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Numerical web-shear strength assessment of precast prestressed hollow core slab units

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ABSTRACT

The shear strength of precast prestressed hollow core (PPHC) slabs is numerically assessed for 200, 265, 320, 370, 400 and 500 mm thick units, the cross-sections of which present both circular and non-circular voids. The evolution of shear stress distributions and crack patterns is predicted by detailed nonlinear solid finite element (FE) analyses, matching experimental test data. A comparison is provided between experimental results and analytical estimates obtained by common design Codes (EC2, EN 1168, ACI and CSA), quantifying the inaccuracy of previous proposals which was shown to be particularly evident for deep slab sections with flat webs where the shear stress peak is localized below the centroidal axis. Numerical observations revealed the sensitivity of web-shear failure mechanism and related shear capacity to hollow core shape and related non-circularity of the voids, inherent web width variation along depth and concrete chords above and below the void. In light of these trends, a closed-form expression is proposed to be used as a preliminary-design-stage tool for analytical web-shear strength assessment of these members.

1. Introduction

PPHC slabs are plant-fabricated members, typically manufactured by extrusion or slip-forming and mostly used as floor and roof framing elements but also as wall panels and spandrel members. Due to their versatility, their multipurpose potential and their low cost [1–3], these precast products have found wide application in building construction, in combination with conventional precast prestressed reinforced concrete [4,5] or alternative composite steel [6,7] beams.

The use of precast elements positively affects both quality level and construction time. After the slabs are set in place, the joints between the slab and the beam are reinforced and grouted with cast-in-situ concrete to obtain the diaphragm action required. During the assembly phase, the connection with the framing beams is usually achieved by proper transverse reinforcement in correspondence to the joints and longitudinal reinforcement in correspondence to the grooves of the plate. The concentrated loads acting on single span PPHC units are transversely distributed to the adjacent members by shear keys in the longitudinal joints [8] that frequently play out the required load transfer mechanism in combination with concrete topping [4,5,9]. By contrast, the unit itself is commonly reinforced only by straight longitudinal prestressing steel strands, since the use of typical transverse reinforcement is inhibited by the production process. Because stirrups and draped strands are unfeasible for such precast members and carbon fiber polymers [10] or fiber reinforced concretes [11] are at the moment promising strengthening techniques analyzed in research applications but not so diffused in building practice, the only reserve against shear is provided by the resistance of the traditionally used medium/high-strength concrete that, anyway, presents some intrinsic criticalities [12]. Different contributions to the shear transfer mechanism with respect to traditional normal-strength concretes were observed, as well as smoother cracks, implying a significant reduction of the potential for shear transfer through the aggregate interlock action, which is not explicitly accounted in conventional design approaches against web-shear failure mechanism. As shown by Cladera and Marí [13] and reported in Fig. 1, shear failure surfaces can be possibly propagated through coarse aggregate particles rather than around them.

Concrete tensile strength is a controlling factor in the response and design of hollow core units and more in general in the behavior of high-strength members, as recognized by a number of research contributions [2,14,15]. In particular, the stress state in

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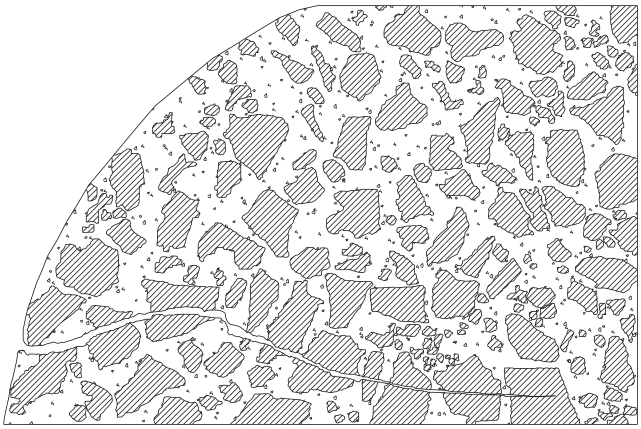

Fig. 1. Example of crack through aggregates in high-strength concrete (adapted from Cladera and Marí [13]).

the webs of PPHC slabs consists of biaxial principal tension and compression and the tensile strength of concrete is reduced in the presence of a compressive stress acting orthogonally to the tensile stress. Additionally, the nature of the dry mixture and casting method used in production may imply a non-uniform level of compaction throughout the depth of the unit, which could result in varying levels of concrete strength throughout the depth that may affect the shear capacity and the transfer length [2].

Furthermore, the "classification" of concrete, as normal-, medium-, high- and ultra high-strength, is another critical aspect that was deeply investigated in the literature. Even if the compressive strength of the members analyzed in this paper was in the range 47–78 MPa, a "race for more MPas" [16] has been observed through the years and hence the concrete strength used to identify "high-strength" concretes has shifted reaching strengths of up to 120 MPa [17–19]. In addition to that, typical classifications solely based on strength were replaced by ones based on performance as a combination of workability, durability and ultimate strength. High-strength and high-performance concrete are not synonymous and those two terms identify mixtures potentially possessing different characteristics, as observed by several studies [16,20–24].

Therefore, this scenario contributes to some of the major uncertainties in the shear strength assessment of such members according to current design approaches, as already pointed out in the literature [2,3,25–29]. As it will be discussed in the following, most of the current predictive methods are based on tests performed on members (i.e. beams) with concrete compressive strength lower than 40 MPa and subjected to conditions rather different from those experienced at the end of a PPHC unit. In addition, geometric features other than those of conventional beam cross-sections can be observed for such members and the present paper is aimed to investigate their influence on the shear response, predicting behavioral changes as a consequence of geometric variations in the cross-section shape. Even though a standard width of approximately 120 cm is common for these slabs, their cross-section shape, usually characterized by relevant void ratios, depends, among other factors, on the thickness of the slab itself. The first examples, characterized by circular voids, were mainly 200 or 265 mm thick units, while, through the years, the need for material saving has led manufacturers to adopt deeper and increasingly optimized cross-sections with non-circular voids. Gradually, 320, 370, 400 and 500 mm thick PPHC slabs became intensively used products, even though it was realized that their shear capacity against web-shear failure mechanism is significantly lower than expected according both to U.S. [27,28] and European [25,26] Standards.

2. Review of current design methods against web-shear failure mechanism

In the last three decades, PPHC units have been extensively studied, experimentally [2,3,26–28] and numerically [1,7,25,29,30], to understand and calculate the shear strength of these members, but no consensus has been reached on this issue [30,31]. In addition, the current design methods for shear resistance are derived from experimental results [32] and elastic theories [33,34] that are not usually directly related to the behavior at the ultimate limit state, which may be affected by many sources of nonlinearity and complex thermo-hygro-mechanical effects [35]. Recently, Sgambi et al. [1] have shown the mismatch between EN 1168 [34] and numerical simulations that were based on classical principles of nonlinear fracture mechanics [36–42]. Similarly, Araujo et al. [30] have performed nonlinear FE modeling on PPHC slabs to show the inaccuracy of CSA [43], when applied for these elements, and to propose an alternative analytical design methodology, based on modified compression field theory (MCFT) [44] and concepts of Eurocode 2 (EC2) [33].

In light of this scenario, a review of four shear capacity predictive equations available in current Codes (EC2 [33], EN 1168 [34] ACI [32] and CSA [43]) will be furnished by estimating the shear strength of 49 specimens tested in past experimental programmes and collected by Pajari [26]. The database is composed of single span, simply supported PPHC slabs without filling concrete in the voids at their ends. All the units, subjected to transverse line loads, had failed in shear. The mean concrete compressive strength in the slabs was measured to range from about 47 to 78 MPa according to specimen type, while seven-wire, low-relaxation, Grade 270 ksi (1860 MPa) strands, with a 12.5 mm diameter, were used for all the specimens. Further details regarding slab depth, cross-section features, strands arrangement, initial prestressing force and test setup can be found in [26] and [29]. In this study, prestress losses of 5% and 15% are assumed for web-shear strength predictions, as proposed by Pajari [26]. These upper and lower bounds, confirmed by direct computations according to Zia et al. [45], agree with a reduced level of knowledge about concrete mix and storing conditions of the slabs tested. Analogous range was observed and used by Palmer and Schultz [28] for similar PPHC units. Concrete tensile strength (f_{ctm}) was derived in accordance with EC2 [33] and EN 1168 [34], using the following model:

$$f_{ctm} = \begin{cases} 0.30\,(f_{cm} - 8)^{\frac{2}{3}} & \text{for concrete classes} \leqslant \text{C50/60} \\ 2.12\,\ln\left(1 + \frac{f_{cm}}{10}\right) & \text{for concrete classes} > \text{C50/60} \end{cases} \quad (1)$$

where f_{cm} is the mean compressive strength of concrete. Mean values were assumed to perform the analytical predictions shown in this paper, being the shear design equations used for assessment purposes in this case.

Shear strength estimates according to Codes' provisions [32–34,43] are collected in Fig. 2 for different nominal slab depths, by assuming a prestress loss of 5%, while a comparison between the four approaches considered is shown in Fig. 3(a). Finally, Table 1 summarizes the average and standard deviation of experimental-to-analytical estimates and Fig. 3(b) presents the slight discrepancy between the predictions obtained by 5% and 15% prestress losses.

Eq. (6.4) of EC2 [33], based on "plane sections" assumption and Mohr's circle theory in combination with the maximum principal tensile stress failure criterion, leads to slightly unconservative estimates for cross-section shapes characterized by circular voids. Conversely, the unsafety level tends to clearly increase, if deeper slab sections with flat webs are considered; in some cases, the