Steel Fiber-Reinforced Concrete in Slab-on-Ground Foundations for Buildings

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Summary

The use of fiber-reinforced concrete (FRC) in slab-on-ground is an efficient solution for building foundations. The case analyzed refers to a 19 floors concrete-wall building, constructed on a 827 m² slab-on-ground. The slab-on-ground was chosen due to the soil bearing conditions and was implemented as the foundation solution. In the structural analysis, the slab was modelled as resting on an elastic subgrade, with the design following ABNT NBR 16935. The adopted solution was a steel fiber-reinforced concrete slab-on-ground, 80 cm thick, with a compressive strength of 35 MPa, and residual tensile strengths of f_{R1} = 4.0 MPa and f_{R3} = 3.8 MPa. The quality control of the FRC followed ABNT NBR 16938, including Preliminary Qualification and Technological Control. The application of FRC proved to be economically viable, optimizing time and resources on the construction site.

1 INTRODUCTION

Fiber-reinforced concrete (FRC) utilized in slab-on-ground constructions represents an efficient solution for building foundations, providing significant technical and economic advantages, including enhanced resistance to cracking, increased durability, and reduced lead time. This structural solution is addressed in the Brazilian standard ABNT NBR 16935 [1], which delineates guidelines for developing fiber-reinforced concrete structure projects. The present work presents a case study wherein FRC was implemented within the slab-on-ground of a building featuring concrete walls that were cast-on-site.

2 DESCRIPTION OF THE CONSTRUCTION PROJECT

The case study addressed in this article refers to the Nassau Garden project carried out by the construction company Vianna & Moura in the municipality of Caruaru/ PE. The development consists of two independent towers of reinforced concrete walls cast-on-site, each with 20 floors. Table 1 shows the details of each of the mentioned floors.

Table 1 Details of the building

Floor	Floor to floor hight (m)	Elevation (m)	Area (m²)
Water tank floor	2.80	57.00	2.27
Penthouse	3.80	54.20	61.00
Duplex	2.80	50.40	692.74
Mid floors (16x)	2.80	44.80	734.22
Ground floor	2.80	2.80	733.72
Total	57.00	-	13237.20

3 CHARACTERISTICS OF THE FOUNDATION

The soil support conditions, presented in Table 2, were defined by a geotechnical company, which defined the solution of the foundation in slab-on-ground.

Table 2 Soil support condition

Bearing capacity of the soil	0.6 MPa
Vertical subgrade reaction coefficient (k_v)	0.12 N/mm³

For the base of the slab-on-ground, a surface regularization with 20 cm of soil-cement was defined, as shown in Figure 1.

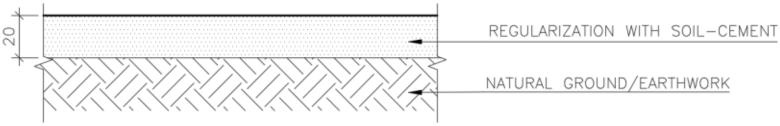

Figure 1 Terrain base profile

4 STRUCTURAL DESIGN OF THE SLAB-ON-GROUND

The ABNT NBR 6118 [2] standard, which deals with concrete structure design, establishes the minimum requirements for the quality of the structure, which are divided into three groups: stability and safety to ruin, performance in service, and durability. To develop a suitable concrete structure design, that provides safety and economy for the buildings and meets the quality requirements set in that standard, you should follow the steps shown in Figure 2.

Figure 2 Project development stages

5 STRUCTURAL CONCEPTION

5.1 Geometry

The shape of the slab-on-ground was defined from the architectural design, hydraulic and electrical installations, considering the external delimitation of the building increased by 50 cm regarding the width of the sidewalk and the delimitation of the elevator pit area, resulting in a total area of 827 m² and a volume of 631 m³ of concrete. For the passage of the installations (electrical, hydraulic, among others) were considered channels with 20 cm depth. To make the process of the channels executive feasible, the concreting of the slab-on-ground was carried out in two stages (Figure 3 and Figure 4). After the second stage of concreting, the channels were filled with compacted sand. To ensure the adhesion between the concrete layers of the first and second stages, a bonding reinforcement and structural adhesive were provided. The final thickness of the slab-on-ground was 80 cm.

Figure 3 Slab-on-ground concreting process (1st stage)

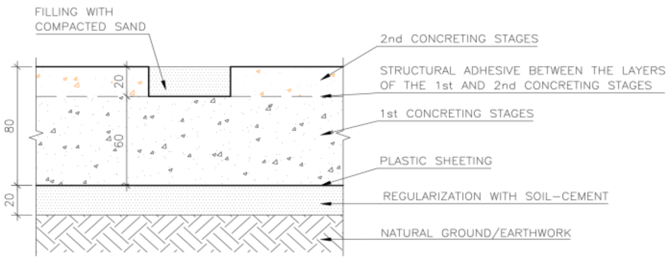

Figure 4 Slab-on-ground section

Figure 5 shows the shape of the slab-on-ground after the first and second concreting stage, with the placement of the channels.

Figure 5 Slab-on-ground: (left) 1st concreting stage; (right) 2nd concreting stage

5.2 Actions

Permanent and variable actions were considered in the project. Among the permanent actions are the weight of the slab-on-ground, the weight of the filling layer of the channels, the regularization layer, the coating, and the load related to the weight of the structure. The variable actions are considered the load of use of the ground floor and the actions of use and wind of the structure. The actions related to the structure (permanent and variable) were provided by the responsible designer of the building structure.

6 STRUCTURAL ANALYSIS

An elastic analysis was performed using a flat slab grid model supported on elastic means. The model was developed in TQS software. The grid model is composed of linear elements (bars) arranged in the same horizontal plane, which allows the evaluation of the slab-on-ground behaviour. Each grid node has 3 degrees of freedom, which allows the displacement and forces (shear force, bending moment, and torsion) at each end of an element. The consideration of the support in an elastic medium was given using the insertion of a support restriction at each crossing of the grid, using the spring coefficient defined for the project. The forces obtained from the structural model were used for the design of the bending slab-on-ground.

7 DESIGN

After model processing, the maximum positive and negative characteristic applicant moments were extracted from the grid and verified according to ABNT NBR 16935 [1], where a comparison between the applicant and resistant efforts was performed. The dimensioning in Ultimate Limit State (ULS) was considered met whenever the moment of resistance was greater than or equal to the requesting moment.

For the calculation of the resistant moment, the constitutive models presented in ABNT NBR 16935 [1] were considered. The stress-crack opening diagram under direct traction is defined by the post-cracking behaviour of the FRC, which should be applied in the ULS. ABNT NBR 16935 [1] presents two hypotheses of constitutive laws for application in sections normally requested for traction, which can be extracted from bending tests. The rigid-plastic model and the linear model, considering the postcrack behaviour hardening or softening (Figure 3), where f_{Fts} is the service direct tensile strength of FRC and f_{Ftu} is the ultimate direct tensile strength of FRC.

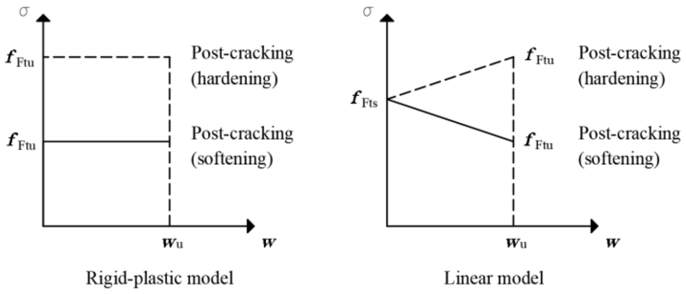

Figure 6 Constitutive laws post-cracking according to ABNT NBR 16935 [1]

In the rigid-plastic model a single reference value, f_{Ftu} (based on ultimate behaviour) given by Equation 1 is used.

$$f_{Ftu} = \frac{f_{R3}}{3} \tag{1}$$

The moment resistance is given by Equation 2.

$$M_U = \frac{f_{R3} \cdot b \cdot h^2}{6} = \frac{f_{Ftu} \cdot b \cdot h^2}{2} \tag{2}$$

Where:

b is the width of the cross-section

h is the height of the cross-section

The linear model uses two reference values, f_{Fts} and f_{Ftu}, obtained by means of Equations 3 and 4.

$$f_{Fts} = 0{,}45 \cdot f_{R1} \tag{3}$$

$$f_{Ftu} = f_{Fts} - \frac{w_u}{CMOD_3} \cdot (f_{Fts} - 0{,}5 \cdot f_{R3} + 0{,}2 \cdot f_{R1}) \geq 0 \tag{4}$$

Where:

wu is the ultimate crack opening for the CMOD value considered in the design, expressed in millimeters (mm).

Considering w_u equal to 2.5 mm (equivalent to $CMOD_3$), Equation 4 can be simplified and written according to Equation 5.

$$f_{Ftu} = 0{,}5 \cdot f_{R3} - 0{,}2 \cdot f_{R1} \tag{5}$$

The moment resistance is obtained by Equation 6.

$$M_U = \frac{f_{Fts+}f_{Ftu}}{2} \cdot \frac{b \cdot h^2}{2} \tag{6}$$

The design values of the post-cracking resistance parameters of the FRC worked in the ULS are obtained from Equations 7 and 8.

$$f_{Ftsd} = \frac{f_{Ftsk}}{\gamma_c} \tag{7}$$

$$f_{Ftud} = \frac{f_{Ftuk}}{\gamma_c} \tag{8}$$

The elastic bending moment is calculated according to Equation 9.

$$M_e = \frac{\sigma_{ct} \cdot b \cdot h^2}{6} \tag{9}$$

Where:

$$\sigma_{ct} = f_{ctm} = 0{,}3 \cdot f_{ck}^{\frac{2}{3}} \tag{10}$$

The values for the safety factor are presented in Table 3.

Table 3 Safety factor for the materials in Ultimate Limit State (ULS)

Resistances	Coefficients
Compression stress of FRC	$\gamma_c = 1.4$
Tensile stress of FRC	$\gamma_c = 1.5$
Residual stresses of FRC	$\gamma_c = 1.5$

According to the ABNT NBR 16935 [1] standard, for situations of plate elements with interface with the elastic means, the values of the tensile strengths in bending of the FRC can be specified as mean values. Thus, the calculation of the FRC resistant bending moment for both rigid-plastic and linear models was performed considering the average values of tensile strength of concrete. Table 4 presents a summary of the FRC slab-on-ground sizing.

Table 4 Summary of the dimensioning of the slab-on-ground in FRC

Rigid-plastic model			Linear model				Elastic bending moment	
f_{Ftum} (MPa)	M_{fd} (kNm/m)	M_{fk} (kNm/m)	f_{Ftsm} (MPa)	f_{Ftum} (MPa)	M_{fd} (kNm/m)	M_{fk} (kNm/m)	f_{ctm} (MPa)	M_{ek} (kNm/m)
1.27	27.02	19.35	1.80	1.10	30.93	22.10	3.21	34.24

From the values obtained of FRC resistant moment by rigid-plastic and linear models, the highest value is adopted, in the case M_{fk}=22.10 kN. m/m.

After processing the model of the slab-on-ground by means of a grid of flat slabs, the values of bending moment were obtained, being the maximum positive characteristic moment (M_p) of 33.60 MPa and the maximum negative characteristic moment (M_n) of 14.00 MPa.

In the plastic analysis of ULS, positive bending moments should be limited to the resistant moment of FRC (M_{fk}=22.10 kNm/m), and negative bending moments should be limited to the elastic moment (M_{ek}=33.24 kNm/m). When the positive or negative moments exceed the established limits, a plastic redistribution analysis of the efforts can be performed, considering a redistribution coefficient (δ). ABNT NBR 6118 [2], in item 14.6.4.3, establishes a limit for the coefficient of redistribution in the case of mobile node structures 0.90 and 0.75 for the other cases. Considering that the slab-on-ground is a supported structure on an elastic base and that there is no formation of mechanisms (plastic bearings) that compromise structural safety, lower redistribution coefficients can be used, and in this work was considered acceptable up to the limit of 0.65.

Thus, for each region of the grid, the diagrams of bending moments are verified and whenever the moment requesting exceeds the resistant moment is carried out the redistribution, respecting the minimum coefficient of 0.65, as shown in Figure 7.

Considering all the regions analysed, redistribution coefficients between 0.65 and 0.74 were used in 20.5% of cases, in 6.25% of cases coefficients between 0.75 and 0.92 were used and in 73.25% it was not necessary to perform redistribution.

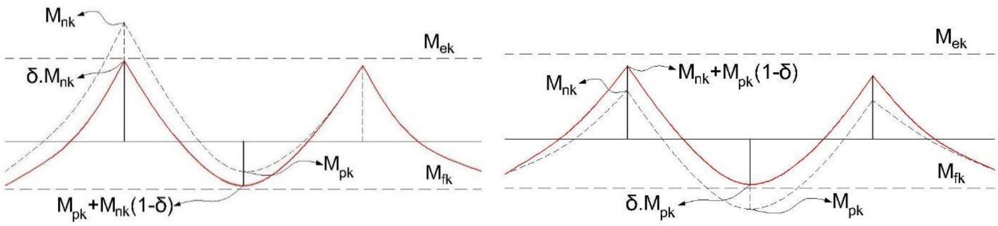

Figure 7 Moment redistribution: negative moment (left) and positive moment (right)

8 SPECIFICATIONS

Table 5 presents the technical specifications of the FRC used in the design of the slab-on-ground.

Table 5 Properties of the concrete used in the project

Compression stress	C35
Young's Modulus of concrete (GPa)	Between 28 and 33
Residual stress f_{R1m} (MPa)	4.00
Residual stress f_{R3m} (MPa)	3.80
Cement consumption	Between 280 kg/m³ and 350 kg/m³
Water/binder ratio	≤ 0.60
Maximum aggregate diameter	19 mm
Dry mortar content (mass)	Between 55% and 60%

In this case study, steel fiber was used as reinforcement of the concrete and polymer microfiber for retraction control. The fibers specifications are presented in Table 6.

Table 6 Specification of metallic fibers and polymer microfibers

Retraction control	Type	Microfibers
	Material	Polypropylene
	Nominal length (mm)	12
	Maximum nominal diameter (µm)	18
	Minimum dosage (kg/m³)	0.90
Reinforcement of concrete	Type	Metallic fibers
	Material	Steel
	Nominal length (mm)	60
	Maximum nominal diameter (µm)	0.80

	Dosage (kg/m³)	To be validated as per design residual resistances specification (minimum 25kg/m³)

9 QUALITY CONTROL OF FRC

In the case study presented, the quality control of the FRC was done according to ABNT NBR 16938 [3], contemplating the previous qualification and technological control of the FRC. The FRC qualification involved the qualification steps of steel fibers (according to the standard ABNT NBR 15530 [4]) and composite. For the qualification of FRC, tensile tests were performed in bending to determine the resistance at the limit of proportionality (LOP) and residual resistances f_{R1m}, f_{R2m}, f_{R3m} and f_{R4m}, according to ABNT NBR 16940 [5]; compressive strength, according to ABNT NBR 5739 [6] and double punching tests for determination of tensile strength and residual resistances $f_{R0,5m}$, $f_{R1,5m}$, $f_{R2,5m}$, $f_{R3,5m}$, according to ABNT NBR 16939 [7].

After the analysis of the results obtained in the qualification stage and the necessary adjustments to meet the project specifications, the FRC was validated and released for concreting. In the stage of execution of the slab-on-ground was performed the technological control of FRC, which involved consistency tests by the cone trunk flattening - ABNT NBR 16889 [8], compression resistance test - ABNT NBR 5739 [6], for the control of tensile strength and residual resistances, in accordance with the ABNT NBR 16938 [3] standard, the double punching test was adopted (ABNT NBR 16939 [7]). This adoption was possible because in the composite qualification stage, the correspondence between the strengths determined in the flexural tensile test (ABNT NBR 16940 [5]) and the strengths determined in the double punching test (ABNT NBR 16939 [7]) was established.

For the formation of batches, as established by ABNT NBR 16938 [3], was used the control type A: applications with basic control of the FRC. The standard also establishes type B control that must be adopted for applications that perform preliminary performance tests of at least two structural elements, produced to verify design parameters, and a strict production control of the FRC, that must be certified by a third party. Table 7 presents a summary of the tests performed in the technological control of the slab-on-ground and the criteria for formation of batches.

Table 7 Technological control of FRC

Test	Standard reference	Sampling
Fluidity of concrete	ABNT NBR 16889	1 test for each truck
Compression strength	ABNT NBR 5739	2 tests specimens for each truck
Residual resistance by double punch test	ABNT NBR 16939	3 specimens with 2 samples for every 100 m³ or daily concreting time

For the design requirements specified in mean values, as is the case of the project presented in this study, compliance was verified by direct comparison of the average results obtained in the flexural tensile tests (f_L and residual) and double punching (f_t and residual), with the average value specified in the design.

In some cases, the results obtained in the technological control for the double punching tests were lower than the parameters obtained in the qualification step. However, the residual resistance fr1m obtained in the qualification step was lower than the design specification, on the other hand, the result of fr3m was higher. Thus, the FRC resistance moment calculated with the values obtained in the qualification step was higher than the resistance moment calculated with the design values and the general analysis of the average values together with the other results, it was possible to consider as accepted the FRC applied in the slab-on-ground, without the need for reinforcements or monitoring. In Figure 8, the execution of the structure on the slab-on-ground is observed, demonstrating the current stage of the work.

Figure 8 Execution of the structure on the slab-on-ground of FRC

10 CONCLUSIONS

The case study presented demonstrates the effectiveness of the use of fiber-reinforced concrete (FRC) in the construction of slabs-on-ground foundations for buildings. The application of FRC provided significant improvements, both in terms of better crack control, and therefore greater durability, as well as in the more agile execution of the foundation. The structural analysis and design carried out according to ABNT NBR 16935 [1] and ABNT NBR 6118 [2], ensured that the project met the safety and performance requirements, ensuring the adequacy of the proposed structural solution.

In addition, adequate quality control, according to the ABNT NBR 16938 [3] standard, was essential for the validation of the FRC used on the construction site, guaranteeing the conformity of materials and process reliability. The analysis of test results and resistance parameters in technological control showed that the applied FRC met the design requirements.

Therefore, the use of FRC in the slab-on-ground of this project proved to be a technically and economically viable solution, aligned with current standards, and capable of providing a safe foundation for the building.

Acknowledgements

The authors would like to thank Construtora Viana & Moura for innovating the solution and adopting fiber reinforced concrete and TECOMAT Engenharia, which worked on the quality control of the FRC.

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