Comparative Evaluation of CFRP Modeling Approaches for the Simulation of Strengthened HCS

Ilinca-Florina Moldovan[1*)], Mihai Nedelcu[2)], Stefan-Marius Buru[3)]

[1*)] Technical University of Cluj-Napoca, Faculty of Civil Engineering, 15 Constantin Daicoviciu Street, Romania; ilinca.lungu@mecon.utcluj.ro;
[2)] Technical University of Cluj-Napoca, Faculty of Civil Engineering, 15 Constantin Daicoviciu Street, Romania; mihai.nedelcu@mecon.utcluj.ro, ORCID: 0000-0002-6832-6635;
[3)] Technical University of Cluj-Napoca, Faculty of Civil Engineering, 15 Constantin Daicoviciu Street, Romania; marius.buru@mecon.utcluj.ro; ORCID: 0000-0002-3029-5749.

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Abstract

The objective of this study is to assess, through numerical simulation, the effect of CFRP sheet strengthening on the structural behavior of prestressed hollow-core slabs (HCS), using the ABAQUS 6.13 software suite. Extensive research over the past decade has identified externally bonded CFRP as an effective solution for strengthening prestressed concrete elements, including HCS with non-circular voids. The numerical simulation of CFRP-strengthened hollow-core slabs is inherently complex, influenced by factors such as construction methodology, loading scenarios, and nonlinear material properties. Several modeling approaches have been proposed in the literature, each aiming to address specific aspects of these complexities. The retrofitting technique in this study involved applying CFRP sheets to the internal end regions of the slab voids, over a length of 300 mm, using one and two layers, respectively. To simulate the CFRP material, two modeling approaches were examined. The first involved skin reinforcement, which consists of applying a bonded layer to a part's surface and incorporating defined material and structural properties. The second modeling approach involved contact interaction with cohesive behavior, aiming to capture potential debonding effects. The developed finite element models were validated by comparison with test results from an extensive experimental investigation. The Concrete Damage Plasticity (CDP) model was adopted for concrete behavior, while the Mises yield surface was used for modeling isotropic metal plasticity. For the CFRP material, the simulation process included two stages. First, orthotropic elasticity in plane stress (lamina) was defined using ABAQUS 6.13. In the second stage, Hashin's failure criteria for unidirectional fiber composites were applied to evaluate the failure response of the CFRP sheets. Results are presented in terms of the load–deflection relationship, crack patterns, and von Mises stress distribution. In addition, a parametric investigation was carried out to analyze the influence of CFRP strengthening length and thickness on the load-bearing capacity and stiffness of the specimens.

Keywords: *Hollow-core slabs, Carbon fiber reinforced polymers, Finite element modeling, Structural performance*

1. Introduction

In the context of modern structural engineering, the strengthening and rehabilitation of existing concrete infrastructure has become increasingly critical, prompted by aging structural assets, evolving regulatory standards, and heightened functional demands. Among the various retrofit solutions, carbon fiber reinforced polymers (CFRP) have garnered considerable attention due to their exceptional mechanical properties, including a high strength-to-weight ratio, excellent corrosion resistance, and ease of application. Externally bonded CFRP systems have proven particularly effective in enhancing the structural performance of prestressed concrete components, such as hollow-core slabs (HCS), which are widely utilized in floor and roof systems for their efficient load- bearing and long-span characteristics [1].

While extensive experimental research has established the efficacy of CFRP strengthening in enhancing the structural performance of concrete elements, the accurate numerical simulation of CFRP-strengthened hollow-core slabs remains a complex undertaking. This complexity is attributed to several contributing factors, including the construction sequence, complex loading conditions, and the nonlinear mechanical behavior of both concrete and composite materials. A critical aspect of this modeling challenge lies in the representation of the CFRP-to-concrete interface, where accurately capturing failure phenomena such as debonding or fiber rupture necessitates the careful selection and calibration of constitutive models and interaction properties [2] [3].

Despite the development of various numerical strategies in the existing literature, a standardized and widely accepted methodology for simulating CFRP-strengthened HCS with non-circular voids has yet to be established. Moreover, the comparative influence of different modeling techniques: such as skin reinforcement definition for the composite material and cohesive behavior modeling for the CFRP-concrete interface remain insufficiently investigated, particularly in the context of prestressed HCS systems. Given the well-established effectiveness of bonding fiber-reinforced polymer composites to structural elements in enhancing their load-carrying capacity, this study investigates the efficacy of a novel strengthening technique involving the application of CFRP to the internal surfaces of the voids in HCS.

This research investigates two distinct configurations for strengthening hollow-core slabs with carbon sheets: the first configuration involves a single ply of CFRP with a width of 300 mm, while the second employs a double-ply system, consisting of two CFRP layers each measuring 300 mm in width. These configurations were selected to assess the influence of varying CFRP thickness on the structural response of the slabs. The finite element models developed for both cases are rigorously validated through comparison with comprehensive experimental data, part of a vast experimental program, ensuring the accuracy and reliability of the numerical simulations.

2. Finite element method (FEM) analysis

Finite element analysis proves particularly effective in assessing the structural performance of prestressed hollow-core slabs

strengthened with carbon fiber reinforcement, as it enables the accurate representation of both material and geometric nonlinearities. The structural behavior of such composite systems is governed not only by the intrinsic properties of the constituent materials: namely, concrete, steel, and CFRP, but also by the quality of the interface interaction between them [4] [5].

In the present study, the numerical analyses were carried out using the Abaqus 6.13 [6] finite element software suite, selected for its robust capabilities in addressing complex nonlinear problems with high computational efficiency and accuracy**.** Simulations encompass the development of a comprehensive modeling framework that entails : formulation of the concrete constitutive model, CFRP material behavior and adhesive interface between the concrete substrate and CFRP reinforcement. The CFRP-to-concrete interface is characterized by comparing 2 distinct modeling techniques: a contact interaction model incorporating cohesive behavior and a skin reinforcement option from Abaqus 6.13. The cross-sectional geometry of the analyzed HCS, characterized by non-circular voids is illustrated in Fig. 1. This configuration reflects typical precast prestressed concrete elements, where the voids are constructed to reduce self-weight while maintaining structural efficiency. The non-circular shape of the voids introduces additional complexity in both structural behavior and numerical modeling, requiring a detailed representation in the finite element analysis.

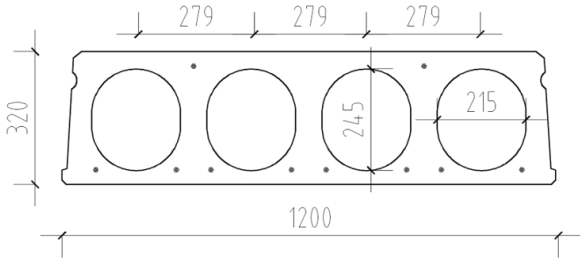

Fig. 1. Cross-section of the HCS [unit:mm]

The slab specimen had overall dimensions of 1200 mm (width) × 320 mm (depth) × 5000 mm (length). Moreover, it incorporated ten prestressing tendons, consisting of 7-wire, low-relaxation strands with a nominal diameter of 13 mm and a cross-sectional area of 100 mm². The prestressing layout featured a high level of prestressing force concentrated at the bottom of the slab through eight longitudinal tendons, while a lower level of prestressing is provided at the top flange via two longitudinal tendons. This study investigated the structural implications of applying CFRP retrofitting over a length of 300 mm and two distinct thicknesses of the CFRP sheets: 1 and 2 layers on each specimen's voids.

2.1 Finite element types, mesh and solution control

In the current finite element analysis, carefully selected element formulations were employed to accurately capture the complex mechanical behavior of the concrete substrate and the CFRP reinforcement. This strategic selection is critical to ensuring numerical stability and fidelity, particularly in simulating material nonlinearity and interfacial interactions characteristic of strengthened structural systems [7]. The CFRP-strengthened hollow-core slab comprises three principal elements, including the concrete body, prestressing tendons, and externally bonded CFRP sheets.

Concrete component of the prestressed HCS was discretized using the three-dimensional, eight-node linear brick element with full integration, denoted as C3D8 in the Abaqus element library, prestressing tendons were modeled using the three-dimensional, two-node linear truss element (T3D2) while the FRP were simulated using the 4-node quadrilateral in-plane stress/displacement shell element with reduced integration and a large-strain formulation(S4R) [6].

A comprehensive mesh sensitivity study was undertaken to identify an optimal element size that would ensure accurate stress distribution and displacement predictions in the finite element analysis of CFRP-strengthened hollow-core slab (HCS) beams. The analysis revealed that a global mesh size of 25 mm yields consistent and reliable results without incurring excessive computational cost. Accordingly, this mesh size was adopted throughout the study. A schematic representation of the meshing strategy employed for the studied specimen is presented in Fig. 2 [1] [6]**.**

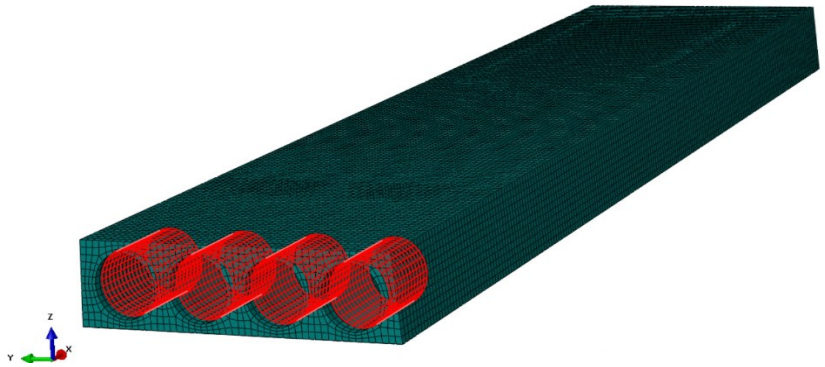

Fig. 2. Finite element mesh of the HCS

Numerical simulation was structured into three sequential analysis steps to accurately replicate the structural behavior of the prestressed hollow-core slab system under loading. In the initial step, prestressing was introduced into the tendons using the Predefined Field functionality available in Abaqus, simulating the initial stress state imparted during the prestressing process. The second step accounted for the gravitational effects by applying the self-weight of the structure. Finally, in the third step, the external loading was imposed through a displacement-controlled analysis, allowing for precise monitoring of the load–deflection response and capturing post-yield behavior. To appropriately capture the nonlinearities arising from material behavior and contact interactions, a static general analysis procedure with nonlinear geometry considerations (NLGEOM on) was employed.

2.2 Material constitutive models

Concrete. Concrete damage plasticity (CDP) model, available in the Abaqus software suite, has been utilized to simulate the nonlinear constitutive behavior of concrete. This model effectively captures both tensile cracking and compressive crushing phenomena, accounting for the degradation of stiffness under cyclic and monotonic loading. Its ability to incorporate key material nonlinearity: such as plasticity, damage accumulation, and strain softening, makes it particularly suitable for simulating the complex interaction between concrete and CFRP sheets [8] [9]. Several studies have reported that the CDP model provides robust and accurate predictions of load-deflection response, failure modes, and crack propagation patterns in FRP-strengthened elements. When calibrated with appropriate material parameters, it has been shown to replicate experimental results with high fidelity, thus making it a reliable tool for numerical investigations in structural strengthening applications.

According to the experimental results, the concrete employed in this study corresponds to class C50/60, in accordance with the European standard classification. The average compressive strength determined from laboratory tests was 51.87 MPa. Additionally, the material exhibited a Young's modulus of elasticity of 35240.55 MPa and a Poisson's ratio of 0.20. These mechanical properties were derived through standardized experimental procedures to ensure reliable input parameters for the finite element analysis.

The dilation angle (ψ) was set to 30°, reflecting the typical volumetric expansion behavior observed in concrete under shear loading. The flow potential eccentricity (ε), which governs the shape of the plastic potential surface, was assigned the default value of 0.1 to ensure realistic flow characteristics. The ratio of the initial equiaxial compressive yield stress to the initial uniaxial compressive yield stress (f_{b0}/f_{c0}) was defined as 1.16, in accordance with established experimental observations for concrete materials. Additionally, the parameter K_c, representing the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian at initial yield under any pressure invariant p condition (with the maximum principal stress being negative), was set to 0.667 to accurately capture the differential behavior of concrete in tension and compression. Finally, a viscosity parameter (μ) of 0.0001 was incorporated to enhance numerical stability and convergence during the nonlinear analysis, while having negligible influence on the physical response [6].

Prestressing tendons. The constitutive behavior of the prestressing tendons is represented by a bilinear stress-strain curve, consisting of an initial elastic stage followed by a plastic stage that begins when the yield stress of 1796 MPa is reached. Experimental tests on the prestressing strands determined a Young's modulus of 195,558.7 MPa and a Poisson's ratio of 0.3. These parameters are used to accurately model the tendons' mechanical response in the numerical analysis.

CFRP. The mechanical properties of the CFRP material, specifically the modulus of elasticity and Poisson's ratio, were obtained from the technical specifications provided by the manufacturer of the carbon fiber sheets. Young's modulus was considered 235000MPa and Poisson's ratio 0.3. These properties are essential for accurately capturing the anisotropic behavior of the composite material. In the initial elastic stage, the carbon fiber reinforcement was modeled using the orthotropic elasticity formulation under plane stress conditions (Lamina), available in Abaqus. This approach accurately captures the anisotropic mechanical behavior of unidirectional fiber-reinforced composites. The material definition requires the specification of elastic properties in a tabular format, including the longitudinal and transverse moduli of elasticity, Poisson's ratios, and shear moduli. The specific values used in the simulation are presented in Tab. 1 [7]. These material property values were derived from and aligned with the experimental findings presented in the research carried out by Bsisu et al., which offers a comprehensive characterization of the mechanical behavior of CFRP composites under similar conditions. The referenced study serves as a validated source, ensuring the reliability and applicability of the adopted parameters within the context of finite element modeling.

Tab. 1. Specification of the CFRP elastic properties [5]

Property	**Value**
Longitudinal modulus of elasticity, E_1(MPa)	235000
Transversal modulus of elasticity, E_2(MPa)	1350
Longitudinal-transversal Poisson's ratio, μ_{12}	0.23
Shear moduli, G_{12} (MPa)	7067
Shear moduli, G_{13} (MPa)	3000
Shear moduli, G_{23} (MPa)	3000

The post-elastic behavior and damage evolution of the carbon fiber material were modeled using Hashin's failure criteria, which provide a comprehensive framework for predicting damage initiation and progressive failure in unidirectional fiber-reinforced composites according to the studied FEM program [6]. Within Abaqus, this damage model was implemented by defining a set of material parameters that govern the onset and progression of different damage modes, including fiber tension, fiber compression, matrix tension, and matrix compression. The specific numerical values of these parameters, as summarized in
Tab. ***2*** , were adopted from the literature, relying primarily on the experimental investigations and characterization conducted by Bsisu et al [5]. These parameters ensure an accurate representation of the complex failure mechanisms observed in the carbon fibers under various loading conditions, enabling a realistic simulation of the structural response and degradation of CFRP-strengthened elements.

Tab. 2 . Damage variables for Hashin model [5]

Variable	**Value**
Longitudinal tensile strength, X^T (MPa)	3000
Longitudinal compressive strength, X^C (MPa)	248
Transverse tensile strength, Y^T (MPa)	1.5
Transverse compressive strength, Y^C (MPa)	50
Longitudinal shear strength, S^L (MPa)	40
Transverse shear strength, S^T (MPa)	40

Simulation of the CFRP-to-concrete interface. In the present numerical investigation, the interface between the carbon fibers and the

concrete substrate was simulated using two distinct modeling strategies: a surface-based cohesive interaction and a skin reinforcement approach. The cohesive behavior was employed to capture potential debonding mechanisms at the CFRP–concrete interface, defined through a traction–separation law coupled with damage initiation and evolution parameters. This method allowed for a more realistic representation of the interfacial bond behavior and the progressive degradation under increasing load. In parallel, the skin reinforcement technique was utilized to simulate the CFRP layers as perfectly bonded surfaces, wherein the carbon fibers were defined as a thin layer embedded on the concrete surface with prescribed orthotropic material properties. This approach assumes a fully composite action between the CFRP sheets and the concrete, without accounting for debonding effects. The use of both techniques enabled a comparative analysis of the influence of interface behavior on the global structural response of CFRP-strengthened hollow-core slabs.

The first modelling approach consists in a surface-based cohesive behaviour. The epoxy resin bond between CFRP sheets and concrete was modeled using surface-to-surface contact in Abaqus, employing a "hard" contact formulation. To enhance accuracy, the "only slave nodes initially in contact" option was enabled, restricting cohesive behavior to nodes initially in contact. Additionally, the mechanical properties of the epoxy resin: namely, a modulus of elasticity of 2060 MPa and a shear modulus of 665 MPa were adopted based on values reported in the literature [10] [11]. These values align with the guidelines provided in the Abaqus manual and are further validated by the findings of Obaidat et al. Consequently, the stiffness coefficients essential for modeling the CFRP-to-concrete interface are outlined in Tab. 3.

Tab. 3. Mechanical Parameters Governing the CFRP–Concrete Interaction

Property	Value
Young's modulus (MPa)	2060
Normal stiffness, K_{nn} (MPa/mm)	1594.09
Shear stiffness, K_{ss} (MPa/mm)	542.218
Shear stiffness, K_{tt} (MPa/mm)	542.218

The second modelling technique used for the CFRP-to-concrete interaction was the one using the skin reinforcement option, which facilitates the representation of thin composite layers affixed to the surface of structural elements without explicitly meshing the reinforcement as a separate part, thereby enhancing computational efficiency while preserving accuracy under the assumption of perfect bond conditions. This approach defines a reinforcement layer that is fully bonded to the host element surface, effectively transferring stresses between the CFRP and concrete substrate. The CFRP material behavior was defined using orthotropic elastic properties under the lamina formulation, appropriate for unidirectional fiber-reinforced composites. By assigning this material model to the skin, the method ensures that the anisotropic stiffness characteristics of the CFRP are accurately captured.

3. Numerical model validation

To assess the reliability of a finite element model, validation is essential, ensuring that the simulation results are sufficiently accurate for the intended application [12]. Load–deflection response provides a comprehensive representation of the structural behavior of the hollow-core slab throughout the entire loading process. Consequently, a graphical comparison between the numerical predictions and experimental findings is conducted for each of the studied CFRP-strengthened configurations.

Fig. 1 presents the load–displacement response of the HCS retrofitted with a single layer of CFRP over a 300 mm length, highlighting a comparative assessment between experimental findings and two distinct finite element modeling strategies. FEM1 represents the cohesive surface interaction model, while FEM2 represents the skin reinforcement model. All three curves exhibit similar initial stiffness up to approximately 2 mm of displacement, suggesting that the elastic characteristics of the concrete, prestressing tendons, and CFRP were appropriately captured in both finite element models. As noticed from the graph, FEM1 underpredicts the peak load and shows an early onset of stiffness degradation. On the contrary, FEM2 slightly overestimates the peak load and more closely replicates the experimental trend, sustaining post-peak load capacity over a broader displacement range, which is an indicative of a more ductile and distributed failure mode. This modeling technique inherently assumes a strong bond between the CFRP and concrete, which may overlook localized debonding phenomena but contributes to an improved overall load-bearing response. The 2-layers CFRP sheets applied on the same 300mm length layout is depicted in Fig. 4. It may be concluded that the cohesive model (FEM1) provides a more realistic representation of the interface behavior and the initiation of failure, particularly valuable for capturing local damage mechanisms such as debonding at the CFRP–to-concrete interface. Conversely, the skin reinforcement model (FEM2), despite assuming a perfect bond which may constrain local failure modes, exhibits a load–displacement response that more closely replicates the experimental trend, especially in terms of post-peak ductility and residual load capacity. This indicates its suitability for assessing the global structural performance of CFRP-strengthened hollow-core slabs.

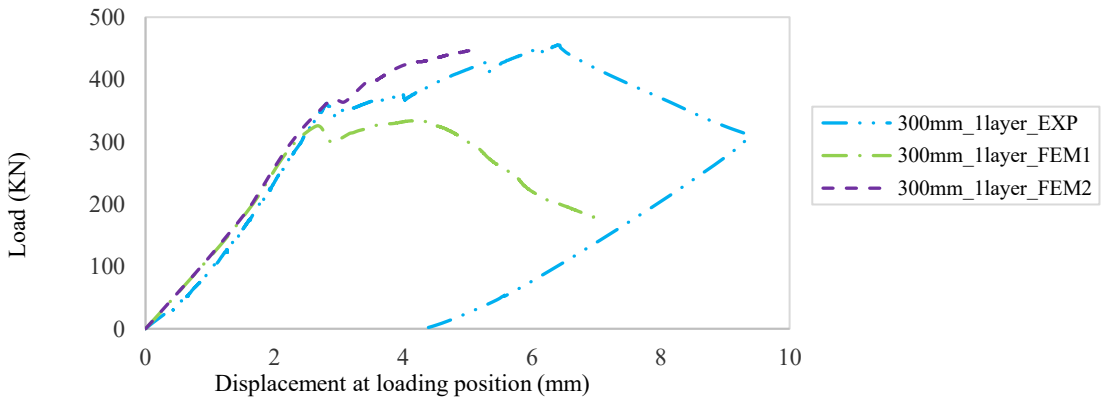

Fig. 3. Load-deflection response for the 300 mm_1layer CFRP configuration

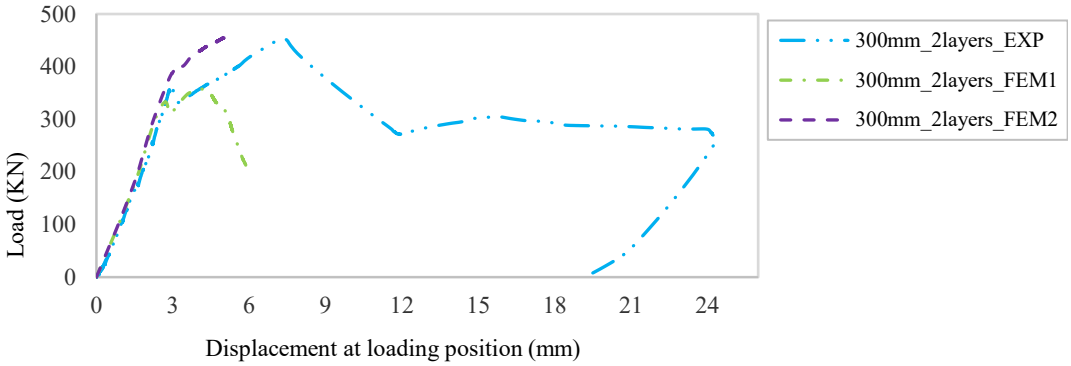

Fig. 4. Load-deflection response for the 300mm_2layers CFRP configuration

Fig. 5 illustrates the Von Mises stress distribution within the CFRP strips for the cohesive model, highlighting a concentrated stress region along the median zone of the retrofitting. This stress localization suggests a significant load transfer from the concrete substrate to the CFRP, particularly in the central portion of the bonded area.

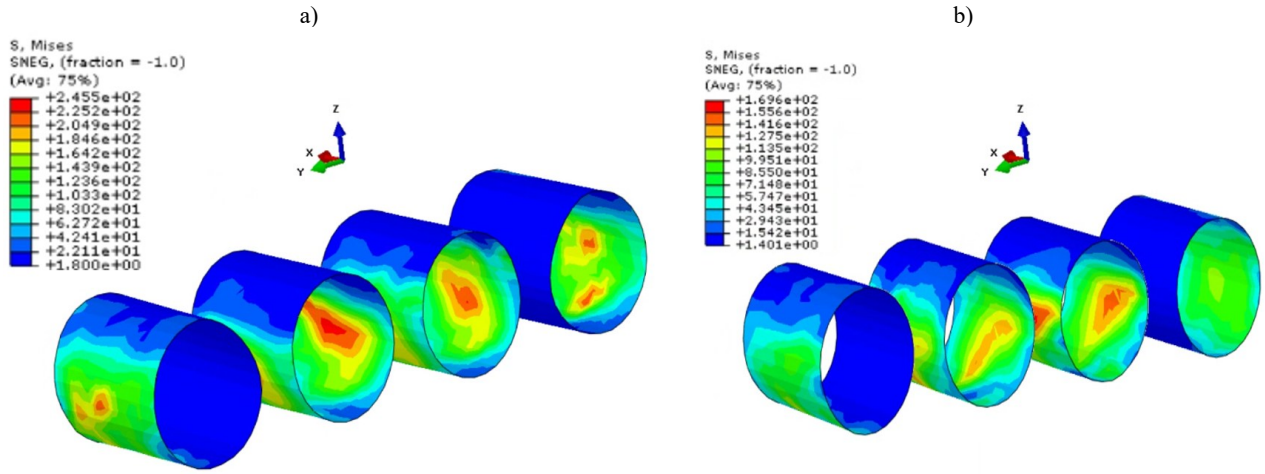

Fig. 5. Von Mises Stress Contours in the CFRP sheets for the cohesive model. a) 300 mm_1layer. b) 300mm_2layers.

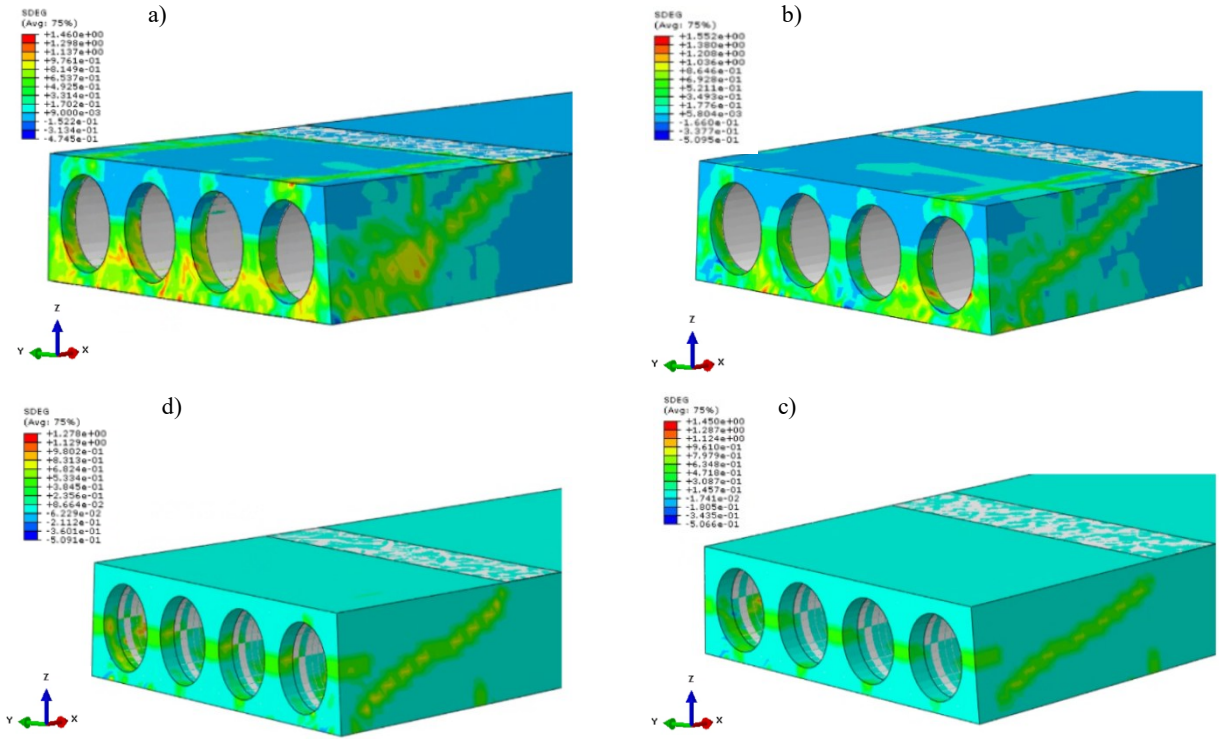

Fig. 6. SDEG distribution for the FE models. a) Cohesive model with CFRP_300mm_1layer. b) Cohesive model with CFRP_300mm_2layers. c) Skin reinforcement model with CFRP_300mm_1layer. d) Skin reinforcement model with CFRP_300mm_2layers.

Additionally, in Fig. 6 the crack pattern predicted by the finite element model is illustrated using the SDEG field output variable in Abaqus, which quantifies the scalar damage in concrete by representing the progressive degradation of material stiffness. This damage variable effectively delineates the initiation and propagation of cracks within the slabs, accurately capturing the failure mechanisms simulated under applied loading conditions [6] [13]. The graphical results indicate that the cohesive model provides a more pronounced representation of damage progression, exhibiting sharper crack localization and more distinct stiffness degradation compared to the skin reinforcement model. This underscores the cohesive approach's enhanced capability to accurately simulate fracture mechanisms within the slabs.

4. Effect of CFRP Geometric Variations: A Parametric Study

This section presents a finite element investigation examining the effects of carbon ply application, varying in strengthening length and thickness, on the load-bearing capacity and stiffness of the specimens. The cohesive model was employed in the present parametric analysis.

To systematically assess the influence of strengthening length, numerical analyses were conducted for lengths of 200 mm, 400 mm, 500 mm and 600 mm, maintaining a constant single-ply thickness. Fig. 7 illustrates the load-deflection behavior, with the un-strengthened specimen serving as the control. Application of a 200 mm CFRP strip resulted in an approximate 6% increase in ultimate load capacity, while the average enhancement across the models was 3.5%. The least improvement was observed for the 600 mm length, indicating a threshold beyond which further extension of the strengthening zone yields negligible benefits. Furthermore, the model with 200 mm strengthening exhibited the highest ultimate deflection, whereas stiffness characteristics remained consistent among all configurations.

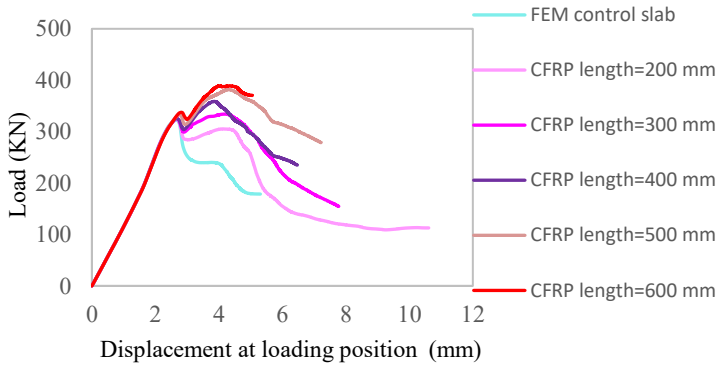

Fig. 7. Role of CFRP strengthening length

To evaluate the influence of CFRP thickness on the numerical response, the thickness was increased to 3 plies, complementing the initially studied 1 and 2-ply configurations. Fig. 8 presents the load-deflection curve for the 300 mm CFRP length. Results indicate a proportional increase in ultimate load capacity, averaging 6% with increasing thickness, while the ultimate displacement exhibits a decreasing trend, averaging a 19% reduction. The stiffness response of all models follows a similar pattern regardless of CFRP thickness.

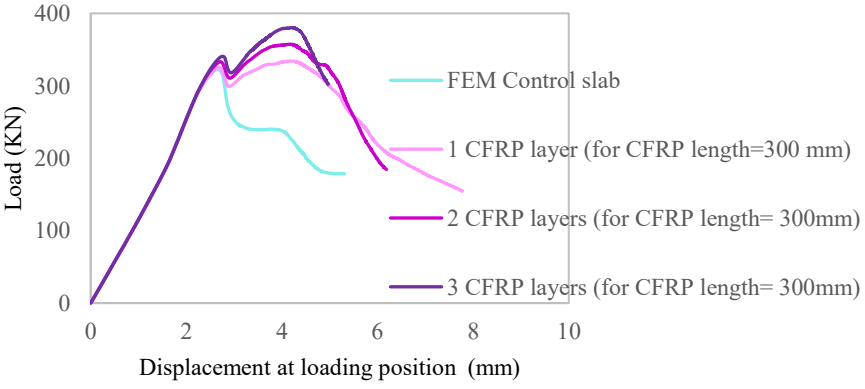

Fig. 8. Role of CFRP thickness

5. Conclusion

Finite element simulations were conducted to analyze the structural behavior of hollow core slabs (HCS) strengthened with carbon fiber-reinforced polymer composites. The CFRP configuration investigated consisted of 1-ply and 2-ply layouts applied over a 300 mm strengthening length. Two modeling approaches were employed to simulate the CFRP material. The first implemented cohesive contact interaction to capture potential debonding effects, while the second one used skin reinforcement, applying a bonded surface layer with defined properties. Numerical results were validated against experimental data, with comparisons focused on load–deflection behavior. In addition, crack patterns were also pointed out and the distribution of Von Mises stresses within the CFRP sheets. The comparative evaluation of the two finite element modeling strategies indicates that the cohesive surface interaction model (FEM1) offers a more realistic representation of interfacial behavior, particularly in capturing localized failure mechanisms such as CFRP–concrete debonding. In contrast, the skin reinforcement model (FEM2), despite its assumption of a perfect bond, demonstrates

superior agreement with the experimental load–displacement response, notably in replicating post-peak ductility and residual load capacity. Accordingly, FEM1 is more appropriate for detailed investigation of failure initiation at the interface, while FEM2 proves more effective for assessing the global structural performance of CFRP-strengthened hollow-core slabs. Moreover, the Von Mises stress distribution for the cohesive model reveals concentrated tensile stresses along the median zone of the CFRP strips. This localization suggests an efficient load transfer from the concrete substrate to the CFRP, predominantly within the central bonded area. The SDEG-based crack pattern demonstrates that the cohesive model more effectively captures damage progression with sharper crack localization and pronounced stiffness degradation. In contrast, the skin reinforcement model, while exhibiting less distinct damage localization, offers a smoother representation of damage evolution, providing advantages in simulating the overall structural response and post-peak behavior of CFRP-strengthened slabs. Together, these findings highlight the complementary strengths of both modeling approaches. The study confirms that the effectiveness of CFRP strengthening is dependent on both the length and thickness of the reinforcement. Load capacity improves with an increasing strengthening length until reaching a critical limit, after which additional length produces minimal benefits. Shorter lengths correspond to higher ultimate displacements, while overall stiffness remains relatively constant. Similarly, increasing CFRP thickness enhances load-bearing capacity but leads to reduced ultimate displacement, with negligible impact on stiffness.

Acknowledgments

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