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Research paper

Optimal design of prestressed concrete hollow core slabs taking into account its fire resistance

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ABSTRACT

Prestressed hollow core slabs are a concrete element widely used as construction floor product, which manufacturing process has greatly been improved in recent years. Several research studies focused on hollow core slab performance, mainly related to its fire behavior, have provided new limit states to be assessed throughout its life cycle. Therefore, the hollow core slab design needs to be reviewed to allow for these improvements, a process which may involve changes to its geometry. In order to deal with this review, modern computational optimization techniques offer an alternative approach to traditional structural product design procedure, mainly based on the engineer's prior experience.

This paper proposes a hollow core slab model (including variables and constraints) to develop heuristic search algorithms, such as simulated annealing, in order to find the most economical slab design including the fire resistant constraint and taking into account all available manufacturing technologies. The optimal designs obtained by this process save up to 20% in cross-section area compared with common circular void designs from market, which is taken as a comparison pattern. The results show that traditional designs are deficient when the fire resistant constraint is considered, so that precast manufacturers and machinery designers should use optimization techniques to modify their hollow core slab geometry.

1. Introduction

Precast prestressed hollow core concrete slabs are widely used to make floors in both residential and non-residential buildings and provide efficient structural behavior for long spans and high loads [1]. Furthermore, the estimated total stock of hollow core floors currently installed in Europe is 1.000 million square meters.

Since the early seventies, hollow core slabs have been thoroughly studied in research campaigns, in the USA [2,3] and Europe [4] and many aspects of the product have been intensively tested, including its fire resistance [5–7]. Specific standards have been issued related to its structural behavior, including the PCI Manual for the design of hollow core slabs [8], FIB Special design considerations for precast prestressed hollow core floors [9] and the European product standard EN 1168 [10].

This type of slab is now widely used and its manufacturing process has been greatly improved to include strictly controlled design parameters. Specifically, hollow core slabs are manufactured in highly industrialized precast factories. The manufacturing process is to run the machines on steel beds up to 200 m long, equipped with stressing abutments where tendons are initially positioned and prestressed, see Fig. 1a. These tendons may change in position, quantity and cross-section. The concrete casting is continuous and three specific procedures are available in the market: *Slipformer, Extruder* and *Flowformer*. The final geometry of the slab hollows is defined by a specific and interchangeable part of the casting machine called the finishing mold, see Fig. 1b. This core mold can be replaced to manufacture different cross-section designs or slab heights. The slab holes shape, quantity and position may change using the same machine but different finishing mold. Therefore, new proposals of hollow core slab designs may produce changes in this manufacturing finishing mold.

Traditionally, engineers have relied on their experience to design structural products so that the same structural response could be achieved through diverse designs using different resources.

The current design of hollow core slabs is a forward design, which involves three steps. The first one is related to the machinery designer. In this step aspects as manufacturing procedure constraints or the fresh concrete consistency are used to design the finishing mold. Thus, many hollow core geometry designs appear in the market depending on the manufacturing process. This first step of the current hollow core slab design does not take into account any aspect of the final behavior of the slab in floors.

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a) Casting beds b) Finishing mold

Fig. 1. Hollow core slab, manufacturing process. (Manufacturer pictures: HORVITEN S.L & HERMO S.L, Spain).

In the second step, the hollow core slab manufacturers cast the concrete slab with the available machinery; however they only can change the concrete strength, the prestressed tendons position, quantity and tension. The slab geometry comes from the finishing mold, which is established in advance. The slab manufacturers normally define some series of tendon configurations to offer different solutions reaching a specific range of bending capacity.

Finally, in the third step the floor project designer shall choose the proper configuration which provides enough mechanical capacity to the floor.

The forward design described above is clearly uncoupled. The mechanical requirements of the floor have no influence in the real hollow core slab geometry. Therefore, the current hollow core slab design procedure is strongly highly inefficient.

Alternatively, current computational optimization techniques offer another approach to deal with this problem. These techniques can manage all constraints along with the hollow core slab life cycle. Therefore, a coupled design can be defined to provide optimal and efficient solutions.

A wide range of structural concrete products, such as frames [11,12], bridge piers [13], precast road bridges [14], road vaults [15], retaining walls [16] and foundations [17] have been studied using this approach. Economic cost has classically been defined as the standard optimization criterion, although other factors like weight, environmental or constructability indicators have also been used.

The first study on precast hollow core floor optimization was carried out by Koskisto and Ellingwood in 1997 [18]. The objective function defined was economic cost, including the cost of failure, and focused on the bending capacity at room temperature as the performance criterion only. This work used only four design variables and concluded that the slab height and reinforcement increment was an efficient way of increasing the maximum slab span. In contrast, that concrete strength and reinforcement eccentricity were found to not have significant effect.

Noorzaei et al. [19] studied the optimal design of particular geometries of hollow core slabs as circular voids, normally produced by extrusion (*spiroll* manufacturing process) in Northern Europe and America. This work obtained the optimal depth of this slab type using bending moment as the principal constraint.

More recent studies, such as Sgambi et al. [20], focused on the slab's web design defined by five geometric variables, with weight as the objective function. This work only took into account the spalling stress constraint to avoid cracking in the web during the manufacturing process. Specifically, this constraint is related to the transient design situation of prestress transfer.

Surprisingly, few studies have dealt with the optimal design of hollow core slabs and none has considered fire resistance in the optimization process and additional design constraints from manufacturing process as geometrical conditions from production machinery or the definition of stress limits to avoid undesirable crack during slab production and transport.

Additionally, due to catastrophic events like the *Harbour Edge* collapse in Rotterdam [21], hollow core slabs have now been greatly improved as regarding its fire resistance.

In 1999 premature collapse of hollow core slabs was observed in *DIFT* tests [22], due to high temperatures, which was not deducible from the standards. This premature collapse was later analyzed by *van Acker* [5] and *Fontana & Borgogno* [6]. These studies identified a strain compatibility field in the cross-section due to a nonlinear temperature field, which caused stress in the webs. The premature collapse of the slab in the fire tests could be explained by this undesirable web stress. However, subsequent studies [23,24] concluded that this problem did not occur in floors with constrained longitudinal expansion. Advanced finite element models have now been developed to reproduce this behavior [25,26].

Traditionally, fire resistance requirements are achieved for these slabs by adding prestressing steel and/or increasing the steel tendon concrete cover while maintaining the cross-section geometry. Choosing between these options is not always obvious. Besides, it has been observed that these approaches may provide an over capacity of bending moment resistance at room temperature and therefore, inefficient designs.

This paper therefore proposes a new approach using computational techniques and taking advantage of its controlled manufacturing process. A complete definition of the hollow core slab model is presented, including design parameters, variables, and constraints, and a cost-based objective function. This works includes fire resistance as a constraint and the models available to assess hollow core slabs at high temperatures. All of these constraints are added together taking into account all possible interactions.

Different optimal designs for 60 and 120 min of thermal exposure to a standard time-temperature fire ISO curve. These standard fire exposure times are commonly used for residential and non-residential buildings. The optimal designs obtained are compared to determine the influence of fire resistance in the optimal cross-section geometry. All the limit states were considered during the complete hollow core slab life cycle, including the fire event.

2. Optimization problem definition

2.1. Problem definition

In order to solve the disadvantages of the current uncoupled and inefficient design procedure of hollow core slabs, described previously, a new approach is presented. This is based on optimization techniques