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## Numerical investigation on the flexural behavior of an innovative waffle slab

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# Numerical investigation on the flexural behavior of an innovative waffle slab

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**Abstract.** An innovative prefabricated steel-truss waffle slab system has been proposed in this paper, which has obvious distinction in configuration compared with traditional waffle slab and possesses the superiority on multi-storey residence building. In order to investigate the flexural behavior of this innovative waffle slab, the numerical simulation was carried out by ABAQUS software in this paper. The slab model was simply supported at four corner points and subjected to four-point vertical load at the joint of ribs. The results obtained from the numerical simulation had been discussed and analyzed in the context of ultimate flexural load, failure mode, load-vertical deflection relationship and strains on rebar and concrete. The slab failure was governed by the rebar strength. Typical shearing stress developed at one-third span of end beams. It was verified that the ribs was main bearing component. The numerical results showed that the slab behaved as a two-way solid slab.

## 1. Introduction

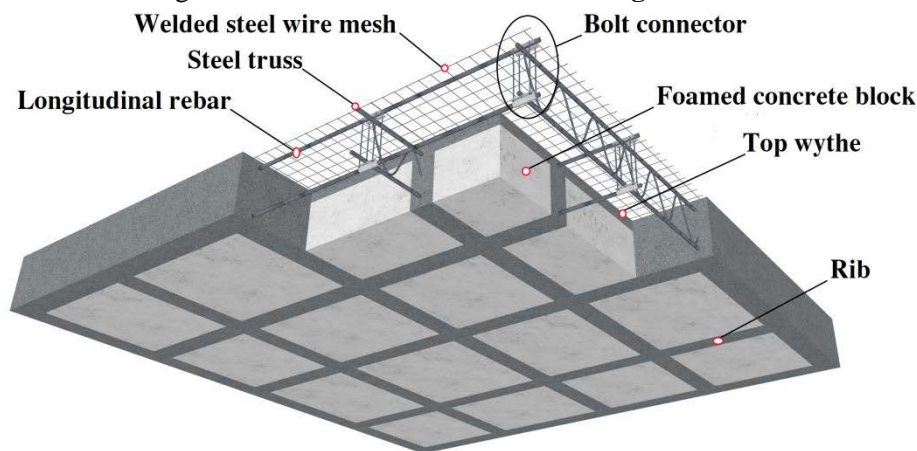
With the purpose of reducing the self-weight of floors, architects and structural designers often deploy waffle slabs to cover a large space, which provide enough flexural strength and rigidity for structure and are quite robust as a structural system to support greater loads over a large span [1, 2].

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 orthogonal ribs. The spacing and height of ribs were set as variable and analyzed. The strength and rigidity was evaluated based on an alternative simplified approximate method. Al-Bayati et al. [11] analyzed the concentric punching shear of waffle slab.

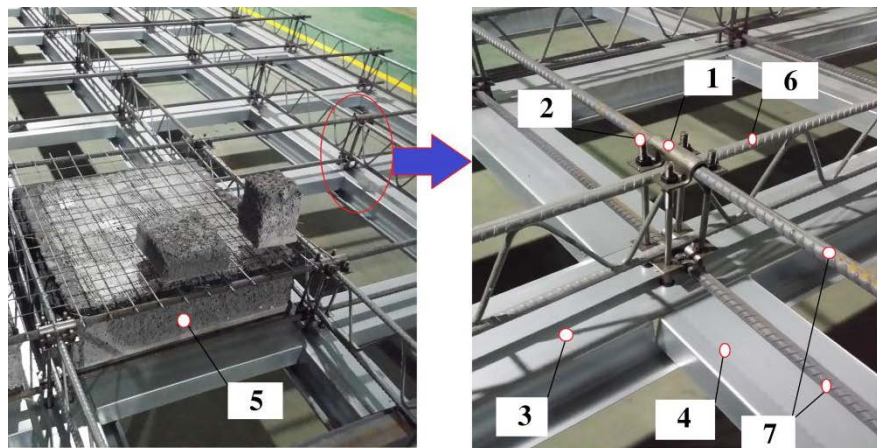
In order to take advanced advantage of precast technology, a new type of prefabricated steel-truss waffle slab has been proposed in this paper. In the waffle slab foamed concrete blocks are laid on the template system to fill between ribs with function of heat insulation and fire resistance, a welded steel



wire mesh is placed on the top of foamed concrete blocks and a serial of steel trusses are adopted to reinforce the concrete ribs whose width is the spacing of foamed concrete blocks. Finally self-compact fine aggregate concrete is cast to form the top wythe and orthogonal ribs at the bottom. The configuration of prefabricated steel-truss waffle slab has been shown in **Figure 1**. In order to achieve the complex configuration of waffle slab, a special template system has been developed for the formation of square voids between the ribs and casting concrete. The template system consists of long module strips and short module strips made by Aluminum alloy sheet, and the long module strips are continuously installed along the long-span of slab while the short module strips are designed to orthogonally connect long module strips. A creative connector which is made up of four bolts and a pair of steel fasteners is fixed on the joint of long and short module strips and its function is to combine steel truss and longitudinal reinforcement as shown in **Figure 2**.



**Figure 1.** The slab configuration details.



**1. Steel fastener 2. Bolt 3. Long module strip 4. Short module strip  
5. Foamed concrete block 6. Steel truss 7. Longitudinal rebar**

**Figure 2.** Details of template system.

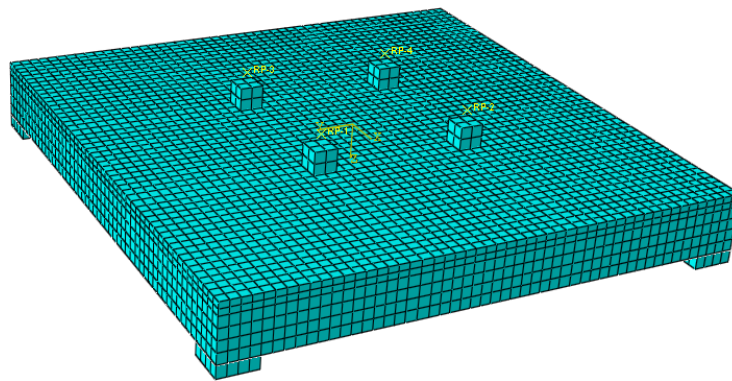
The floor segments, including the welded steel wire mesh, steel trusses, longitudinal reinforcements and foamed concrete blocks, are precast in factory and the whole assembly of floor system and template system are accomplished in construction site. Prefabricated steel-truss waffle slab exhibits obvious advantages on minimizing building period and material and labor saving. An numerical investigation has been carried out to obtain the flexural behavior of this innovative waffle slab under static loading by ABAQUS software.

## 2. Model details

For the purpose of static loading analysis, a 3D model of the slab was established by ABAQUS which is shown in **Figure 3**. The dimension and rebar diameter are listed in **Table 1**. The slab model with aspect ratio of 1 was expected to behave as a two-way slab. The ribs height was 170mm and the width was 90mm, the thickness of top concrete wythe was 50mm. The end beams along four edges were designed as 150mm width and reinforced by four 14mm diameter rebar. The slab model was supposed to bear the flexural load, and the slab model was simply supported at four corner points and subjected to four-point vertical load at the joint of ribs.

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

Length	Width	Depth	Aspect ratio	Diameter of rebar in steel truss		Steel wire diameter	Longitudinal rebar diameter
				chord	brace		
2010	2010	220	1	14	6	2	14



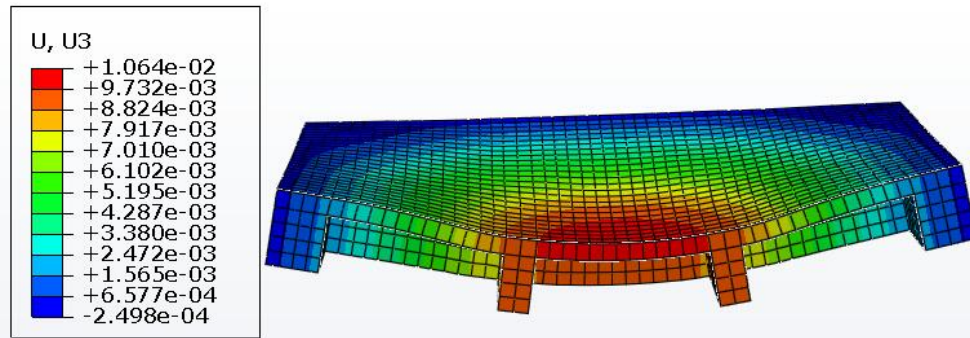
**Figure 3.** The 3D model of the slab.

The element T3D2 was used for rebar in model while C3D8R element for concrete. The elastic modulus and yield strength of rebar was  $2.0 \times 10^5$  MPa and 400 MPa respectively, and the linear harden model had been considered in stress-strain relationship of rebar. Damage-plastic model had been adopted for concrete with compressive strength of 50 MPa, the elastic modulus was  $3.0 \times 10^4$  MPa and Poisson's ratio was 0.2. It was assumed there was no bond-slip behavior between rebar and concrete and the embedment constraint was used to simulate the interaction between rebar and concrete. The Binding constraint was adopted to achieve the connection between steel pads and concrete. The foamed concrete blocks were not created in static loading. The whole model was meshed with cubic cells in a side length of 0.04m.

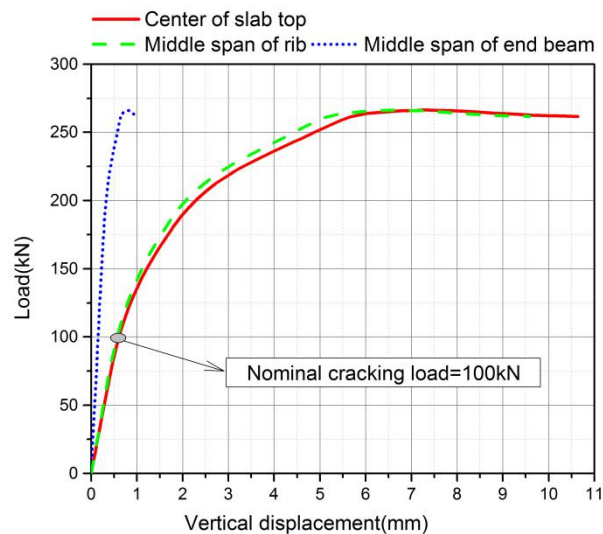
## 3. Analysis results

The displacement loading method was adopted and the increasing applied displacement amplitude was set on constant increment until failure. The vertical displacement of the slab is presented in **Figure 4**. It was found that the vertical deformation decreased from the slab center to the end beams, and the center deformation was 7.054mm at failure. So it was recommended that a beams with greater stiffness should be set in the middle span of the slab. The load-displacement relationship of waffle slab model simulated is shown in **Figure 5**. At the beginning of loading, the load-displacement relationship of slab model presented a linear elastic behavior until concrete cracking at corresponding measuring

location, the deflection was then increased faster and faster with the increase of load, the load-displacement relationship curves became non-linear, which represented the deduction of flexural stiffness. The vertical deflection of end beams was still small at the slab failure. The loading program was terminated when the descending branch was obtained. The nominal yield strength of the slab model was 99.9kN when the tensile strain of bottom concrete reached peak value. The ultimate flexural load of this slab model was 266kN, while the tensile rebar at the bottom reached yield strength.



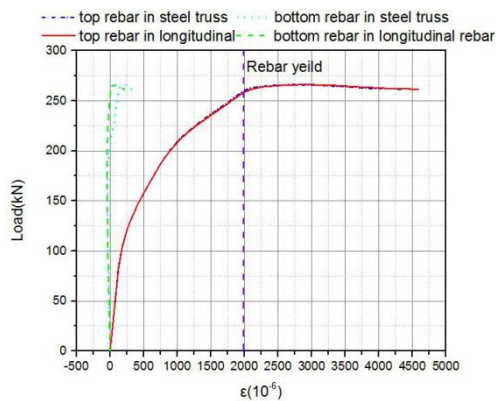
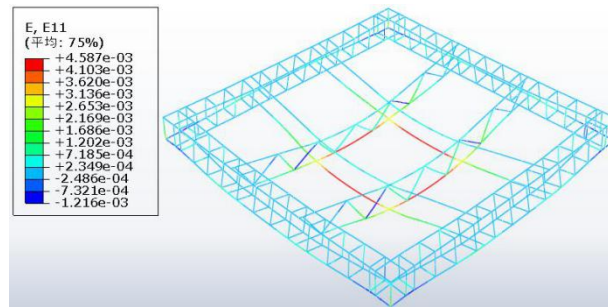
**Figure 4.** The vertical displacement.



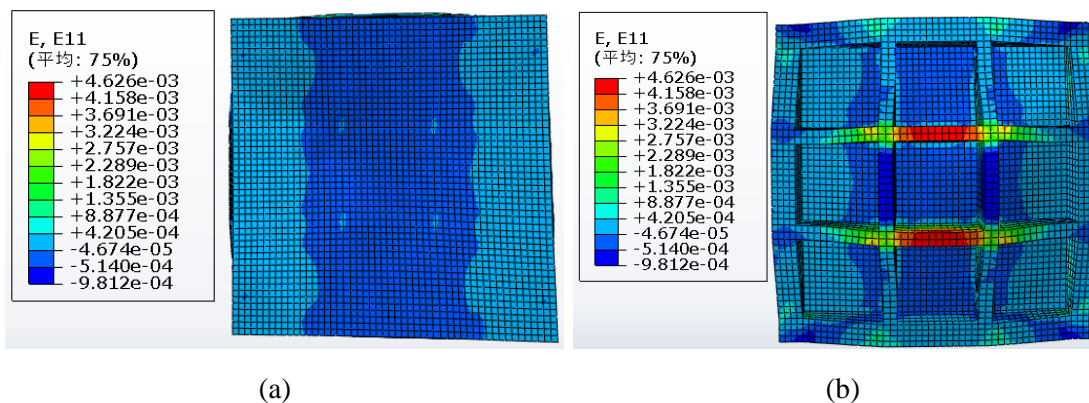
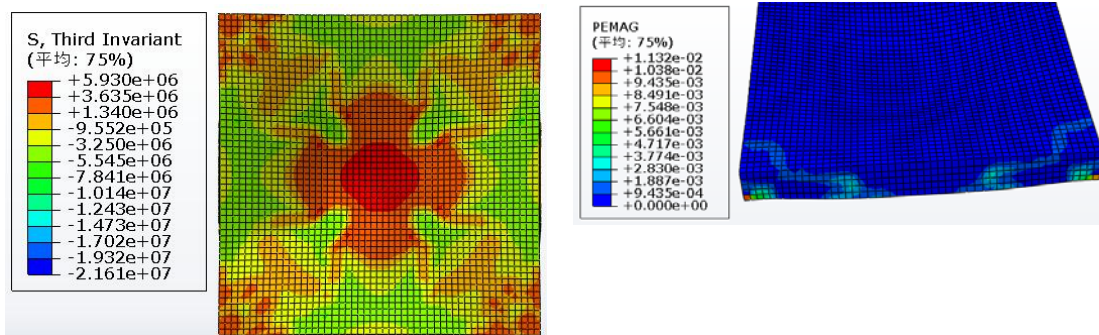
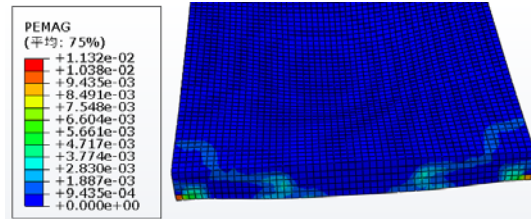
**Figure 5.** The load-vertical deflection curves.

The typical strains developed at the bottom rebar of the steel truss and longitudinal rebar are shown in **Figure 6**. The rebar strains were similar for steel truss and longitudinal rebar at top and bottom, it could be concluded that the slab behaved as a two-way solid slab. There was a two-stage behavior in load-rebar strain curves, the bottom rebar strain development exhibited the elastic behavior at early loading stage, the behavior subsequently became plastic. It was obvious that the slab failure was governed by the rebar strength. The maximum tensile stain at slab failure was  $2469 \mu\epsilon$ . The strain distribution of rebar was exhibited in **Figure 7**. On the whole, rebar strains were larger in the midspan, smaller in end and closely in symmetrical location.



**Figure 6.** Rebar strain curves.**Figure 7.** Rebar strain distribution.

The concrete strain along X axis was shown in **Figure 8**, it was noticed the larger strain was developed at the 1/3 part of the middle. The maximum compression stains at slab failure was  $462.6 \mu\epsilon$ , there was no concrete crushed at the top of the slab. Therefore, the more tensile rebar at the bottom should be supplied. The third invariant gave the X-shaped plastic hinge line at the top of the slab, and the shearing damage mode performed at one-third span of end beams, which are illustrated in **Figure 9** and **Figure 10** respectively.

**Figure 8.** Concrete strain distribution along X axis: (a)at the top, (b)at the bottom.**Figure 9.** The X-shaped plastic hinge line at the slab top.**Figure 10.** Shearing damage mode at end beams.

#### 4. Conclusion

The main aim in this study is to acknowledge the behavior of the innovative waffle slab under flexural load. An numerical investigation was carried out to analyze the load-vertical deflection relationship, rebar and concrete strains, and failure mode. The main conclusions are draw as follow:

According to the numerical results, the vertical deformation decreased from the slab center to the end beams, and the center deformation was 7.054mm at failure. The slab failure was governed by the rebar strength, and there was no concrete crushed at slab failure. The load-vertical deformation curves and load-rebar strain curves exhibited two-stage behavior during loading. It was verified that the ribs was main bearing component. The numerical results showed that the slab behaved as a two-way solid slab.

#### Acknowledgements

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