PERFORMANCE EVALUATION OF PRESTRESSED CONCRETE SLEEPERS REINFORCED WITH STEEL FIBERS

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Abstract

The primary elements of railway superstructures are sleepers, which distribute the wheel loads of trains from rails to the ground. While wood was previously the dominant material used in sleeper construction, concrete is now becoming more common. Over time, a continuous increase of load, speed and traffic on railways have caused a rise in damage to prestressed concrete sleepers but have also stimulated efforts to improve them. This research investigates the performance of prestressed concrete sleepers reinforced with steel fibers, including their load-carrying capacity and energy absorption characteristics. Negative bending moment tests were conducted at mid-span of reinforced concrete sleepers with 0.5% of the 35 and 60 mm long fibers. The results of the research have indicated that the use of steel fibers in concrete leads to an increase in load-carrying capacity, energy absorption, and consequently, improvements in the service life of structures, including sleepers. The experimental results were verified by theoretical calculations. The increment ratio of the ultimate moment by the fiber addition was the same for the theoretical and experimental analyses.

Keywords: Prestressed concrete sleepers; steel fibers; mechanical property; structural behavior.

1. INTRODUCTION

Sleepers are one of the core elements of the permanent track, whose main functions are: to support and maintain the distance between the internal faces of the rails (gauge), the vertical, lateral and longitudinal stability of the track, to transmit to the ballast the loads coming from the rails and to partially cushion vibrations. The aforementioned characteristics make it necessary for the sleeper to have a high resistance, which in general leads to a high stiffness. At the same time, elasticity is also necessary, since it must be able to withstand very high impact forces and dynamic actions [1].

Wood was the first material to be used as a sleeper, when railroads were beginning to emerge in Europe and the United States. Wood is a suitable material for dynamic demands. It is a good electrical and acoustic insulator, however due to a limited supply of resources, the environmental requirements, and difficulty of recycling due to the chemical treatment by which the sleepers pass, the use of this material is decreasing [2].

Prestressed concrete sleepers are the most used sleepers nowadays due to their technical superiority, considering: long-term durability, rails stability, larger self-weight, ideal for high speed and high loads, lower life cycle cost and it is sustainable, considering the fact that it does not need chemical treatments and it can be recycled [3].

Despite the good performance, the prestressed concrete sleepers also present failures. In some of the studies [4–6], the perceived damages in concrete sleepers were largely related to cracking. When cracking occurs, the deterioration of concrete is accelerated, creating pathways for the deterioration of steel. The concrete matrix loses the ability to transfer tension through the crack causing a concentration of stress in the possibly deteriorated prestressing wires, thus leading to rupture of the structure.

Considering the high costs related to the interruption of a track, it is of great interest for the railway industry that its elements have a high lifespan. Cracking on concrete sleepers causes its service life to be reduced. Fiber reinforced concrete controls crack propagation, the use of this reinforcement also allows tensions to be transferred through the cracks, reducing the demand for the prestressing wires. For these reasons, steel fiber reinforcement have been researched as good option to be used on the sleeper industry [7–10].

2. MATERIALS AND MIXING PROCEDURE

The concrete composition is presented on table 1. The values are in mass for the volume of 1 m^3 of material.

Table 1. Concrete composition

Fiber volume ratio		**0%**	**0.25%**	**0.50%**	**1.00%**
Cement CPV	1	410 kg	410 kg	410 kg	410 kg
Sand	1.39	569 kg	569 kg	569 kg	569 kg
Coarse aggregate	3.15	1293 kg	1286 kg	1279 kg	1266 kg
Water		180 kg	180 kg	180 kg	180 kg
Superplasticizer		2.6 kg	2.6 kg	2.6 kg	2.6 kg
Steel fiber			19.6 kg	39.3 kg	78.5 kg
Water/Cement ratio 0.44					

2.1 Materials

The cementitious material used in the production of the concrete was the Brazilian cement type CPV. The sand had the maximum diameter of 4.76 mm and the coarse aggregate 19.1 mm. Superplasticizer (Grace ADVA™ CAST 525) was also mixed together with the other materials. The water/cement ratio of the mix was 0.44 and the average compressive strength after 28 days was 60 MPa

2.2 Fiber type

Two different types of steel fibers were used, all of which had hooked ends and are supplied glued. The first is 35 mm long and it has 0.55 mm diameter, it is named by the manufacturer as RC 65/35. The second is 60 mm long and it has 0.75 mm diameter, it is named as RC 60/80 as shown in Figure 2.

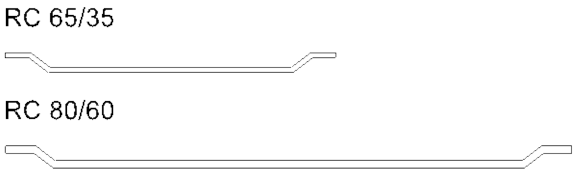

Figure 2. Geometry of the steel fibers used

2.3 Mixing procedure

The mixing procedure was carried out in three stages:

1st stage - the sand and coarse aggregate were mixed together with about 70% of the water for moistening and homogenization for one minute;

2nd stage - the cement was added and mixed for approximately one minute;

3rd stage - the remaining water and the superplasticizer were.

The manufacturing process was terminated after uninterrupted mixing for five minutes. When steel fibers were used, the additions were made gradually, using about two additional minutes of mixing, until it obtained a homogeneous appearance.

3. TEST PROGRAM

Three specimens were produced in total. In order to evaluate the benefits of fiber addition, one of the manufactured sleepers had no fibrous reinforcement, while the other two were reinforced with a 0.5% volume ratio of hooked end steel fiber, being one of the specimens casted with a fiber provided with aspect ratio of 65 and 35 mm long, and the other with fibers with aspect ratio of 80 and 60 mm long, the sleeper geometry is presented in Table 2. In order to compare the bending strength capacity of the different sleepers, negative bending moment test was performed at mid-span on all of the constructed sleepers in accordance with AREMA [11] and Brazilian standards [12]. The test setup is presented in Figure 3. The test machine consists in a hydraulic actuator with 500 kN capacity, controlled by a MTS® central station. The actuator displacement was controlled on a rate of 1 mm/min. The cross-section of the sleeper as well as the prestressing wires distribution is presented in Figure 4.

Table 2. Sleeper geometry

Depth*	28,5 cm
Height*	23 cm
Length*	245 cm
Height at mid-span	24.5 cm
*Maximum dimensions	

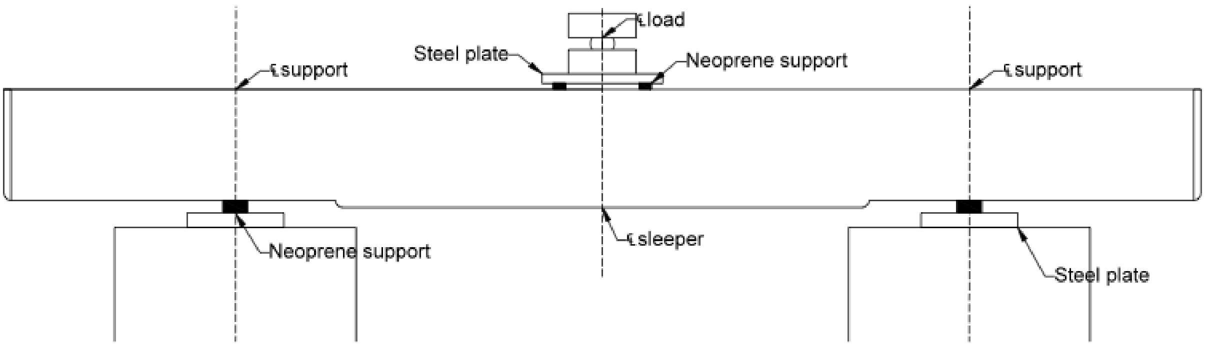

Figure 3. Test setup

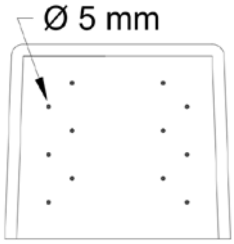

Figure 4. Sleeper cross-section

4. DISCUSSION AND ANALYSES

The Load-Displacement as well as the Load-Strain curves for the three sleepers tested are shown in Figure 5. The point that the lower layer of prestressing wires ruptures is indicated in the graph.

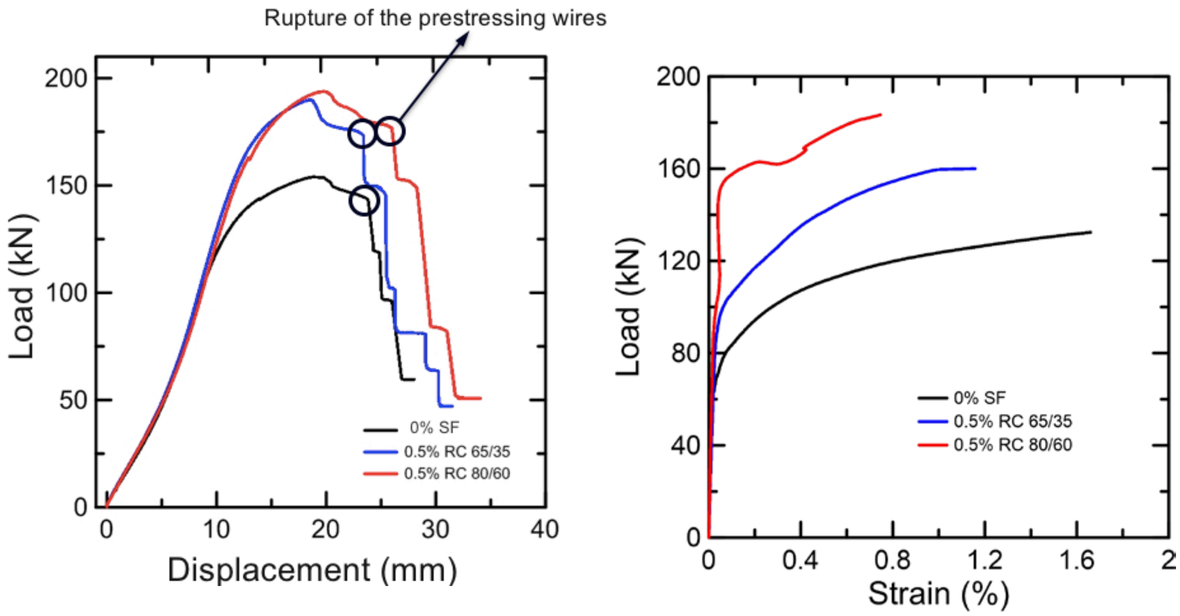

Figure 5. Load-Displacement and Load-Strain curves for each concrete mixture

The sleeper without fiber reinforcement withstood an ultimate load (P_u) of 153.9 kN and had its first crack (P_c) opened with a load of 61.5 kN (Table 4).

The ultimate load capacity of the sleeper reinforced with 0.5% volume ratio of hooked end fibers, with aspect ratio of 65 and 35 mm length was 189.8 kN and its first crack opened with a 83 kN load, resulting in a increment in resistance of 23% for the ultimate load and 35% for the first crack opening.

The ultimate load capacity of the sleeper reinforced with 0.5% volume ratio of hooked end fibers, with aspect ratio of 80 and 60 mm length was 193.7 kN and its first crack opened with a 85 kN load, resulting in a increment in resistance of 26% for the ultimate load and 38% for the first crack opening.

From the graph shown in Figure 5 is possible to conclude that the addition of fibers contributes to the increase of the concrete resistance and improves its post-cracking behavior, resulting in higher residual loads. The fiber contribution in transfer stress can be observed by the delay of the rupture of the prestressing wires. Similar results were obtained by Bastos [10].

The first crack opening point was identified by the change in curvature of the Load-Strain curves obtained by strain gauges positioned in the lower part of the specimen.

Table 4. Values for load at first crack, ultimate load and ultimate moment for each concrete mixture

Mixture	**P_c**	**P_u**	**M_u**
0% SF	61.5 kN	153.9 kN	52.63 kN.m
0.5% RC 65/35	83.0 kN	189.8 kN	64.91 kN.m
0.5% RC 80/60	85.0 kN	193.7 kN	66.26 kN.m

The energy absorbing capacity of the sleepers tested is represented by the Toughness-Displacement curve shown in Figure 6, it was obtained from the calculated area under the Load-Displacement curve for each specimen.

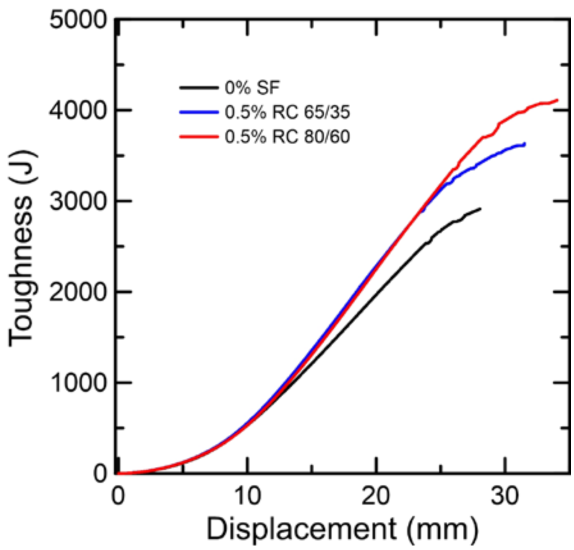

Figure 6. Toughness-Displacement curves for each concrete mixture

It can be seen from the graph shown in Figure 6 that the addition of fibers contributes to the increase in the energy absorbing capacity of the material.

5. THEORETICAL CALCULATIONS

For the purpose of checking the experimental results obtained, the theoretical calculation of the resistant moment of the sleepers tested was performed according to Brazilian code [13]. It was considered in the calculation the losses in prestress such as: elastic shortening, shrinkage of concrete, creep of concrete and relaxation of steel. The steel rupture strain was defined as 10‰ for the bottom layer, that value summed with the strain imposed on the steel to prestress was used to obtain the stress in the wire at that point through a stress-strain curve of the prestressing wire. Since the neutral axis was unknown (x), the software Mathcad® was used to do an iterative calculation so the position of the neutral axis was obtained by force balancing.

By triangle similarity it was possible to obtain the strain in every layer and consequently the stress and force in function of x. The compression component was obtained in function of x, by a simplification of the parabolic stress distribution. A force diagram is presented in Figure 7.

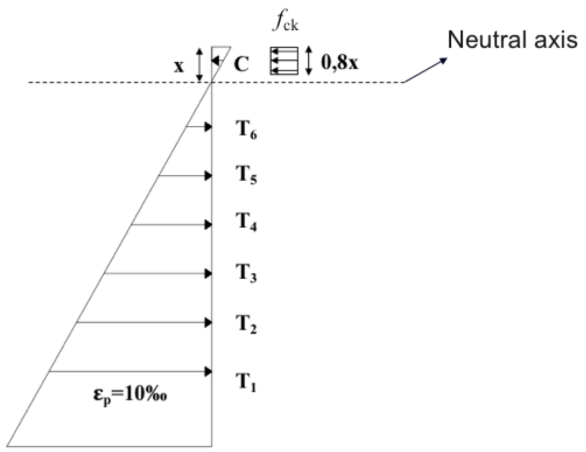

Figure 7. Force diagram for the sleeper without fibrous reinforcement

The neutral axis position of 2.76 cm was obtained, there being no prestressing wires in the compressed zone. The moment was then calculated by multiplying the tensile components by their distance from the compression component. The theoretical resistant moment of the sleeper without fibrous reinforcement was 43.5 kN.m, equivalent to 83% of the experimental value.

The theoretical calculation of the fiber reinforced sleeper was made using the same methodology of the sleeper without the fibrous reinforcement. These differ, since in addition to the tensile components of the prestressing wires, there is also a tensile component from the addition of fibers, as shown in Figure 8.

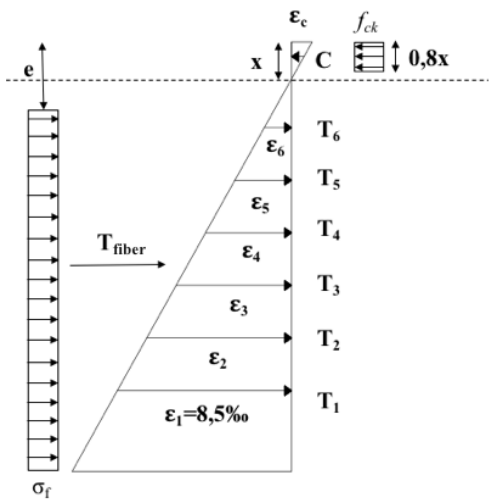

Figure 8. Force diagram for the sleepers with fibrous reinforcement

The calculation of the ultimate moment was done according to ACI 544.4R [14]. The distance between the fiber collaborative area and the top of section (e) was evaluated as a function of fiber strain and neutral axis position. In this case the strain of the prestressing wire is at most 8.5 ‰ as recommended by the ACI [14]. The fiber contribution stress (σ_f) is defined by the ACI as a function of the aspect ratio, volume ratio and fiber efficiency factor, not taking into account its specific geometry and matrix. For this reason, the value of σ_f used in this calculation was obtained experimentally through direct tensile tests in dog bone shaped specimens.

The resulting force of fiber collaboration (T_{fiber}) was calculated as a function of the neutral axis (x), and as was done for the first sleeper, the value of x was calculated per balance of forces. Neutral line position values of 3.25 and 3.30 cm were obtained for reinforced sleepers with RC 65/35 and RC 80/60 fibers, respectively, with no prestressing wires in the compressed zone for both cases. The moment was then calculated by multiplying the tensile components by their distance from the compression component.

The theoretical resistant moment of the sleeper reinforced with 35 mm long fibers (RC 65/35) was 52.3 kN.m, equivalent to 81% of the experimental value and to 120% of the theoretical value of the sleeper without fibrous reinforcement.

The theoretical resistant moment of the sleeper reinforced with 60 mm long fibers (RC 80/60) was 53 kN.m, equivalent to 80% of the experimental value and to 122% of the theoretical value of the sleeper without fibrous reinforcement.

The different moment values obtained experimentally and theoretically are presented in Figure 9.

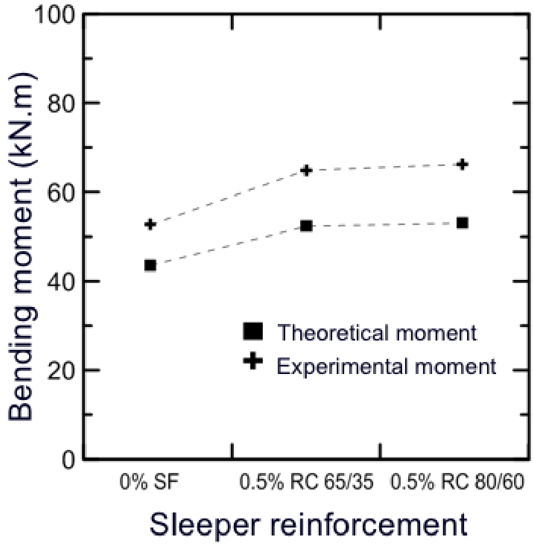

Figure 9. Comparative chart of bending moment values obtained by experimental test and theoretical calculations

It is possible to observe from Figure 9 that the calculated moments follow the same pattern of the values obtained experimentally, being the method used ideal for the analysis of the reinforced concrete with fibers.

6. CONCLUSION

Negative moment tests were performed on concrete sleepers with static loading applied on its mid-span. Concretes mixtures were evaluated with and without reinforcement of 0.5% of steel fibers of 35 and 60 mm length, totaling three specimens. It has been observed that the addition of fibers delays the opening of a macro crack, increases the ultimate load and delays the rupture of prestressing wires. It was obtained the increase of 23 and 26% of the ultimate moment resisted by the structure, promoted by the addition of the fiber of 35 and 60 mm, respectively.

In order to verify the results obtained by the experimental tests, theoretical calculations were made based on the recommendations of Brazilian standards and ACI 544.4R. The calculated ultimate moments were 20% lower than the experimentally obtained ones. However, the increase of resistance promoted by the use of fibers was similar to the experimental, being the increase of 20 and 22% in the ultimate moment, promoted by the addition of 35 and 60 mm fibers, respectively. It can be concluded that the theoretical method used was ideal for the evaluation of the structure.

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