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Moment coefficients for design of waffle slabs with and without openings

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ABSTRACT

The direct design method recommended by ACI is commonly used for the design of flat slabs. Since the flexural stiffness of the waffle slab varies along the span, it is expected that the distribution of moments is different from that of flat slabs. Current design procedures do not provide recommendations specific of waffle slabs. Designers smear the contribution of the ribs and use the design guidelines for flat slabs to design ribbed slabs. In addition, the effect of openings on the response of waffle slabs is not fully explored. Therefore, modified moment coefficients are needed for waffle slabs. In this paper, numerical simulations using ANSYS are used to study the response of waffle slabs with and without openings. The main objectives of this paper are: (1) to obtain the design coefficients for the column and the field strips of the internal panel of a waffle slab and (2) to study the effect of openings and stiffening ribs on the design coefficients. Ninety Linear and non-linear analysis models using ANSYS were performed in the study to evaluate the response of various waffle slabs under uniform loading. The main parameters evaluated are the column size, the solid portion size, the opening size and its location, and the effect of stiffener ribs around the opening. The non-linear finite element model was verified using existing experimental results for two waffle slabs. The moment coefficients developed in this paper were used to modify the existing ACI flat-slab coefficients to be used for waffle slabs.

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1. Introduction

Waffle slab structures are defined as a combination of a flat flange plate, or deck, and a system of equally spaced parallel ribs. Waffle slabs are more efficient in resisting lateral loads than flat slabs, and they are suitable for large spans between columns. Various approximate methods of analysis for ribbed plates based on the analysis of an equivalent orthotropic plate were developed. The individual panels are divided into column and middle strips, and proposed moment distribution coefficients are presented by Reiss and Sokal [1]. The waffle structures are analyzed as grids with ribs having little or no torsional rigidities [2]. In 1979, Tebbett and Harrop [3] proposed alternative theoretical moment coefficients for internal, edge and corner panels of ribbed and solid flat slabs, and concluded that the solid regions around columns attract load and cause a redistribution of the bending moments in the column strips. Kennedy [4] studied the effect of rib orientation in the carrying capacity of waffled slabs. His results indicated that the orthogonal shaped waffle slab had a superior ultimate load carrying capacity of 20% higher than the 45° non-orthogonal waffle slab. Shehab El-din and Elshihy [5] in 1993 evaluated the effect of the size of the solid portion on the bending moment and shearing forces developed in the panel. Abdul-Wahab and Khalil [6] investigated experimentally the response of simply supported, isotropically reinforced, square waffle slabs under a midpoint patch load.

The methods recommended by the design codes, such as ACI 318-08 [7] and BS 8110-1997 [8], allow the waffle slab to be designed in accordance with the provisions for a two-way spanning flat slab. BS 8110 [8] code limits the dimensions of openings in flat slabs according to the location of the openings. In addition, BS 8110 [8] requires that the effective perimeter be modified when the openings are located from the face of the column at a distance less than six times the effective depth of the slab. ACI 318-08 [7] provides limits for the size of the opening according to its location along the panel.

Currently, the equivalent frame method and the direct design methods [7] are commonly used for the design of flat slabs. The direct method is the more popular of the two, which defines moment coefficients to distribute the total panel moment between column and field strips. Since this method was developed for flat plates, engineers either use the direct method for waffle

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Notations

L	Panel dimension
L_c	Column strip width
L_s	Solid portion width or length
t	Slab thickness
M_{panel}	The total moment across the panel width or length
$M_{\text{column strip}}$	The moment across the column strip width
$M_{\text{field strip}}$	The moment across the field strip width
MC	Moment coefficient
c	Column width
X/L	Distance ratio from the column line
W/O	Without opening.

slabs or finite element codes. Therefore, it is necessary to develop appropriate moment coefficients specific for waffle slabs. Nonlinear finite element (FE) models using ANSYS 11 [9] are used in this paper to investigate the response of various waffle slabs under uniform load. The FE stresses were used to determine the moments at different locations in the panel, which were then used to calculate the moment coefficients. The effect of various waffle slab parameters on the moment coefficients were evaluated. These parameters include column size, the solid portion size around the column, the opening size and its location, and the effect of stiffener ribs around the opening.

A full-scale waffle slab was tested experimentally and numerically by Schwetz et al. [10] under localized loaded area with strain and deflection gages at different points. The experimental results were compared by the numerical rid method to verify the results however, some of this paper's results were used to validate the current study. Test results showed a linear behavior and the measured deflection agreed well with the computed ones.

A study on the optimum dimensions of a waffle slab for a medium-sized floor was conducted by Prasad et al. [11]. The study was used to elaborate the results obtained from the analytical study performed on a medium-sized floor system. The author recommended certain dimensions for the spacing of ribs according to certain live and dead load values.

2. Parametric study

The internal waffle slab panel was modeled as shown in (Fig. 1), with a panel width of 6300 mm. The degree of rectangularity of 1.00 was only considered in this study. The location of the opening, as shown in Fig. 1, was studied at three locations: (1) at the intersection of two column strips (zone 1); (2) at the intersection of two field strips (zone 2); and (3) at the intersection of the column and field strips (zone 3). The opening size was taken as a percentage of the column strip width varied from 0% (i.e. the solid case) to 40%.

Different solid region dimensions taken as a ratio of the panel length L were studied. The solid portion dimensions, L_s, selected in this study were 0, 0.25, 0.375, and 0.50 of the panel length L.

Different waffle slabs with an opening size of 30% of the column strip width located in zone 2 were evaluated. The effect of various stiffener rib designs around the opening (Fig. 2) on moment distribution was investigated. Fig. 2, case 1 shows the stiffening ribs are connected to the main ribs from one direction, but case 2 shows that the stiffening ribs are connected to the main ribs from both directions.

3. Numerical analysis

In this paper the parametric study was performed using an implicit nonlinear finite element analysis ANSYS 11 [9]. Mesh convergence was performed to select the most efficient element sizes. The mesh consists of solid elements to represent the concrete and one-dimensional link elements were used to represent the steel reinforcement.

The concrete was modeled using 3D 8-node solid elements SOLID65 [9] with dimensions of $100 \times 100 \times 125$ mm. The flanges were modeled using one layer of solid elements, whereas the ribs were modeled using 3-layers of elements as shown in (Fig. 3). The mesh discretization was established so that the nodes of the concrete coincide with the reinforcement nodes. A perfect bond was assumed between the steel and the concrete. $2 \times 2 \times 2$ Gauss integration points were used for the computation of the element stiffness matrix. The SOLID65 element has the capability of cracking in tension and crushing in compression and only three transitional degrees of freedom per node are allowed with this element.

The steel reinforcement is modeled using a LINK8 spar element [9], which has three degrees of freedom at each node. This element models tension and compression forces in its longitudinal direction.

3.1. Material models

The concrete material model is assumed to be a nonlinear elastic model as shown in (Fig. 4(a)) with an ultimate compressive strength of 26 MPa, which was based on the Desayi and Krishnan [12] model. The stress–strain relationship of concrete in compression is described by the following equation:

$$\sigma = 2f_c \frac{x}{1 + x^2} \tag{1}$$

where: $x = \varepsilon/\varepsilon_0$, $\varepsilon_0 = 0.3\%$, and $\varepsilon_u = 0.4\%$.

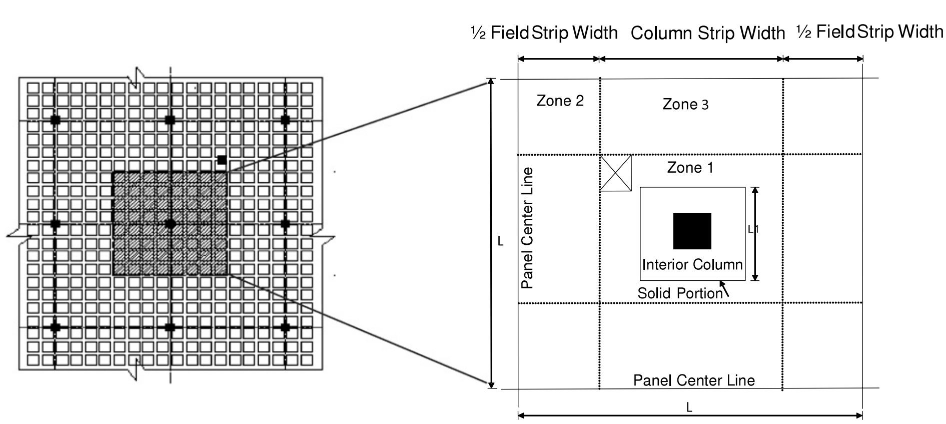

Fig. 1. Plan of a typical waffle slab floor showing the location of opening in zone 1.