Evaluation of the mechanical behavior of concrete wall panels with functionally gradation fiber content by finite element method

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Abstract. Concrete is a material with brittle rupture behavior when subjected to efforts that result in tensile stresses, generating internal micro-cracks, facilitating the action of aggressive agents and reducing its useful life. With the demands of improving the durability and mechanical performance of structures, the functional gradation of concrete properties with the use of fibers has been presented as a promising alternative. With the recent publication of NBR 16935, in addition to contributing to durability, fibers can be used to totally or partially replace steel reinforcement, especially in structural elements where the distribution of internal tensile stresses is not well defined, as in the case of of wall panels and other slender pieces subjected to compression. The production of concrete wall panels with functionally gradation of fiber content allows a more efficient use of materials, distributing the fibers only in the regions that can present a real contribution, enhancing their physical and mechanical properties due to their presence. This work seeks to evaluate the mechanical behavior of functionally graded fiber concrete wall panels through modeling and computer simulation. The model was implemented in the commercial software ANSYS, which is based on the finite element method. Different configurations of the functional gradation of the fibers were simulated along the thickness and in different regions. Each configuration of the functional gradation in the panels were simulated in static and buckling analyses. For calibration of the parameters of the materials of each layer, the values present in the literature for different types and fiber contents were adopted. Finally, the numerical results obtained were compared with experimental results from the literature to validate the proposed model. The functional gradation of fiber content did not compromise the strength of the panels and the model adopted presented an acceptable correspondence with the experimental results found in the literature.

Keywords: finite element method, fiber reinforced concrete, wall panels.

1 Introduction

The civil construction sector is often characterized by low productivity and high waste of materials. The use of the precast system, such as precast wall panels, allows for some benefits such as a reduction in construction time, greater quality control in the manufacture of precast elements and a cleaner construction site, with less waste of materials [1].

Concrete is a brittle material with low tensile strength and little ability to deform and resist cracking. The use of fibers in concrete acts as a stress transfer bridge, hindering the emergence of new cracks and increasing its post-cracking deformation capacity [2]. Fiber reinforced concrete (FRC) can be used to partially or fully replace steel in conventional reinforced concrete. The use of FRC in the production of panels is already part of the scope of the SINAT guideline on innovative construction systems, and becomes more promising with the recent publication of the standard ABNT NBR 16935 for fiber-reinforced concrete structures design [3,4].

Fiber reinforced concrete is an alternative at the time of increasing costs of steel used in civil construction, however, the use of fibers also presents an increase in unit cost compared to conventional concrete [2,5]. Therefore, the use of functional grading of conventional concrete with the use of fibers is presented as an alternative for a distribution of fibers maintaining a greater concentration in the most requested regions [6].

The production of functionally gradation concrete (FGC) wall panels with varying fiber content allows a more efficient use of materials, distributing the fibers only in the regions that can make a real contribution, enhancing their physical and mechanical properties due to the your presence. Therefore, this work seeks to evaluate the mechanical behavior of functionally graded fiber reinforced concrete wall panels through modeling and computer simulation.

2 Methods

The evaluation of the effect of the functional gradation of fiber reinforced concrete on the mechanical performance of wall panels was carried out through a computer simulation, where the model was implemented in the commercial software ANSYS, which is based on the finite element method. To represent the contribution of fibers, a Menetrey-Willam constitutive model was used to reproduce the non-linear behavior of the material.

2.1 Menetrey-Willam constitutive model

In the Menetrey-Willams model, the Haigh-Westergaard stress coordinates F(ξ,ρ,θ), represented in Eq. 1, define the set of points on the flow surface that separate the zones of elastic and elastoplastic deformation. From that point on, there is a gradual reduction in strength with increasing deformation due to the cracking process of the concrete, being represented by the model through stretches of hardening and softening behavior [7].

$$F(\xi,\rho,\theta) = \frac{c_2}{c_3}\left[\sqrt{2}\xi + r\rho\right] + \rho^2 - \frac{1}{c_3} \tag{1}$$

Where:

$$r = \frac{4(1-e^2)\cos^2\theta + (2e-1)^2}{(2e-1)^2\cos\theta + (2e-1)\sqrt{4(1-e^2)\cos^2\theta + 5e^2 - 4e}} \tag{2}$$

$$c_2 = \frac{1}{\sqrt{6}}\left[\frac{1}{R_c} - \frac{1}{R_b} + \frac{R_b - R_t}{{R_c}^2}\right] \tag{3}$$

$$c_3 = \frac{3}{2}\frac{1}{R_c} \tag{4}$$

In the diagram of relative stress (Ω_c) by plastic deformation (κ), illustrated in Fig. 1, the softening region was represented by an exponential function. The main parameters that define the yield surface and the hardening/softening behavior of the materials are presented in Tab. 1. The parameters were calculated from the experimental results of Barros [8], who carried out a detailed study on the effects of steel fibers on concrete.

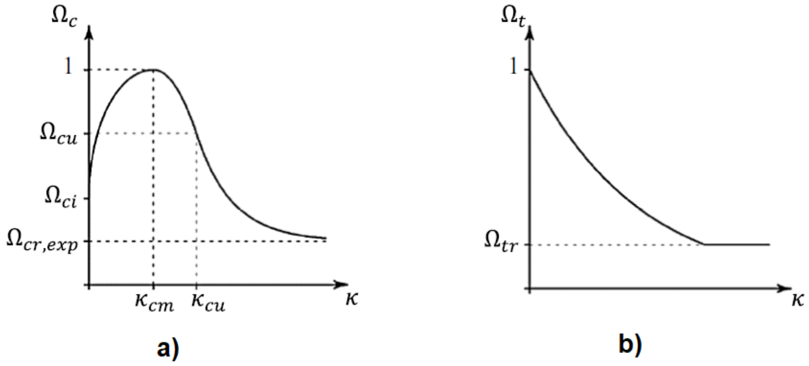

Figure 1. Hardening/softening diagrams with exponential softening: a) in compression; b) in tension [7].

Table 1. Parameters of Menetrey-Willam model [7,8].

Parameters	Units	FRC0 (0 kg/m^3)	FRC30 (30 kg/m^3)	FRC45 (45 kg/m^3)	FRC60 (60 kg/m^3)
Young's modulus (E_{ci})	MPa	20622	19498	19831	18722
Poisson's ratio (ν)	-	0,2	0,2	0,2	0,2
Uniaxial compressive strength (R_c)	MPa	32,6	32,3	33,2	31,2
Uniaxial tensile strength (R_t)	MPa	4,52	4,74	5,44	7,38
Biaxial compressive strength (R_b)	MPa	38,06	37,72	38,74	36,47
Dilatancy angle (Ψ)	degree	10	10	10	10
Plastic strain at uniaxial compressive strength (κ_{cm})	mm/mm	0,002082	0,002061	0,002243	0,002774
Plastic strain at the transition from power law to exponential softening (κ_{cu})	mm/mm	0,004482	0,005861	0,007843	0,010874
Relative stress at the start of nonlinear hardening (Ω_{ci})	-	0,328	0,325	0,333	0,316
Residual relative stress at the point of transition (Ω_{cu})	-	0,5	0,5	0,5	0,5
Residual compressive relative stress (Ω_{cr})	-	0,046	0,108	0,148	0,135
Mode I area-specific fracture energy (G_{ft})	N/m	167,7	4579,7	6577,3	10073,5
Residual tensile relative stress (Ω_{tr})	-	0,020	0,172	0,362	0,423

2.2 Panel and simulation

Three different panel configurations were used, varying only the fiber content in its thickness. The panel has dimensions of 1800x600x10 mm (height x width x thickness), with a rigid metal plate on top for load application. The first configuration was the reference panel (RP), with FRC0 properties from Tab. 1, representing fiber-free concrete. The second configuration was the 3-layers panel (P3L), where the properties of FRC30 for the core layer and FRC60 for the face layers were admitted. The last configuration was the 5-layer panel (P5L), which used FRC30 for the core properties, FRC45 for the two middle layers and FRC60 for the outer layers. Fig. 2 illustrates the three panel configurations.

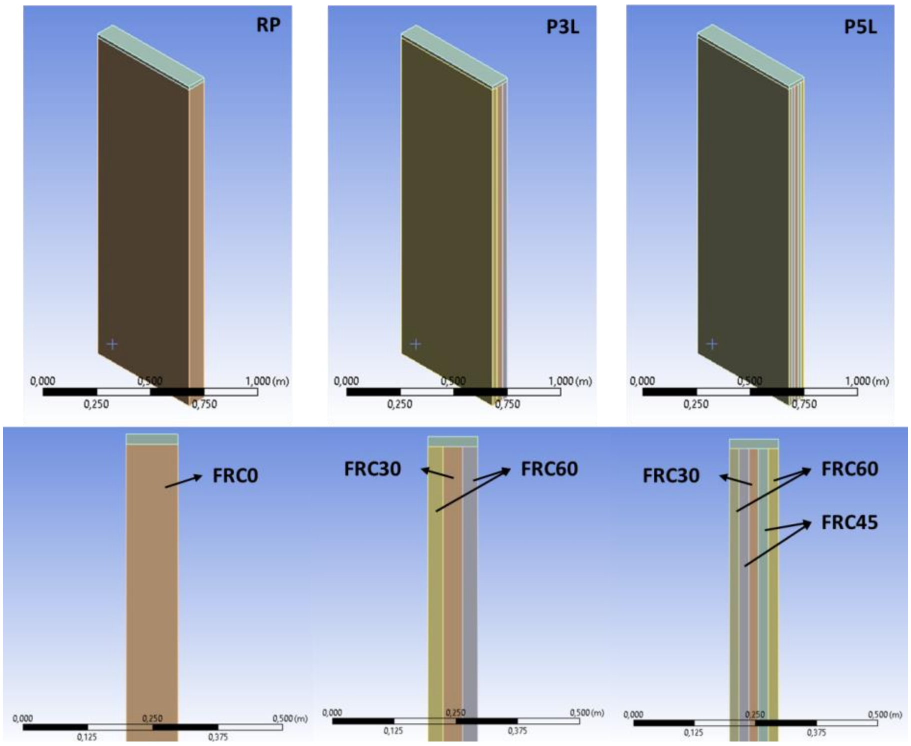

Figure 2. Panels configurations.

The boundary conditions adopted were the restrictions of translations and rotations on the lower face of the panel, and the load was applied by imposing a vertical displacement of 3.0 mm on the metal plate. The contact between the layers of the panels with functional gradation was considered as "bound", since one of the objectives of the functional gradation is to obtain a gradual change in the material properties without generating weaknesses in the interface. Elements SOLID186 were used for concrete and REINF264 for steel. The mesh was generated with a dimension of 2.5 cm. A 3-layers panel with 7 cm thickness (P3L7) was modeled to verify the influence of the slenderness of the element.

3 Results and discussion

The results of the normal stresses acting on the panels are shown in Figures 3, 4 and 5, referring to the reference concrete wall panel, functionally graded concrete wall panel in 3-layers and functionally graded concrete wall panel in 5-layers, respectively.

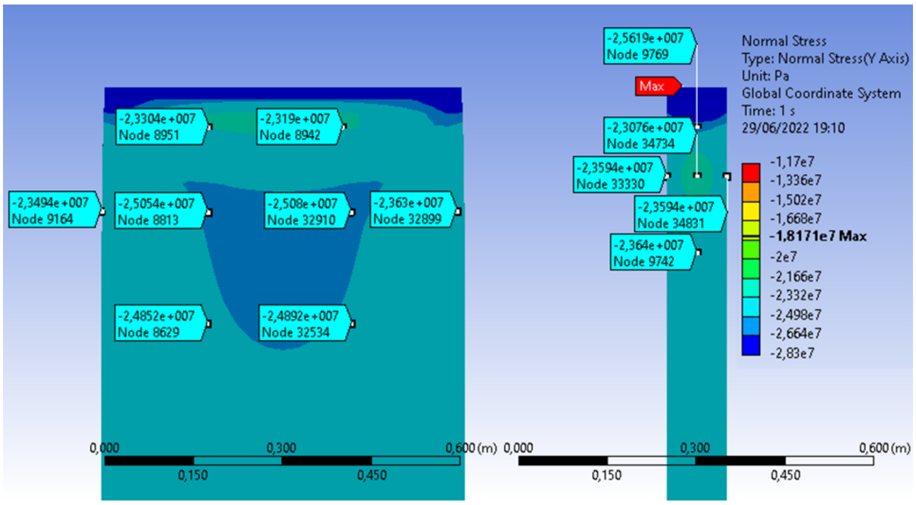

Figure 3. Normal stress in reference concrete wall panel (RP).

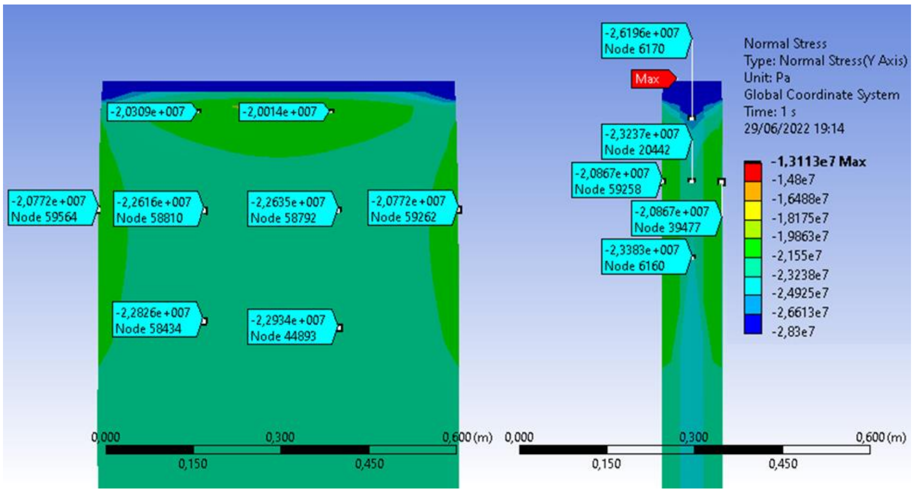

Figure 4. Normal stress in 3-layers FGC wall panel (P3L).

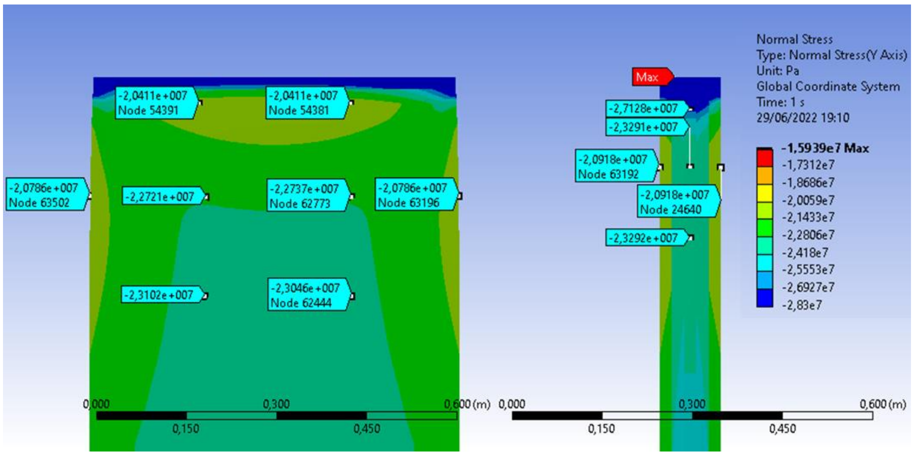

Figure 5. Normal stress in 5-layers FGC wall panel (P5L).

From Figures 3, 4 and 5, it is possible to observe that the normal stresses are distributed in a similar way in all the panels. The average normal stress developed by the panels were close, with 24.52 MPa, 22.59 MPa and 23.20 MPa, corresponding to the RP, P3L and P5L panels. The small difference observed may be due to the reduction in stiffness presented in the panels with functional grading of fiber content.

Regarding the buckling analysis, there was a reduction of 9.1% and 8.2% in the buckling critical load in the P3L and P5L panels, respectively, with the replacement of the conventional reinforcement by a functional classification with fibers. This difference may also be associated with the reduction in stiffness caused by the absence of continuous reinforcement inside the panel.

The lateral deflection of the panels can be seen in Figure 6, where it is possible to see that the deflection of the panel of greater slenderness (P3L7) was greater for the same level of loading. In addition, the solid reference panel (RP) showed a slightly higher lateral deflection resistance than the functional graded panels.

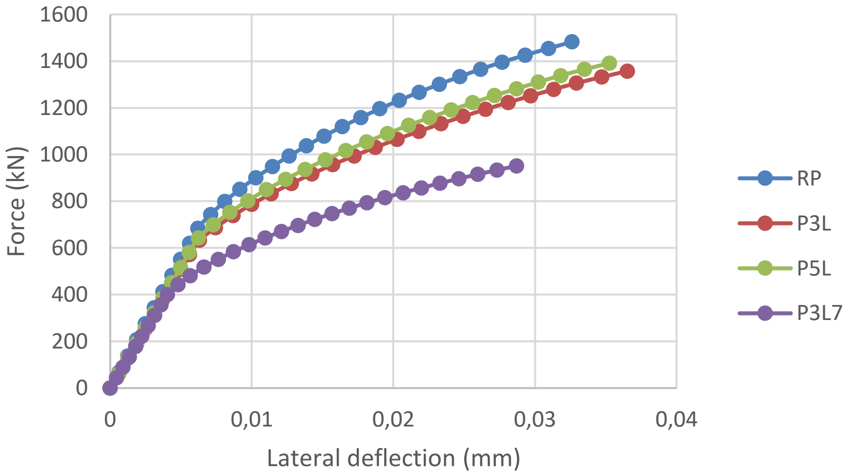

Figure 6. Force x Lateral deflection.

The model presented a lateral deflection much lower than the experimental results found in the literature [9,10]. However, when the dimensions of the modeled panel were adjusted to a slenderness close to the panels found in the literature, the results showed a similar behavior, as can be seen in Figure 7.

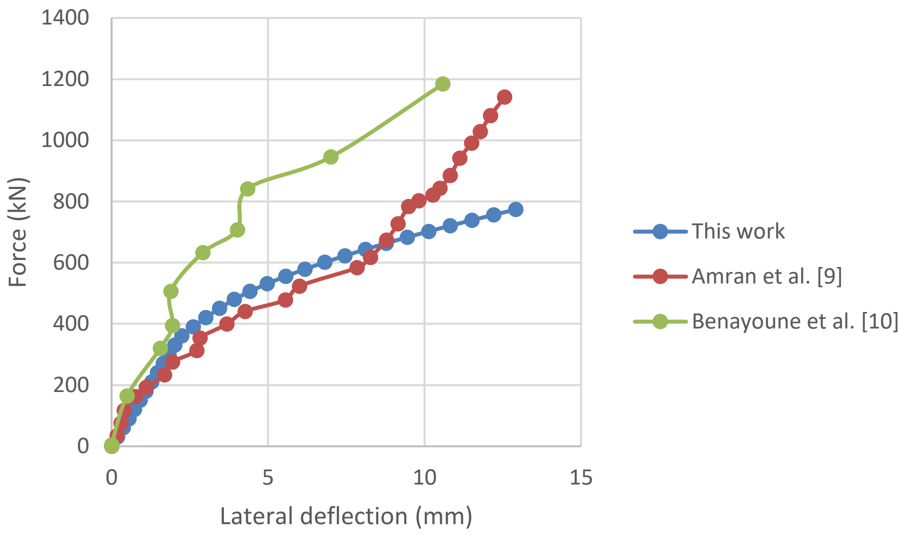

Figure 7. Force x Lateral deflection in literature [9,10].

4 Conclusions

The replacement of the conventional reinforcement by fibers did not compromise the resistant capacity of the panels and the adjusted model presented a behavior corresponding to the literature. However, further studies are needed to assess the impact of the change in the stiffness of the panels due to the total absence of reinforcement.

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