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RC beams with steel fibers under impact loads

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ABSTRACT. The use of steel fibers as addition improves several mechanical properties of concrete, whose tensile strength and resilience are of great interest for designs of structures subjected to impact loads, such as military facilities, nuclear power plants, bridges and overpasses. However, there are few studies that assessed the effects of adding steel fiber on reinforcements of reinforced concrete. To assess these effects, four concrete beams under impact loads were tested, with reinforcements and different amounts of steel fibers being monitored. The results showed a better performance of beams with fibers, presenting lower strains on reinforcements and cracking.

Keywords: composite, strain, drop-weight test, structural failure.

Vigas de concreto armado sob cargas de impacto

RESUMO. A utilização de fibras de aço como adição melhora diversas propriedades mecânicas do concreto, sendo que a resistência à tração e a resiliência são de grande interesse para projetistas de estruturas sujeitas a cargas de impacto, como instalações militares, usinas nucleares, pontes e viadutos. Entretanto, poucos trabalhos avaliaram os efeitos da adição de fibras de aço sobre as armaduras do concreto armado. Para avaliar estes efeitos, foram ensaiadas quatro vigas de concreto armado sob cargas de impacto, com monitoramento das armaduras e diferentes quantidades de fibras de aço. Os resultados mostraram melhor desempenho das vigas com fibras, com menores deformações nas armaduras e fissuração.

Palavras-chave: compósito, deformação, ensaio de queda de peso, falha estrutural.

Introduction

Concrete is the most widely used building material in the world because it is durable and relatively inexpensive. However, concrete also has some negative features. It is a brittle material that has a low tensile strength and low deformation capacity. In recent years fibers have been added to concrete aiming to obtain a composite with greater tensile strength, resilience, ductility and to retard the propagation of cracks through the matrix. Concrete reinforced with steel fibers is a cement matrix material whose composition receives a certain percentage of short fibers.

The most widely used fibers are metallic, glass, synthetic, natural and, more recently, carbon. However, the steel fibers and glass are the most applied in the construction industry due to the improvement of properties and to their low prices and durability. The ability to absorb energy is the property most benefited by the addition of fibers to cement matrix material.

The introduction of short fibers improves the characteristics of concrete with regard to ductility, resistance to shock and fatigue. The cracking control of these benefits is sensitive to the amount and type of fiber added.

Since the advent of reinforced concrete structures, the analysis and calculation of structures under extreme loads, such as earthquakes, explosions and impacts, has been a major goal of many researchers and designers.

Among the various types of extreme loads, impact loads have attracted special attention by the military engineers since the early 20th century, for the design of fortification structures against ballistic weapons.

Subsequently, the nuclear power industry joined to the efforts to better understand the behavior of reinforced concrete structures under impact loads, in order to design containment structures of nuclear power reactors against accidental impact loads, as recommended by Saatci (2007). When the structures suffer from these kinds of loadings, it is necessary further studies on the specific characteristics and properties of concretes in order to avoid damages in the composite which could compromise the structural stability.

Preliminary information

Concrete strengthened with steel fibers

Steel fibers when added to concrete make difficult the propagation of cracks due to their high modules. As for the load bearing capacity of composite, post-cracking, the fibers allow a redistribution of stresses in the material even when used at low levels Figueiredo (2005). To better understand this behavior it should be remembered that the concrete, as a brittle material, is always susceptible to stress concentration, causing the emergence and propagation of a crack from the increased stress imposed, as shown in the Figure 1. According to Tezuka (1989), the cracks that appear in the concrete, when subjected to tensile strain, quickly concentrate the energy at its ends, causing the uncontrolled expansion of these cracks and, consequently, creating a brittle material. When in the concrete matrix short fibers are introduced, they reduce the growth of cracks. The fibers form a connection between the crack edges, so in order to increase the opening more energy is required. In the event of failure, it will occur by sliding of the fiber, due to failure or the collapse of concrete matrix around the fiber. The expected behavior is that the fiber provides the generation of improvements to other properties such as stiffness, ductility, energy absorption, impact resistance and fatigue strength.

Impact loads

The demand for impact-resistant design has a wide spectrum, from barriers to protect shed floors, bridges until industrial facilities. Furthermore, as a result of the levels of terror threatening the world, an impact-resistant design for buildings has become a new focus of attention since then. The impact loads applied to a small region of a concrete plate or shell, tend to produce local effects such as the peeling, penetration, drilling or punching. These effects are more pronounced than the overall effects of the load. In the area of application, the load decreases and the rate of application of load increases. The effects produced by the impact on a structure depend on typical properties of composites that comprise them, such as the tensile strength and the specific energy of fracture, which in turn depend on the nature of the cement matrix used. The response of a concrete structure subjected to impact loads will be completely different from the response of a structure statically charged. This is because, during the impact, the structure will vibrate and sometimes sections of the structural element will be subjected either to tensile or compressive stresses/strains. A dynamic load differs from the static load primarily by the nature of time variation for the dynamic problem, where the strength and the response vary over time due to the fact that, for the balance, the system changes its kinematic positions producing inertial forces. Since the impact load is a type of dynamic loading, in which the loading rate is almost instantaneous, and the damping forces do not dissipate significant amount of energy, the structural response depends on the impact energy and the structure stiffness, the contact rigidity, and the mechanical properties of materials.

Assuming that there is no loss of energy during the impact, this can be studied using a theory of mechanical energy conservation. In a simplified form, it is possible to solve problems as shown in the Figure 2, using the following methodology.

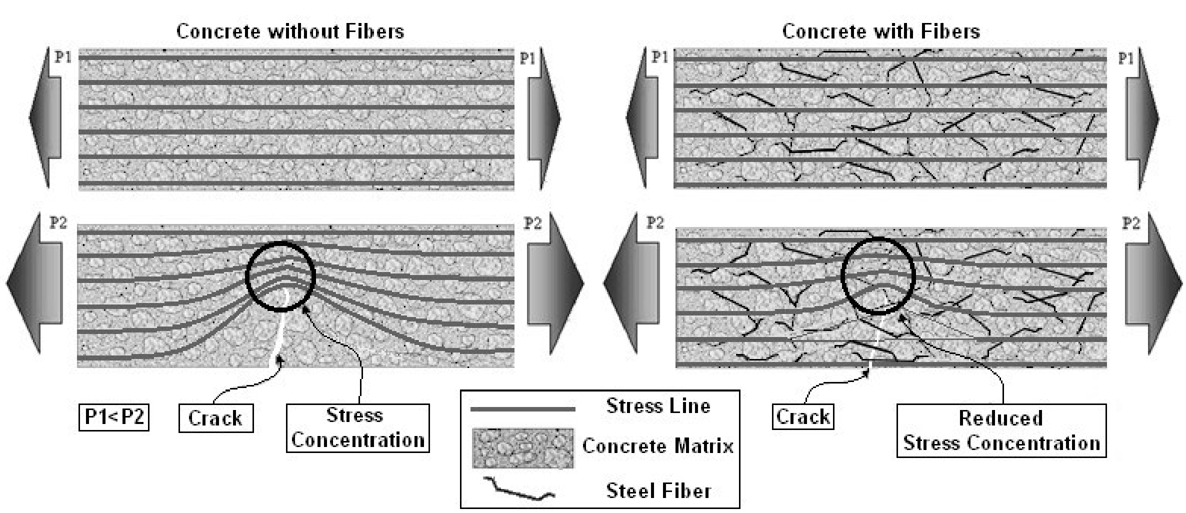

Figure 1. Effect of adding steel fibers on concrete.
Source: Figueiredo (2005).

Whereas a force W is applied in the middle of the span l of a simple supported beam, which displaces vertically its center (Equation 1), in which it is only necessary to determine the impact factor n (Equation 2) in order to estimate the maximum displacement. This factor represents the amplification of the load applied statically so it can be handled dynamically. Once determined the impact factor, the maximum deflection and the dynamic stress (Equation 3) are easily found (SHUAEIB et al., 2004; HIBBELER, 2004). A comparison between the results given by the equations and the results obtained by Zhang et al. (2010), considering the displacements produced by the static and the impact loadings, makes clear the consistency among the results obtained by the researchers, with small differences caused by the nature of the tests, which tends to damage the structural element.

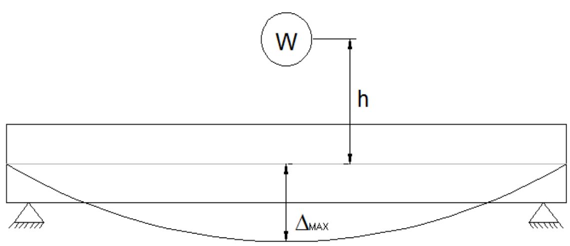

Figure 2. Example of a simply supported beam under impact loading.

$$\Delta = \frac{W \cdot l^2}{48 \cdot E \cdot I} \tag{1}$$

$$\Delta_{max} = \Delta \cdot n = \Delta \cdot (1 + \sqrt{1 + 2 \cdot \frac{h}{\Delta}} \tag{2}$$

$$\sigma_{max} = \frac{W \cdot l \cdot c}{4 \cdot I} = \frac{12 \cdot E \cdot \Delta_{max} \cdot c}{l^2} \tag{3}$$

where:

Δ is the static vertical displacement of beam;

W is the drop weight;

l is the beam span;

E is the elasticity modulus;

I is the cross section inertia of the beam;

h is the drop height;

n is the impact factor;

Δ_{max} is the maximum displacement under impact loads of beam;

σ_{max} is the maximum dynamic stress;

c is the half height of beam.

The Figure 3 shows the test system used by Mylrea (1940), Saatci (2007) and Bhatti et al. (2011) to simulate impact loads. The test system of Bhatti et al. (2011) is essentially a test machine where the drop height, speed, impact energy and displacements are obtained automatically, showing a significant evolution from the system used by Mylrea. Due to the small number of publications on the subject, several situations in which the structural elements are subjected to impact loads should be better investigated, since it is known that not every impact load leads the reinforced concrete element to ruin. In those cases where it is desired to rehabilitate the element it is essential to evaluate the damage caused by the impacts of lower intensity more than those which would lead to the collapse, acting whether repetitively or not. By following this line of investigation, Knab an Clifton (1982) developed a test system where cylindrical projectiles with 5 kg were repeatedly released from a height of 1.7 m, driven by a vertical pipe until reach the surface of small concrete plates with and without steel fiber and reinforcement, with all plates measuring 61 mm x 61 mm x 76 mm. This system is also shown in the Figure 3, and the tests were performed until the failure of plates. Two types of steel fibers were used, with 30 mm or 50 mm length; with the longer fibers in the reinforced concrete plates providing best results, and collapsing with up to 118 impacts, but no information on strains was presented.

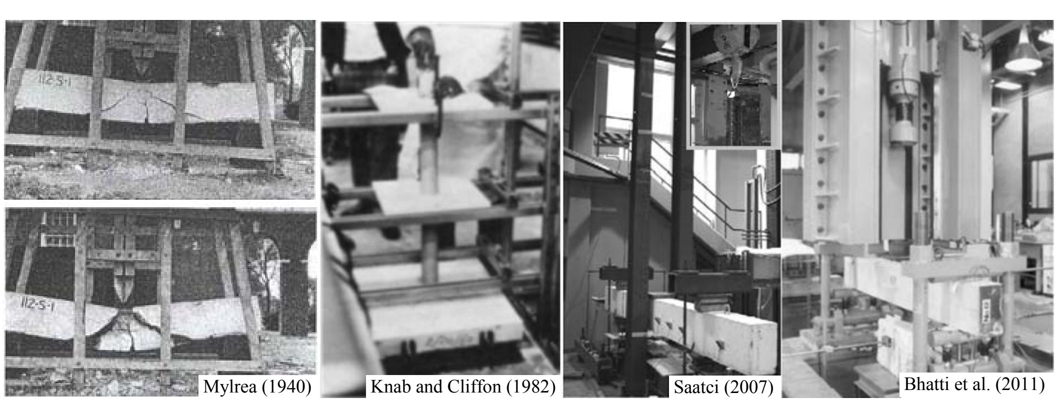

Figure 3. Some impact test systems.

Material and methods

The normal weight concrete used to cast the cylindrical proofs (CP) was provided by a regional factory using common Portland cement and rolled pebble with maximum diameter of 19 mm as coarse aggregate. The proofs demolding was made after 48 hours according to NBR 5738 (ABNT, 2003) and all cylinders were maintained in humid chamber for 28 days. Three proofs were used for each test, i.e. tensile, compression and elasticity modulus, performed in accordance with NBR 5739 (ABNT, 2007a), NBR 7222 (ABNT, 2011) and NBR 8522 (ABNT, 2008), respectively, resulting in an average compression strength of 23.7 MPa, 1.3 MPa for tensile strength (f_{ct}) and 23.9 GPa for the elasticity modulus (E_c). The Table 1 presents the results for the concrete without fibers while the Table 2 lists the results for the concrete with steel fibers. In relation to the compressive strength, the variation in the results was lower for the concretes. The average (Avg) results for the tensile strength and the elasticity modulus of concrete with 2% of steel fiber were 100% and 38% higher than those obtained with the concrete without fibers, respectively. The Table 3 presents the concrete mixture proportions and the amount of steel fiber in relation to the cement weight.

Table 1. Concrete without steel fibers.

Proof	f_c (MPa)	f_{ct} (MPa)	E_c (GPa)
CP 01	26.7	1.2	23.8
CP 02	20.3	1.4	22.7
CP 03	24.2	1.2	25.2
Avg	23.7	1.3	23.9

Table 2. Concrete with steel fibers.

Property	Steel fibers											
	0.5%				1.0%				2.0%			
	CP1	CP2	CP3	Avg	CP1	CP2	CP3	Avg	CP1	CP2	CP3	Avg
f_c (MPa)	24.0	23.5	24.6	24.0	25.2	24.9	25.7	25.3	26.6	27.3	25.9	26.5
f_{ct} (MPa)	2.0	2.2	2.0	2.1	2.2	2.4	2.1	2.2	2.5	2.7	2.6	2.6
E_c (GPa)	23.4	25.3	26.7	25.1	28.7	29.4	27.7	28.6	33.5	31.0	34.9	33.1

Table 3. Concrete mixtures.

Beam	Fibers (%)	Steel fiber (kg)	Cement consumption (kg m^{-3})	w c^{-1}
VR	0.0	0.0		
VT-01	0.5	1.5	301	0.58
VT-02	1.0	3.0		
VT-03	2.0	6.0		

Steel bars

The steel bars (type CA 50) used in the reinforcements of beams were 10.0 and 5.0 mm diameter, all from the same batch, with three samples with 600 mm length taken for tensile test, following the recommendations of NBR 6892 (ABNT, 2002), in order to obtain the mechanical properties of steel. The corresponding yields of stress f_{ys} and strain ε_{ys} to each diameter are shown in the Table 4.

Table 4. Mechanical properties of steel bars.

ϕ (mm)	A_s (mm^2)	f_{ys} (MPa)	ε_{ys} (MPa)	f_u (MPa)	E_s (GPa)
5.0	19.6	548.0	4.2	719.6	212.2
10.0	78.1	580.0	2.1	725.9	251.8

Steel fibers

Regarding physical and mechanical properties of steel fibers used in the beams, fibers presented diameter of 1.05 mm, length of 50 mm, density of 7.84 g cm^{-3}, up to 4 ‰ of failure strain and 1,100 MPa for tensile strength. All dosage instructions suggested by the manufacturer were followed, i.e. a minimum of 20 kg m^{-3} of concrete, cement mortar percentage of not less than 50% and water/cement ratio of up to 0.55.

Characteristics of beams

The length of beams was of 1500 mm in all cases, with cross section of (100 x 200 mm) and the concrete with average compressive strength (f_c) of 23 MPa at 28 days. The geometric rate of the flexural reinforcement was maintained constant in all beams, with 2 bars of steel CA50 and diameter of 10.0 mm. The shear reinforcement bars were composed of 5.0 mm diameter bars spaced at intervals of 100 mm, as shown in the Figure 4. The strain gauges were installed in the flexural reinforcements at 750 mm from the ends of beams, and the shear reinforcements received these sensors at 228 mm from these ends and 100 mm from the bases of beams.

Test system

Impact loads

The test system consisted basically of a bi-supported beam on a large rigid slab under a steel frame for reaction, where the dynamic loading system was set, according to the Figure 5. As for the impact load an alternate system was developed, consisting of a pipe of 100 mm in inner diameter and a metallic piston of 70 mm diameter and weight of 310 N, in which when released from a height of 2200 mm, the system accumulates a potential energy of 682 Joules.

The drop height was measured between the rest positions of the gravity center of the piston, i.e. at the highest position and in contact with the beam to be tested. In order to reduce the oscillations of piston during the fall, metal pins were fixed in two orthogonal directions perpendicular to the longitudinal axis, as shown in the Figure 6. These pins present a convex end in order to reduce the friction with the guide pipe, which was completely greased inside. The beams also received a metal plate, measuring 120 x 120 x 50 mm, positioned on the upper surface of concrete in order to mitigate the damage caused by the 20 impacts of the piston. The number of impacts was defined only in order to maximize the effects of damage on the strains of reinforcements and of deflections. The system was tested several times and proved to be satisfactory.

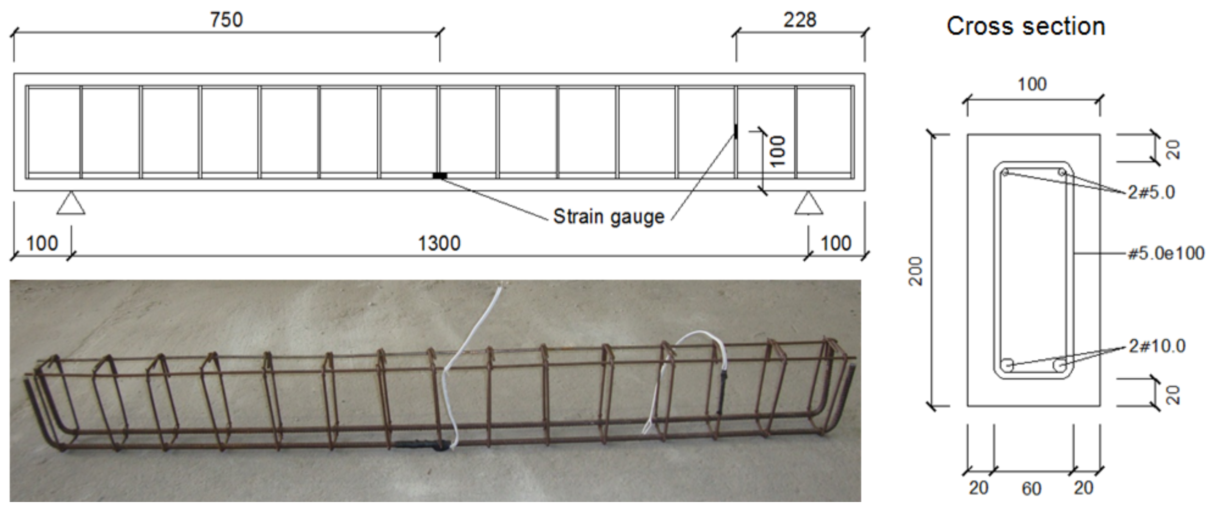

Figure 4. Dimensions and positions of strain gauges in the reinforcements.

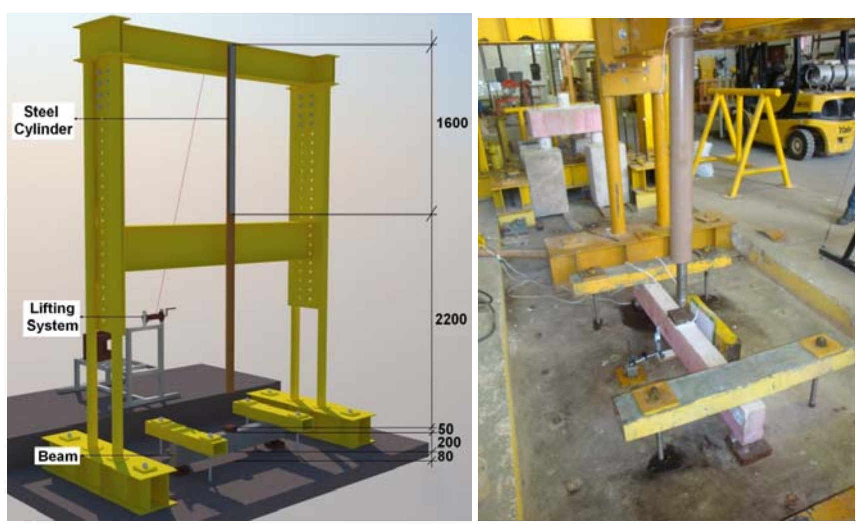

Figure 5. Test system for dynamic loads.

Figure 6. Details of steel piston.

Static loads

The second test system was composed of a steel frame fixed on the reaction slab, two concrete blocks to support the beam and to transfer the forces applied to the slab, one hydraulic cylinder with load capacity of 1,000 kN, one manual hydraulic pump to drive the hydraulic cylinder, one load cell with capacity of 2,000 kN and precision of 0.5 kN, and one digital display to monitor and to control the load applied. The Figure 7 shows the second test system. The loads were applied on equidistant points at 400 mm away from the supports. The span tested was 1,300 mm.

Instrumentation

Maximum deflections of beams were measured during the tests using a digital dial gauge accurate to 0.01 mm, positioned in the middle of the spans tested. The flexural and the shear strains of reinforcement were monitored through electrical strain gauges (EERs) and the readings were performed by a data acquisition system for both sensors installed on the reinforcements and on the concrete surface. The loads were applied in increments of 0.5 kN.

Results and discussion

Impact tests

Displacements

As previously mentioned, vertical displacements were measured with a digital dial gauge recording the maximum value for every impact. This monitoring of displacements is not reliable, because in some cases values lower than those of previous impacts were recorded by the gauge. Even so, these values coincided with the values recorded in an auxiliary system, where a pencil was fixed under the beam and brought into contact with a paper during the impact, in which were also observed lower values than found in previous impacts. In any case, the average results for the vertical displacements are shown in the Figure 8, which provides a general average result of 7.9 mm, very close to the theoretically estimated in the theory of elasticity by adopting the recommendations of the Brazilian standard NBR 6118 (ABNT, 2007b) According to these recommendations, the section inertia can be reduced from 30 to 60% in order to consider the effect of cracking. As for the series of tests carried out, the most appropriate value for the reduction is 50%.

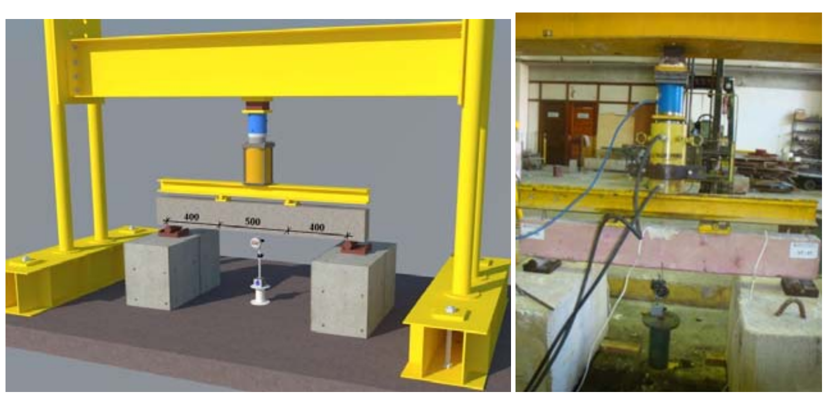

Figure 7. Test system for static loads.

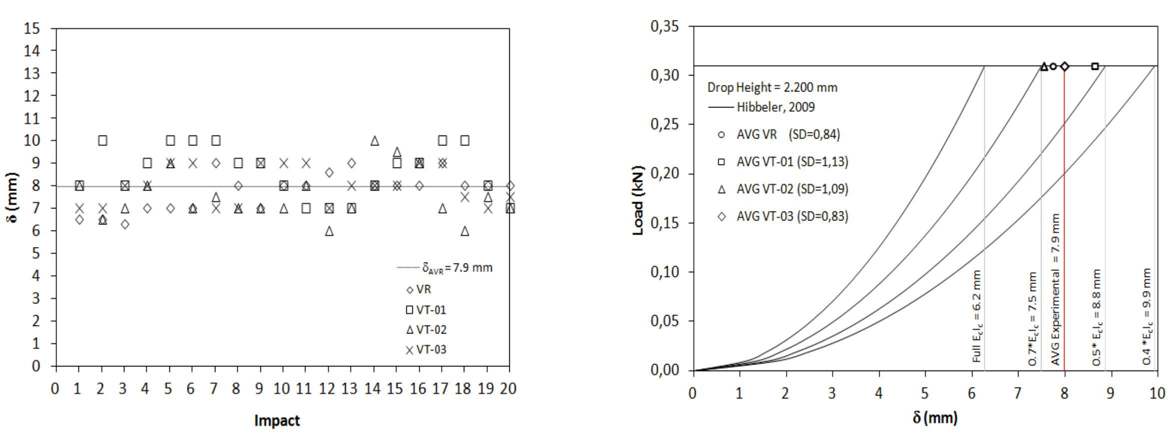

Figure 8. Experimental and estimated displacements under impact loads.

Cracking patterns

The Figure 9 illustrates the cracking pattern of beams. The load responsible for the appearance of the first flexural crack occurred during the second impact, and the number is shown at the side of the cracks in the figure.

In general, beams with concrete containing steel fibers presented less cracking and damage on the upper surface of concrete than those without fibers that received the impact through a steel plate.

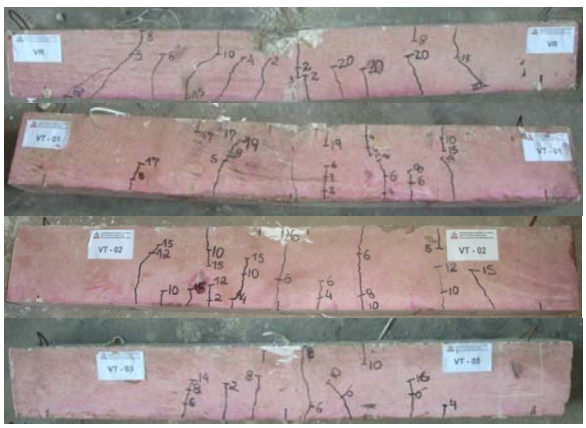

Figure 9. Cracking patterns.

Strains

The strains for the flexural reinforcement have increased with the loads applied, however, lower than the yield strain of steel bars. In addition, this behavior was also observed for stirrups, but with less intensity for beams with concrete containing 1 and 2% of steel fibers, i.e. VT-02 and VT-03, respectively. The Figure 10 shows the strains for the experimental reinforcement and the processing of curves by considering the trend lines and by comparing results of mean values for the beams VT-02 and VT-03 in relation to the reference beam. The results for VT-01 were discarded due to their similarity with those of the reference beam VR. It is clearly observed the positive influence of the steel fibers, preventing higher strains in the case of shear reinforcement during all tests and from the tenth loading for the flexural reinforcement. Except for the beam with 0.5% of steel fiber, in which the presence of fibers had significantly reduced the strains. The strain estimated for the first load, considering the principles of the theory of elasticity, was 0.36 ‰, similar to that observed experimentally for the beams VT-02 and VT-03, 0.34 ‰, however, slightly above the observed for the reference beam, 0.28 ‰. This behavior can be better explained by a non-linear analysis, but it is clear the contribution of the addition of steel fiber to increase the ductility of beams.

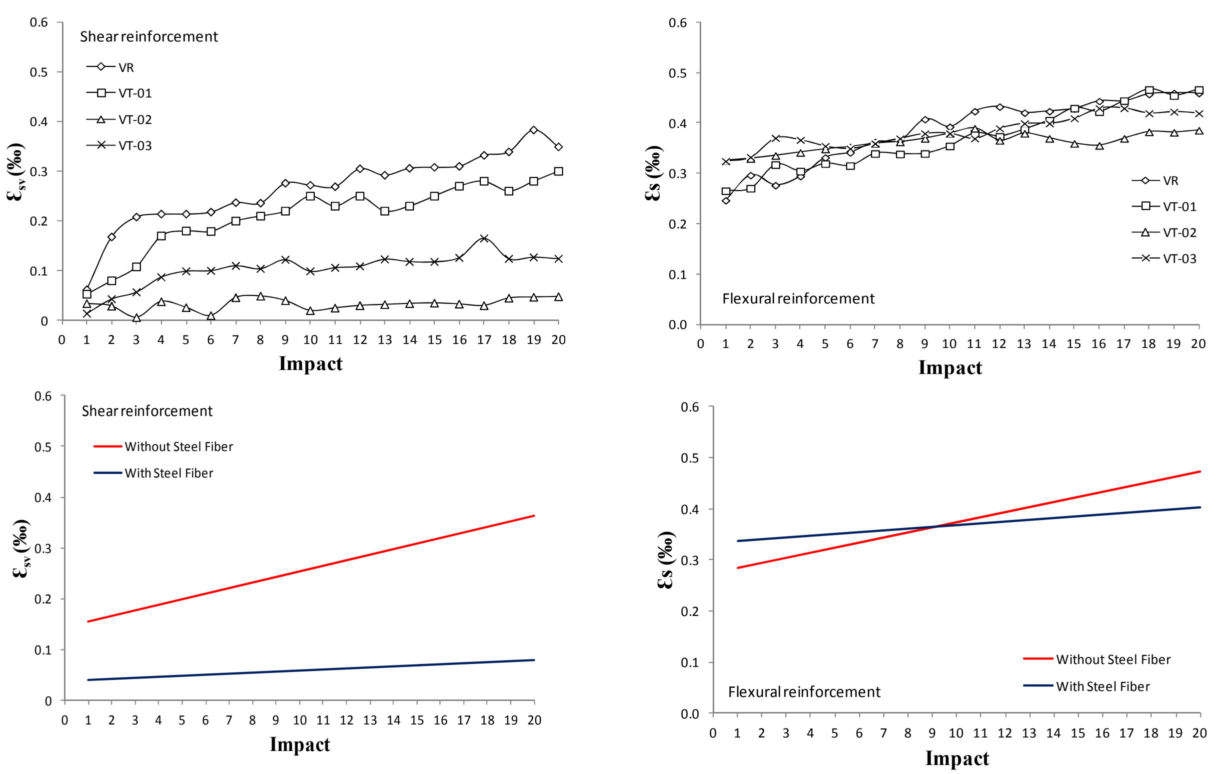

Figure 10. Strains of reinforcements under impact loads.

Static tests

Displacements

The vertical displacements observed for the loads applied are shown in the Figure 11. It is possible to observe the ductility gain of beams by increasing the amount of fibers embedded in the concrete.

The maximum displacement of the beam with 1% of steel fiber was 33% higher than that presented by the reference beam, while for other beams with steel fiber the maximum displacement was closer to the maximum displacement of this beam.

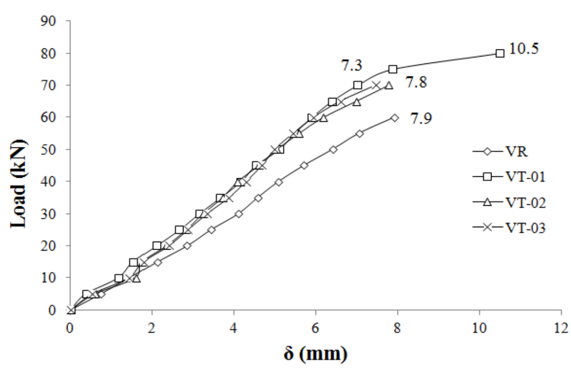

Figure 11. Maximum experimental displacements.

Strains

Considering the flexural reinforcements, results were consistent because after recording the yield strain, there was a little increase of the loading up to failure.

The stirrups reached the maximum strain of 1.02 ‰ for the beam with 1% of steel fiber. The Figure 12 shows the curves obtained for the flexural and shear strains of reinforcements.

Failure loads and modes

The flexural failure load with the reinforcement yield was estimated at 68.7 kN (P_{Flex}) for all beams, and the shear failure load was estimated in 90.0 kN (V). Static tests were performed after the impact tests, being expected that beams would not achieve the estimated flexural failure load.

However, all beams with the addition of steel fiber exceeded the estimated flexural failure load by up to 24% as observed in the Table 5, and the reference beam exceeded the expectations for the strength and the vertical displacements. All beams failed by flexure with excessive strains in flexural reinforcements.

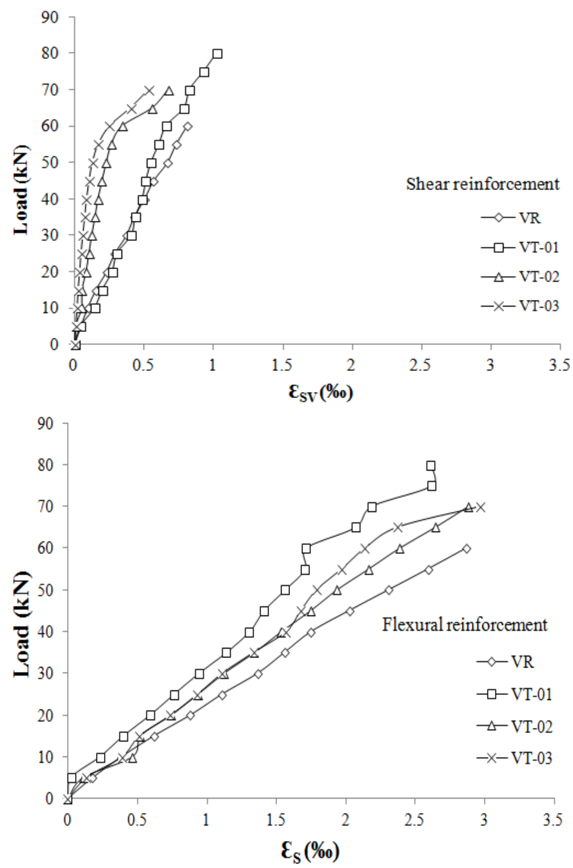

Figure 12. Strains of reinforcements under static loads.

Table 5. Failure loads.

Viga	δ (mm)	P_{Flex} (kN)	V (kN)	P_u (kN)	P_u / P_{Flex}
VR	7.9	68.7	90.0	62.0	0.90
VT-01	10.5			80.5	1.17
VT-02	7.8			75.0	1.09
VT-03	7.3			74.5	1.08

Conclusion

Experimental results to four reinforced concrete beams under dynamic and static load (impact) were presented and discussed. One beam was used as reference and the other presented between 0.5 and 2% of steel fiber in their composition, relative to the weight of cement used in the concrete mixture. As for the impact tests, 682 Joules of energy were used, through a drop weight load that damaged the concrete of beams, but with low strains in the reinforcements. In the general, the addition of steel fibers to concrete improved its ductility and tensile strength, contributing to their resilience, distributing better the stresses applied.

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