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Analytical Investigation on Performance of Stiffened Waffle Slabs with Openings

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Abstract: *Waffle slab is a monolithic construction of slab and narrow beams spanning in both directions. These slabs are used to cover a large column free area and therefore are good choice for public assembly halls. In this paper the structural behaviour of reinforced concrete waffle slab with square opening at three different locations strengthened with stiffening ribs were investigated by nonlinear finite element analysis. The three dimensional feature available in the commercial analysis package ANSYS was used to model the specimens. The model accommodates the material nonlinearities, cracking and crushing of concrete and yielding of steel. Verification of study was calibrated with numerical model by available experimental data. Based on the results and observations of the numerical investigations presented in this research regarding the effectiveness of stiffening ribs in strengthening waffle slab with opening, it can be seen that stiffening ribs with same dimensions of waffle slab main ribs can be successfully used for increasing the ultimate carrying capacity and strength. The results showed that use of stiffening ribs enable the slabs to restore its full load capacity and increased its ultimate load carrying capacity by 19%.*
Keywords – *Finite element, Non-linear static analysis, Opening, Stiffening slab, Waffle slab*

I. Introduction

Waffle slab system consists of beams spaced at regular interval in perpendicular directions, monolithic with slab. They are generally employed for architectural reasons for large rooms such as auditorium, theatre halls, and show rooms of shop where column free spaced void formed in the ceiling is advantageously utilized for concealed architectural lighting. In this grid structure, beam is the key sectional property which takes maximum contribution of load carrying in the waffle slab. The sizes of beam running in perpendicular directions are generally kept the same. It gives pleasing appearance and maintenance cost of these floors is less. However, construction of waffle floors is cost prohibitive.

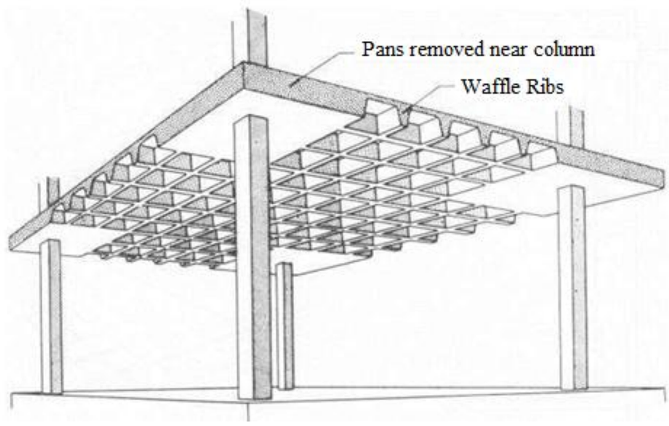

Fig. 1. Waffle slab

Not only the normal reinforced concrete waffled slab has benefits over the normal reinforced solid flat plate, but also a pre-stressed waffle-type bridge is found to be much more efficient in carrying load than a pre-stressed bridge with constant thickness slab as presented by Kennedy [2]. Kennedy [1] studied the effect of orientation of rib in the load carrying capacity of waffled slab. His results indicated that the orthogonal shaped waffle slab has a superior ultimate load carrying capacity of 20% higher than the non-orthogonal (45°) waffle slab. Abdul-Wahab and Khalil [3] investigated experimentally the response of simply supported, isotropically reinforced, square waffle slabs under a midpoint patch load.

Openings in floor slabs of buildings are needed for many purposes like stairs, air conditioning ducts and elevators. But introducing openings in slabs can severely weaken the slabs due to the cut-out of both concrete and reinforcing steel. Hence, the aim of this study was to investigate the effect of introducing large openings and providing stiffening beams around the openings to restore the flexural capacity of the waffle slabs.

II. Scope and Objective

Small openings can be provided in slabs without much detailing while when large openings have to be provided in slabs special analysis is to be done as it adversely affects the structural behaviour of slab. Here, an attempt has been made to analyze the waffle slab with opening surrounded by stiffening rib or not. Openings are considered to be located in three different regions selected based on column and middle strips of an interior panel of a waffle slab. Structures are analyzed using non-linear static analysis and response is studied in terms of displacement, stress and ultimate load carrying capacity. Finally, the conclusions are made based on the observations.

III. Description of Model

The test specimens were given with a symmetrical boundary condition along the four edges. The dimensions of slab specimens were 1500x1500x95 mm and orthogonally spanning ribs had a dimension of 52x75 mm. Ribs were spaced at 300 mm centers, i.e., there were five ribs in each direction. Opening size was selected as 40% of column strip width [9], i.e., 300x300 mm square opening was provided. Topping slab consisted of wire mesh of average diameter 0.7 mm and mesh size 25 mm at the middle of the slab. Ribs were reinforced with 8 mm Φ rebars at a clear cover of 8 mm. All slabs have no additional reinforcement along the opening sides. Normal concrete, designed to achieve a compressive strength of about 30 MPa at 28 days is used for casting waffle slabs. Flexural reinforcement of ribs consisted of steel bars with yield strength of 398 MPa. A displacement control incremental loading was applied at the top surface of waffle slab models as pressure loads.

IV. Parametric Study

The location of the openings was investigated at three various locations:
(1) at the intersection of two column strips (zone 1);
(2) at the intersection of two middle strips (zone 2); and
(3) at the intersection of the column and middle strips (zone 3).

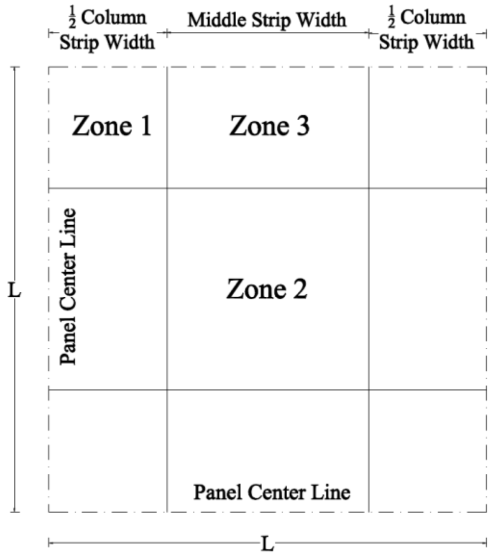

Fig. 2. Opening locations

The size of opening was taken as a 40 percentage of column strip width and hence a size of 300x300 mm was adopted.

Slab models with openings and without stiffening ribs were compared with models having stiffening ribs. Stiffening rib considered in the study just connects the cut ribs and has the same properties of ribs.

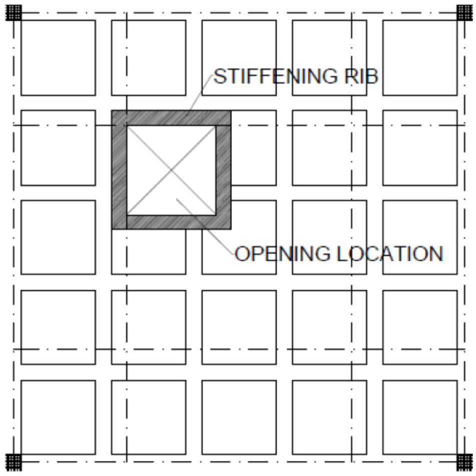

Fig. 3. Stiffening rib around the opening in Zone (2)

V. Finite Element Analysis

5.1 Finite Element Modeling

The general-purpose finite element program ANSYS 14.5 is used in the present study to investigate the flexural behaviour of strengthened RC waffle slabs with opening. SOLID65, the eight-noded three dimensional solid element, that is available in the ANSYS library, was used to model concrete. SOLID65 element, which is a eight-node solid element, used to model the concrete with or without reinforcing bars. This element has capability to model the concrete while the rebar capability is available for modelling the reinforcement behaviour. At eight nodes of SOLID65 element, there are three translational degrees of freedom in the nodal x, y, and z directions. The element can simulate concrete with plastic deformation and cracking in three orthogonal directions, and crushing. The most important feature of this element is that it can represent both linear and nonlinear behaviour of material. The rebar reinforcement feature of this element was used to model the discrete steel bars used to reinforce the original specimens. The reinforcing steel bars were adopted using LINK180 element.

5.2 Finite Element Discretization

After constructed a model with key points, lines, areas and volumes, a finite element analysis requires discretization of the large model to small elements. This is termed as meshing the numerical model. The model is then meshed into a number of small elements. In the current study, the dimensions of the finite element meshing are 25x25 mm and thicknesses are 12.5 and 15mm; respectively. This means that the slab thickness was divided into two layers, and the thickness of rib is divided into four layers.

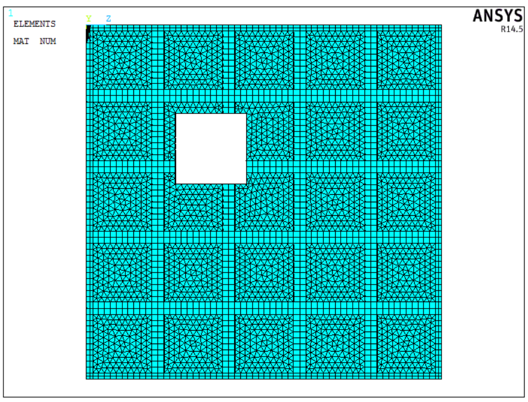

Fig. 4: Numerical model of waffle slab with opening in zone (2)

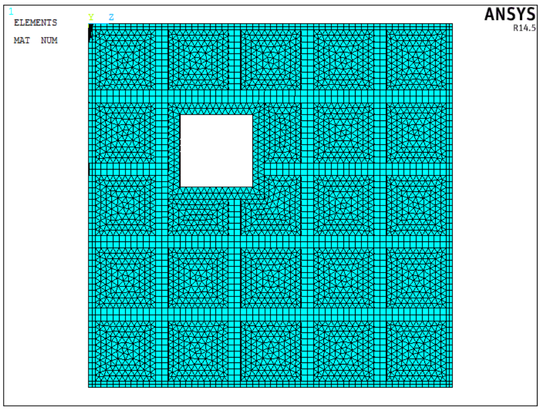

Fig. 5: Slab model with stiffening rib around the opening in zone (2)

VI. Results and Discussion

Here the results of non-linear static analysis of different waffle slab models with openings and stiffening rib are compared. By reviewing the journal [8], Anjaly et al., "Waffle slabs with unstiffened openings up to 10% the column strip width, in zone (1) and that with openings up to 20% column strip width in zone (3) are within the safe limit. Above these limits, the slab should be properly strengthened." Hence, in the present study, to investigate the strength characteristics of stiffened waffle slab, opening of size 40% the column strip width (300x300 mm) is stiffened by providing ribs around it. Ultimate load carrying capacities of the structures then are used to compare the performance of slab models under gradually increasing load.

6.1. Ultimate Load Carrying Capacity

In the case of waffle slabs with large openings, the strength of slab is found to be reduced when these openings are located in zone (1) and zone (3) [8].

It is clear from the given table that the ribs around the opening significantly increase the ultimate load carrying capacity of the slab having no stiffening ribs. Presence of ribs can result in 19% increase in ultimate load. Since the large openings decrease the strength of slab, especially in zone (1) and zone (3), it is essential to strengthen those areas with stiffening ribs of same properties of the main waffle ribs to redistribute the moments between the column and middle strips.

Table 1: Ultimate load of slab models with and without stiffening ribs

Location of opening of size 0.4C*	Sl. No.		Ultimate Load (kN/m^2)	Percentage Increase
Zone (1)	1	Without stiffening rib	771.81	-
	2	With stiffening rib	911.81	18.14
Zone (2)	3	Without stiffening rib	863.86	-
	4	With stiffening rib	970.78	12.38
Zone (3)	5	Without stiffening rib	799.80	-
	6	With stiffening rib	987.95	19.04

*C-Column strip width

6.2. Displacement And Stress

Vertical displacements and von-mises stress corresponding to a uniformly distributed load of 700kN/m^2 is taken to compare the distribution and range of displacement and stress in the waffle slab models without and with stiffening rib.

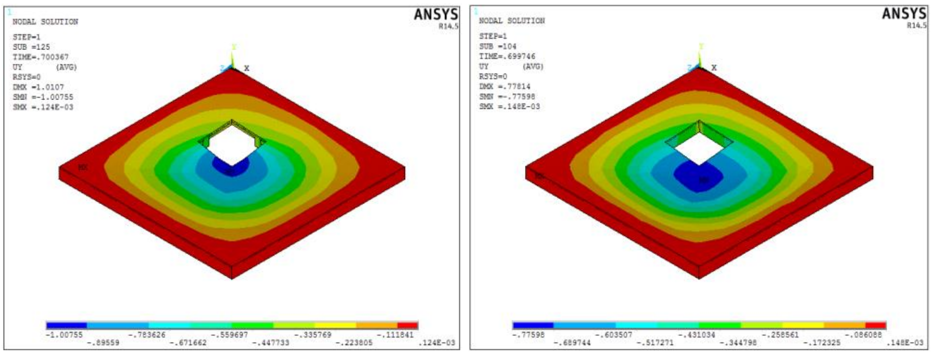

Fig. 6. (a) Displacement diagram of unstiffened slab model, **(b)** Displacement diagram of stiffened slab model

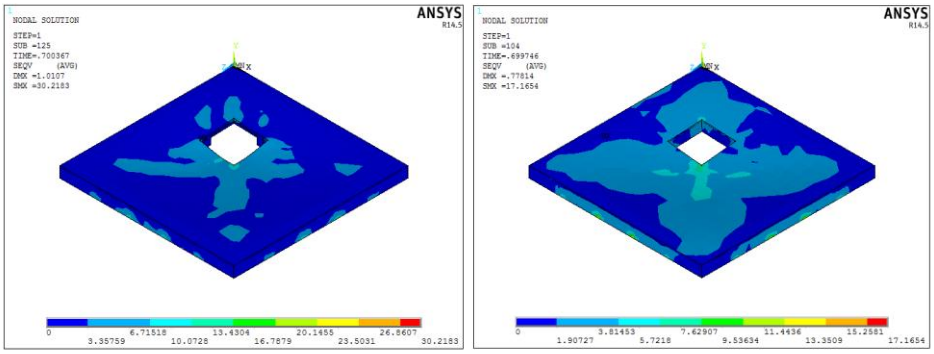

Fig. 7. (a) Von-mises stress diagram of unstiffened slab model, **(b)** Von-mises stress diagram of stiffened slab model

Table 2: Displacement and stress values of slab models

Location	Displacement (mm)		Percentage reduction	Stress (N/mm^2)		Percentage reduction
	Without Rib	With Rib		Without Rib	With rib	
Zone 1	0.94	0.79	15.96	26.68	17.61	34.00
Zone 2	1.01	0.78	22.77	30.21	17.16	43.20
Zone 3	1.02	0.74	27.45	29.59	16.15	45.42

From Table 2, it can be seen that in addition to increasing the load carrying capacity, providing stiffening rib around the openings can reduce the displacement of slab up to 27% whereas stress intensity by 45%. Even if openings in zone (2) have a little effect in ultimate load carrying capacity, stress concentration is more near the corners of openings. This may lead to material failure near the corners. To avoid such a situation, stiffening ribs can be provided around the opening, in which case stress is distributed throughout rather than concentrating near the corners of opening. Thus the serviceable life of waffle slab gets increased.

VII. Conclusions

A finite element program (ANSYS) suitable for nonlinear analysis of three dimensional reinforced concrete members under monotonic increasing pressure loads has been used to simulate the behaviour of waffle slabs with opening strengthened with stiffening rib. The following conclusions may be drawn from the present research:

- Nonlinear finite element method based on three dimensional models created by ANSYS is a powerful and relatively economical tool which can be effectively used to simulate the actual behaviour of strengthened reinforced concrete slabs.
- In general, it is concluded that, the stiffening rib can be successfully used for increasing ultimate load of waffle slab with opening.
- Large openings located at the area bounded by two column strips or at the intersection of column strip and middle strip should be stiffened using additional ribs around the opening, having the same properties of the main waffle ribs. This may increase load carrying capacity by 20%.
- Load carrying capacity of waffle slab with opening at the area bounded by two middle strips is much higher

compared to other two zones. However, stiffening rib can also be provided in this zone as it results in lower stress concentration and deflection.

Acknowledgement

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