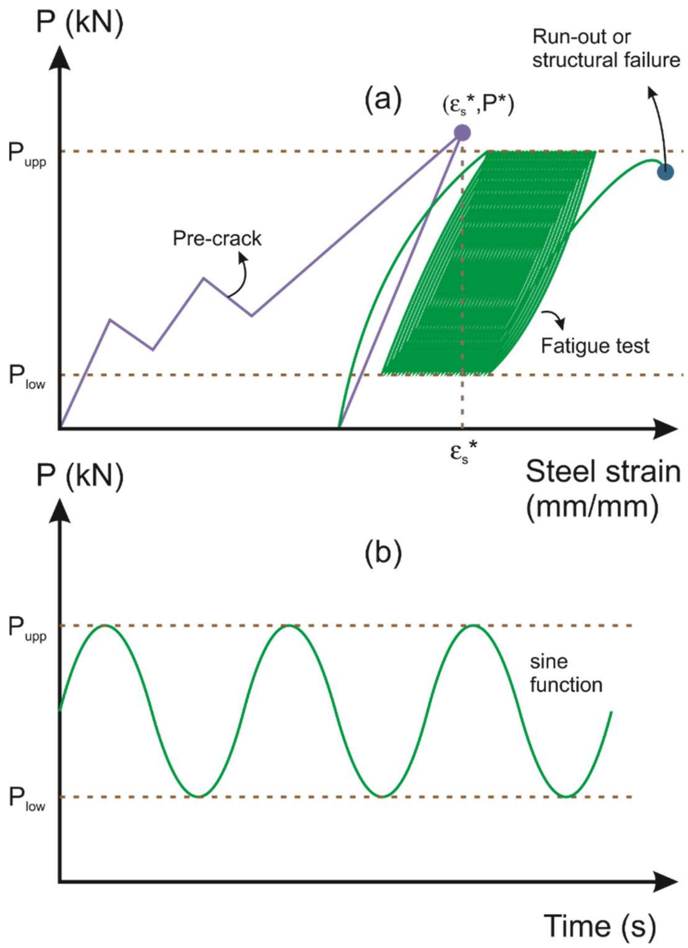

Figure 3: Fatigue test program: (a) test stages from the pre-crack until the fatigue loading and (b) loading oscillation at 6 Hz of frequency.

3 Discussion and analysis

Figure 4 brings the results of the fatigue hysteresis cycles for the longitudinal reinforcement strain for plain (C0SF) and steel fiber (C40SF) reinforced concrete structural beams. Both beams were subjected to the same fatigue loading range, oscillating between 15 kN and 4.7 kN. Although the RC beam at figure 4(a) reached failure after 935,022 cycles, the R/SFRC beam in figure 4(b) reached the test end after 1,000,000 cycles (run-out). The quasi-static tests were studied in previous research developed by Cardoso et al. (2019).

The addition of fibers promoted a significant influence on the rebar strain evolution of RC structures. When comparing the same loading range, R/SFRC beams reported a significant lower strain value at the first strain cycle. While C0SF structures reported a higher strain increase along the fatigue life, C40SF beams presented a much more modest strain evolution throughout the cycles. The addition of fibers is responsible for promoting a bridging effect in the tensile region of the reinforced structure. The fiber bridging capacity significantly enhances the post-crack strength of the composite, resulting in significant increase on the yielding resistance of the structure under flexural loading as also shown by Cardoso et al. (2019). As a consequence of the higher yielding resistance of R/SFRC, much lower fatigue damage accumulation on the rebar takes place along the cycles. Figure 5(a) summarizes the strain evolution along the cycles for C0SF and C40SF structures.

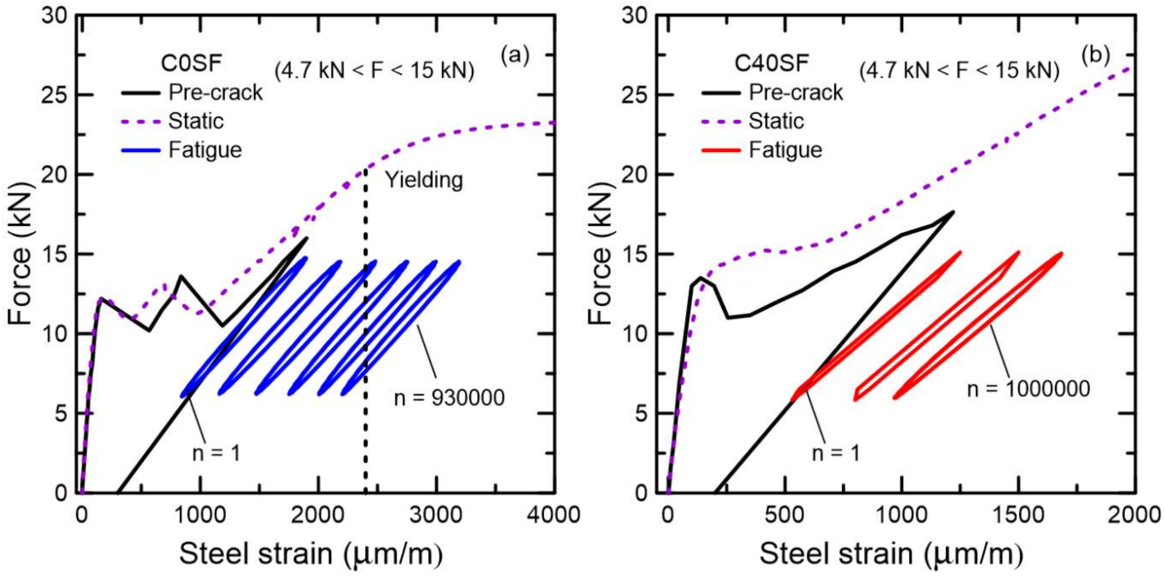

Figure 4: Fatigue longitudinal rebar strain evolution, quasi-static and pre-crack results for (a) C0SF and (b) C40SF under the same fatigue loading range.

During the almost linear strain increase through the cyclic loading, the fatigue induced degradation of the beam was primarily caused by the tensile bar yielding after continuous damage accumulation along the cycles. When the crack expanded until certain opening, the reinforcement could not withstand the applied load anymore, leading to structural failure of the beam The failure was observed on the RC beam without fiber addition and is displayed in figure 5(b).

While under quasi-static loading RC beams multiple cracks are formed (Cardoso et al. (2019)), only one major crack controls the failure mode in the fatigue tests. The growth of one major crack reveals that fatigue rupture is controlled by the stress concentrations on the tensile bars at the major crack location of loaded beam. Similar response was also observed by Gao et al. (2020) during its experimental program.

Another major parameter to verify mechanical degradation along the fatigue test is the stiffness variation as a function of the cycles. Figure 6(a) illustrates the methodology to assess the structure stiffness subjected to fatigue loading. For each cycle, the flexural stiffness was evaluated as the ratio between the applied fatigue loading range by the measured deflections on the LVDTs. Figure 6(b) summarizes the stiffness degradation in this research.

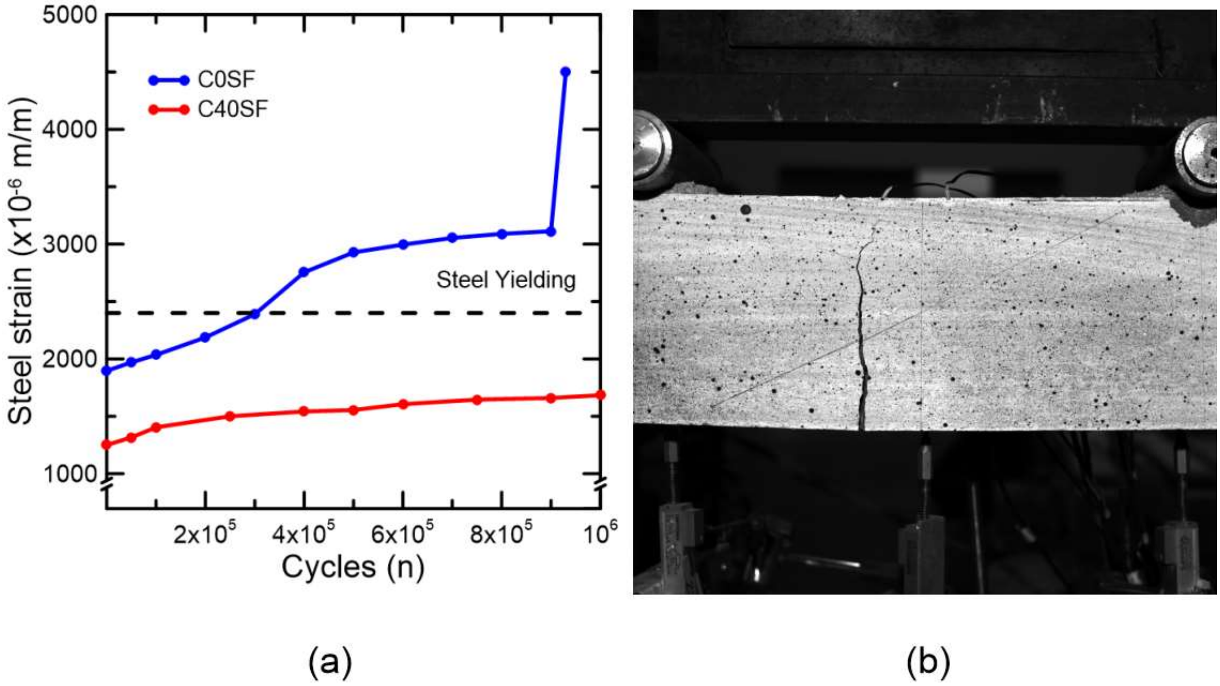

Figure 5: Fatigue damage evolution for C0SF and C40SF reinforced concrete beams: (a) longitudinal rebar strain evolution along the cycles and (b) failure mode observed for C0SF.

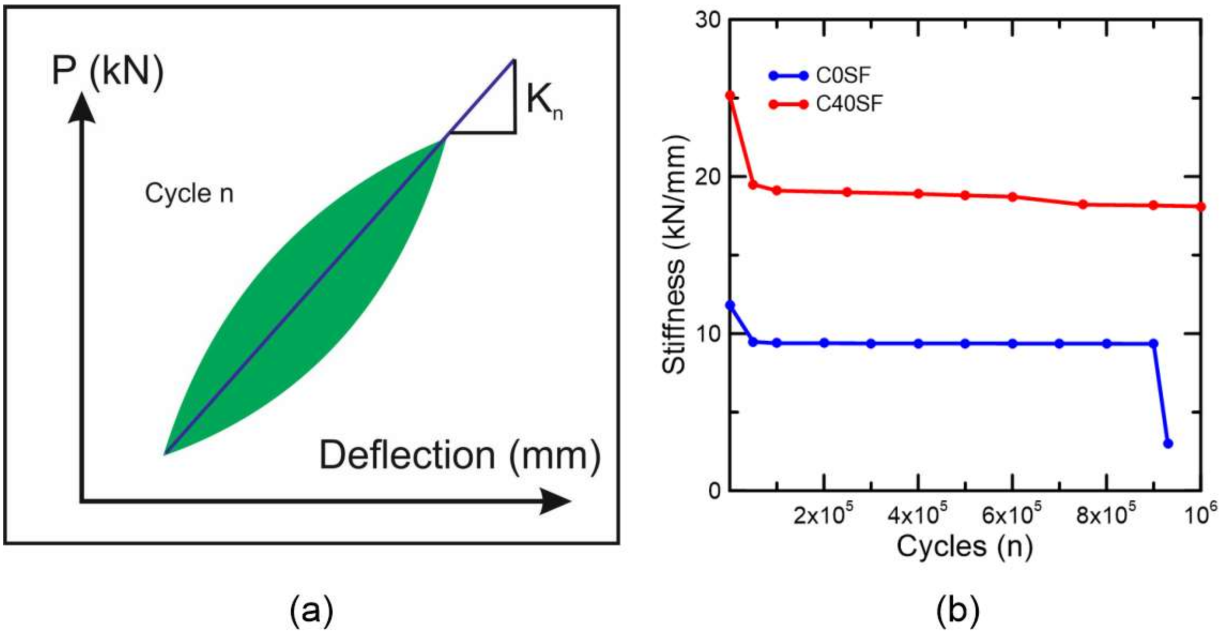

Figure 6: Stiffness decay along the cycles: (a) stiffness calculation methodology and (b) stiffness variation for C0SF and C40SF reinforced concrete beams.

When it comes to the analysis of stiffness degradation, R/SFRC reported a massive increase in stiffness. While C0SF beam presented approximately 10 kN/mm along the fatigue life, C40SF under the same loading range resulted in almost 20 kN/mm. The capacity in increasing the composite post-crack stiffness has already been verified in the literature in quasi-static loadingstudies, such as Cardoso et al. (2019). Based on the presented results, the same phenomena can be affirmed in cyclic loading. The increase in stiffness in directly associated to the fiber capacity in controlling crack opening in cementitious composite in tension.

4 Concluding remarks

The present research brings an overall analysis of the fatigue mechanical degradation of RC structures under flexural fatigue loading. The main focus of the experimental program was to verify the potential gain in mechanical performance by the addition of fibers in reducing the mechanical deterioration of the structural members under cyclic loading. The beam degradation was primarily studied through rebar strain evolution under fatigue and stiffness decrease for each cycle. The following conclusions were drawn from this work:

- The addition of steel fibers on the matrix composition promotes a significant influence on the rebar strain evolution of RC structures. When comparing the same loading range, steel fiber reinforced concrete structural beams reported much lower strain values along the fatigue test. The fiber showed a very effective capacity to redistribute the stresses in the traction zone and, consequently, reducing the measured strains on the longitudinal reinforcement.
- The capacity of stiffness retention along the fatigue cycles was also studied in the present work, since it is considered one of the main parameters to verify the mechanical degradation of RC structures. The use of fibers in the concrete mix promoted a significant increase in stiffness of the studied beams under flexural fatigue loading. The increase in stiffness is directly associated to the fiber capacity in controlling crack opening in cementitious composites under tension. The addition of fibers showed a major potential in enhancing the RC structures capacity to resist the fatigue degradation along the structure service life.

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