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A design method for the prediction of load distribution in hollow-core floors

P. Bernardi, R. Cerioni, F. Leurini *, E. Michelini

Department of Civil, Environmental, Land Management Engineering and Architecture, University of Parma, P.co Area delle Scienze 181/A, 43124 Parma, Italy

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ABSTRACT

A general design method is provided to predict the load distribution at serviceability condition in hollow-core floors formed by precast units linked together through cast in place reinforced concrete joints. Each panel forming the floor is schematized as a Saint-Venant beam connected to the others by means of rotational hinges. In this way, the only unknowns of the solving system, characterized by an exponential dichotomy, are represented by shear forces transmitted along joints. The model is first validated through comparisons with significant experimental results available in the literature, and subsequently applied to the construction of design charts to be used in current practice. These latter are also compared with the provisions on load distribution effects suggested by European Standard UNI EN 1168, pointing out some limitations of current design procedures and suggesting possible improvements.

1. Introduction

A widespread method for the construction of roofs, floors and decks consists in placing side by side precast reinforced or prestressed concrete elements, which are then longitudinally linked together through reinforced concrete (RC) joints.

This is the case of precast prestressed hollow-core (HC) units, which are frequently used for the realization of ground and intermediate floors in industrial and commercial buildings. The presence of RC joints, which are able to transfer shear forces, allows a certain redistribution among the units of both line loads acting parallel to the span of the floor (e.g., due to the presence of partition walls), and of localized point loads directly applied on a single slab. In this way, in the absence of seismic prescriptions, HC floors can be used without a cast in place topping, since they are able to ensure anyhow adequate structural performances.

Another frequent application of the above described construction technique is represented by multi-beam bridges, which are similarly constituted by precast girders connected to each other by means of cast in place joints [1,2] that allow the transfer of vehicle loads from one beam to the next.

One of the main issues in the study of these structural systems is to determine the proportion of load transferred from the directly loaded unit to the adjacent ones (often referred to as "load distribution factor"), in order to correctly evaluate the state of stress in each element forming the floor or the deck (see e.g., [1–4] for multi-beam bridges and [5–11] for HC floors). In current practice, each precast unit is indeed usually designed as a simply supported individual element subjected to bending. However, when a single slab forming the assembled floor is loaded with a point or line load, the adjacent ones are forced to deflect and also twist because of the forces transmitted along the joints (e.g., [12]). This behavior generates a different distribution of internal forces on each unit, which should be properly taken into account in the design of slab reinforcement.

Many Authors have tried to solve the problem by following different numerical approaches. Spinelli [3] proposed to model the floor/deck as a sequence of adjacent beams connected to each other through joints that work as rotational hinges, able to transmit only shear forces. A different but quite common approach is based on the orthotropic plate formulation, so considering the floor/deck as a plate with different elastic properties in the two directions (e.g., [2,13]). Another possible methodology to solve the problem, which represents an improvement over the orthotropic plate theory, is the one proposed by Stanton [7,8] and based on the use of the finite strip method. In this case, each member is modelled as a plate made up from a number of interconnected strips, while in turn the plates are connected together by rotational hinges with full-shear continuity. More recently, the finite element (FE) method has been widely used in the analysis of precast floors and different assumptions, characterized by an increasing degree

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* Corresponding author.
E-mail address: filippo.leurini@studenti.unipr.it (F. Leurini).

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of accuracy, have been proposed for the modelling of both units and joints, so to correctly catch their behavior (among others, e.g., [9,11,14–19]). These refined analyses allow taking into account different aspects of the structural behavior of HC floors, not only related to the evaluation of load distribution among panels, but also to the estimate of the actual shear resistance of the system, which represents a quite critical aspect for this type of structures (see e.g., [9,10,14,15,17,19–22]). Due to the lack of transverse reinforcement (which is indeed inhibited by the production process), HC panels could be subjected to web shear cracking at the end regions, resulting into critical brittle failure mechanisms, especially in case of deeper cross-sections. Moreover, the shear capacity of the slabs could be further reduced in presence of flexible supports [18].

In this paper, the attention is focused on the analysis of load distribution effects in HC floors. To this aim, a numerical model, which represents an extension of a previous work by Donida and Cerioni [23], is developed herein. The effectiveness of the proposed procedure is first verified through comparisons with significant experimental data available in the literature [24,25]. The model is then applied to the definition of simplified design charts, which provide the load distribution factors at serviceability to be used in current design practice. The so obtained curves are also compared to those suggested by the European Standard EN 1168 [26]. As pointed out in other works available in technical literature [24,27], the approach followed in the European Standard does not allow distinguishing between the distribution of bending moments and of shear forces in the floor and consequently a not correct use of the available curves could lead to an unsafe design. On the contrary, for a same loading case, the proposed model provides two distinct design charts respectively relative to bending and shear effects on the panels, whose trend is quite different from each other. The obtained results are rather similar to those found in [9], based on a simplified global FE model for the analysis of HC floors. Moreover, the proposed approach allows taking into account properly the dependence of the results from the ratio between bending and torsional stiffness of the HC cross-section, which is explicitly included as dimensionless parameter in the analytical solution of the problem.

2. Numerical model for the evaluation of load distribution in HC floors

The numerical model proposed herein represents a general approach for the determination of load distribution effects in precast floors, in presence of point or line loads. In these cases, a correct design of the units forming the floor requires indeed the evaluation of their interaction and the estimate of the load percentage carried by each of them at serviceability conditions.

The adopted model is based on two main simplifying hypotheses. First, it is assumed that all the units forming the floor are characterized by the same span and the same geometric and inertial properties, so to treat them as Saint-Venant beams. In this way, the behavior of each element is completely defined by simply considering its centerline. This assumption, which is obviously valid when the units can be considered as transversely nondeformable, is reasonably acceptable in case of HC panels.

Secondly, it is hypothesized that the units are connected to each other by means of rotational hinges, schematizing the behavior of cast in place RC joints. These latter, which are often cracked (for example because of shrinkage), are indeed able to transfer shear forces, but they do not usually have enough rotational stiffness to transmit bending moments [9,11,12]. Nevertheless, a partial moment continuity can be achieved by introducing additional restraints in the floor, such as a cast in place RC topping [28,29], which is commonly used in earthquake prone countries. In case of a thin collaborating concrete slab, the proposed method can be still used, by only changing the flexural and torsional stiffness parameters of the HC cross-section. On the contrary, for increasing values of topping thickness, the simplified assumption of rotational hinges may provide too conservative results and consequently more refined methods (such as FE analysis) could be advisable.

2.1. Loading and constraints

Applied loads are modelled through a Fourier series expansion. This choice allows avoiding numerical problems in the calculation of derivatives, especially in case of point loads. As regards boundary conditions, it is assumed that the precast concrete floor is simply supported at the ends and that its lateral edges are free. This is a quite common hypothesis, since floors are usually designed and constructed as one-way spanning in the direction of precast units. On this point, it can be however observed that the proposed approach is rather general, since different boundary conditions can be easily included in the model by simply modifying some terms in its governing equations.

2.2. Determination of the solving system

Based on the above described assumptions, the only unknown of the problem is represented by the shear force transmitted among the units, whose intensity is variable along each longitudinal joint. Since the floor is schematized as a set of beams connected together through rotational hinges, the two fundamental relations governing the problem are the Euler-Bernoulli beam equation and the Saint-Venant torque-twist relationship.

With reference to conventions reported in Fig. 1a and b, for the i-th element forming the floor the Euler-Bernoulli beam equation can be written as:

$$v_i^{IV}(x) = \frac{q_i\ (x)}{E\,J}, \tag{1}$$

where $v_i\,(x)$ indicates the transverse displacement of the i-th beam, E and J are respectively the Young modulus of elasticity and the moment of inertia of the cross-section (so EJ represents the flexural stiffness, assumed equal for all the beams), and $q_i\,(x)$ is the equivalent transverse load. This latter can be in turn evaluated as:

$$q_i(x) = p_i(x) - H_{i-1}(x) + H_i(x), \tag{2}$$

$p_i\,(x)$ being the external load, while H_{i-1} and H_i represent the shear forces transmitted along two adjacent joints (Fig. 1b).

The second-order differential equation relating the angle of twist $\vartheta_i\,(x)$ at location x of the i-th element to the distributed applied torque $m_{ti}\,(x)$ can be written as:

$$\vartheta_i^{II}(x) = \frac{m_{ti}(x)}{G\,I_0} \tag{3}$$

where G and I_0 are respectively the shear modulus of elasticity and the torsion constant for the cross-section (so $G\,I_0$ represents the torsional stiffness of the beam, assumed equal for all the elements forming the floor). The distributed torque $m_{ti}\,(x)$ can be evaluated as a function of the applied external load $p_i\,(x)$ and of the shear forces transmitted along the joints adjacent to the considered beam (H_{i-1} and H_i) through the following expression:

$$m_{ti}(x) = -p_i(x)e_i - H_{i-1}(x)\frac{b}{2} - H_i(x)\frac{b}{2}, \tag{4}$$

b being the width of each single beam and e_i the load eccentricity with respect to beam centroid axis, according to Fig. 1b.