

Numerical investigation on the thermal behavior of an innovative waffle slab

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Abstract. This paper proposed an innovative waffle slab, which had obvious distinction in configuration compared with traditional waffle slab and possessed the superiority on multi-storey residence building. In order to investigate the thermal behavior of this innovative waffle slab, the numerical simulation was carried out by ABAQUS software in this paper. The bottom of slab model was exposed to fire and the ISO-834 standard temperature curve was adopted. The temperature distribution was first analyzed and discussed, and the results showed the ribs behaved as the single side fire-exposed beam. The maximum temperature of slab top could reach up to 200°C after a fire-exposed of two hours. And a calculation formula was proposed by model data to predict the fire ablation depth.

1. Introduction

With the purpose of reducing the self-weight of floors, architects and structural designers often deploy waffle slabs to cover a large space, which provide enough flexural strength and rigidity for structure and are quite robust as a structural system to support greater loads over a large span[1]. The dimensions and spacing of ribs are determined in a manner so as to achieve better load distribution without requiring the shear reinforcement[2]. This paper proposed an innovative waffle slab, which adopts precast technology to speed up the construction and reduce the consumption of labor and material. All steel segments are precast and then assembled to form steel system in site. Compared with traditional waffle slab, there are several typical characteristics of this floor system, including welded steel wire mesh laid in top concrete wythe, orthogonal steel trusses used to reinforce concrete ribs and foamed concrete blocks filled among the ribs with the purpose of heat insulation and fire resistance. The configuration details are illustrated in **Figure 1**. A special template system is designed for the installation and concrete cast of the slab, which is showed in **Figure 2**.



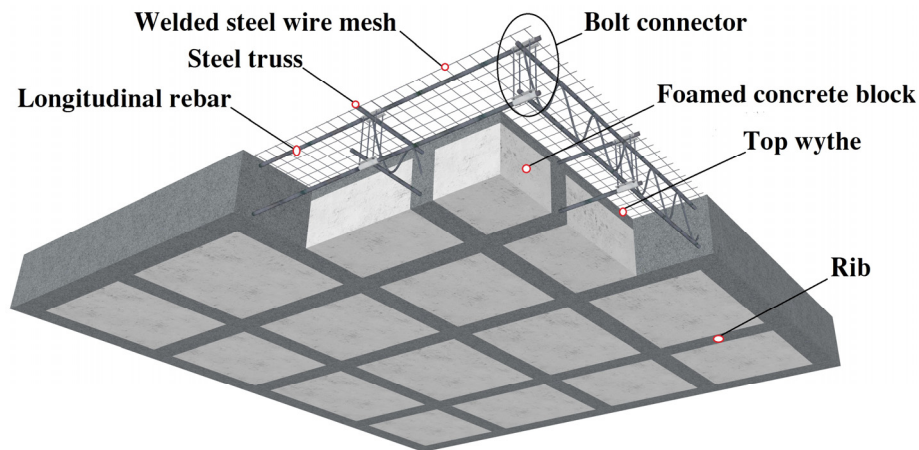


Figure 1. The slab configuration details.

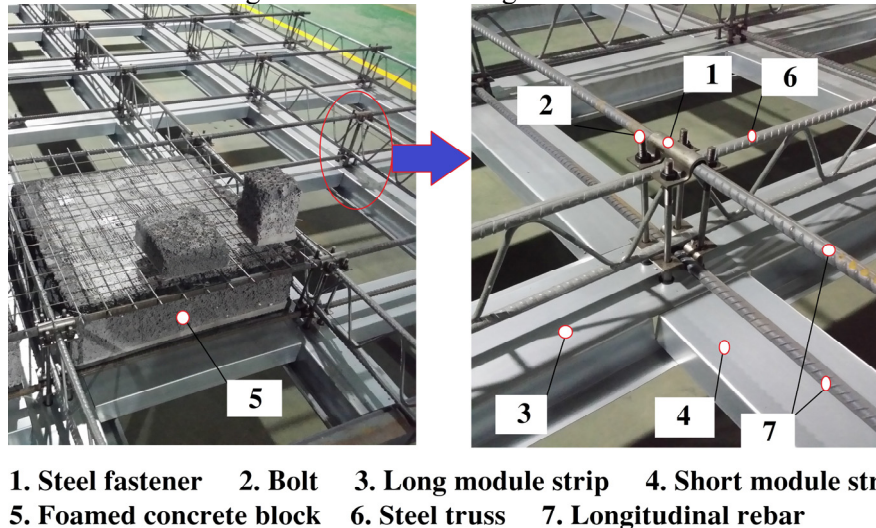


Figure 2. Details of template system.

Several theoretical analysis on waffle slab were successively developed, including the orthotropic plate theory[3], the equivalent thickness method[4-5], the moment distribution coefficients method[6-7], the grillage method[8] and the yield line theory[9]. In addition, large-scale experimental tests were also conducted. Abdul-Wahab HMS and Khalil MH[10] studied the behavior of reinforced concrete waffle slabs with a square layout of ribs. Tests to failure were carried out on eight large-scale models with varied rib spacing and rib depth. The strength and rigidity was evaluated based on an alternative simplified approximate method. Guo et al.[11] had investigated the rigidity and moment distribution of steel-concrete composite waffle floor systems considering the spatial effect. Al-Bayati et al.[12] analyzed the concentric punching shear of waffle slab. Although many researchers had conducted investigations on waffle slab, more attention was focused on the statistic and dynamic performance of waffle slab under ambient temperature, less investigations about waffle slab were found on the thermal behavior. However, fire disaster frequently happened in buildings, it is essential to obtain the the fire behavior of waffle slab and furthermore make a reasonable fire resistance design. This paper aimed to discussed the thermal behavior of the innovative waffle slab.

2. Model details

For the purpose of heat transfer analysis, the 3D model of the slab was established by ABAQUS which is showed in **Figure 3**. The dimension and rebar diameter are shown in **Table 1**. The specimen with aspect ratio of 1 is expected to behave as two-way slab. The ribs height is 170mm and the width is 90mm, the thickness of top concrete wythe is 50mm, thus, the dimension of foamed concrete blocks

is 510mm×510mm×170mm. The end beams along four edges are designed as 150mm width and reinforced by four 14mm diameter rebar.

Table 1. The dimension and rebar diameter in the model [unit: mm].

Length	Width	Depth	Aspect ratio	Diameter of rebar in truss		Steel wire diameter	Longitudinal rebar diameter
				chord	brace		
2010	2010	220	1	14	6	6	14

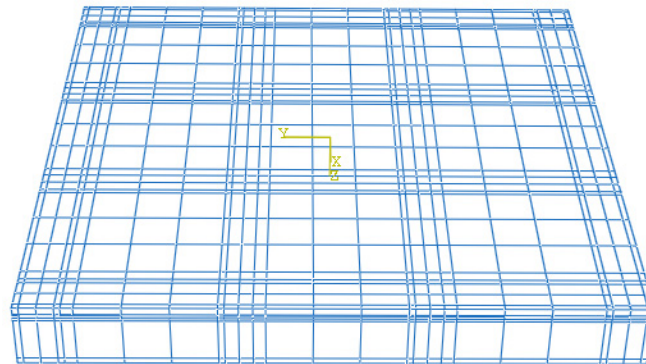
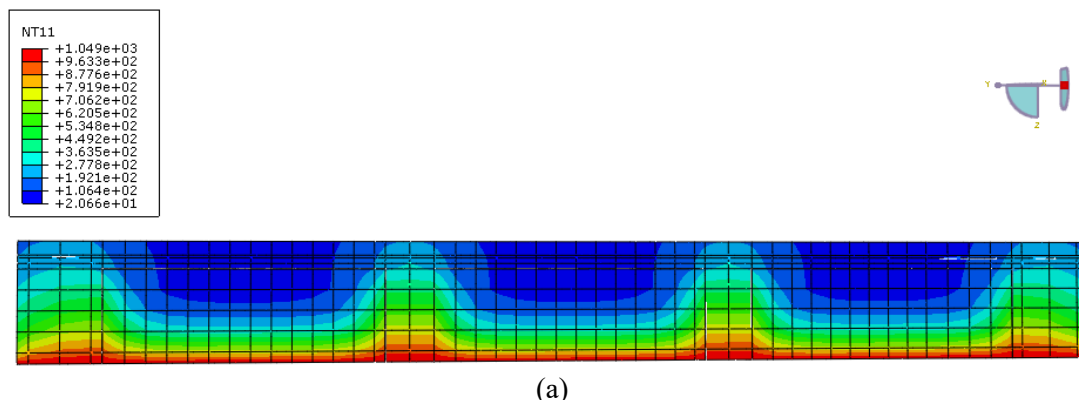


Figure 3. The 3D model of the slab.

The element DC1D2 is used for rebar in model while DC3D8 element for concrete. Binding constraint is considered to simulate the connection between rebar and concrete at temperature analysis phase. The Binding constraint is also used to achieve the connection between foamed concrete blocks and concrete component. The whole model is meshed with cubic cells in a side length of 0.04m. The slab model is expected to be exposed to fire at the bottom, and the ISO-834 standard temperature curve is used in this research. In order to obtain accurate temperature field along the ribs cross-section, more refined mesh was conducted on the ribs. A room temperature 20°C is specified as an initial condition and it is assumed that the initial temperature is uniformly distributed throughout the whole model.

3. Analysis results

The temperature distribution of the slab at ISO-834 standard temperature curve was presented in **Figure 4**. The results showed the foamed concrete blocks exhibited an important effect on the temperature field along the ribs cross-section, where the temperature decreased from the bottom to the top. The ribs behaved as the single side fire-exposed beam. At same height level, the temperature of foamed concrete blocks were lower compared with ribs. The parabolic temperature curves were distributed at the cross-section of foamed concrete blocks.



(a)

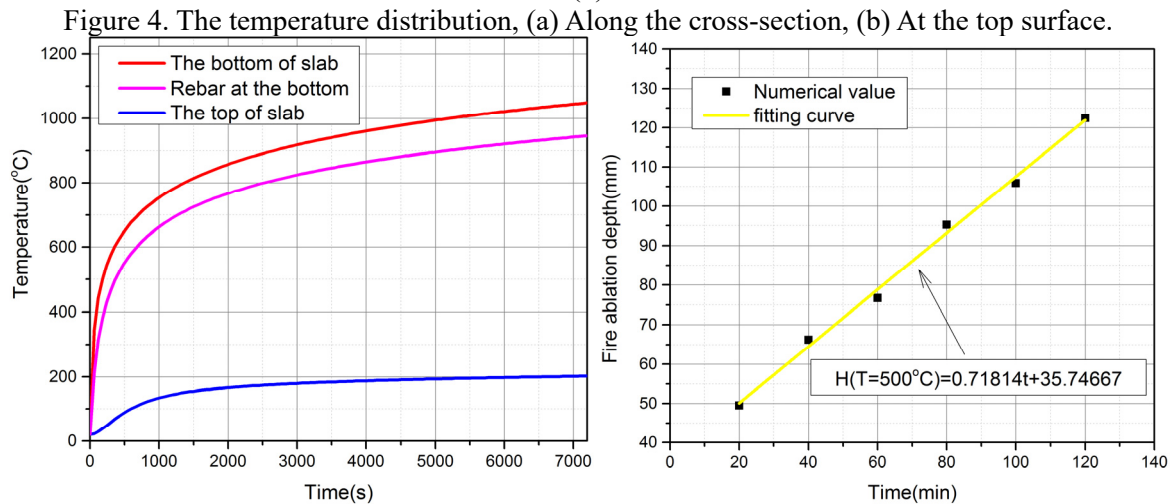
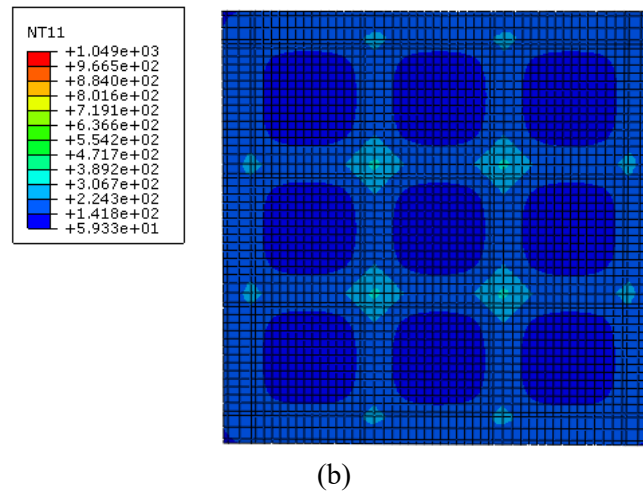


Figure 5. The temperature development.

Figure 6. The fire ablation depth calculation formula.

Figure 5 exhibited the temperature development of the concrete and rebar, it was noticed that the temperature of the bottom concrete was the same as the ISO-834 standard temperature curve, sharp temperature rise was obtained at the begin for the bottom concrete and rebar. The maximum temperature of slab top concrete could reach up to 200°C after a fire-exposure of two hours. In fire resistance design, it is often ignored for $T > 500^\circ\text{C}$ concrete, therefore, the average height of the 500°C isotherm located at the ribs was defined as the fire ablation depth of the slab. The fire ablation depth of the slab at different fire-expose time could be calculated according to the numerical simulation of the temperature field, the linear interpolation method was employed in the calculation and the results were listed in **Table 2**, where $H/t=500^\circ\text{C}$ means the fire ablation depth. Furthermore, a calculation formula was linearly fitted to predict the fire ablation depth of the slab as shown in **Figure 6**, where t is the fire exposure time.

Table 2. The fire ablation depth of the slab at different fire-expose time.

Time	$t = 20 \text{ min}$	$t = 40 \text{ min}$	$t = 60 \text{ min}$	$t = 80 \text{ min}$	$t = 100 \text{ min}$	$t = 120 \text{ min}$
$H/t=500^\circ\text{C}$	49.5mm	66.2	76.7	95.3	105.9	122.5

4. Conclusions

An innovative waffle slab with unique configuration has been proposed in this paper, which adopts precast technology to speed up the construction and reduce the consumption of labor and material. To

investigate the thermal behavior, a numerical simulation was carried out by ABAQUS software. The results can be shown as following:

(1) The foamed concrete blocks exhibited an important effect on the temperature field along the ribs cross-section, where the temperature decreased from the bottom to the top. The ribs behaved as the single side fire-exposed beam.

(2) The height of the 500°C isotherm located at the ribs was considered as the fire ablation depth of the slab. The fire ablation depth of the slab at different fire-expose time had be calculated, and a calculation formula was linearly fitted to predict the fire ablation depth of the slab.

Acknowledgements

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