Experimental and finite element modelling of prestressed hollow-core slabs

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Abstract. This paper presents the results of a study conducted on prestressed hollow-core slabs (HCS), both experimentally and numerically. The research has been carried out on real scale HCS manufactured at a local precast factory. The concrete specimens were prestressed using ten 12.9 mm diameter steel tendons placed both at the bottom and the top flange of the cross-section. They were tested under concentrated load until shear failure. Validation of the numerical results undertaken using ABAQUS 6.13 software demonstrated that the values obtained from the numerical simulation match the experimental ones in terms of force-displacement relationship.

1. Introduction

Prestressed hollow core slabs (HCS) are structural elements predominantly used in the construction of residential, industrial buildings and bridges also. Hollow core slabs are floor and wall elements made from prestressed concrete with voids in the cross-section. The presence of the voids leads to a significant reduction of the element’s weight in comparison to solid slab units. As in the construction industry nowadays the main characteristics are energy and cost effectiveness together with sustainability, and because prestressed concrete elements accomplish all the aforementioned aspects, HCS represent a future-oriented choice. The development of hollow core HCS dates back from the 1950s, when long-line pre-tensioning systems emerged [1] [2]. HCS are generally produced either through extrusion, when a low-slump concrete is pushed through the casting machine or by using a higher slump concrete with the voids being obtained by slip forming with long tubes attached to the casting machine [3].

Shear behaviour of HCS and other concrete structures too is a sophisticated issue and a problem studied for decades. The traditional techniques of adjusting the shear capacity of these units consisted in the increase of slab thickness and or filling the voids. Nevertheless, it has been confirmed that these practices had basically a negative effect on the shear capacity and the HCS particularities self-weight and low cost. Consequently, the process of retrofitting the shear capacity of HCS remains the most notable measure to prevent shear failure [4].

2. Experimental work

Experimental investigation represents a significant and efficient tool for a better understanding of HCS behaviour. Two full-scale precast prestressed HCS were tested to failure under monotonic load. The specimens were supplied by a local precast factory. The experimental program was carried out in the Test Laboratory of the Faculty of Civil Engineering. The specimens had a length of 5000mm, a depth of 320mm and a width of 1200mm. Figure 1 shows the cross-section of the HCS tested:
Each test specimen has ten prestressing tendons, composed of 7-wire, low relaxation strands with a 12.9 mm diameter and a cross-sectional area of 100 mm². Moreover, they present high prestressing level at the bottom of the slab (eight longitudinal tendons with a 110 KN value of the prestressing force) and a low prestressing level at the top flange (two longitudinal tendons with a 50 KN value of the prestressing force).

Materials

Concrete samples tests were undertaken in the Structures Laboratory of the Faculty of Civil Engineering and resulted in an average value of 64.87 N/mm² for the compressive strength. Splitting tensile tests performed in the same Structures Laboratory obtaining a mean tensile strength of 2.02 N/mm². The modulus of elasticity has also been determined and the value obtained was 35240.55 N/mm². The results obtained were in concordance to the ones supplied by the precast factory’s laboratory for a C 50/60 concrete class.

The mechanical properties of the prestressing tendons provided by the strand manufacturers included the values of the nominal tensile strength of 1860 N/mm² and modulus of elasticity of 195000 N/mm². However, after tests performed in the Structures Laboratory on these prestressing strands resulted a value of 195558.74 N/mm² for the Young’s modulus of elasticity.

Test setup

The HCS elements were simply supported at each end. In addition, the point load acted along the width of the element through a 250mm H steel beam. In order to satisfy the value of 2.5h of the shear span-to-depth ratio the point load was placed at a distance of 850mm from the hinged support. Figure 2 depicts the unit static scheme. The supports of the tested units consisted of two steel H profiles with the dimensions 250x1500mm and a third one having the dimensions 100x1500mm, which were fixed on the laboratory’s floor.
The tested specimens were instrumented at the loaded end, as displayed in figure 3. Two linear variable differential transformers (LVDTs) were installed both on the left and the right side of the element to measure the vertical displacements along the significant location on the slab’s length. Furthermore, electronic dial gauges were positioned on the specimen’s loaded end for a manually strain measurement. The force was applied with a hydraulic press of 1200kN and an extension of 40 cm.

![Figure 3. Experimental setup.](image)

**Experimental observations**
The main purpose of this section is to outline the experimental results for the specimens tested in this study. These observations are going to be emphasized in terms of failure load and crack appearance. The two tested specimens presented a typical shear failure, as it can be noticed from figures 4 and 5. The crack appeared at a distance of approximately 110mm from the edge of the support close to the point load and extended until the loading plate. Regarding the failure load, the first specimen reached up to 313 kN while the second one failed at 345 kN.

As noticed from figure 6, the second unit exhibited a longitudinal crack which developed suddenly on the top surface of the first void.
3. Numerical studies and calibration versus the experimental program

Finite element modelling represents an effective means for a better understanding of structural elements with a complex nonlinear behaviour. Finite element programme Abaqus 6.13 was used during the numerical analysis carried out in this study [5]. The details of the adopted model will be described and then the calibration of the numerical model with the data obtained from the experimental investigation will be highlighted.

The concrete damage plasticity model has been chosen for the simulation of the precast HCS[6]. This model is distinguished for the fact that crushing in compression and cracking in tension causes the principal failure mechanism of concrete [7]. The parameters used have been detailed in table 1.

| Table 1. Concrete damage plasticity model parameters |
|-----------------------------------------------------|
| Dilation angle | Eccentricity | $f_{c0}/f_{c0}$ | $k$ | Viscosity parameter |
|----------------|--------------|-----------------|-----|---------------------|
| $30^\circ$     | 0.1          | 1.16            | 0.667 | 0.0001               |
The constitutive model for the prestressing tendons is expressed by the idealised bilinear stress-strain curve [8].

The element type adopted for modelling concrete volumes was C3D8 (8-node linear brick, fully integrated) and T3D2 (2-node, three-dimensional truss element) for the prestressing tendons modelling.

It has been demonstrated that the accuracy of the results obtained in numerical analysis is highly dependent on the mesh size of the elements used. Therefore, a mesh sensitivity analysis has been undertaken and three different mesh sizes were studied: a fine (25mm), a medium (50mm) and a coarse mesh (75mm). The comparison of the three mesh sizes is emphasized in figure 7. Thus, it has been adopted the optimum size of 25mm for the finite elements modelling.

![Mesh sensitivity analysis](image)

**Figure 7. Mesh sensitivity analysis.**

Figure 8 illustrates the studied finite element's geometry for hollow core slab.

Regarding the boundary conditions, the support plates were represented with 3D discrete rigid elements which were then connected to the hollow-core slab with a ‘surface-to-surface’ contact interaction option. The contact property consisted in a ‘hard’ contact normal behaviour and a frictionless tangential behaviour. The loading plate has been defined as a 3D discrete rigid element also, but the Tie constraint was used for connecting it to the concrete part, an option which allows the fusion of the two surfaces.

![Finite element model geometry](image)

**Figure 8. Finite element model geometry.**
Numerical analysis is divided into two steps. The first step consists of the application of prestress in the tendons, using the Predefined field option, while in the second step of the analysis, the HCS is subjected to the self-weight as a uniform load on the element and moreover, to a vertical load gradually applied. A displacement control analysis was adopted for the load application. The static geometric nonlinear general method has been chosen to conduct the nonlinear static analysis. A Riks-Wempner analysis has also been performed, but the results obtained were not satisfactory.

The load-deflection relationship represents a significant assessment criterion for a finite element model performance because it depicts the specimens’ structural performance during experimental tests. Figure 9 contains the comparison between the data from the finite element modelling and the experimental results. Exp 1 and Exp 2 represent the load-deflection curves obtained from the two experimental tests investigated. It can be concluded that the modelling method adopted estimates the behaviour of HCS in an adequate manner, with reference to the initial stiffness and the failure load.

Figure 9. Load-deflection results.

The plastic strain magnitude (PE MAG) is shown in Figure 10, illustrating a classical crack expansion inside the shear-tension region. As noticed from Figures 4 and 5, the results obtained from the numerical analysis match the crack pattern obtained from the laboratory tests.

Figure 10. Plastic strain magnitude (PE MAG) results.
4. Conclusions
The experimental program presented in this paper, consisting in testing two hollow core units illustrated the shear behaviour of such structural elements. Finite element simulation undertaken predicts the overall behaviour of the precast prestressed HCS tested. A mesh sensitivity analysis has also been concluded and its results contributed to the overall findings. It is noteworthy that the difference between the experimental data and the numerical data is under 5%, in terms of the load-deflection behaviour. The curves exhibit similar behaviour both in the elastic and in the post-elastic range, which concludes that the characteristics of the numerical model have been thoroughly studied and analysed.

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