

**Ministry of Higher Education
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**Structural Performance of Reinforced Concrete Two-
Way Composite Waffle Slab**

**A Thesis Submitted to Council of College of Engineering,
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Requirements for the Degree of Master of Science in Civil
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Abstract

Waffle slabs are an innovative structural solution that have gained popularity in recent decades due to their structural, architectural, and economic advantages. Their unique design, which incorporates regular voids, significantly contributes to reducing the self-weight of buildings. This study explores innovative methods to enhance the performance of these slabs through an experimental investigation of 14 specimens, each measures 1100x1100x130 mm and utilizes concrete with a strength of 35 MPa. Two main approaches were followed the first, replacing reinforcing steel with an equivalent amount of steel plate in three different void shapes (traditional square, truncated pyramidal, and square with vertical diagonal) and two void ratios (15% and 20%) and the second, strengthens waffle specimens with steel plates in the void region with maintaining the same void shapes and ratios. The study compares the performance of 12 proposed specimens with a solid reference specimen and a reference waffle model with traditional square voids and a 15% void ratio, which achieved an ultimate load capacity of 293.8 kN. In the first method (replacement), the group with a 15% void ratio has showed an improvement in ultimate load capacity, with the three specimens achieving values of 316.4 kN, 293.8 kN, and 305.1 kN, corresponding to percentages of +7.7%, 0%, and +3.8% respectively, compared to the reference waffle model. The group with a 20% void ratio has achieved values of 299.45 kN, 282.15 kN, and 282.15 kN, corresponding to percentages of +1.9%, -3.9%, and -3.9% respectively. In the second method (strengthening), the strengthened models exhibited significantly higher ultimate load capacities. The three specimens with a 15% void ratio achieved values of 418.1 kN, 429.4 kN, and 339 kN, corresponding to percentages of +42.3%, +46.1%, and +15.4% respectively. Meanwhile, the three models with a 20% void ratio achieved.

values of 310.75 kN, 361.6 kN, and 299.45 kN, corresponding to percentages of +5.8%, +23.1%, and +1.9% respectively. The results of this study indicate that the use of steel plates, particularly in strengthening the void region of waffle slabs, can significantly improve their ultimate load capacity. Furthermore, the design of both, the shape and size of the voids has an impact on the structural performance of these specimens.

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Chapter One

Introduction

1.1 Introduction

The global construction sector is experiencing structural growth driven by rapid urbanization and the steadily increasing demand for residential, commercial, and industrial infrastructure. Reinforced concrete remains the most prevalent and utilized construction material in the construction of diverse structures, owing to its superior physical and mechanical properties (Mehta, 1986), including high compressive and shear strength, exceptional durability in the face of harsh environmental conditions and temperature fluctuations, as well as its economic viability and the availability of basic raw materials for its production. In this context, there is a growing interest in the pursuit of innovative construction solutions aimed at achieving enhanced structural efficiency, reducing the self-weight of structural elements to decrease the overall loads on the structural system, and consequently realizing cost savings and minimizing the consumption of natural resources in line with sustainability principles. Waffle slabs have emerged as a promising alternative construction technology characterized by a unique geometric design that incorporates a regular grid system of internal voids. This intelligent design allows for a delicate balance between the required flexural and shear resistance and the reduction of the slab's self-weight, which in turn leads to decreased loads on columns, walls, and foundations, in addition to providing flexibility in architectural design and the potential for easier integration of mechanical and electrical services within the voids. (Chowdhury, 2012)

1.2 Behavior of the Deck Slab

The behavior of a surface panel as a horizontal structural element, is governed by the principles of mechanics of materials and structural theory where it responds to vertical loads by generating internal stresses and strains proportional to the loading, cross-sectional shape and material properties; under the influence of bending. The panel exhibits deflection that is directly proportional to the load and the cube of the span and inversely proportional to the modulus of elasticity and the moment of inertia. While linear bending stresses develop across the depth to resist shear loads. Internal shear forces are generated with a non-uniformly distributed shear stress stiffness which depends on material properties and geometry, serves as a measure of resistance to deformation in the presence of in-plane compressive forces. stability must be considered to prevent buckling. (Clarke, 1984)

1.3 Behavior of Waffle Slab

Waffle slabs, also known as two-way ribbed slabs, are characterized by a unique design featuring a regular grid of square or rectangular voids separated by intersecting concrete ribs. As shown in Figure (1-1). This design aims to achieve a delicate balance between reducing self-weight and increasing both stiffness and load-bearing capacity. Unlike hollow core slabs, which may increase in thickness to support their weight, the waffle design reduces the need for large quantities of concrete compared to solid slabs with equivalent load capacity, as the voids significantly decrease weight, consequently reducing loads on vertical structural elements and allowing for more economical dimensions. The high stiffness resulting from the distribution of concrete in intersecting (Nie, Jianguo and Ma, Xiaowei and Wen, Lingyan, 2015) (Al-Issawi, 2023)



Figure 1-1: Waffle Slab molds (Al-Issawi, 2023)

ribs can limit low-frequency sound transmission, and thanks to their two-way design and uniform mass distribution, waffle slabs offer good resistance to seismic vibrations and reduce the likelihood of progressive collapse compared to one-way slabs. Although shear resistance may be lower than that of solid slabs with the same overall thickness due to the voids, a suitable rib design and the addition of shear reinforcement where needed can compensate for this. Typically, the voids are square or rectangular, resulting from the use of standard forms, while altering the shape of these voids may affect stress distribution and shear resistance. In situations requiring additional shear resistance in specific areas, such as near columns or load concentration points, some voids can be filled to create partial solid sections. (do Socorro Melo de Souza, 2016)

1.4 Behavior of Composite Slabs

Composite panels exhibit mechanical behavior that differs from traditional composite construction materials such as reinforced concrete, hybrid steel, and prestressed beams. The stresses of the constituent materials are determined based on an analysis of their longitudinal and transverse behavior, influenced by the reinforcing section characteristics. Assuming the plate can develop maximum bending resistance the test aims to evaluate the bond strength that corresponds to the ultimate resistance of the reinforcement resulting from tensile resistance. Shear connections are essential components for creating an effective connection between the metal and concrete surfaces when they overlap as the upper edge facilitates the connection of fittings of steel columns. The design of these connections is based on the principle of achieving the maximum possible bending resistance for the final element. Cases where the connectors are insufficient to ensure appropriate linkage are referred to as 'partial shear connections' while the ultimate bending resistance of the element is primarily determined by its length, construction method, efficiency, and the number of shear connections used. (Hajjar, 2002) As shown in Figure (1-2).



Figure 1-2: Shear connections

1.5 Objective of the Study

The main objective of this scientific study is to investigate the enhanced structural behavior of composite waffle slabs. This goal branches into the following specific research points:

Study Objectives

- 1- Study the effect of replacing the existing reinforcing steel in waffle slab ribs with an equivalent amount of steel plates.
- 2- Analyze the role of strengthening the waffle slab in the waffle box areas using steel plates.
- 3- Study the effect of the shapes of waffle boxes on the structural behavior of the slab.
- 4- Study the effect of void ratios on waffle slabs.
- 5- Study the reduction of weight, materials, and sustainability provided by composite waffle slabs

6- 1.6 Research Questions or Hypotheses

This study seeks to answer the following questions:

- i What is the effect of replacing part of the reinforcement steel with steel plates on the ultimate load capacity of Waffle slabs?
- ii Does reinforcing the void areas of the slabs with steel plates significantly improve their resistance to bending and shear?
- iii Does the structural performance of Waffle slabs vary with different shapes of the voids used?

1.7 Thesis Structure

Chapter One establishes the overall framework and objectives of the research.

Chapter Two reviews existing literature on waffle slabs, identifying research gaps that this study addresses.

Chapter Three details the scientific methodology, including the design of experimental specimens, controlled variables (e.g., void dimensions, strengthening materials), laboratory testing procedures, and data collection.

Chapter Four presents and analyzes experimental results using tables and graphs, with statistical and engineering analysis to determine variable impacts on waffle slab performance.

Chapter Five provides key conclusions based on the results, answers research questions, and offers recommendations for future research and engineering practices.