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Rigidity and moment distribution of steel-concrete composite waffle floor systems considering the spatial effect

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ABSTRACT

A steel-concrete composite waffle floor system (SCCWFS) that consists of orthogonal steel beams and a flat RC slab has potential applications in long-span building floors because of its large loading capacity, low depth-to-span ratio, and excellent ductility, as demonstrated by a previous experimental program. According to the test results, the spatial composite effect between the orthogonal steel beams and concrete slab significantly influences the performance of the SCCWFS. However, the complexity of the spatial composite effect in the SCCWFS makes it much more difficult to determine the rigidity and the internal force distribution in a routine design practice than the one-way steel-concrete composite floor or the RC waffle slab. To address this problem, a parameterized grillage method is developed in which intrinsic factors are defined to describe the critical properties of the deformation pattern, the reaction force and moment distribution of the SCCWFS; relation factors are defined to relate these properties of the SCCWFS to that of its corresponding steel grillage. Based on the parameterized grillage method, parametric analyses are conducted using a beam-shell mixed finite-element (FE) model and the influence of various parameters on intrinsic and relation factors is investigated, in which the beam height, slab thickness, length-to-width ratio, and so on are shown to be of importance. The data of a total of 5190 numerical models associated with seven parameters covering almost all the practical cases are then obtained, and a step-shaving procedure is proposed to derive formulas that are influenced by multiple variables. Based on the parameterized grillage method and the step-shaving procedure, formulas to predict the vertical displacements, reaction force and moment distribution of the SCCWFS are derived and verified. Finally, design procedures, recommendations and simplified forms of the formulas are proposed, in which the formulas are proved to have an error of approximately 10%.

1. Introduction

The traditional RC waffle slab usually consists of a concrete slab and ribs in two directions that could transfer vertical loads in either direction (two-way slab). Compared with a one-way slab, by introducing the advantage of a two-way load transferring mechanism, a waffle slab efficiently utilizes the bidirectional capacity of materials and could be used to reduce the structural weight and depth-to-span ratio in building floors and bridge decks.

By replacing concrete ribs with a steel grillage connected to the flat concrete slab by shear studs, a new type of steel-concrete composite waffle floor system (SCCWFS) was conceived by Nie et al. [1]. Experimental programs of two simply supported specimens were reported, and an FE model was used in the simulation. The yield line theory was utilized to predict the ultimate flexural capacity of the SCCWFS. It was found that the SCCWFS has a high capacity, rigidity and ductility and has a broad prospect for application.

Except for the work performed by Nie et al. [1], related information on the SCCWFS is rather limited. There are several theoretical and experimental studies of the RC waffle slab that can be referenced. The analytical methods of plates and shells were studied, and the orthotropic plate theory was founded by Timoshenko and Woinowsky-Krieger [2]. The equivalent plate method based on the orthotropic plate theory was then developed to analyze RC waffle slabs used in building floors and bridge decks [3–4], in which the ratio of torsional rigidity to flexural rigidity was essential. By dividing panels into columns and middle strips, the moment distribution coefficients method for both solid and ribbed flat slabs was proposed [5] and later modified [6–7]. The grillage method, which treats waffle structures as grids parallel to column

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lines, was presented [8]. Several large-scale experimental research studies had been conducted [9–11], and the yield line theory was used to predict the ultimate performance of RC waffle slabs based on the testing results. A real scale RC waffle slab model was tested, and it was found that the grillage method can be used to estimate the deflection and bending moment of RC waffle slabs [12]. The orientation of the ribs in RC waffle slabs was investigated; the experimental results indicated that the orthogonal-shaped waffle slab had a higher ultimate capacity than the 45° non-orthogonal waffle slab, even for skew bridges [13]. There have also been a few experimental research studies performed investigating the dynamic behaviors of RC waffle slabs [14–15]. Design codes, such as ACI 318-08 [16] and BS 8110 [17], allowed to design the RC waffle slab as a two-way flat slab, neglecting the different torsional and flexural rigidity characteristics between the flat slab and waffle slab.

Despite the large amount of work that has already been performed on RC waffle slabs, these methods for RC waffle slabs cannot directly be used for the SCCWFS since the two types of structures have significant differences in their structural arrangement and material properties. Moreover, the spatial composite effect due to bidirectional compatible deformation between the steel beams and concrete slab makes the SCCWFS completely different from the one-way steel-concrete composite floor system. According to the test, bidirectional compression of concrete enhances the stiffness of concrete and, as a result, increases the rigidity of the SCCWFS, and the shear force in the interface influences the internal force distribution of the SCCWFS.

This paper focuses on the rigidity and moment distribution of rectangular steel-concrete composite waffle floor systems that has orthogonal equal rigid beams considering the spatial effect. Existing theoretical methods for RC waffle slabs are discussed, and a developed parameterized grillage method considering the factored reaction forces, factored moments and deformation pattern is presented, in which intrinsic factors are defined to describe the deformation and internal force properties of the SCCWFS and relation factors are defined to relate the behaviors of the SCCWFS to those of its corresponding steel grillage. Based on the parameterized grillage method, the intrinsic properties of the SCCWFS and the relation properties between the SCCWFS and its corresponding steel grillage are investigated though a three-dimensional (3D) elastic beam-shell mixed finite-element (FE) model. The FE model is verified by comparison with experimental results. Parametric analyses are then conducted considering the influence of the beam height, slab thickness, grid number, grid size, concrete modulus, among others on structures. Based on a total of 5190 FE model results covering almost all the possible ranges of parameters that are used in practice, formulas for vertical displacements, elastic reaction forces and internal moments are derived. A step-shaving procedure is proposed and utilized in the formulation. The formulas have good accuracy compared with the FE models, and simplified forms of the formulas are also proposed for design. Finally, the design procedures and recommendations of the SCCWFS are proposed and further study in need of the SCCWFS is discussed.

2. Analytical considerations

2.1. Theoretical method overview

The orthotropic plate method considers a waffle slab as a plate with an equivalent thickness by utilizing differential equations and the corresponding solutions of the orthotropic plates. This plate method assumes that the number of ribs in RC waffle slabs is large enough (five or more) and the neutral plane of each direction coincides with the centroid of the total section in the corresponding direction [11]. The classical differential equation of the elastic orthotropic plate is given as (Timoshenko and Woinowsky-Krieger, 1959):

$$D_x \frac{\partial^4 w}{\partial x^4} + 2H \frac{\partial^4 w}{\partial x^2 \partial y^2} + D_y \frac{\partial^4 w}{\partial y^4} = P(x, y) \tag{1}$$

where D_x and D_y are the flexural rigidity; $2H$ is the total torsional rigidity; w is the out-plane deflection; and $P(x, y)$ is the distributed load. For an orthotropic plate of which the load distribution and boundary conditions are given, an analytical or numerical solution could be derived according to this equation. Studies utilizing the orthotropic plate theory were mainly focused on formulating that D_x, D_y and H of RC waffle slabs with different geometries. For a practical design, it was suggested that [3,4]:

$$D_x = \frac{EI_{sx}}{S_x}; D_y = \frac{EI_{sy}}{S_y} \tag{2}$$

$$2H = B_{xy} + B_{yx} + \frac{Et^3}{6(1-\nu^2)} + \frac{\nu E t_x t_y}{2 S_x S_y} h_y \left\{ (h_y + t)[(h_y + t) - (e_x + e_y)] + \frac{h_y^2}{3} \right\}, \tag{3}$$

where I_{sx} and I_{sy} are the moment of inertia respect to the neutral axis of the section in each direction; S_x and S_y are the spacing of ribs in each direction; B_{xy} and B_{yx} are the torsional rigidity of the ribs in each direction; t_x and t_y are the width of ribs in each direction; e_x and e_y are the eccentricity in each direction; t is the thickness of the slab; h_y is the height of the ribs in the direction with lower rigidity; E is the elastic modulus; and ν is Poisson's ratio. When Poisson's ratio is small, the fourth term in Eq. (3) can be neglected.

The moment coefficients method was suggested by both ACI 318-08 [16] and BS 8110 [17] when designing a waffle slab as a two-way flat slab. It is a simplified method based on the analysis of flat slabs that directly distributes the total section moment to different slab strips. When utilizing this method in designing RC waffle slabs, both codes utilized several restrictions. ACI 318-08 required at least three continuous spans in each direction and that the beams (relatively lager rigidities compared to ribs) should be located at the edges of the panel [16]. BSI 8110 required that the ribs should be spaced at a distance not exceeding 1.5 m and that their depth should not exceed four times their width [17].

Unlike the orthotropic plate method or the moment coefficients method, the grillage method considers a waffle slab as grids of orthogonal ribs and investigates the relation and difference between the two types of structures. This is an approximation method which uses each grillage member to represent a portion of the beam-slab. The target is that the deflections, moments and shears the grillage represents are the same in the slab. The reduction of torsional rigidity of the grillage reduces the redistribution of the moment across the total section and results in a less uniform pattern of moment distribution [8]. Equations of the torsional rigidities of the grillage were derived to simulate the slab more accurately [18]. Techniques were developed and suggestions were proposed to simulate slabs in more complicated shapes using the grillage method [19]. The concentrated internal force of the grillage was divided by grid spacing to derive the distributed internal force of the slab [20]. In a simplified design, RC waffle slabs are divided into appropriate grids of ribs with flanges, in which the flange width is in accordance with T-beams in concrete structure design codes [20].

In conclusion, theoretical methods could be categorized into plate or grillage methods. Plate methods commonly demand a large number and relative small rigidity of ribs so that a RC waffle