Numerical Modeling of the Elastoplastic Flexural Response of Ultrahigh Performance of Fiber Reinforced Concrete (UHPFRC) using the XFEM Fracture Model

Giulia T. Caravello[1], Marcello Congro[1,2], Deane Roehl[1,2]

[1]*Department. of Civil and Environmental Engineering, Pontifical Catholic University of Rio de Janeiro, PUC-Rio, Brazil.*
[2]*Multiphysics Modeling and Simulation Group, Tecgraf Institute, Pontifical Catholic University of Rio de Janeiro, PUC-Rio, Brazil.*
Rua Marquês de São Vicente, 225, Gávea, Rio de Janeiro, Brazil
giuliatcaravello@tecgraf.puc-rio.br, marcellocongro@tecgraf.puc-rio.br, deane@tecgraf.puc-rio.br

Abstract. Recently, several experimental and numerical models have been carried out to investigate the mechanical behavior of fiber-reinforced concrete (FRC), especially concerning their flexural response to structural applications. Modern developments regarding these materials involve using ultrahigh performance fiber-reinforced concrete (UHPFRC) in strengthening layers or jackets. This particular type of FRC is a relatively new construction material with excellent mechanical properties and a crack propagation control. However, for the structural applications and design, it is necessary to carry out direct tensile and bending tests to obtain the tensile stress-strain behavior and the flexural response of the composite. In this sense, this paper proposes the elastoplastic numerical modeling of the mechanical behavior of UHPFRC, including the fracture evolution analysis using the Extended Finite Element Method (XFEM). Mixed-mode fracture behavior is considered. The finite element models reproduce a four-point bending test reported in the literature by Lampropoulos et al. (2021). The results show that the concrete damage plasticity constitutive model can efficiently predict the load-displacement behavior since the load capacity ranges present a good agreement with the experimental reference. Moreover, it is possible to predict the fracture path of the beam in a mixed mode based on the application of the XFEM model.

Keywords: fracture, fiber reinforced concrete, bending, UHPFRC.

1 Introduction

Recently, a significant increase in the use of composite materials has been observed with the addition of fibers in structural engineering. Therefore, fiber-reinforced concrete has been progressively applied in the construction engineering industry because of its high energy absorbing capacity and ability to control fracture propagation when compared to conventional concrete [1, 2, 3]. Alternatively, regarding the macroscale numerical models for the composite, different methods are being carried out in the literature [2, 5], including the adoption of equivalent parameters to simulate the mechanical behavior of the composite subjected to flexural stress.

Figueiredo [3] states that the increment in the composite fracture energy is explained due to the fiber bridging mechanism, where fibers work transferring the stresses from the matrix to the reinforcement during crack propagation. This bridging mechanism decreases the crack opening velocity in the cement matrix and gives the composite a bigger post-cracking carrying capacity [4]. The incorporation of fibers also increases the concrete ductility and improves its post-peak mechanical parameters [6], such as residual flexural strength. Therefore they can be incorporated into structures that support locally placed loads.

The four-point bending test (4PBT) with fiber reinforced concrete is used to analyze the load capacity of structural elements, the post-peak residual flexural behavior of the material, and its crack propagation path.

Nevertheless, the 4PBT frequently demands the concreting of large beams and can lead to the waste of materials, which is labor-intensive and time-consuming. In that sense, finite element models have been carried out to predict the load capacity of structural elements and the crack patterns in the cement matrix.

2 Methodology

The computational analyses were carried out using the commercial finite element software Abaqus ® and considered equivalent homogeneous parameters for the composite. These models were based on the four-point bending experimental tests reported by Lampropoulos et al. [1], considering an ultra-high-performance steel fiber-reinforced concrete (UHPFRC). The steel fiber aspect ratio is 21.7 (13 mm of length and diameter of 0.16 mm); the steel fiber volumetric fraction adopted for the test is 3%; the specimen dimensions are 100x100x500 mm. Table 1 presents the input parameters reported by the experimental tests for the composite, where E refers to the Young modulus, v refers to the Poisson ratio, f_c is the composite compressive strength and f_t is the composite tensile strength.

Table 1. UHFRC homogenized parameters considering Lampropoulos et al. [1].

Parameter	Value
E (GPa)	57.5
v (-)	0.3
f_c (MPa)	164.0
f_t (MPa)	12.5
δ (mm)	11.0

Moreover, the elastoplastic behavior of UHPFRC is included in the numerical model through the stress-strain curve given by Lampropoulos et al. [1] and indicated in Figure 1. The concrete damaged plasticity model (CDP) is adopted for the numerical simulations. Figure 2 presents the finite element mesh considered for the numerical analysis and the boundary conditions (BCs) for the four-point bending test. The displacement BCs include simple support (preventing vertical displacements) and pinned support (preventing horizontal and vertical displacements). Moreover, a concentrated load of 37 kN is applied in two nodes of the model (Figure 2). Linear quadrangular plane stress elements with full integration were considered for the simulations. The XFEM model is adopted to model the fracture propagation in the central region of the beam. Finally, the trapezoid method assessed the composite fracture energy (Gf) by integrating the area from the peak load under the stress-displacement curve.

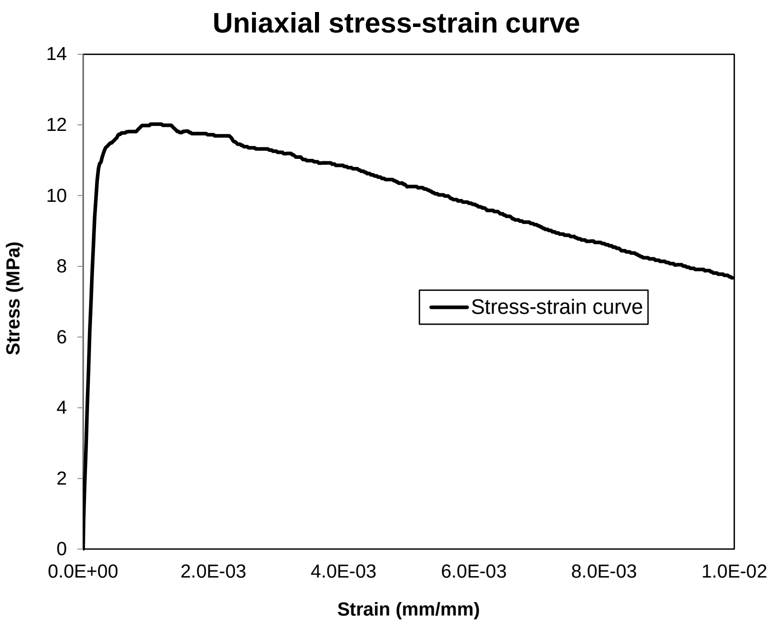

Figure 1. Stress-strain curve for the UHPFRC [1].

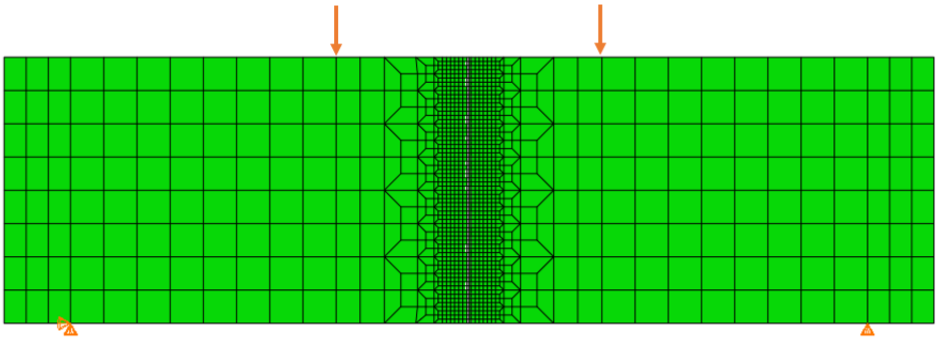

Figure 2. Finite element model and boundary conditions.

3 Results and Discussion

Figure 3 compares the experimental curves Lampropoulos et al. [1] obtained for the UHPFRC and the finite element analyses using the XFEM methodology to simulate the fracture propagation pattern in the cement matrix. A good accuracy can be observed between the pre-peak stage for both curves. In the softening stage of the curve, close responses are also observed.

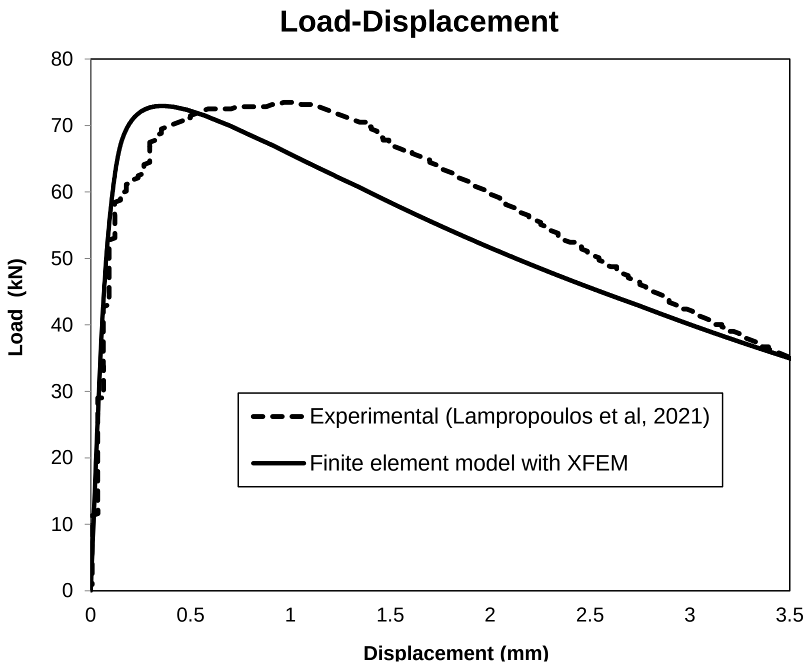

Figure 3. Load-displacement curve for UHPFRC: experimental results and finite element analyses using XFEM fracture model.

Figure 4 presents the crack propagation patterns obtained using the XFEM fracture model in the middle region of the beam. Specific stages with the crack path evolution provided by the fibers are also shown in this figure. It is also possible to observe that the fracture propagation behavior is consistent with the global load-displacement behavior of the composite.

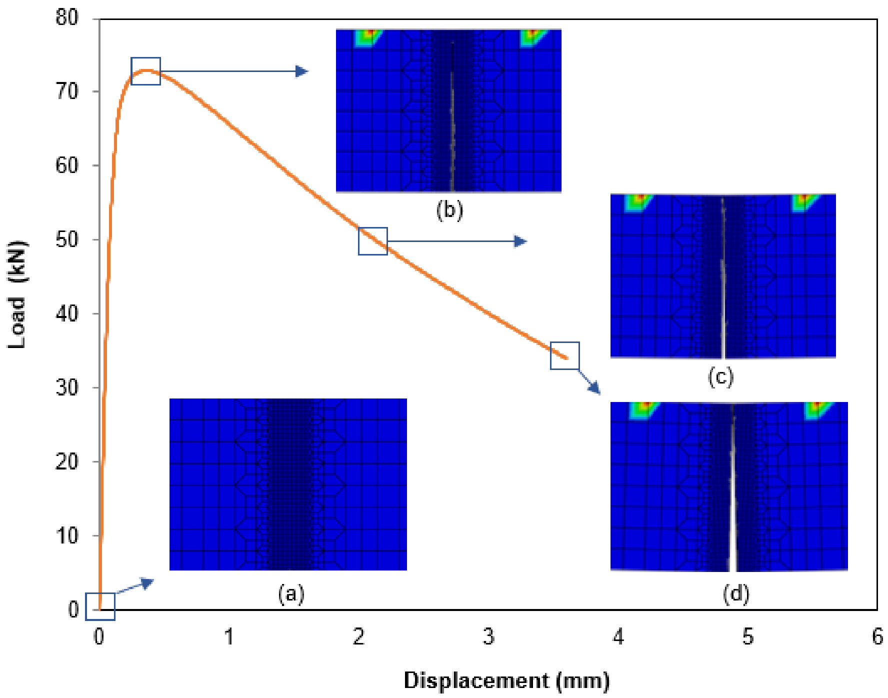

Figure 4. Fracture patterns identified in the load-displacement composite behavior for the four-point bending test carried out by Lampropoulos et al. [1]

4 Conclusions

This paper proposes a numerical model to describe the mechanical behavior of UHPFRC considering homogeneous properties for the composite and the XFEM fracture model. The numerical models created obtained satisfactory results compared to the results obtained experimentally. The load-displacement results are close to the experimental curves regarding global and local fracture behavior. Therefore, in conclusion, the finite element method numerical models created and the XFEM fracture model simulate the flexural behavior of UHPFRC. The addition of fibers to the cement matrix expanded the material's load capacity and provided greater fracture energy and ductility than conventional concrete. In this sense, the numerical model has captured all these points. Moreover, the crack pattern paths are similar to the expected patterns.

Acknowledgements. The authors would like to thank Tecgraf Institute for all support and assistance during the execution of this project. The current work was financed in part by Conselho Nacional de Desenvolvimento Científico e Tecnológico (PIBIC/CNPq).

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] Lampropoulos, A.; Nicolaides, D.; Paschalis, S.; Tsioulou, O. Experimental and Numerical Investigation on the Size Effect of Ultrahigh-Performance Fiber-Reinforced Concrete (UHPFRC). Materials 2021, 14, 5714.

[2] Congro, M.; Sanchez, E. C. M.; Roehl, D.; Marangon, E. Fracture modeling of fiber reinforced concrete in a multiscale approach. Composites Part B: Engineering, v. 174, 2019.

[3] Figueiredo, A.D. Concreto com Fibras de Aço. Boletim Técnico da Escola Politécnica da USP, 2000.

[4] Zanotto, L.; Congro, M.; Roehl, D. Damage evolution investigation in steel and polypropylene fiber

reinforced concrete. Proceedings of XLI Ibero-Latin American Congress on Computational Methods in Engineering. Foz do Iguaçu, Paraná/PR, Brazil, 2020.
[5] Congro, M.; Mejia, C.; Roehl, D. Probabilistic assessment of load capacity of fiber-reinforced concrete. Proceedings of IV Brazilian Conference on Composite Materials (BCCM4). Rio de Janeiro, Brazil, 2018.
[6] S. Chen, Strength of steel fibre reinforced concrete ground slabs, Structures and Buildings, v. 157, p. 157–163, 2003.