Analysing the Performance of Hollow Core Slabs Strengthened with CFRP

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Abstract. External bonding with CFRP (Carbon Fiber Reinforced Polymers) has been investigated over the last decade, as it represents a viable technique of strengthening existing prestressed concrete structures, including hollow-core slabs (HCS) with non-circular voids. The high performance of these carbon fibers has been validated through a large volume of experimental and numerical research and yet there are a few issues which remain controversial in simulating their behaviour with the finite element modelling. Although the CFRP mechanical properties are provided by the manufacturers, they are not satisfactory for a complete understanding of the analysis and design approach of HCS strengthened with CFRP. The present research is conducted on prestressed HCS with non-circular voids. The strengthening method consisted in the application of the composite material on the slab’s end internal regions of the voids, on a 500mm length: 1 layer and 2 layers. The objective of this study is to emphasize the effect of damage in the CFRP strips and moreover the interface effectiveness on the CFRP strengthened HCS. Damage is predicted using Hashin’s initiation criteria and the cohesive behaviour in the interface is used to analyse the epoxy resin which bonds the CFRP sheets to the hollow-core units. A plastic damage model was used for modelling the concrete, after a parametric study regarding the dilatancy angle and viscosity parameter was conducted for the most appropriate choice of concrete damage plasticity parameters. The overall procedure consists of numerical FE modelling in Abaqus software. Two different modelling possibilities of CFRP-to-concrete interface were studied: a tie constraint connection was first used and secondly the contact bonding was defined with the cohesive behaviour option of the contact interaction property. The results are provided in terms of load-displacement response, equivalent plastic strain and distribution of Von Mises stresses in the CFRP strips.

1. Introduction

Presently, Fiber Reinforced Polymers are an excellent choice of material in the construction industry, due to their little maintenance and other favourable material properties, such as low volume-to-weight ratio, an increased strength-to-weight ratio, a brittle pattern and a satisfactory fatigue and corrosion resistance capacity [1]. A Fiber Reinforced Polymers composite material has two fundamental features: resin and reinforcement. The reinforcing fibers may be carbon, glass and are all known for possessing high stress capacity and exhibiting a linear elastic until failure behaviour [2] [3]. The most common fiber orientations in these composites are unidirectional, bi-directional and multi-directional. Epoxy resin applied for connecting the fiber sheets to concrete surface produce a high bond strength.
and is an important component of the Fiber Reinforced Polymers material from its actual application to the finite element modelling techniques.

Prestressed hollow core slabs represent one of the most well-known precast structural elements due to their technical and economical properties. In the last decades, their use grew significantly in roofs and floors of commercial, residential and industrial buildings [4]. Hollow core slabs (HCS) have a constant cross-section and are produced using high tensile strength prestressing strands or single wires which are embedded within the element. As it has been demonstrated that bonding the FRP composites to structural members improve their load-carrying capacity, this study highlights the benefits of a relatively new strengthening method, one in which the carbon fiber reinforced polymers (CFRP) are applied on the internal surface of the HCS voids. Modelling techniques of two different configurations of CFRP strengthened HCS are analysed in the present research: 1 ply of carbon fiber of a 500 mm width and 2 plies of 500 mm width carbon fibers. To conclude, the results obtained from the numerical studies are validated against test results.

2. Finite element modelling
2.1. Description of the model geometry
The finite element method (FEM) has vigorously evolved throughout the years due to its capacity of solving wide-ranging problems in engineering and applied science [5]. Moreover, FEM represents an efficient and powerful means in conducting the complexities related to materials nonlinearity and structural behaviour of CFRP strengthened HCS. Numerical analysis of a composite element relies both on the material characteristics and on the interaction between the component materials [6]. The numerical studies undertaken in this study are performed with the Abaqus 6.13 software suite and consist in the development of the concrete model, the CFRP model and the adhesion interface between the concrete and the CFRP material. The cross-section of the studied hollow-core slab with non-circular voids is illustrated in figure 1 [7].

![Figure 1. Cross-section of the HCS unit. [unit: mm]](image)

The units’ dimensions were 1200 mm width, 320 mm depth and 5000 mm total length and were internally tensioned with ten prestressing tendons of 13 mm diameter each and a cross-sectional area of 100 mm². Also, they present high prestressing level at the bottom flange (eight longitudinal prestressing tendons) and a low prestressing level at the top flange (two longitudinal prestressing tendons).

2.2. The Concrete Model
Based on experimental testing, the concrete class is C50/60, with an average value of the compressive strength 51.87 MPa, Young’s modulus of elasticity 35240.55 MPa and Poisson’s ratio 0.2. The concrete damage plasticity model is used for the prediction of the concrete’s constitutive behavior. This approach considers that the fundamental failure mechanisms of concrete are compressive crushing and tensile cracking [8] [7]. The concrete damage plasticity parameters assumed in this
simulation are: the dilatancy angle, $\psi = 30^\circ$; the default flow potential eccentricity $\varepsilon = 0.1$; the ratio of the initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress $f_{bo}/f_{co}=1.16$; the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian at initial yield for any given value of the pressure invariant $p$, so that the maximum principal stress is negative, $K_c=0.667$; the viscosity parameter $\mu=0.0001$ [7].

2.3. The Reinforcement Model
The constitutive relationship of the prestressing tendons is outlined by the typical bilinear stress-strain curve, characterized by two stages: the elastic stage and the plastic stage, which starts after the steel reaches the value of 1796 MPa of the yield stress. Tests performed on the prestressing strands concluded in a value of Young’s modulus of 19558.7 MPa and Poisson’s ratio 0.3.

2.4. The CFRP Model
The modulus of elasticity and Poisson’s ratio of the CFRP materials were provided by the fibers’ manufacturer. In this study, the CFRP was modelled using the orthotropic elasticity in plane stress(lamina) option [7]. The material properties are: Young’s modulus 230000MPa and Poisson’s ratio 0.3. The failure phase of the CFRP sheets was analyzed using Hashin’s failure criteria for unidirectional fiber composites [10]. Damage initiation indicates the starting point of degradation at a material point. In Abaqus, the damage initiation feature for fiber reinforced materials are in conformity with Hashin’s theory. The Hashin damage model predicts anisotropic damage in elastic – brittle materials and includes four distinct failure modes: fiber tension, fiber compression, matrix tension and matrix compression [7]. The damage parameters used for the present finite element calculations are shown in table 1. The values are taken from literature results obtained by different researchers [6].

| Table 1. Damage parameters of CFRP |
|-----------------------------------|
| 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) | 10 |

2.5. Modelling the CFRP-to-concrete interaction
For the interface between concrete and CFRP two different techniques were used. The first one considered a tie constraint option for the connection of two separate surfaces together (master surface-concrete and slave surface-CFRP) so that there is no relative motion between them [11]. This option allowed the fusion of the two regions and yet, the meshes created on the surfaces of the regions were distinct [7]. The second technique consisted in a simulation using the cohesive zone model. The “hard” contact relationship has been adopted for this simulation, as it reduces the expansion of the slave surface into the master surface at the constraint locations and does not allow the transfer of tensile stresses across the interface [7]. In addition, the option: only slave nodes initially in contact (no new adhesion) has been chosen. The mechanical properties of the interface material (epoxy resin) were supplied by the CFRP producers and a part of them were extracted from literature. Table 2 highlights the epoxy resin properties used in the present numerical study:
Table 2. Mechanical properties of the interface CFRP-to-concrete.

| Property                          | Value  |
|----------------------------------|--------|
| Normal stiffness, $K_{nn}$ (MPa/mm) | 1650   |
| Shear stiffness, $K_{ss}$ (MPa/mm)  | 626    |
| Shear stiffness, $K_{tt}$ (MPa/mm)  | 626    |
| Normal strength, $\sigma_n$ (MPa)  | 1.81   |
| Shear-1 strength, $\tau_1$ (MPa)    | 1.5    |
| Shear-2 strength, $\tau_2$ (MPa)    | 1.5    |
| Normal fracture energy, $G_{nn}$ (mJ/mm²) | 0.09   |
| 1st Shear fracture energy, $G_{ss}$ (mJ/mm²) | 0.9 |
| 2nd Shear fracture energy, $G_{tt}$ (mJ/mm²) | 0.9 |
| Benzeggagh-Kenane exponent, $\eta$ | 1.45   |
| Stabilization                    | 0.00001|

2.6. Finite element mesh and analysis

The finite element types used in the finite element formulation are listed in table 3:

Table 3. Finite element types for numerical simulation

| Material      | Type | Description                                                                 |
|---------------|------|-----------------------------------------------------------------------------|
| Concrete      | C3D8 | 8-node linear brick with hourglass control                                   |
| Prestressing  | T3D2 | 2-node, three-dimensional truss element                                      |
| FRP           | S4R  | 4-node quadrilateral in-plane stress/displacement shell element with reduced integration and a large-strain formulation |

For an increased accuracy of the finite element results, a fine mesh with a 25 mm element size was applied to the model and provided satisfactory results following a convergence study. Figure 2 shows the mesh model.

Figure 2: Finite element mesh.
Numerical simulation is performed in three steps: in the first step, prestress is applied to the tendons via the Predefined field option, the second step is for the application of the self-weight to the entire element and the third step consists of the actual load application, with a displacement control analysis. The nonlinear static general analysis was employed in the modelling.

3. Results
The load-displacement results embody the behaviour of the studied prestressed hollow core slabs through the entire loading history for it is a significant performance evaluation factor. Figures 3 and 4 illustrate the comparison between results from the finite element modelling and data extracted from an experimental program undertaken by the authors, for two different CFRP configurations: 1 layer of a 500 mm width and 2 layers of a 500 mm width. FEM 1 show the finite element results for a cohesive behaviour of the interface between concrete and the carbon sheets, while FEM 2 represent the results of the numerical studies for a tie constraint of the CFRP-to-concrete interface. It can be concluded that the FEM 1 results predict in a more satisfactorily way the behaviour of the studied elements, demonstrating that there is a good agreement between the nonlinear simulations and the experimental tests. Thus, the material constitutive models as well as the CFRP-to-concrete interface portray the fracture behaviour accurately.

Figure 3. Load-deflection curve for 1 layer of a 500 mm width CFRP.

Figure 4. Load-deflection curve for 2 layers of a 500 mm width CFRP.
Furthermore, figures 5 and 6 reflect the plastic strain magnitude (PEMAG) results in concrete for both CFRP configurations, indicating a typical shear crack growth development.

**Figure 5.** Plastic strain magnitude (PEMAG) for 1 layer of a 500 mm width CFRP strengthened unit.

**Figure 6.** Plastic strain magnitude (PEMAG) for 2 layers of a 500 mm width CFRP strengthened unit.
The distribution of the Von Mises stresses in the CFRP surfaces is illustrated in figures 7 and 8.

**Figure 7.** Distribution of Von Mises stresses for 1 layer of a 500 mm width CFRP strengthened unit.

**Figure 8.** Distribution of Von Mises stresses for 2 layers of a 500 mm width CFRP strengthened unit.

### 4. Conclusions

Finite element simulations were developed for an analysis of CFRP strengthened HCS. Two different configurations were studied: 1 layer and 2 layers of the same 500 mm width. The results were reported in terms of load-deflection behaviour, plastic strain and Von Mises stressed in the CFRP strips. The finite element results matched satisfactorily the experimental ones in terms of initial stiffness and maximum capacity. The cohesive model used for the CFRP-to-concrete interface demonstrated a more accurately behaviour of the specimens than the models with a tie constraint for the interface between
concrete and CFRP. Material constitutive properties and the cohesive interaction between concrete and CFRP capture the fracture behaviour well.

References
[1] J. Swinnen, “Modelling FRP open-hole tensile tests in Abaqus,” pp. 1–37, 2018.
[2] Y. T. Obaidat, “Structural retrofitting of reinforced concrete beams using carbon fibre reinforced polymer,” p. 78, 2010.
[3] A. Carolin, "Carbon Fibre Reinforced Polymers for Strengthening of Structural Elements," vol. 1992, no. 10, 2003.
[4] A. Adawi, M. A. Youssef, and M. E. Meshaly, “Experimental investigation of the composite action between hollowcore slabs with machine-cast finish and concrete topping,” Eng. Struct., vol. 91, pp. 1–15, 2015.
[5] O. C. Zienkiewicz and R. L. Taylor, “The Finite Element Method: its basis and fundamentals,” 2005.
[6] K. A.-D. Bsishu, H. H. Hussein, S. M. Sargand, "The use of Hashin damage criteria, CFRP-concrete interface and Concrete Damage Plasticity Models in 3D finite element modeling of retrofitted reinforced concrete beams with CFRP sheets," Arab J Sci Eng, vol. 42, pp. 1171-1184, 2016.
[7] Simulia, “Abaqus 6.13 Abaqus/CAE User's Guide),” p. 1138, 2013.
[8] J. Lee, G. L. Fenves, “Plastic - damage model for cyclic loading of concrete structures,” Journal of Engineering Mechanics, vol. 124(8), pp. 892-900, 1998.
[9] R. K. Devalapura, M. K. Tadros, “Stress-strain modeling of 270 ksi low-relaxation prestressing strands,” PCI J., vol. 37, no. 2, pp. 100–106, 1992.
[10] Z. Hashin, “Failure criteria for unidirectional fiber composites,” Journal of Applied Mechanics, vol. 47, pp. 329–334, 1980.
[11] I. F. Moldovan, M. S. Buru, M. Nedelcu, “Nonlinear analysis of hollow-core slabs with and without FRP reinforcement,” Bulletin of the Transilvania University of Brasov , vol. 11 (60) special issue, series I: Engineering Sciences, 2018.