XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

Study of the Behavior of SFRC Tunnel Segments using a Multiscale Model

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Abstract. Considering the recent increase of investments in underground infrastructure, progress and innovations are needed to build in a safe, efficient, and economical way. This paper aims to contribute to the state of the art on the numerical modeling of hybrid tunnel segments for mechanized tunneling constructed with Tunnel Boring Machines (TBMs). In this way, a 2D multiscale model was applied to predict the mechanical behavior of individual segments reinforced partial- or fully with steel fibers in a three-point bending setup. The multiscale model proposed presented good accuracy to represent the nonlinear post-cracking behavior, propagation of fracture and interaction between reinforcement and concrete. Finally, the results demonstrate that the application of the numerical strategy adopted for modeling the mechanical behavior of reinforced tunnel segments is highly promising.

Keywords: 2D multiscale model, tunnel segments, steel fibers, mechanical behavior.

1 Introduction

Tunneling plays a great role in the development of a country, among several aspects the use of underground space is an attempt to solve problems of urban mobility and water supply in big cities, for example. This kind of constructions has grown in recent years, especially where infrastructure must supply and raise population growth. Comparing the investments made in tunnel construction for transportation (including roadways, subway and railways), Germany had a total of 175 km tunnels built in 2015 [1], while was excavated in Brazil only 66km between 2006 and 2017 [2]. Also, according to Andrade and Guimarães [2], subways and roadways constructions using tunnels have grown considerably in the past few years counting together approximately 54% of the total built.

As a result of this increase, TBM (Tunnel Boring Machines) technology has been used as a safe, efficient, and economical choice to overcome the significant struggles in big cities [3]. The company, designers, and administrators adopted this alternative in Line 4, Line 5, and future Line 6 construction of the subway in São Paulo. The TBM's structural system consists of precast tunnel segments installed creating several lining rings inside the ground. Normally these precast segments are made of concrete reinforced with conventional rebar, but the use of steel fibers reinforcement is increasing to mitigate problems applying steel bars, i.e. vulnerability to corrosion, loss of structural capacity, and several cracking due transitional stages (demolding, storage, transport, and installation) [3]. The steel fiber reinforced concrete (SFRC) can be used to replace all or part of the conventional reinforcement and promote the resistance to carry diffuses and localized stresses. Thus, the reduce of the amount of conventional steel rebar contributes to save high investments with material and manufacture [1][4].

Therefore, numerical models have been proposed to improve the reinforcement system and understand the mechanical behavior of conventional, only with steel fibers, and hybrid precast tunnel segments. Those methods applied to the study of tunnel structures response are responsible to develop concrete elements' process of design [5]. Despite the approximations needed, it is possible to reduce the problem, develop multiple scenarios, and verify only areas of interest inside the model without major efforts. Also, applying multiscale approaches in numerical modeling of concrete elements, specially for tunnel segments analysis, can be helpful due its potential to develop full discretization only in regions of interest.

Hence, all the pathologies found in precast concrete segments can be controlled with correct design, and with an improvement of the reinforcement applied using calibrated and efficient numerical models. Especially, this study contributes for a better understanding of the mechanical behavior of SFRC and hybrid tunnel segments, contribuiting for future national standards regarding the general design of SFRC tunnel segments.

2 Multiscale Modeling for Concrete Elements

In the last few years, multiscale models have been applied even more for detailed studies to predict the behavior of concrete structural elements. Especially, because the mesoscale has a fundamental role in the formation of the cracking pattern, mainly in composite materials such as concrete. Due the multiscale phenomena involving concrete elements that consist of mortar, aggregates, and reinforcement, some FE approaches applying only the macroscopic scale effects of the problem are not proper enough. In other words, it is crucial to take into account the nonlinear and heterogeneous behavior, mainly for damaged concrete structures [6][7]

Recently, a multiscale model for SFRC was proposed by Bitencourt Jr. [8]. Applications of this model can be also found in Trindade [9][17][18] (fig. 1(a) - analysis ofthree-point bending beams – EN 14651). In general, the division between regions is prioritized in the proximity to the notch that determines the crack propagation plan. There is no significant difference in results between the concurrent multiscale model proposed by Trindade [17], fig. 1(b), and the complete mesoscale approach. However, it is common to find differences in the results, since the approximation made at the proposed numerical model. Besides that, this approximation does not compromise the results obtained and its forecasting capacity. In this context, a similar study is proposed for precast concrete segments for tunnel linings.

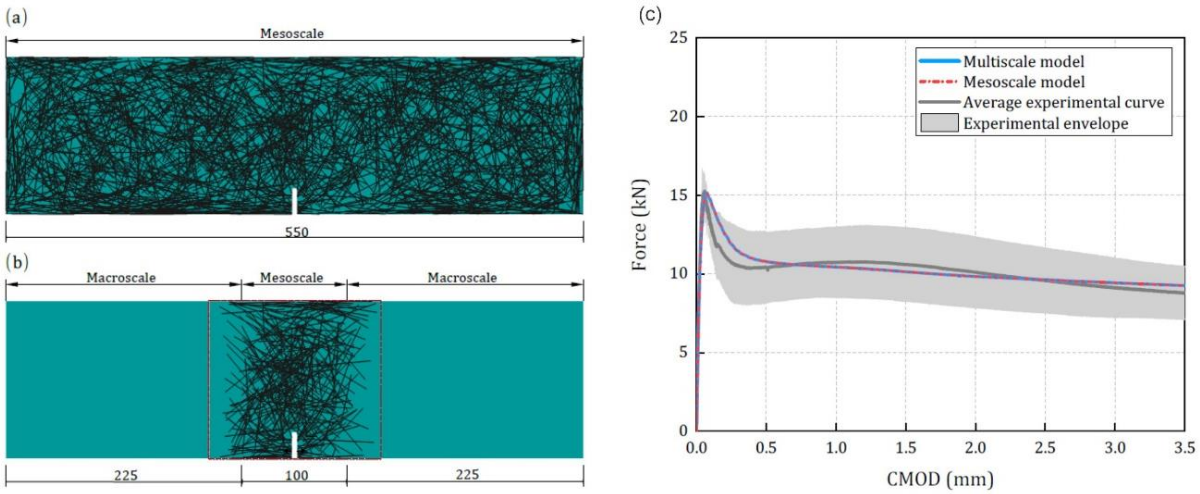

Figure 1. Example of a multiscale problem [9]: (a) three-point bending beam simulation applying discretization of fibers; (b) comparison between numerical and experimental responses.

2.1 Application for Precast Segments for Tunnel Linings

As it is well known, homogenized models are largely used to obtain structural response due their simplicity and computional efficiency. For tunnel enginnering applications, the same concept is used as a result of the number and mainly the sizes of elements studied [10]. However, such kind of approximation does not exhibit the real behavior of heterogeneous structural systems.

Wang et al. [6] proposed a simple and intuitive method to evaluate the problem and define a concurrent multiscale model applied to precast segments. In general, the main idea is to perform a simple evaluation considering a homogeneous macroscale FE model to investigate the potential damaged zones. Later, the complete multiscale problem is used to understand the random crack pattern obtained using the discratization of aggregates at the mesoscale, and cohesive interface elements (CIE's) inside mortar.

2.2 Discrete and Explicit Representation of Reinforcement and CFE's

For the reinforcement of concrete elements with the addition of fibers, a model developed by Bitencourt Jr. et al. [11] was applied. In this model, a cloud of fibers are generated and distributed in a random isotropic uniform algorithm. Thus, simple bar elements (truss elements) are added to represent the steel fibers within the concrete elements. The fibers can be either smooth or end-hooked. However, the interaction between the reinforcement elements (fibers and rebars) and the concrete mesh must be considered. Coupling Finite Elements (CFEs) proposed by Bitencourt Jr. et al. [12] have been adopted due the overlapping meshes with discrete and explicit representation. It is important to explain that the coupling elements used in this paper consider the loss of adherence through the use of a damage model to represent the interaction along fibers and the concrete matrix [8][9] Also, the IMPL-EX integration scheme for the tension damage model is applied regarding the increase of stability and the robustness of the solution, as proposed by Oliver et al. [13] and Prazeres et al. [19]. The aim of this paper is to work on the distribution of individual fibers inside the concrete matrix, and the aggregates will not be considered explicitly in this model, unlike the proposal by Wang et al. [6].

3 Numerical Simulations

3.1 Description of the Numerical Model for Precast Concrete Tunnel Segments

In order to analyze the complex structural behavior of concrete elements for tunnels, isolated segments of precast concrete were simulated, very similar to the proposal of Wang et al. [6]. The influence of the type of reinforcement, integration convergence, and validation of the concurrent multiscale proposal were evaluated. Laboratory experiments weren't performed with the segments, this study aims at presenting only the capacity of the numerical models for tunneling structural elements. The scenarios embrace plain concrete segments (PC), segments reinforced with steel fiber (SFRC) with content of 15, 40 and 60 kg/m³, and hybrid segments (H) containing 40 and 60 kg/m³ of fibers combined with top/bottom conventional rebars.

The staves have all the same dimensions, as shown in Fig. 2(b), and the distance between supports was considered to be 2.8 metes with centralized load that even for distinct dimensions, the analyzed gap between supports will always be the same. Therefore, there is no significant difference in results for larger or smaller precast segments, as long as their thickness is maintained. The rate of leading was controlled by a constant increment rate of the vertical displacement due to its similiraty with experimental analyses.

Top and bottom steel conventional reinforcement were used in the hybrid model with 4ϕ 8mm diameter both and concrete covering of 40 cm. The geometrical properties of the steel fibers considered (DRAMIX ® RC 80/60 BN) are length (L_F) = 60 mm, diameter (D_F) = 0.75 mm, L_F/D_F = 80, and cross-sectional area (A_F) = 0.44 mm².

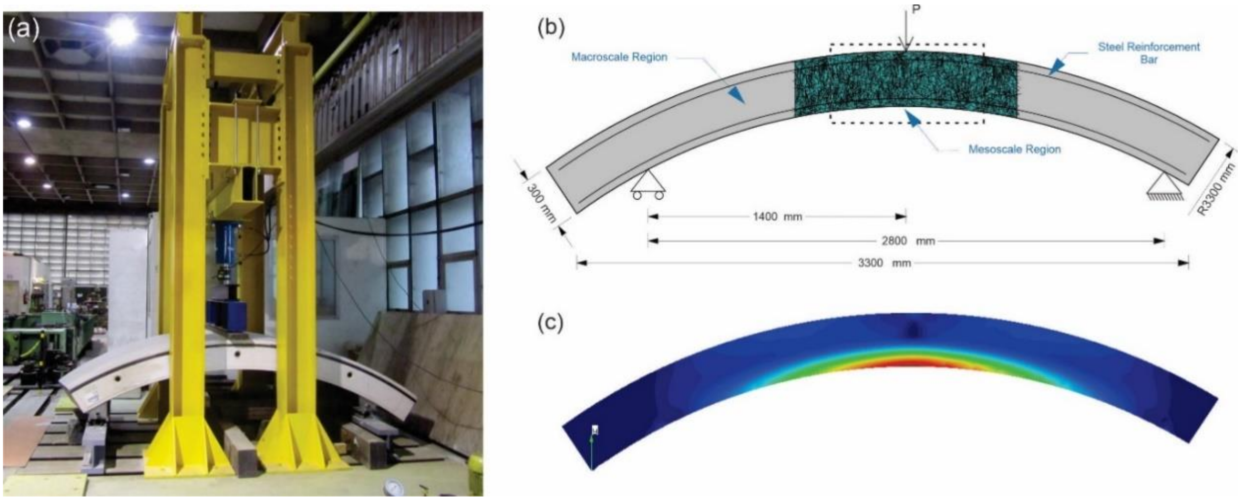

Figure 2. Analysis of hybrid tunnel lining segment: (a) generic three-point bending loading experiment at Polytechnic School (USP); (b) numerical model setup with geometric properties and boundary conditions; (c) pre-analysis of stress distribution to identify potentially damaged zone with macroscale homogeneous model.

To describe the concrete behavior, it was applied a constitutive model based at the continuum damage mechanics, composed of two independent damage variables, one for traction and one for compression, proposed by Cervera et al. [14]. In this way, the model can be calibrated to describe the behavior of the two stretches of stress vs. strain curve independently.

Three node triangular finite elements were used for the concrete with linear interpolation for the displacement field. Also, fine mesh was applied at the potential damaged zone due its capacity to better capture the crack distribution (multiscale model). Hence, for the macroscale was adopted a coarse mesh. The steel bars are represented by two-noded linear finite elements (truss elements). Each fiber was subdivided in three finite elements to improve the representation of stress propagation through the fracture. In the other hand was applied 150 divisions with the same purpose.

To describe the behavior of reinforcement (rebars and steel fibers) was adopted a perfect elastoplastic constitutive model [15].

3.2 Parameters of the Finite Element Model

In the concrete domain, the following mechanical properties were adopted for the continuum damage model porposed by Cervera et al. [14]: compressive strength (f_c) = 45 MPa; tensile strength (f_{ct}) = 3.5 MPa; young's modulus (E_c) = 37 GPa; poisson rate (ν) = 0.2; fracture energy (G_f) = 0.15 N/mm; A^- = 1.0; B^- = 0.89; and β = 1.16. Also, it was considered at the macroscale a linear elastic model with Young's modulus of 37100 MPa ad poisson rate of 0.2, applying the Mixture Theory [9]. Steel fibers and rebars were discretized using unidimensional linear finite elements.The material parameters adopted are listed in Table 1.

Table 1. Material parameters adopted for reinforcements.

Parameters		Rebars	Steel Fibers
Yield strength	f_y	500 [MPa]	1100 [MPa]
Young's Modulus	E_s	210 [GPa]	210 [GPa]

Perfect adherence was applied to represent the bond-slip behavior between fibers and concrete, by assuming for the coupling parameters: $c_n = c_s = 10^6$ MPa/mm. In adittion, for hybrid segments simulation, it was adopted an adherence model based on the *fib* Model Code 2010 [16] with the following mechanical properties for rebar-concrete interface with *good bond conditions* and loss of adherence ($c_n = 10^3$ MPa/mm; $c_s = 10^6$ MPa/mm): τ_{max} = 18.2 MPa; τ_{bf} = 7.2 MPa; s_1 = 1.0; s_2 = 2.0; s_3 = 4.0; α = 0.4. It was assumed the following parameters for fiber and concrete interface: τ_{max} = 12.5 MPa; τ_{bf} = 4.5 MPa; s_1 = 0.01; s_2 = 6.5; s_3 = 7.0; α = 0.4.

4 Results and Discussion

4.1 Convergence and Multiscale Validation

To illustrate the sensitivity of the damage constitutive model and the convergence of the IMPL-EX integration scheme adopted, a three-point bending analysis is performed using segments with plain concrete. Fig. 3 illustrates the response obtained increasing the number of steps applied and different size of the meshes.

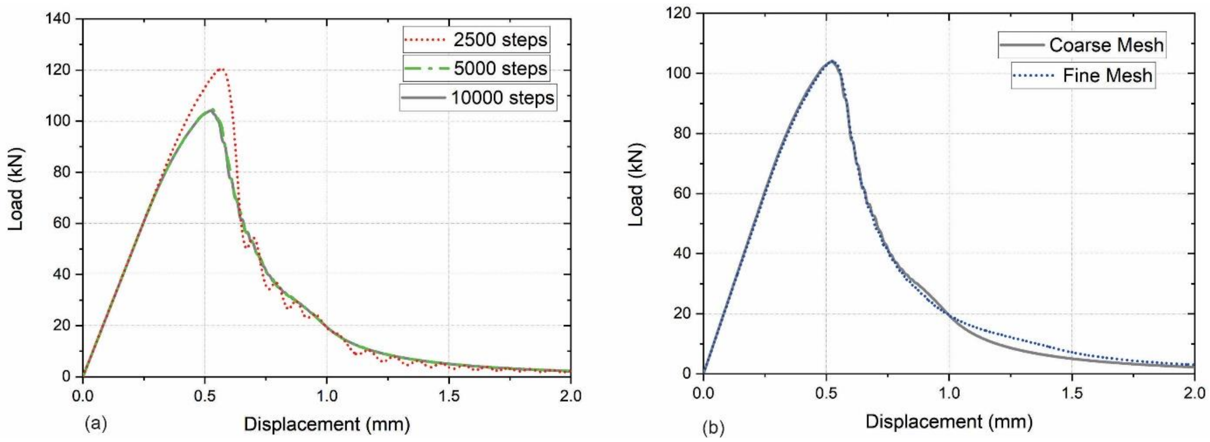

Figure 3. Force vs. Displacement curves for PC: (a) convergence for different number of load steps; (b) mesh sensitivity for two different mesh sizes adopted.

In the following analyses, a total of 10000 steps have been employed due the error associated with a small number of load steps, as expected for the convergence of Impl-Ex. Also, based on the results, the fine mesh is adopted to other simulations, considering its precision compared to coarse mesh.

To validate the concurrent multiscale model proposed, a three-point bending simulation is performed using an addition of 15 kg/m³ of steel fibers at the critical zone previously identified. As can be seen in Fig. 4(a), the numerical curves presented similar behavior almost overlapping each other, as expected. It is also important to understand that divergence occurs due the approximations made, besides that the multiscale model could be implemented.

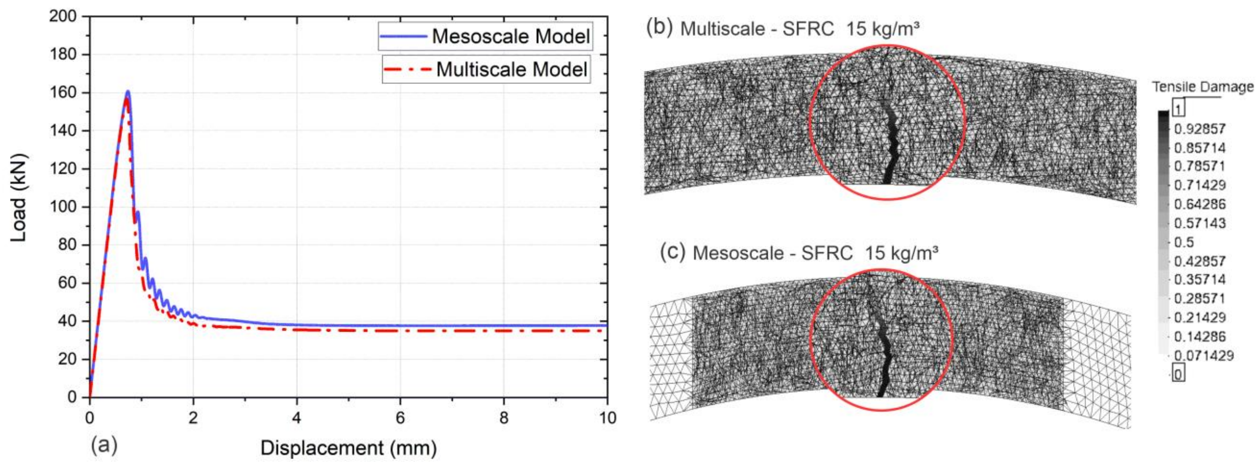

Figure 4. Comparison and validation between mesoscale and concurrent multiscale model for SFRC precast segments: (a) Force vs. Displacement curves; (b) and (c) crack propagation pattern for 1.1 mm displacement with fiber content of 15 kg/m³.

Figures 4(b) and (c) show the differences and similarities between the crack propagation obtained for mesoscale approach and the concurrent multiscale numerical model, respectively.

4.2 Steel Fiber Reinforced Concrete Segments (SFRC)

The results of the finite element modeling for SFRC tunnel segments are illustrated in Figure 5(a) with two different fiber content. In Figure 5(b) and (c), the crack patterns obtained considering perfect adherence are compared for 40 (0.5%) and 60 kg/m³ (0.75%).

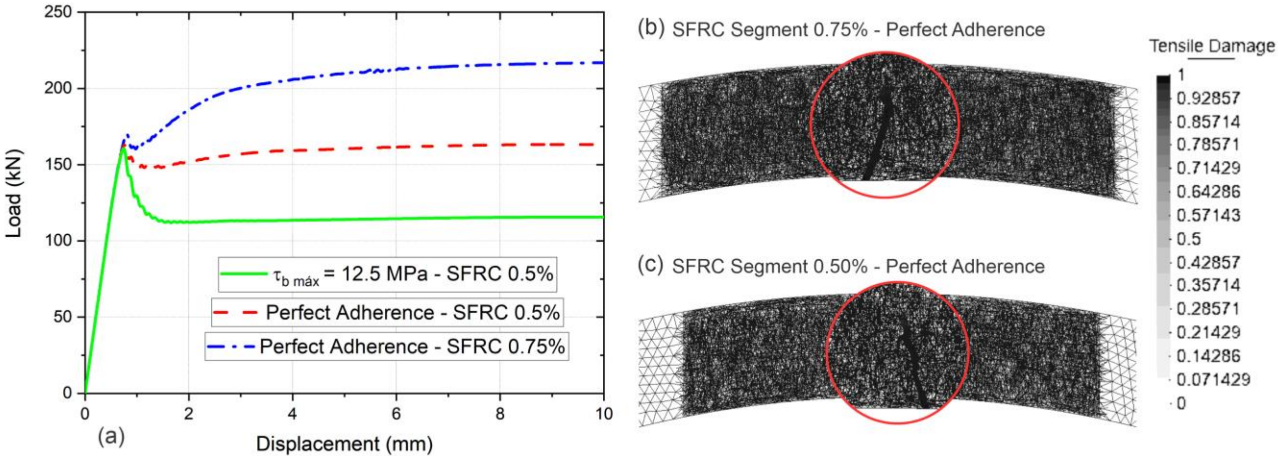

Figure 5. Numerical simulation results for SFRC segments: (a) Force vs. Displacement curves; (b) and (c) crack propagation pattern for 2.1 mm displacement.

Microfissures appears on the bottom surface (tension) for both cases for a vertical displacement of approximately 0.6 mm. The results considering loss of adherence, green line – see Fig. 5(a), presented softening behavior as expected. In this way, it is possible to conclude that the use of a higher content of fibers does not affect the crack load (150 kN), but changes the crack pattern and the residual resistant capacity of the segment.

4.3 Hybrid Segments

The results of the finite element modeling for hybrid tunnel segments are illustrated in Figure 6(a) with two different fiber content, top and bottom rebar, and considering perfect adherence for fibers.

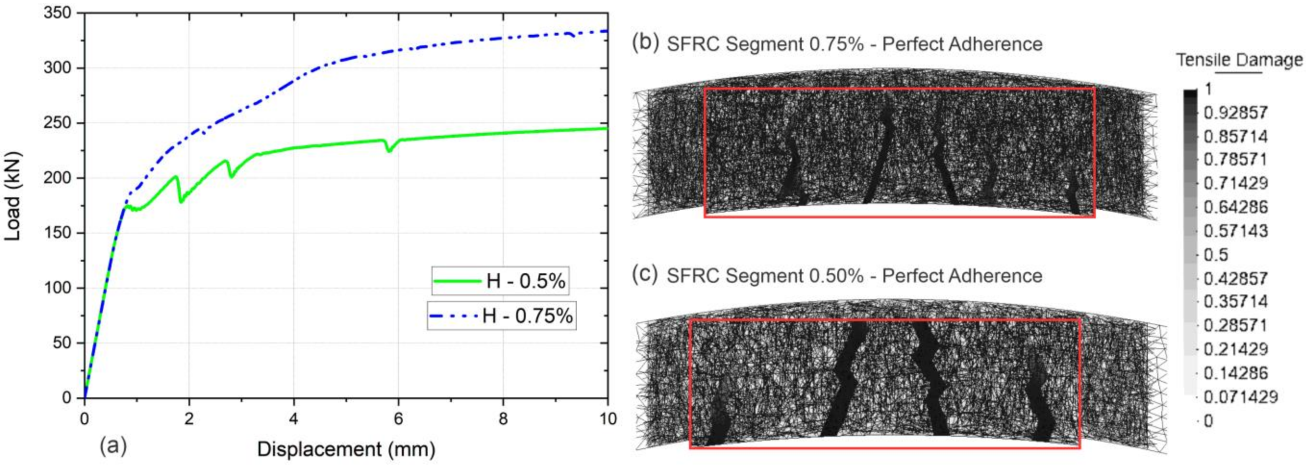

Figure 6. Numerical simulation results for hybrid segments: (a) Force vs. Displacement curves; (b) and (c) crack propagation pattern for 6.1 mm displacement.

Clearly, the major reinforcement contribution is made by fibers. This approximates the behavior of hybrid reinforcement to fibers only, however, with an optimization of performance. In other words, the hybrid system expands the reinforcement capacity of the segments, as expected.

5 Conclusions

According to the simulation proposed of the segment with different reinforcement configurations, some remarkable conclusions can be drawn regarding the characteristics and behavior showed as results. The concurrent multiscale model proved to be a viable alternative approach with satisfactory approximation compared to the full mesoscale model and saving computational time. Other scenarios must be implemented to prove possible applications and simplify the problem. Regardless of the type of reinforcement (SFRC and H), the crack load obtained was approximately 150kN for a vertical displacement of 0.6 mm for all cases analyzed. For future studies, it is important to take into account the effect of distinct bond-slip parameters, the impact of distribution and orientation of fibers inside the matrix, and the interaction between reinforcement and discrete aggregates that were not considered in this paper. Also, experimental characterization and validation are important for reliable results. Thus, the results demonstrate that the application of the numerical strategy adopted for modeling the mechanical behavior of reinforced tunnel segments is highly promising.

Acknowledgements. Guilherme G. Andrade acknowledges that this study was financed in part by the Coordination for the Improvement of Higher Education Personnel (CAPES) – Finance Code 001. Luís A. G. Bitencourt Jr. would also like to extend his acknowledgments to the financial support of the National Council for Scientific and Technological Development (CNPq) – grant #310401/2019-4 and São Paulo Research Foundation (FAPESP) – grant #2019/24487-2.

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