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LONG SPANNED, CONTINUOUS, TWO-WAY, RIBBED SLABS

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Master's Thesis

Supervisor

Prof. Dr. Tuncer ÇELİK

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The thesis titled LONG SPANNED, CONTINUOUS, TWO-WAY, RIBBED SLABS prepared by SAJAD ABBAS ALI AL-KHAZRAJI and submitted on 07/12/2022 has been **accepted unanimously** for the degree of Master of Science in Civil Engineering.

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I hereby declare that this thesis meets all format and submission requirements of a Master's thesis.

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I hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Sajad Abbas Ali AL-KHAZRAJI

Signature

DEDICATION

I dedicate my research to my lovely father and my dear mother, who have continuously shown their love, support, help, and enthusiasm to me while I have pursued my research. The staff at Altinbas University, my supervisor, and all civil engineering doctors are also thanked for their assistance, guidance, and the invaluable expertise they provided in this study. In addition, my supervisor gave me a ton of support and direction for my study analysis and numerical work. I also want to express my gratitude to everyone at Altinbas University who offered me time and assistance so I could conduct my research and complete my thesis analysis.

PREFACE

I want to begin by thanking God Allah for giving me the abilities, stamina, and perseverance required to complete this master's thesis. I also want to express my gratitude to the lecturers and the civil engineering department for their assistance in writing my results and helping me to complete my work. I also want to convey my sincere gratitude to my Advisor, Prof. Dr. TUNCER ÇELİK, who was extremely patient, upbeat, and supportive of me. I wouldn't have been able to finish my numerical study without his crucial counsel and inspiration. I also hope my supervisor will be pleased with the findings of my research. Additionally, I want to thank the members of the examination committee who supported me by offering advice and constructive criticism. I also want to express my gratitude to Altinbas University's faculty and personnel for their unending assistance.

ABSTRACT

LONG SPANNED, CONTINUOUS, TWO-WAY, RIBBED SLABS

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This work is carried out to examine the contribution of adding steel fibers into concrete to improve its strength and performance. A comparative analysis is conducted to achieve the study goal, considering seven case studies through which the relevance and critical benefits of integrating steel fibers into concrete are assessed and identified. The SAFE® software package was employed to numerically model and simulate the waffle slab and other slabs in the seven cases. Significant parameters are taken into account to evaluate the beneficial impact of adding steel to concrete, namely reinforcement ratios in slabs and beams, long-term deflection, and punching shear. Furthermore, the influence of some factors on the waffle slabs' behavior is examined. Based on the numerical analysis executed via the SAFE® program, it was found that there are several critical factors that play a significant role in achieving robustness, workability, and optimum mechanical properties when the steel fiber is integrated into self-compacting concrete, including the impact of steel fiber integration into concrete, the effect of drop beams as a supporting system, and the influence of solid sections at columns. Also, it was found that waffle slab deflections are greater than solid slab system deflections. This aspect proves how flexible waffle slab systems are compared with solid slab systems.

In addition, it was found that as the volume of concrete increases, the self-weight also increases, resulting in more loads. Also, when the two waffle systems are analyzed, the waffle slab with beams C1 has 49% more top reinforcement than the waffle slab with solid sections C4.

Furthermore, the waffle system C1 has 114% more top reinforcement area than the waffle slab with solid panels C4.

Keywords: Two-Way Ribbed Slabs, Self-Compacting Concrete, Steel Fibers, Numerical Analysis.

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ABBREVIATIONS

ASTM	:	The American Society for Testing and Materials
ANOVA	:	Analysis of Variance
HC	:	Hooked-Corrugated
LVDT	:	Linear Variable Differential Transformer
LL	:	Live Load
R&D	:	Research and Development
SDL	:	Super-Imposed Dead Load
SFSCC	:	Steel Fiber Self-Compacting Concrete
SPHB	:	Split Hopkinson Pressure Bar
SCC	:	Self-Compacting Concrete
SFRC	:	Steel Fiber Reinforced Concrete
SC	:	Steel-Concrete
CFC	:	Carbon Fibre Composites
SFs	:	Steel Fibers
TWRS	:	Two-Way Ribbed Slabs
UPV	:	Ultrasonic Pulse Velocity
UHP-GPC	:	Ultra-High-Performance Geopolymer Concrete
WSs	:	Waffle Slabs

1. INTRODUCTION

1.1 RESEARCH BACKGROUND

Slabs are one of several critical structural components characterized by their horizontal surface and are responsible for carrying the building load [1]–[18]. They formulate the ceiling, floor, and roofs. These elements are typically supported by the walls, columns, or beams. Generally, slabs can be classified into five major categories, including (1) flat plate, (2) flat slab, (3) solid slab, (4) ribbed slab, and (5) waffle slab. Table 1.1 illustrates major slabs' classifications and their key features. One significant category of slabs is the ribbed slab. As indicated in Table 1.1, ribbed slabs are mirrored by their lower weight, higher acoustic and thermal energy insulation, and savings in the amount of concrete and steel. Ribbed slabs can be classified into two main types: (1) one-way ribbed slabs and (2) two-way ribbed slabs. Figure 1.1 presents an example of each category.

Figure 1.1: An architecture of (a) one-way ribbed slab [19], and (b) two-way ribbed slab [20].

Ribbed slabs are greatly common in several construction projects. They are characterized by their effective potential in saving significant concrete and steel amounts in the ribs, which help reduce the ribbed slab's overall weight. Ribbed slabs comprise a set of ribs connected through the concrete topping.

One-way and two-way ribs are aligned according to longitudinal and orthogonal arrangements, respectively. These ribs can behave like beams in resisting loads, stresses, and moments [21].

Table 1.1: Major types and properties of slabs [22].

Slab Type	Distance between Columns (m)	Live Loads (kN)	Advantages and Key Characteristics	Drawbacks
Flat Plate	6 to 8	3 to 5	Flexibility of accomplishing mechanical works. Higher capability to change the location of walls.	It increases the steel and concrete costs. No insulation of thermal energy and sound.
Flat Slab	8 to 12	4 to 7	Flexibility of accomplishing mechanical works. Higher capability to change the location of walls.	It increases the steel and concrete costs. No insulation of thermal energy and sound.
Solid Slab	Up to 9	3 to 7	Its thickness is relatively lower.	It increases the steel and concrete costs. No insulation of thermal energy and sound.
Ribbed Slab	Up to 9	3 to 6	Its weight is low. Higher insulation of sound and thermal energy. Savings in concrete and steel.	Difficult to execute its mechanical works. Its thickness is high.
Waffle Slab	5 to 17	3 to 7	Its weight is very low. It provides kind view. Higher insulation of thermal energy and sound. Savings in concrete and steel.	Difficult to execute its mechanical works. Its thickness is high.

Normally, the thickness of ribbed slabs is more than 7 cm, depending on the American Construction Code ACI-318-14 [22].

1.2 PROBLEM STATEMENT

TWRS is prevalent in the construction industry due to the significantly reduced concrete and steel quantities needed for the slab. However, designers and engineers face some critical problems and key challenges related to the two-way ribbed slabs (TWRS) drawbacks, which are mirrored by the difficulty of executing its mechanical work and its higher thickness. In this context, several research and developments (R&D) efforts have been conducted to resolve these limitations. One of the state-of-the-art solutions investigated to enhance the TWRS performance and resolve its drawbacks is the implementation of Steel Fiber Self-Compacting Concrete (SFSCC) [21], [23]–[37]. SCFRC can be used as an alternative material inside the TWRS. SCFRCE are featured with their higher reliability and strength, despite their lower density compared to other structural materials, as indicated in Table 1.2.

Table 1.2: The density of some structural elements [21].

Content	Density (kg/m^3)
Cement	465
Fly Ash	85
Coarse Aggregate	590
Fine Aggregate	910
Water	228
Steel Fiber Self-Compacting Concrete	40

The use of SFSCC provides a practical and efficient construction material that can withstand numerous flexural loads. In addition, SFSCC can mitigate the macro-cracking formulated into micro-cracking. Thus, the concrete ductility can be improved. Figure 1.2 displays different types of fibers used in concrete.

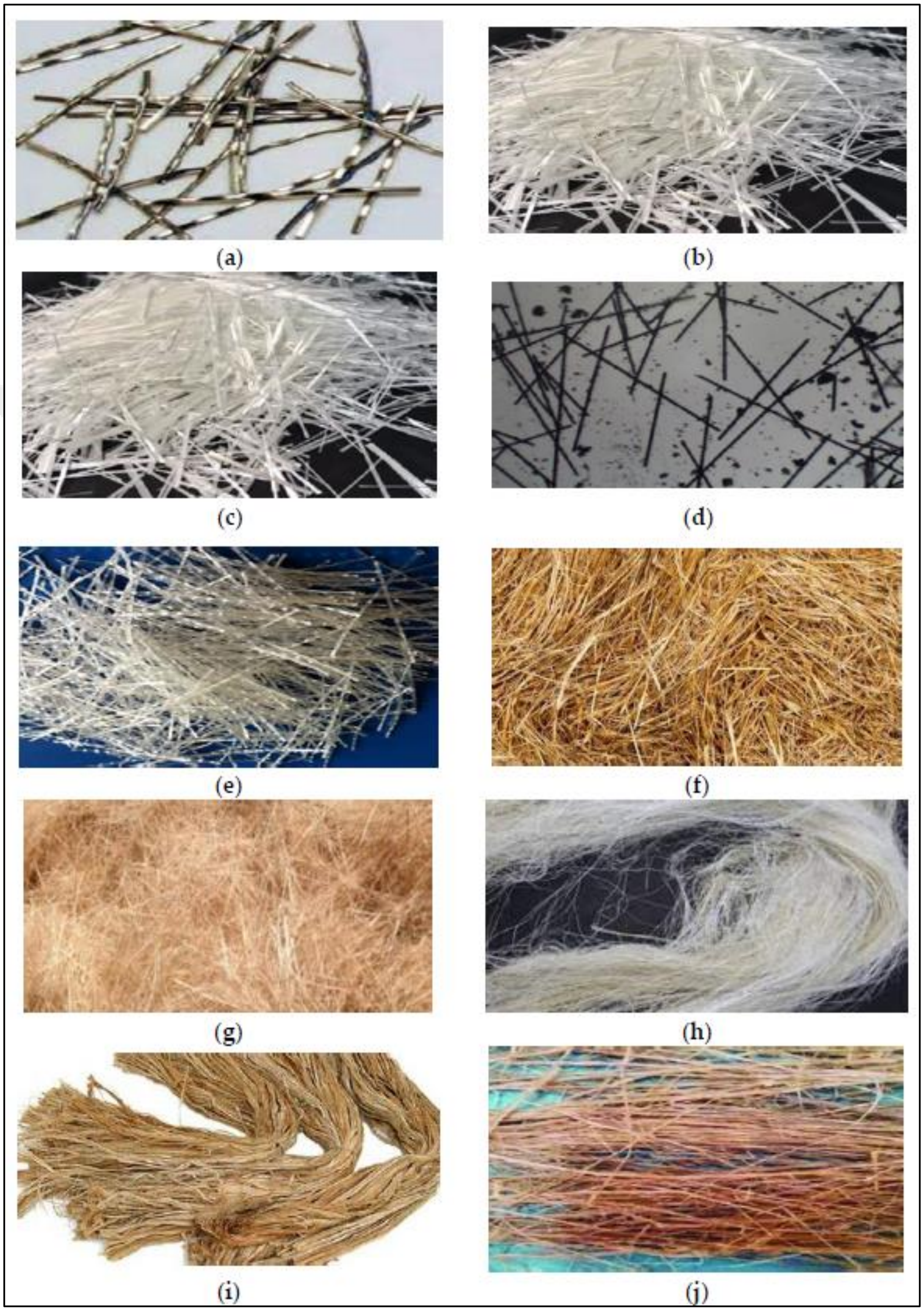

Figure 1.2: Different types of fibers used in construction, a) Steel fibers, b) Glass fibers, c) Polypropylene fibers, d) Carbon fibers, e) Plastic fibers, f) wheat straw, g) Sugarcane fibers, h) Sisal fibers, i) Jute fiber, and j) Bamboo fiber [38].

Moreover, SFSCC is vital to significantly enhance the TWRSs in mitigating stresses and improving their ability to resist deflection. Using SCFRC can also offer perfect concrete mixing and properties without compaction [21], [39], [40].

1.3 RESEARCH SIGNIFICANCE

This research is carried out depending on a set of distinct significances. Through the first significance, this study will shed light on major SFSCC characteristics and critical contributions in the construction industry, especially on their beneficial role in improving the TWRS's application in different structural projects. A systematic literature review is conducted to achieve the goals of the first relevance. Through the second relevance, this work will investigate a case study in which a numerical exploration is applied to make a comparative analysis between two cases. The first case consists of a conventional TWRS that does not use any innovative or enhanced material. The second case uses SFSCC in the TWRS to improve its performance. This numerical analysis will be implemented via a simulation software package that can mimic real cases to analyze and simulate the critical role of SFSCC in the construction industry to improve the TWRS performance. The third relevance of this study is mirrored by identifying substantial aspects and key recommendations that help improve the TWRS using the SFSCC according to the results obtained through simulations executed by the software. The research outputs of the comparative study will be validated with respect to construction professionals' and engineering professionals' points of view.

1.4 RESEARCH MAJOR AIM AND MINOR OBJECTIVES

This research aims to investigate and analyze the remarkable role of the SCFRC in improving the TWRS performance and resolving its major drawbacks faced by engineers and designers in the construction industry. A set of objectives are followed and executed to accomplish the major aim of this study, which are presented in the following paragraphs:

i. To shed light on major SFSCC characteristics and critical contributions in the construction industry, focusing especially on their beneficial role in improving the TWRS's application in different structural projects.

ii. To make a modeling of a TWRS, relying on two case studies: (1) conventional TWRS and (2) TWRS that uses SFSCC via a simulation software package.

iii. To execute a comparative analysis and determine which case study (TWRS) will be the most effective and practical depending on the cost, efficiency, and workability.

iv. To validate the results with respect to construction professionals' and engineering professionals' points of view.

1.5 RESEARCH QUESTIONS

The research work conducted to analyze the substantial contributions and major role of SFSCC will provide some answers to the research questions, which are described in the following articles:

i. What are the main limitations and problems of TWRS that limit its wide implementation in the construction industry?

ii. What are the SFSCC's major characteristics and critical contributions for TWRS?

iii. Could the use of SCFRC reduce the quantity of concrete and steel in the construction industry when implemented for TWRS?

iv. Would the application of SFSCC in the TWRS provide a reliable and cost-effective solution to improve the TWRS performance in the construction sector?

1.6 RESEARCH HYPOTHESES

The study is executed to determine and identify the critical benefits and the crucial role of SFSCC implementation in TWRS. A comparative analysis will be implemented using a numerical software package. A group of research hypotheses will be validated or invalidated depending on the research outputs. These hypotheses are illustrated in the following articles:

i. Null Hypothesis, H_o, which states: “The SFSCC implementation in the TWRS would not resolve the limitations and drawbacks related to the TWRS in the construction sector.”

ii. First Alternative Hypothesis, $H_{1,a}$. This Hypothesis states: “Using the SFSCC to replace the conventional material in the TWRS would provide better concrete properties.”

iii. Second Alternative Hypothesis, $H_{2,a}$. This Hypothesis states: “Implementing the SFSCC is greatly beneficial in improving the cost-effectiveness of the TWRS.”

iv. Third Alternative Hypothesis, $H_{3,a}$. This Hypothesis states: “Utilizing the SFSCC in the TWRS could improve the slabs’ concrete mechanical properties.”

v. Fourth Alternative Hypothesis, $H_{4,a}$. This Hypothesis states: “Exploiting the SFSCC is greatly beneficial for the TWRS as it enhances its performance.”

vi. Fifth Alternative Hypothesis, H_5. This Hypothesis states: “Employing the SFSCC is significantly practical for the TWRS as it fosters its reliability and workability in the construction industry.”

1.7 THESIS STATEMENT

The title of this study is “LONG SPANS CONTINUOUS TWO-WAY RIBBED SLABS.” This research is executed to investigate the major role of SFSCC in optimizing the major TWRS characteristics in the construction industry via a numerical analysis and a comparative study.

1.8 THESIS ORGANIZATION

The layout of this thesis includes five chapters. These chapters will cover several topics and key ideas associated with the critical benefits and significant relevance of using SFSCC in the TWRS.

The thesis layout can be summarized through the following articles:

i. Chapter One, which has the title INTRODUCTION, illustrates various data on the research background, problem statement, research significance, study questions, hypotheses, and study goal and objectives.

ii. Chapter Two, which has the title of LITERATURE REVIEW, presents major SFSCC characteristics and critical contributions in the construction industry. Chapter two will also focus on SFSCC's beneficial role in improving the TWRS's application in different structural projects. The data will be collected in chapter 2 from publications found in Ph.D. and master dissertations and web research engines, including ScienceDirect, ResearchGate, Google Scholar, and Academia. In addition, a database on the significance and key contributions of SFSCC will be gathered from several conference proceedings.

iii. Chapter Three, which has the title RESEARCH METHODOLOGY, illustrates the major approach and methodology applied to conduct this thesis's research. It also indicates some variables and parameters that will be investigated in this study to assess the role and performance of SFSCC in the TWRS.

iv. Chapter Four has the title RESULTS AND DISCUSSIONS. This chapter will present the findings of this work and results linked to the key role and main contribution of the SFSCC in the construction industry. Also, chapter four will show the research discussions and relate the findings to other scientists' results.

v. Chapter Five, which has title CONCLUSIONS AND RECOMMENDATIONS, indicates the substantial conclusions summarizing the major numerical software findings and results from the comparative analysis of the two case studies. Furthermore, chapter five will explain some recommendations and key suggestions related to future work to help scientists and engineers carry out further enhancements and analyses on the SFSCC's leading contribution to the construction industry.

2. LITERATURE REVIEW

2.1 GENERAL

Chapter 1 presented the research background, problem statement, study goal and objectives, questions, hypotheses, and study significance. This chapter presents more detailed data and illustrations on major SCFRC characteristics and critical contributions to the construction industry. Chapter two will also focus on SCFRC's beneficial role in improving the TWRS's application in different structural projects. The data are collected from several publications from Ph.D. and master dissertations and web research engines, such as ScienceDirect, ResearchGate, Google Scholar, Academia, and conference proceedings and journals.

2.2 KEY CHARACTERISTICS AND CONTRIBUTION OF THE STEEL-FIBER AND SELF-COMPACTED CONCRETE IN THE CONSTRUCTION INDUSTRY

[41] Guided a study to investigate the performance of steel fibers self-compacted concrete using a high amount of fly ash. Several mixes were prepared by blending cement, fly ash, lime powder, fine sand, polycarboxylate, and steel fibers. Scc mixes were carried out by replacing cement with powder lime and fly ash (50%, 60%, and 70%). Also, The performance of the SCC was studied using a percentage (60%) of fly ash in without steel fibers, and the performance of SCC was also studied by adding 60% of fly ash and the following percentages of steel fibers (0%,0.25%,0.5%,0.75,1%) .The blends were prepared by mixing the materials mentioned in specific proportions and then conducting a sump flow experiment to study the flexibility and workability of SCC mixes. The diameters of the mixtures were measured in both directions after the mixture stopped flowing, as shown in Figure 2.1.

Figure 2.1: Configuration of the slump flow and ring flow testing process [41].

Furthermore, the strengthened properties of self-compacted concrete were studied by estimating the compressive and flexural resistance. Cubic samples with dimensions of (100 mm × 100 mm × 100 mm) were selected to study the compressive strength. In addition, they were employed to assess the flexural strength. The dimensions of the samples were (100mm × 100 mm × 400 mm). The study confirmed that adding fly ash with a percentage of (between 50% and 70%) increased the performance of self-compacted concrete compared with other samples that do not contain fly ash. Furthermore, flexibility mixes by adding steel fibers of different proportions decreased and reached a severe value by adding more amount of steel fiber and a high amount of fly ash. Additionally, it was found that adding fly ash to the self-compacted concrete and steel fibers enhances the compressive strength significantly. Moreover, the results revealed that its effect was noticeable on the tensile and flexural properties, as adding steel fibers by 1% and in the presence of fly ash by 60% helped improve the tensile capacity by 22% and the flexural resistance by 58%.

[42] Studied the impact of adding steel fibers on self-compacted concrete. The goal of their research was to understand the behavior of self-compacted concrete as a result of adding steel fibers by conducting a series of experimental tests. The following materials were used for the blends tested: silica, limestone powder, cement, and steel fibers with 60 and 80 proportions. Then, various methods have been adopted to increase the performance of the blends by using materials in different proportions, such as reducing the rough lime stone to decrease fractioning between particles, boosting the flexibility of the blends using Viscocrete superplasticizer utilizing lime stone and silica fume to make the solid particles more viscosity. After that, blends were prepared, seven specimens were mixed, and one sample was considered as a control without adding fibers.

A fresh concrete test was executed to study the capability of mixes to flow. The samples have been experimentally proven to be flowable. Moreover, The compressive strength of nine cubes of dimensions 150 × 150 × 50 mm for each blend was calculated. Also, a split tensile strength test was carried out to know the value of tensile strength with (100 mm × 100 mm) cylindrical samples.

A flexural strength test was made by casting beams with dimensions 100 mm × 100 mm × 500 mm using all mixes cases and applying load until failure, and load capacity was calculated. Enhancement of self-compacted concrete after adding steel fibers has been determined utilizing an impact resistance test in which the first crack happens, and the sample reaches the ultimate failure. Finally, the durability of the concrete was demonstrated by using a permeability test by recording the driven depth value of the water inside the sample.

The researchers proved The addition of steel fibers to self-compacted concrete met all the criteria that self-compressible concrete would achieve without using fibers as flowability and filling capability. Also, The specimen reinforced with steel fibers by a proportion of 80 L/d, 0.45%, gave the most considerable compressive resistance. Furthermore, researchers found that using curved steel fiber in SCC mixes helps to increase tensile resistance and flexural strength. Also, adding silica fume has a positive effect in enhancing the tensile resistance and hardening the specimens by filling the voids between particles.by conducting a comparative between strengthening samples and control specimens, it was noticed that SFR-SCC supplemented high permeability.

[40] conducted experimental work examining the flexural behavior of (SF-SCC) by adding silica fume. Moreover, four blends were prepared to mix cement, water, silica fume, and fine sand. Additionally, a superplasticizer was utilized to boost blend properties**.** Blends were prepared and mixed with a constant amount of cement and silica fume With variable proportions of steel fibers. The first blend contains 20% cement and does not contain steel fibers. The other blends contain the following percentages of steel fibers:0.25%-0.5%-0.75%-1%. A compressive resistance experiment was conducted on cubic, prismatic and cylindrical samples, and a series of experiments were conducted on fresh and hardened blends. Passing capability was investigated using the L-BOX test. Flexibility was checked by means of a slump flow test, and a v-funnel test was conducted to determine filling capacity. However, hardened properties were studied by means of a compressive strength test, split tensile test, and flexural resistance test. Researchers affirmed adding 20% silica fume and 5% steel fiber) SCC blends can give high flexibility, and these proportions were recommended in construction buildings. Moreover, adding 0.5% steel fiber increased the compressive strength by 12.5% .

Also, in the event that 20% of the cement was replaced with silica, the concrete samples achieved more economical resistance.

[43] executed research to investigate the durability and flexibility of concrete using steel fiber. Variable parameters in this study are volume ratios of steel fibers ranging from 1% to 4% of cement mass. Cylindrical specimens were used to estimate compressive resistance and to determine tensile resistance value. Researchers concluded that although the samples' flexural strength increased by 2%, steel fiber strength decreased when 2% of steel fibers was used. Also, the durability of specimens has been increased.

[44] studied different properties of hybrid steel fibers, such as flexibility, strength, and rigidity**.** They were also passing the capability and stability of fresh concrete by slump flow test. Moreover, the mechanical properties of concrete specimens were determined by compressive strength test, tensile strength test, and flexural tensile strength tests. Three cubic samples were utilized with dimensions (150 mm × 150 mm × 150 mm) for conducting the compressive strength test. Additionally, three cylindrical samples were used to execute the tensile test. The four-point bending test employed in their research is shown in Figure 2.2. It was applied on prismatic samples with dimensions (of 100 mm × 100 mm × 400 mm). Linear Variable Differential Transformer (LVDT) was located at mid-span to measure the deflection. Also, hardening and softening behavior were studied in order to present flexural rigidity. Macro and micro steel fibers were utilized with different ratios.

Test results demonstrated hybrid fiber steel concrete samples showed that hardening-deflection took place when the least index has a value of 0.69. At the same time, when FR-index reaches 1.04, the specimen has the best hardening-deflection behavior. Additionally, researchers proved that the American Society for Testing and Materials (ASTM) C1018 code was not effective in estimating the flexural behavior of fiber steel concrete .it was noticed hybrid reinforced SCC gave ductility achievement compared with macro steel fiber specimens. Furthermore, the flexibility of SCC mixes decreased by adding a steel fiber ratio. All specimens reinforced by steel fiber achieved high tensile than specimens without fiber reinforcements.

[45] performed research to check the performance of steel fiber compacted concrete due to repeated drop weight using the Split Hopkinson pressure bar (SPHB) test and Ultrasonic Pulse velocity (UPV). To conduct this test, six cylindrical specimens for each test were prepared and cast. Additionally, cubic samples with dimensions 150 mm × 150 mm were utilized to estimate compressive resistance and to carry out ultrasonic pulse velocity nondestructive tests. Moreover, a split tensile test was performed.

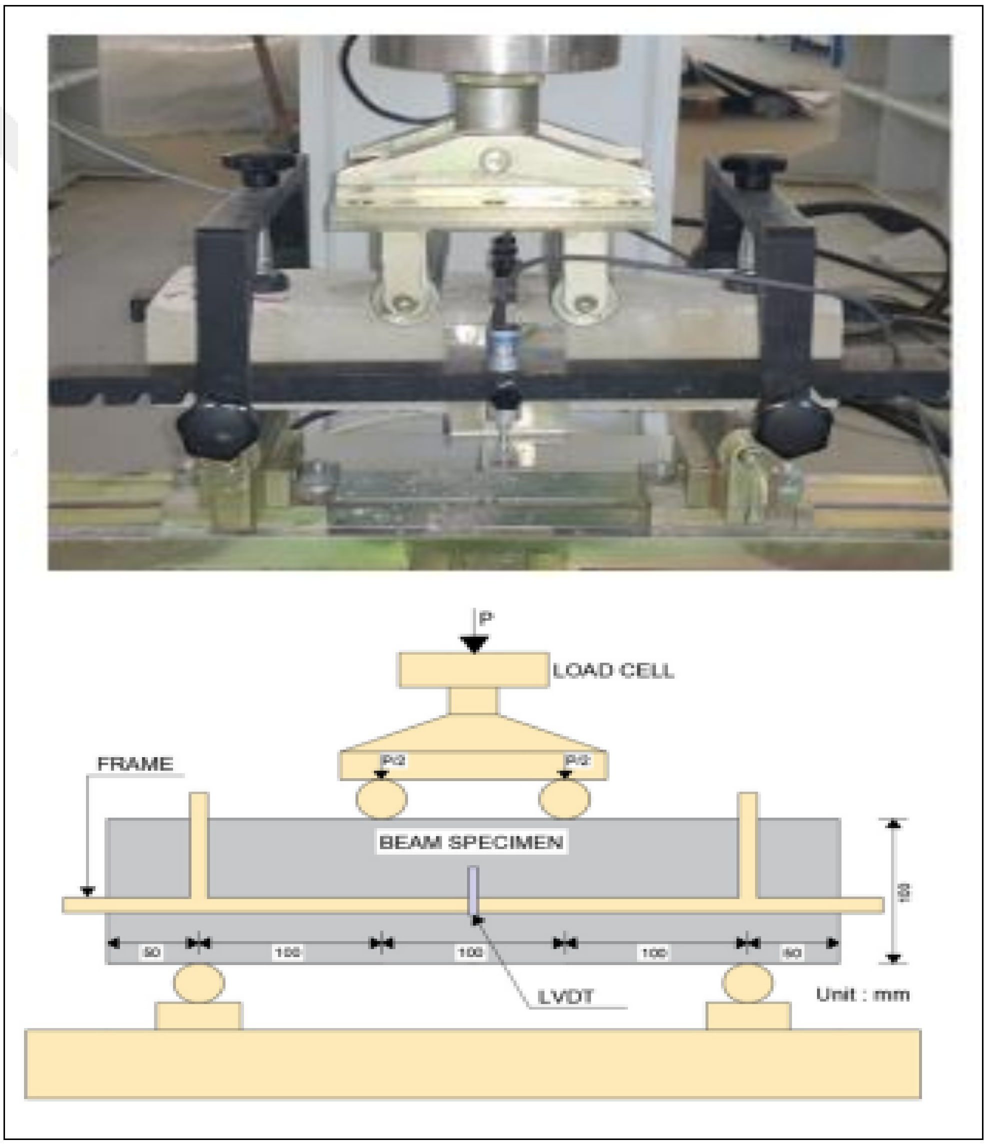

Figure 2.2: Four-point bending test employed to assess the deflection in the self-compacting concrete [43].

The following volume fractions of steel fiber were studied: 0%, 0.5%, 0.75%, and 1%. These steel fibers were added to self-compacted concrete blends. The diameter and length of the steel fiber were 15 mm and 0.2 mm, respectively. The SPHB test apparatus is shown in Figure 2.3. It depends on a regularly repeated fall of weight on the surface of the sample from a constant height and a constant weight. The number of strikes is measured at the appearance of the first crack. The strikes are also assessed when the sample arrives to collapse. This experiment was studied according to variable values of height fall (700 mm, 575 mm, and 457 mm). The weight employed in their research related to the fallen body had a value of 4.5 kg. Then, variable values of weight were used, including 4.5 kg, 6 kg, and 7.5 kg.

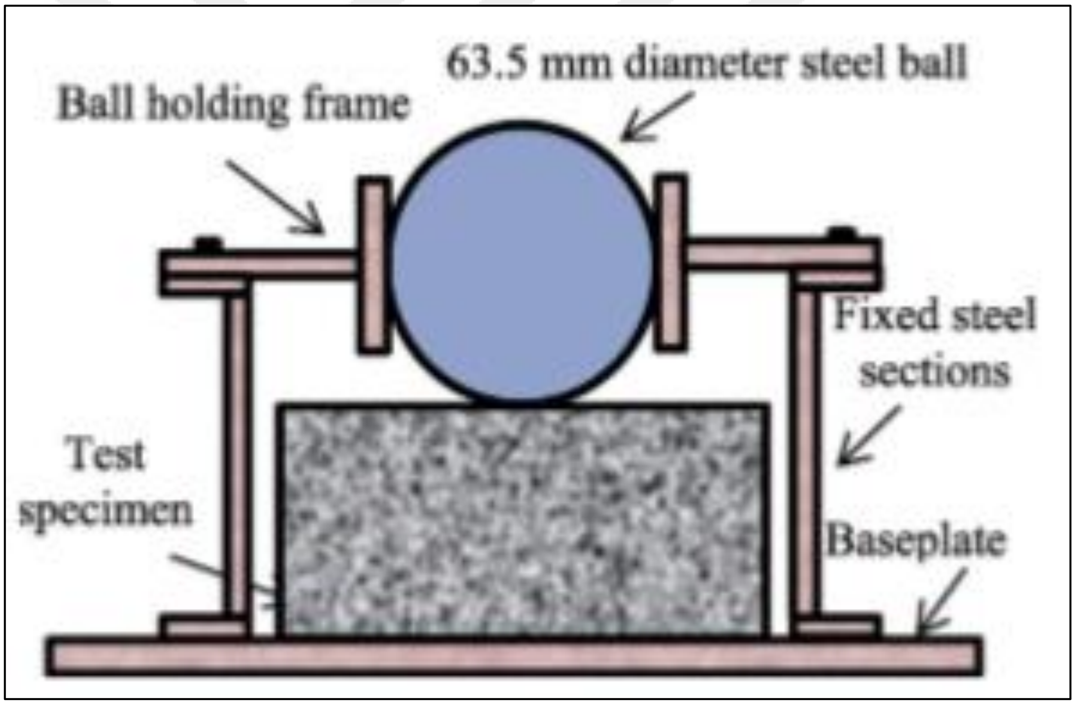

Figure 2.3: The drop-weight test utilized in the research of [45].

The experiment was repeated for samples of self-compacted concrete by adding different percentages of steel fibers (0, 0.2, 0.5, and 1%), as this research aims to study the effect of the height of the fall and the weight of the falling body on the samples reinforced with steel fibers. The results showed that the increase in the proportion of steel fibers leads to a rise in tension resistance.

The results of the SPHB and UPV tests were conducted depending on six cylindrical specimens for each test were prepared and cast. Additionally, UPV test showed ultrasonic pulse velocity reduced by increasing fiber content as a result of the spread of these waves in the concrete layers randomly and their fading out. The results of the SPHB test showed that the number of blows when the first crack appears and when collapsing increases as the content of steel fibers in the sample increases compared to the sample that does not contain steel fibers. The researchers also indicated that the number of blows decreases when the height of the fall is constant, and the weight of the falling body increases in addition to the fact that the number of crashes decreases with the increase in the height of the fall and the more the weight of the falling body is constant Compared to the sample without steel fibers.

[39] carried out a study about the behavior of steel compacted concrete with steel fibers by carrying out a series of tests. Blends were prepared by adding the following materials: cement, fine sand, rough gravel, and fly ash. Fly ash was used to achieve acceptance cohesion of mixes. Superplasticizer was utilized to achieve high flowability. Two-volume portions (between 0.5% and 1%) of curved steel fibers were added. Four blends were prepared by mixing the previously mentioned material and adding the curves steel fibers with the portion (0.5% and 1%). One combination is from regular concrete. At the same time, the other is from self-compacted concrete. Also, two blends were mixed by adding steel fibers with percentages of 0.5% and 1%. After that, six samples of cubic concrete with dimensions (100 mm × 100 mm × 100 mm) were fabricated in order to check compressive resistance. A maximum value of the load of 300 kN was applied to the sample's surface, where the experiment began by applying a load on the sample with a value of 30% of the maximum load and then continued to apply the load until the sample reached failure. A slump flow test was carried out. The research results indicated that the addition of steel fibers helped to improve the load capacity of the samples, as it was noted that an improvement in the forms of collapse and a reduction in cracks.

[46] published a research paper that contains experimental work that deals with the study of the improvement in the behavior of self-compacted concrete by using recycled steel fibers after they have been treated for reuse using advanced methods. Steel fibers were classified according to diameter and length, as steel fibers with diameters ranging from 15-18 cm were collected.

The most significant amount of steel fibers, which constituted 78%, had diameters ranging from 0.12 cm to 0.27 cm. The steel fibers were also classified according to their lengths using a device. The most considerable amount of steel fibers, with sizes ranging from 30 mm to 60 mm, constituted 0.67% of the entire quantity. Figure 2.4 illustrates a configuration of the recycled steel fiber.

Figure 2.4: A Configuration of the recycled steel fiber [46].

SF-SCC blends were mixed using Portland cement, granular sand, rough lime stone, and water. Different volume portion (1%, 2%, 3%, 4%, and 5%) of recovered steel fiber was utilized to prepare mixes. All specimens were cast and fabricated, including 54 cubic specimens with dimensions (of 100 mm × 100 mm × 40 mm). Six cylindrical samples with dimensions (150 mm × 65 mm) mm, and six prismatic samples with dimensions (100 mm ×100 mm × 40 mm). A slump flow test was conducted to study the flexibility of fresh concrete. It was noted that adding steel fiber reduces the flexibility of fresh concrete. Also, the compression test was conducted on cubic samples with dimensions 100 mm × 100 mm to investigate hardened concrete properties. The compressive resistance was also measured, and tensile resistance was calculated using a split tensile test on (100 mm ×200 mm) cylindrical samples. Finally, a four-point bending test illustrated in Figure 2.5 was carried out to check flexural strength.

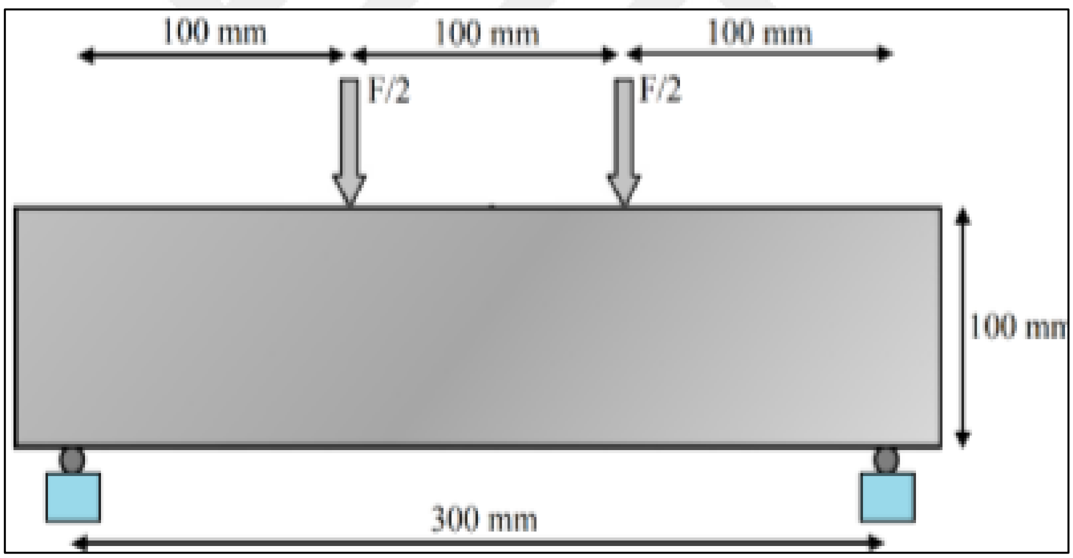

Figure 2.5: The four-point bending test utilized in the study of [46].

The test dealt with 100 mm × 100 mm × 500 mm beam specimens with different steel fiber content. The researchers found that employing the steel fiber to reinforce self-compacted concrete helped enhance the load capacity of samples. Also, it was found that cracks were reduced compared to SCC without steel fiber. Additionally, the durability of specimens was boosted by adding steel fiber by percentages (3% and 4%). Moreover, the researchers noted that using the length of steel fiber 3 mm gave remarkable enhancement in load capacity.

[47] carried out research to study the influence of steel fiber content on fresh and hardened properties of self-compacted concrete. SCC blends were mixed by adding cement, fly ash, lime stone, fine sand, and steel fibers. Many tests were used to determine the flexibility and stability of fresh concrete, and these tests were: L-box, V-tunnel, and slump flow. Additionally, to investigate flexural and compressive strength, compressive and indirect tensile tests were conducted. Figure 2.6 represents the fresh and hardened concrete tests.

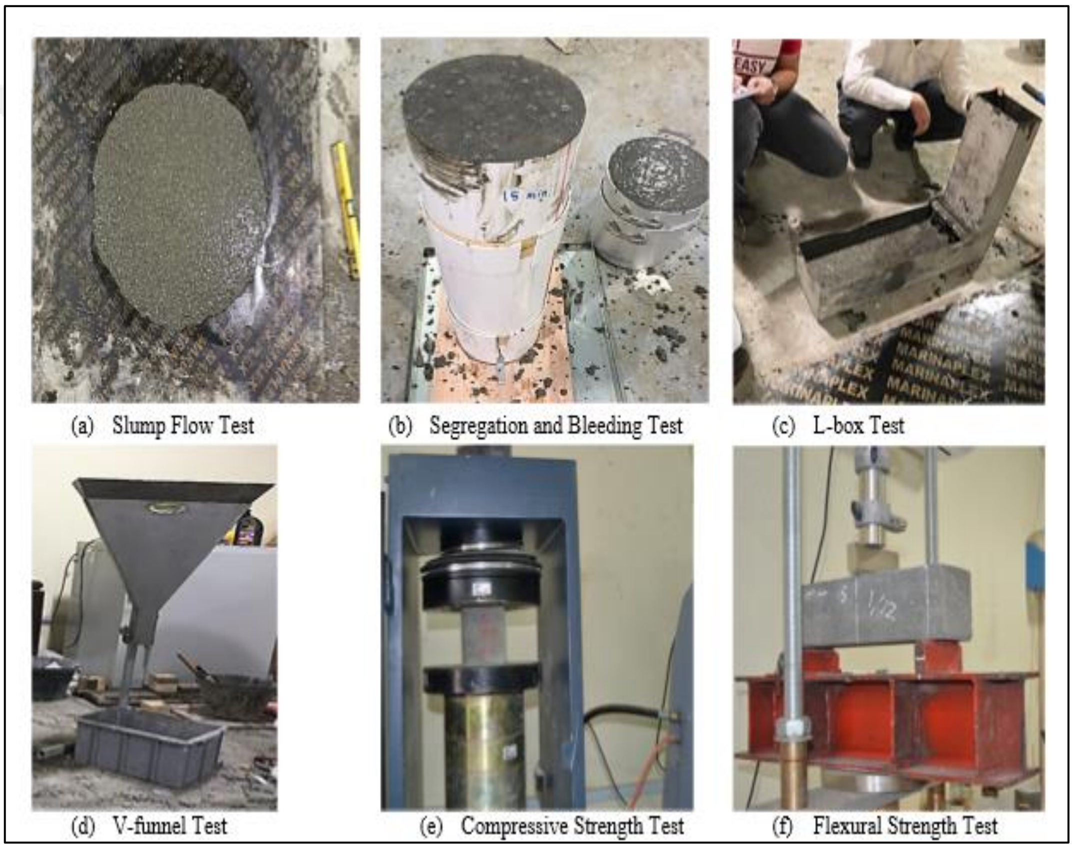

Figure 2.6: Fresh and hardened concrete tests [47].

A comparative analysis was conducted between SCC and OPC, including 60 mm of HSF, by replacing part of the cement with fly ash. SCC can be enhanced by adding 0.25% of hooked steel fiber. Replacing cement with fly ash has a significant effect in improving the properties of SCC and reducing separation and discontinuities in mixes by a percentage up to 68%.

The slump flow of SCC mixes is reduced by strengthening SCC with steel fiber. Also, flexural and tensile resistances could be enhanced by 25% and 11%, respectively. Therefore, using 60 mm hooked steel fiber would help improve the performance of the SCC.

[48] executed research to study the mechanical behavior of steel fiber reinforced self-compacted concrete panels by estimating the physical and mechanical properties of SFR-RCC blends .series of tests were conducted, such as slump flow test, compressive test, and V-funnel test. Different steel fibers ratio were utilized in the study. Dimensions of the tested panels were (500 mm × 500 mm × 30 mm). Major variables and parameters considered in their study included the steel fiber content (0 kg/m^3, 30 kg/m^3, and 60 kg/m^3). The research findings confirmed that the flexibility of SCC mixes decreased by increasing steel fiber amounts. Also, Load- deflection behavior is enhanced by adding steel fibers.

2.3 CRITICAL CONTRIBUTIONS AND BENEFICIAL IMPACTS OF EMPLOYING STEEL-FIBER SELF-COMPACTING CONCRETE TO THE CONSTRUCTION INDUSTRY

[49] carried out research examining the critical role of steel fibers integration into the concrete slabs on their punching shear resistance. Their experimental analysis affirmed that adding steel fibers could significantly increase the punching shear resistance of the concrete slabs. [50] executed research analyzing the integration of steel fibers into slabs. They found that adding steel fibers to the slabs would reduce the deflection amount and minimize the cracking growth. [51] studied the impact of adding steel fibers into concrete slabs. Their analysis confirmed that integrating these fibers into concrete slabs would improve the cyclic and flexural performance related to the bridge deck slabs and reduce deflection and increase its stiffness. [52] studied the impact of fiber type on the flexural behavior of two ways slabs with an opening .two slabs specimens were tested with dimensions (800 mm × 800 mm × 100 mm). Bar reinforcement with a diameter of 12 mm was utilized in both directions. Details of slab specimens are illustrated in Figure 2.7.

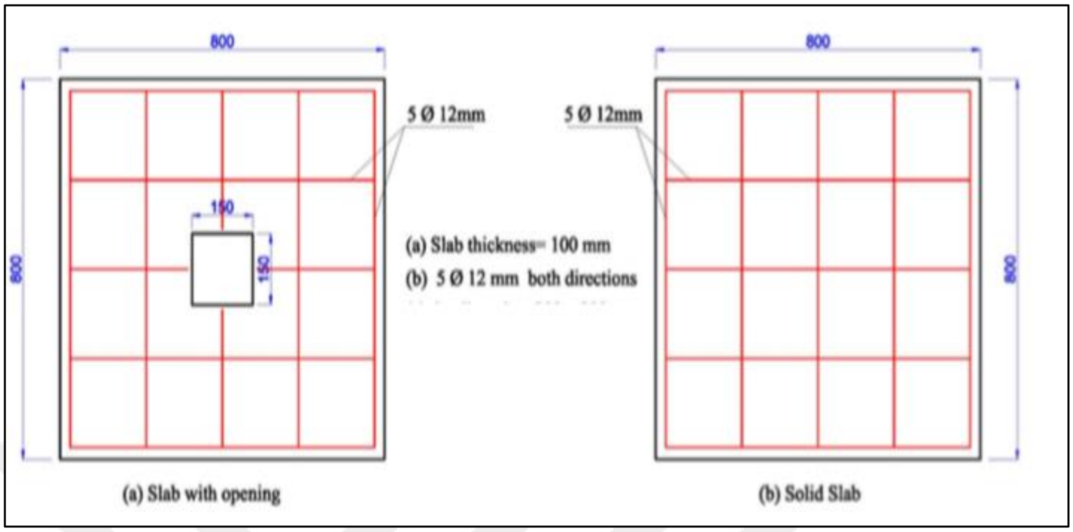

Figure 2.7: Major slab specimens investigated in the work of [52].

Five concrete mixes were tested using different fiber types (straight-hooked-corrugated-polyolefin) to investigate compression resistance, modulus of collapse, and splitting tensile resistance. Concrete samples reinforced with steel fibers showed an improvement in compressive strength when using steel fibers of the (hooked-corrugated (HC)) type. As for the polyolefin type, it contributed a small improvement in the compressive strength compared to the non-reinforced samples, and the improvement rate in the compressive strength ranged from 11.3% to 24.8%. The steel fibers of type (hooked-corrugated) gave the most outstanding value for the improvement in the tensile strength of the samples in comparison with other classes, and the percentage of improvement in the tensile strength ranged from 77% to 99%. When the modulus of rupture factor was studied, the steel fibers achieved the best performance of the samples with a percentage of 109%. A significant reduction in the crack was observed in the models when using hooked-type steel fibers.

[53] published a paper estimating the punching shear resistance of fiber-reinforced concrete flat slabs. Flat slab specimens were reinforced by rebars with 12mm and 16 mm dimeters, and steel fibers with a length of 40 mm were used during mixing blends with an aspect ratio of 90. Seventeen flat slab specimens were cast and fabricated for the test with dimensions (1500 mm × 1500 mm). The load was applied at the center of the specimen.

A load cell was used to record punching shear load. Also, LVDT was used to measure the deflection. Figure 2.8 presents the testing apparatus and setup employed.

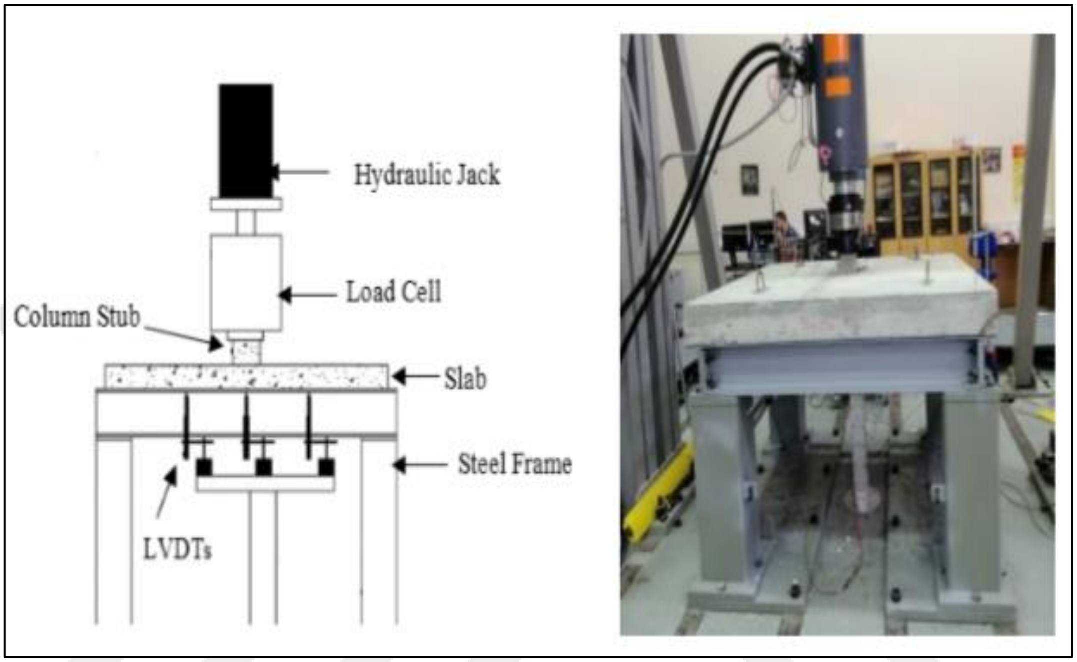

Figure 2.8: The testing apparatus and setup employed in the work of [53].

Statistical analysis was done by Analysis of Variance (ANOVA), and residual plots were utilized to check the results. The research affirmed punching shear capacity enhanced by increasing fiber amount, steel portion, and slab thickness. However, the thickness slab is the most factor that impacts the punching shear strength of the flat slab.

[54] presented studying the mechanical properties of fiber concrete flat slabs by investigating the impact of flat slabs in compressed zones. The volume ratio of steel fiber and polypropylene fibers was 1% of the concrete mix. The study included calculating the modulus of elasticity, flexural strength, and compressive strength. 30 mm of the concrete layer was reinforced using steel fiber and polypropylene fibers. Results of Experimental tests were compared to numerical modeling. Numerical modeling was performed by the Autodesk robot structure program, which depends on the finite element method. The model of the case is represented in Figure 2.9.

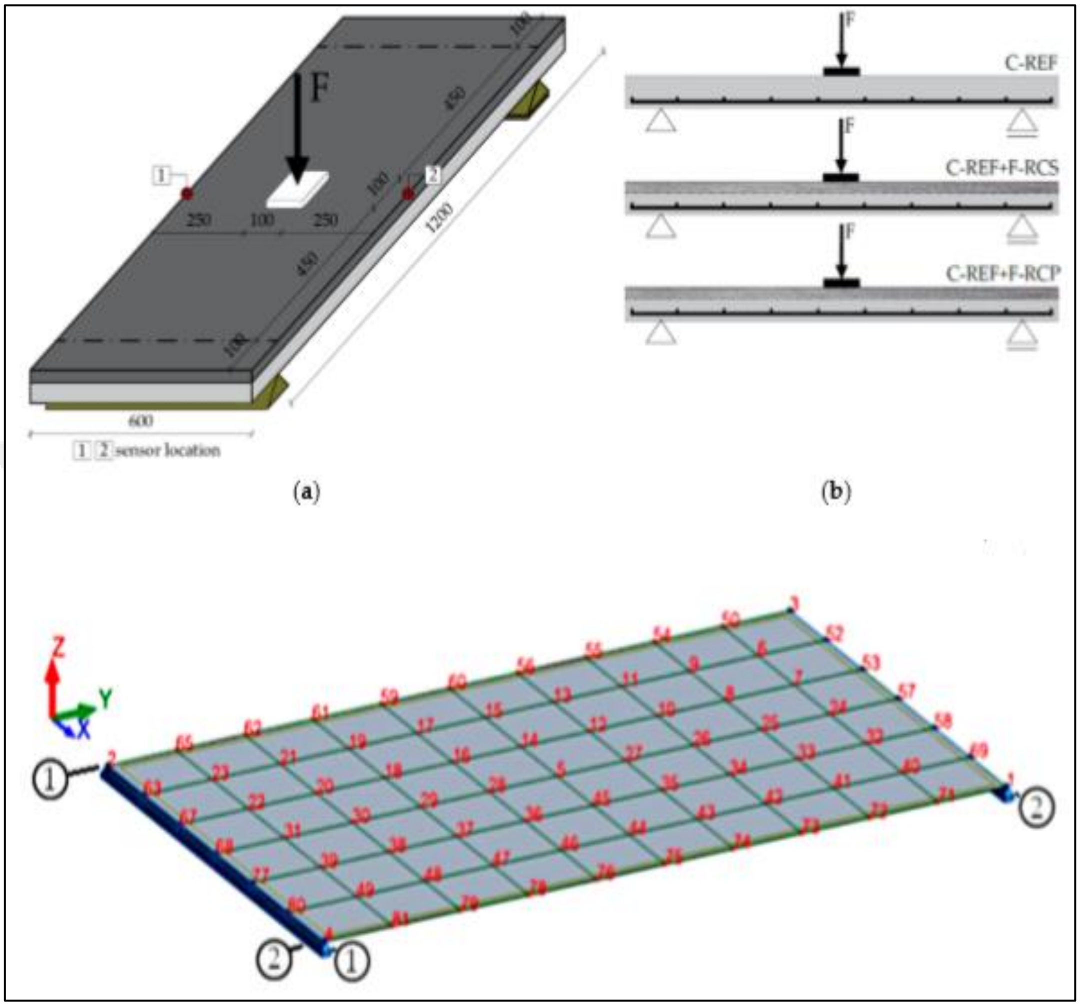

Figure 2.9: The numerical model of the fiber-reinforced slab [54].

It was found Reinforcing 30 mm of the slab with steel fibers was found to increase the load capacity by 12%. The composite fibers helped to reduce the cracks, as the study proved that the compressed region needs great forces until the cracks begin to appear.

[55] compered between predicted shear resistance of flat slabs estimated by kinematic theory and punching shear calculated by experimental test**s**. The kinematic approach relies on an analytical study considering steel fiber effects as a function of the standard opening of the failure crack, as illustrated in Figure 2.10, which calculating by two degrees of freedom.

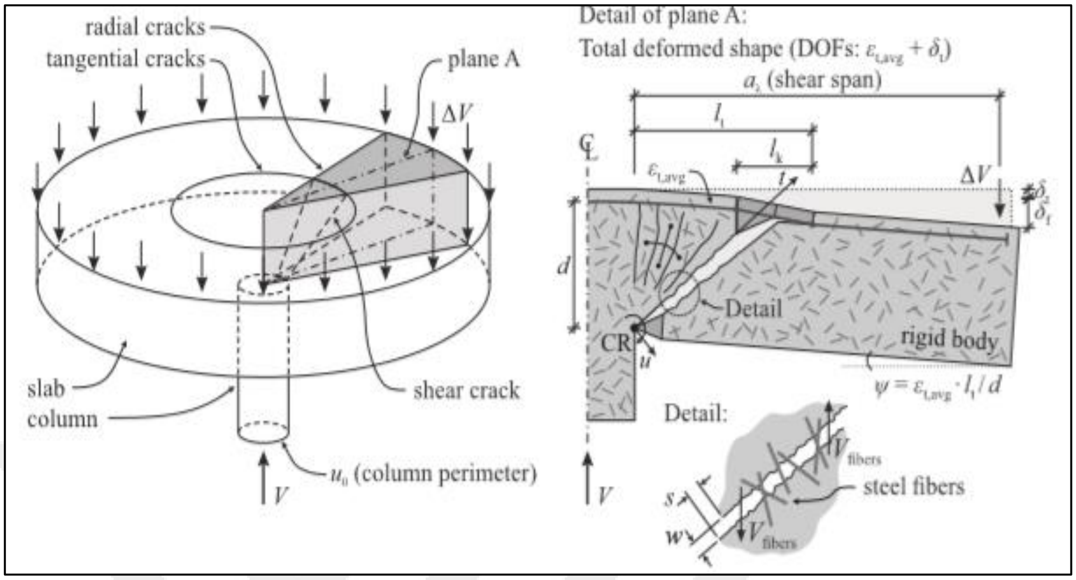

Figure 2.10: Major two parameters associated with the kinematic theory [55].

Furthermore, the punching shear tests were conducted by adding different volume fractions of steel fibers. Additionally, a parametric study was carried out to investigate the critical role of the punching shear resistance and the utilization of steel fibers in improving the robustness of concrete. The predicted punching shear resistance was compared to the results obtained from the mechanical tests. The basic parameters of the study were the fiber type (end hooked-crimped- straight). The research outcomes revealed that there was a significant agreement between the predicted shear resistance and kinematic theory. Further, using steel fibers has an outstanding impact on the punching shear behavior of flat slabs. By comparing steel fiber-reinforced slabs with non-reinforced slabs, the study showed an improvement in shear strength behavior and deflection as a result of adding steel fibers.

[56] carried out a study to assess and investigate the compressive strength, tensile, and flexural resistance of slabs by utilizing steel fibers. Slab specimens with dimensions (400 cm × 400 cm × 15 cm) were loaded using a two-point loading test. The length of the steel fibers was 60 mm, and the diameter was 0.75 mm. Volume ratios of steel fibers range from 1% to 5%. Slabs were reinforced by 10 mm with 20 cm space. Steel fibers were added to the concrete, with a thickness of 2/3 of the thickness of the concrete slab.

The results showed maximum compressive resistance is achieved by adding 3% steel fibers, and it was compared with the compressive resistance of concrete slabs without adding steel fibers. The improvement rate was 14.21%, but there is no point in adding more than 3% of steel fibers as the resistance begins to decrease. As for the tensile strength, it improved by 38.15% when adding 2% of steel fibers compared to a sample without steel fibers. Also, with the increase in load, it was observed A slowdown in the appearance of cracks with the use of steel fibers between 4% and 5%.

[57] indicated by research to flexural behavior of one-way slabs. Experimental work was carried out by mixing blends consisting of cement, fine sand, and silica fumes. Steel fiber with a length of 30mm and diameter of 0.55 mm was added to the mixes. A strengthening process was carried out, replacing different volume ratios of primary reinforcement with (0.125% and 3.75%) steel fibers. Distorted steel reinforcement has a diameter of 6 mm and was utilized down the slab to withstand tensile stresses.

A compressive strength test was carried out by loading cubic specimens with dimensions (150 mm × 150 mm × 150 mm). Additionally, cylindrical models (150 mm × 300 mm) were used to perform the splitting tensile strength test .tension collapse occurred by applying compressive load. Furthermore, the modulus of rupture was estimated by testing three (100 mm × 100 mm × 50 mm) prism samples. One way-slab was investigated by the flexural strength test. Also, load-deflection curves were presented. The research concluded that flexural failure and deflection reduced by 20.09% to 59.91%of maximum applied load. Moreover, the steel replacement portion of 0.125% achieved the best enhancement of load capacity and deflection. The top value of ductility was achieved by replacing 0.125% of primary steel with fiber steel.

[21] conducted an analysis examining the impact of adding steel fibers to concrete slabs on the punching shear resistance .they found that integrating steel fibers into concrete would reduce the punching shear and increase the slabs’ punching shear resistance.

2.4 LITERATURE REVIEW SUMMARY

The literature review publications reviewed in this work can be summarized in Table 2.1.

Table 2.1: Summary of significant contributions related to the literature publications addressed in this work.

#	Author(s)	Year	Paper Title	Major Contributions
1	Liu, Pan, et al.	2022	Mechanical Properties and Axial Compression Deformation Property of Steel Fiber Reinforced Self-Compacting Concrete Containing High Level Fly Ash.	The study confirmed that the addition of fly ash with a percentage of (50-70%) increased the performance of self-compacted concrete compared to other samples that do not contain fly ash. Also, Flexibility mixes by adding steel fibers of different proportions decreased, and reached a severe value by adding more amount of steel fiber and high amount of fly ash.Additionally, Adding fly ash to the self-compacted concrete and steel fibers enhances the compressive strength significantly, and its effect was noticeable on the tensile and flexural properties, as adding steel fibers by 1% and in the presence of fly ash by 60% helped improve the tensile capacity by 22% and the flexural resistance by 58%.
2	Majain, N., et al	2018	Effect of steel fibers on self-compacting concrete slump flow and compressive strength	The researchers indicated the addition of steel fibers helped to improve the load capacity of the samples, as it was noted that an improvement in the forms of collapse and a reduction in cracks.

Table 2.1: Summary of significant contributions related to the literature publications addressed in this work "tables continued".

3	Saba, Abdalla M., et al	2021	Strength and flexural behavior of steel fiber and silica fume incorporated self-compacting concrete	Researchers affirmed adding 20% silica fume and 5% steel fiber)to SCC blends can give high flexibility, and these proportions were recommended in construction buildings. Moreover, adding 0.5% steel fiber increased the compressive strength by 12.5% Also, in the event that 20% of the cement was replaced with silica, the concrete samples achieved more economical and resistance
4	Ahmad, Jawad, et al	2020	A study on mechanical and durability aspects of concrete modified with steel fibers (SFs)	Researchers concluded Although the flexural strength of the samples increased by 2%, steel fiber strength decreased when 2% of steel fibers was used. Also, the durability of specimens has been increased.
5	Turk, Kazim, Mahmut Bassurucu, and Rifat Enes Bitkin	2020	Workability, strength and flexural toughness properties of hybrid steel fiber reinforced SCC with high-volume fiber	Researchers proved ASTM C1018 CODE wasn't beneficial to estimate the flexural behavior of fiber steel concrete .it was noticed hybrid reinforced SCC gives ductility achievement compared to macro steel fiber specimens. Also, the flexibility of SCC mixes decreased by adding a steel fiber ratio. All specimens reinforced by steel fiber achieved high tensile than specimens without fiber reinforcements.

Table 2.1: Summary of significant contributions related to the literature publications addressed in this work "tables continued".

7	Pająk, Małgorzata, Jacek Janiszewski, and Leopold Kruszka	2019	Laboratory investigation on the influence of high compressive strain rates on the hybrid fibre reinforced self-compacting concrete.	The results of the RBDWI test showed that the number of blows when the first crack appears and when collapsing increases as the content of steel fibers in the sample increases compared to the sample that does not contain steel fibers. The researchers also indicated that the number of blows decreases when the height of the fall is constant. The weight of the falling body increases in addition to the fact that the number of crashes decreases with the increase in the height of the fall and the more the weight of the falling body is constant Compared to the sample without steel fibers.
8	Köroğlu, Mehmet Alpaslan	2018	Behavior of composite self-compacting concrete (SCC) reinforced with steel wires from waste tires.	The researchers found that employing the steel fiber to reinforce self-compated concrete helped to enhance the load capacity of specimens. Also, cracks were reduced compared to those without steel fiber. Additionally, the durability of specimens was boosted by adding steel fiber by percentages (3% and 4%) .researchers indicated using the length of steel fiber 3 mm) gave remarkable enhancement in load capacity.
9	Nehme, Salem G., Roland László, and Abdulkader El Mir	2017	Mechanical performance of steel fiber reinforced self-compacting concrete in panels..	The results confirmed that the flexibility of SCC mixes is decreased by increasing steel fiber amounts. Also, Load-deflection behavior is enhanced by adding steel fibers.

Table 2.1: Summary of significant contributions related to the literature publications addressed in this work "tables continued".

10	Zeyad, A. M., et al	2018	Influence of steel fiber content on fresh and hardened properties of self-compacting concrete	The results showed that comparison between SCC and OPC, including 60 mm of HSF by replacing part of the cement with fly ash. SCC can be enhanced by adding 0.25% of hooked steel fiber. Replacing cement with fly ash has a significant effect in improving the properties of SCC, as well as reducing separation and discontinuities in mixes by a percentage up to 68%. The slump flow of SCC mixes is reduced by strengthening Scc with steel fiber.
11	Saadoon, A. M., Mashrei, M. A., & Al Oumari, K. A	2022	Punching shear strength of recycled aggregate-steel fibrous concrete slabs with and without strengthening	The experimental analysis affirmed that adding steel fibers could significantly increase the punching shear resistance of the concrete slabs.
12	Eren, N. A	2022	Punching shear behavior of geopolymer concrete two-way flat slabs incorporating a combination of nano silica and steel fibers	They found that adding steel fibers to the slabs would reduce the deflection amount and minimize the cracking growth.
13	Xiang *et al*	2022	Improvement of flexural and cyclic performance of bridge deck slabs by utilizing steel fiber reinforced concrete (SFRC).	Their analysis confirmed that integrating these fibers into concrete slabs would improve the cyclic and flexural performance related to the bridge deck slabs and reduce deflection and increase its stiffness.

Table 2.1: Summary of significant contributions related to the literature publications addressed in this work “tables continued”.

14	Hussain, Haleem K., Abdulnasser M. Abbas, and Mohammed Farhan Ojaimi.	2017	Fiber-type influence on the flexural behavior of rc two-way slabs with an opening	Concrete samples reinforced with steel fibers showed an improvement in compressive strength when using steel fibers of (hooked-corrugated) type. As for the poly type, it contributed a small improvement in the compressive strength compared to the non-reinforced samples, and the improvement rate in the compressive strength ranged from 11.3% to 24.8%. The steel fibers of type (hooked-corrugated) gave the greatest value for the improvement in the tensile strength of the samples in comparison with other types, and the percentage of improvement in the tensile strength ranged from 77% to 99%. When the modulus of rupture factor was studied, the steel fibers achieved the best performance of the samples with a percentage of 109%. A significant and obvious improvement in crack reduction was observed in the samples using hooked-type steel fibers.
15	Nassif, Nadia, et al	2021	Assessment Of Punching Shear Strength Of Fiber-reinforced Concrete Slabs Using Factorial Design Of Experiments	The research affirmed punching shear capacity enhanced by increasing fiber amount, steel portion, and slab thickness. However, the thickness slab is the most factor that impacts the punching shear strength of a flat slab.

Table 2.1: Summary of significant contributions related to the literature publications addressed in this work “tables continued”.

16	Sadowska-Buraczewska, Barbara, et al	2021	Flexural behavior of composite concrete slabs made with steel and polypropylene fibers reinforced concrete in the compression zone	It was found that reinforcing 30 mm of the slab with steel fibers would increase the load capacity by 12%. The composite fibers helped reduce the cracks, as the study proved that the compressed region needs great forces until the cracks appear.
17	Kueres, Dominik, Maria Anna Polak, and Josef Hegger	2019	Two-parameter kinematic theory for punching shear in steel fiber reinforced concrete slabs	The researchers revealed agreement between prediction shear resistance and kinematic theory. Also, using steel fibers has a remarkable impact on the punching shear behavior of flat slabs. By comparing steel fiber-reinforced slabs with non-reinforced slabs, the study showed an improvement in shear strength behavior and deflection due to adding steel fibers.
18	Ananda, Faisal, et al	2020	"Effect the used of steel fibers (Dramix) on reinforced concrete slab.	The results showed maximum compressive resistance is achieved by adding 3% steel fibers, which was compared with the compressive resistance of concrete slabs without adding steel fibers. The improvement rate was 14.21%, but there is no point in adding more than 3% of steel fibers as the resistance begins to decrease. The tensile strength improved by 38.15% when adding 2% of steel fibers compared to a sample without steel fibers.

Table 2.1: Summary of significant contributions related to the literature publications addressed in this work "tables continued".

19	Jomaa'h et al	2018	Effect of replacing the main reinforcement by steel fibers on flexural behavior of one-way concrete slabs	The research concluded that flexural failure and deflection reduced by 20.09% to 59.91%of maximum applied load. Moreover, the steel replacement portion of 0.125% achieved the best load capacity and deflection enhancement. The top value of ductility was achieved by replacing 0.125% of primary steel with fiber steel.
20	Suparlan *et al*	2018	Preliminary investigation on the flexural behaviour of steel fibre reinforced self-compacting concrete ribbed slab	they found that integrating steel fibers into concrete would reduce the punching shear and increase the slabs' punching shear resistance.

2.5 CHAPTER SUMMARY

It can be inferred from the literature carried out in this chapter that the steel fiber material gave great effectiveness in improving the performance of concrete structures, as it was able to give great tensile strength, compression strength and reduce the flexural behavior of concrete slabs .in addition to, its role in enhancing flexibility and rigidity.

3. RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter shows the analysis work done on two-way ribbed slabs (Waffle Slabs (WSs)). Two waffle slabs system are considered: waffle with internal beams and waffle with solid sections at columns. As for materials, the effect of adding steel fibers to concrete on the structural behavior of waffle slabs is investigated. Several outputs are extracted: maximum deflection, flexure reinforcement ratio, and shear reinforcement ratio. These outputs are essential to reach the final conclusion about the best two-way ribbed slab system to be adopted in slab design.

3.2 ANALYSIS PROCEDURE

3.2.1 Cases Description

In this thesis project, a floor system of three by three panels was examined; each board has a span of 12 m by 10 m to be utilized for residential purposes. To evaluate two optimal waffle slab systems in terms of performance, seven cases, as described in Table 3.1, representing two waffle slab support systems and a concrete additive, were studied.

Case C1 is a beam-supported two-way waffle slab. To investigate the behavior of a standard solid slab, case C2 was included. Fibers were introduced into concrete in Case C3 to study the effect of fibers on waffle slabs with beams. Case C4 depicts a waffle slab with solid sections at the columns for the second slab system. Furthermore, in Case C5, a flat plate was investigated to assess the effect of adding substantial sections in Case C4. Therefore, Case C6 investigated the influence of fibers in a waffle slab with a solid unit at the columns. Finally, Case C7 displays a concrete waffle slab with beams, substantial parts, and fibers.

Table 3.1: Cases description related to the research work.

<table>
<tr><th>Case ID</th><th>Number of panels</th><th>Span length (m)</th><th>Presence of beams along support lines</th><th>Presence of solid sections in columns</th><th>Addition of fibers to concrete</th></tr>
<tr><td>C1</td><td>3x3</td><td>12x10</td><td>√</td><td>X</td><td>X</td></tr>
<tr><td>C2</td><td rowspan="6">3x3</td><td>12x10</td><td colspan="3">Solid slab</td></tr>
<tr><td>C3</td><td>12x10</td><td>√</td><td>X</td><td>√</td></tr>
<tr><td>C4</td><td>12x10</td><td>X</td><td>√</td><td>X</td></tr>
<tr><td>C5</td><td>12x10</td><td colspan="3">Flat plate</td></tr>
<tr><td>C6</td><td>12x10</td><td>X</td><td>√</td><td>√</td></tr>
<tr><td>C7</td><td>12x10</td><td>√</td><td>√</td><td>√</td></tr>
</table>

3.2.2 Slab Sections

Slab topping depth is typically 10 cm thick. The width of the ribs is 15 cm, and ribs usually have steel rod reinforcements. The voids between ribs' dimensions are (60 × 60 × 28) cm in length, width, and height, respectively, and have 54 × 54 cm maximum dimensions. The slab section is shown in Figure 3.1. For both situations, the preliminary slab thickness was 38 cm.

3.2.3 Columns and Beam Sections

The cross-sectional dimensions of all columns were assumed to be 50 x 50 cm. Meanwhile, the cross-section of the beams was set to be 30 x 70 cm. The floor height was assumed to be 3 m.

3.2.4 Analysis Strips

In the X and Y directions, the two-way slab with beams along the support was subdivided into exterior and interior beam strips, as mentioned in Figure 3.1.

Similarly, the two-way slab with a solid section at the columns was divided in both directions into exterior and interior column strips, as shown in Figure 3.2.

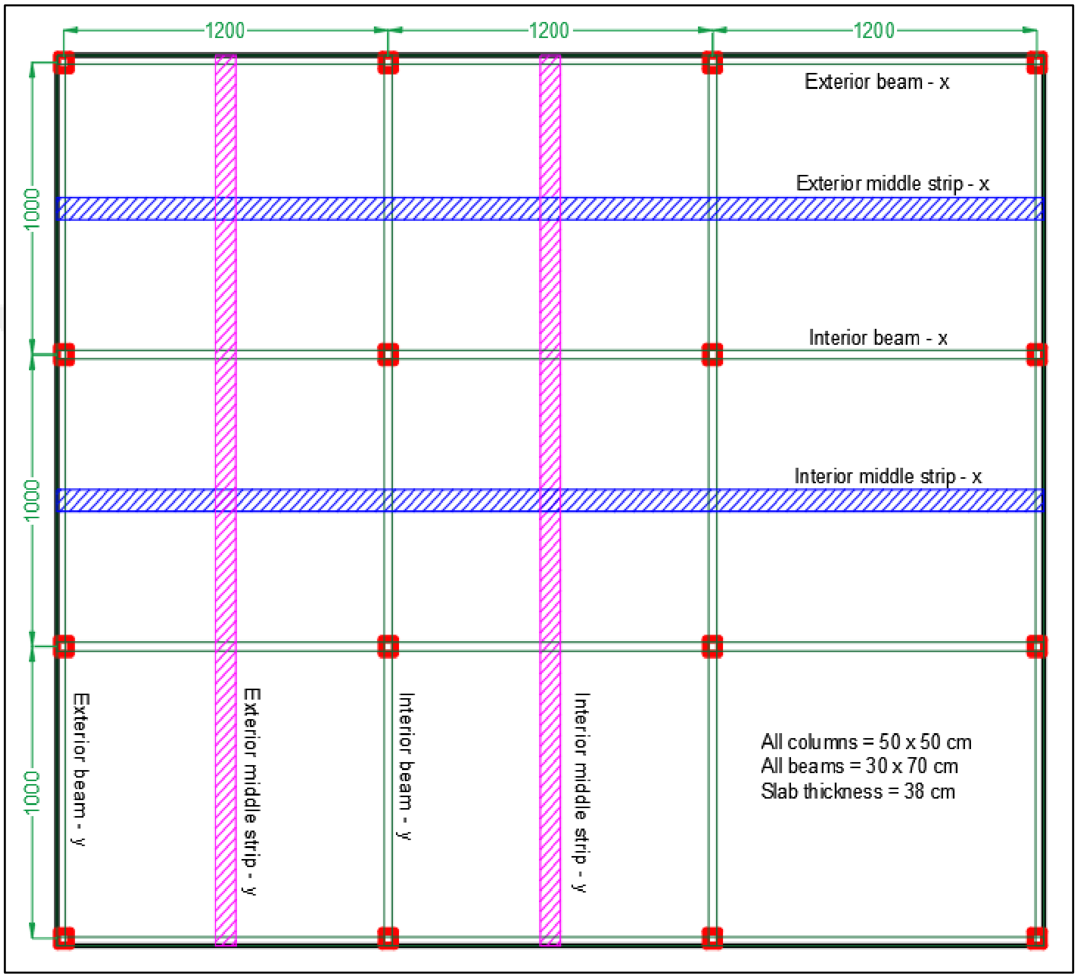

Figure 3.1: A representation of the slab plan.

Furthermore, exterior and interior middle strips were assessed in short and extended directions.

The width of the strip was calculated as follows:

W = Void Width/2 + Void Width/2 + Rib Width

W = 60/2 + 60/2 + 15 = 75 cm.

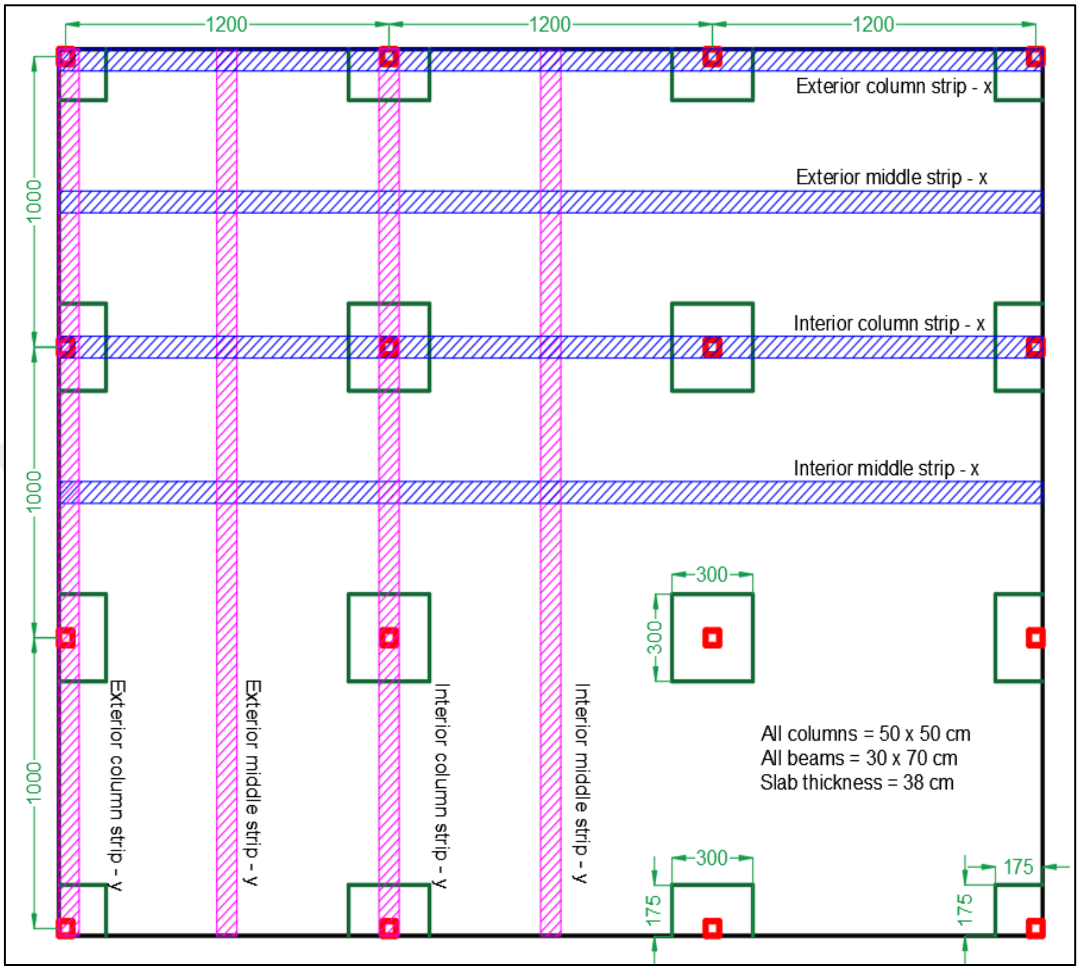

Figure 3.2: Analysis strips for waffle slab with solid sections of exterior and interior column strips.

3.3 RESEARCH METHOD

The research methodology related to this work depends on some critical steps and research phases necessary to achieve the goals of this thesis. Firstly, the research relied on a comprehensive review to help identify critical contributors and beneficial impacts of integrating steel fiber into the SCC to enhance its workability, performance, structural behavior, and mechanical properties. Furthermore, the literature is vital to collect the essential secondary data that address the relevance of steel fiber in two-way ribbed slabs to foster its practicality and functionality in the construction project. Following this step, a numerical approach is adopted. In this approach, seven case studies are taken into account. The seven case studies differ in some aspects, translated by:

i. The presence of beams along support lines,

ii. The existence of solid sections in columns,

iii. The addition of fibers to concrete.

The aim of mathematical simulations and numerical modeling of the seven cases related to the two-way ribbed slabs includes investigating the effect of the addition of steel fibers on the structural behavior of waffle slabs. After carrying out the numerical analysis, the following aspects will be assessed, which include:

i. The impact of the waffle system adopted,

ii. The effect of adding steel fibers to concrete on a waffle slab with beams,

iii. The influence of adding steel fibers to concrete on a waffle slab with solid sections,

iv. The effect of adding steel fibers to concrete on a waffle slab with both beams and solid sections.

Then, modifications and amendments are conducted on the research findings based on construction experts and numerical modeling professionals' points of view.

Finally, conclusions and recommendations are drawn to help scholars, students, and professionals conduct significant improvements and enhancements to the study outcomes.

Figure 3.3 represents the research methodology flowchart.

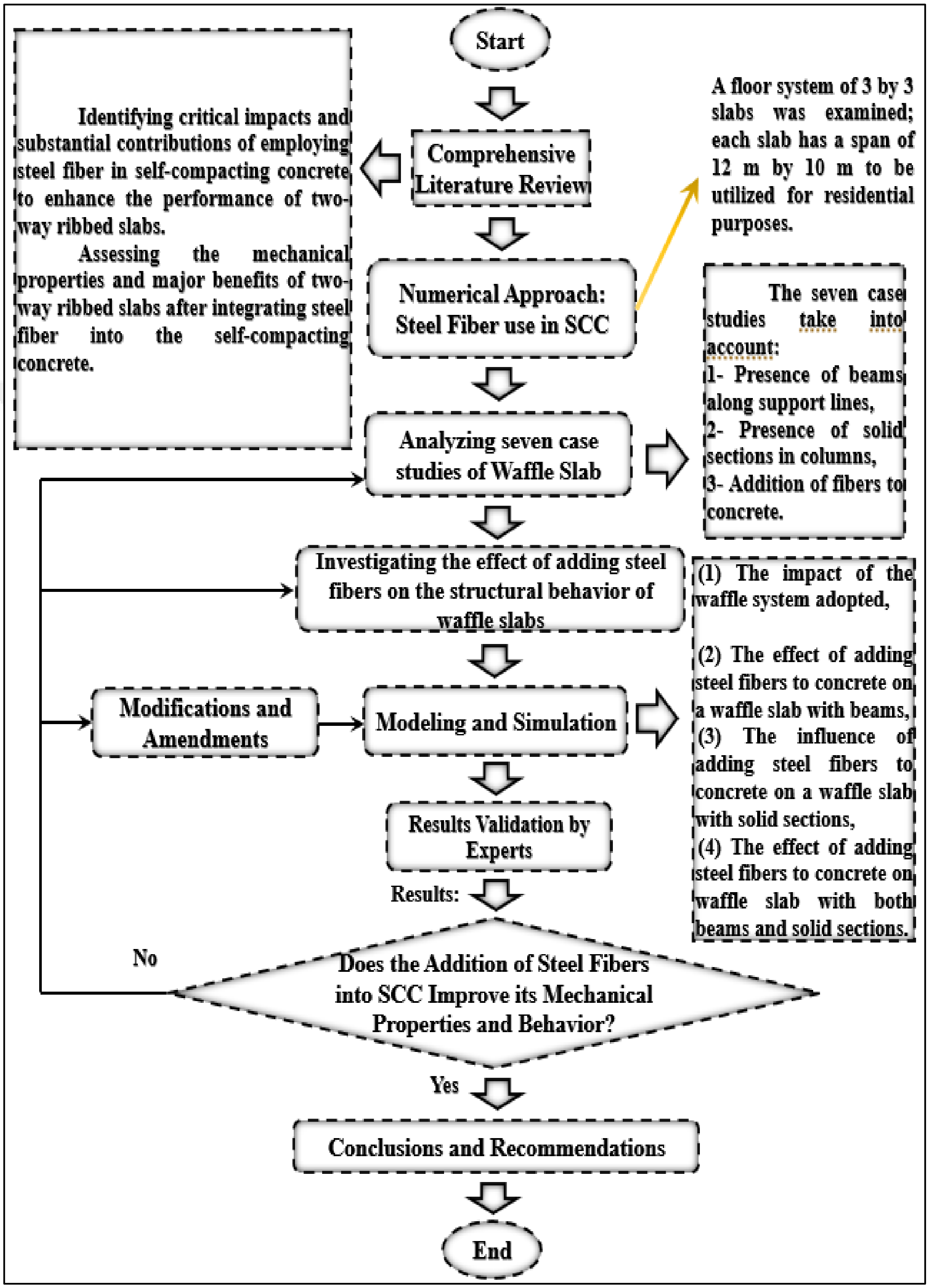

Figure 3.3: The research methodology flowchart.

3.4 MATERIAL PROPERTIES

The compressive strength of concrete without fibers was chosen to have "f'c= 45 Mpa Referring to the experimental study done by [58], the compressive strength of concrete with fibers had an "f'c=70". Regarding the steel properties, the yield stress for flexural steel was chosen to be 400 MPa and 320 MPa for shear reinforcement. Concrete properties are represented in Table 3.2.

Table 3.2: Major concrete properties.

Concrete mix	Compressive strength (MPa)	Flexural strength (MPa)	Elasticity modulus (MPa)
C45	45	5.5	37,900
C70	70	11.5	42,200

Furthermore, the significant characteristics of the steel are described in Table 3.3.

Table 3.3: The significant characteristics of the steel.

Steel grade	Yield strength (MPa)	Ultimate strength (MPa)	Elasticity modulus (MPa)
T400	400	500	200,000
T320	320	400	200,000

3.5 NUMERICAL MODELING

Two waffle slab systems were analyzed by finite element using CSI SAFE 2016 program, including seven Cases. The design of the slab was done as a shell element. The shell is a three or four-node area object that models plate bending behavior. Otherwise, beams and columns were designed as frame elements. In the finite element method, the slab is divided into elements to create a mesh. The mesh size has to be small in order to have more accurate results. The meshing of the slab specimen is shown in Figure 3.4.

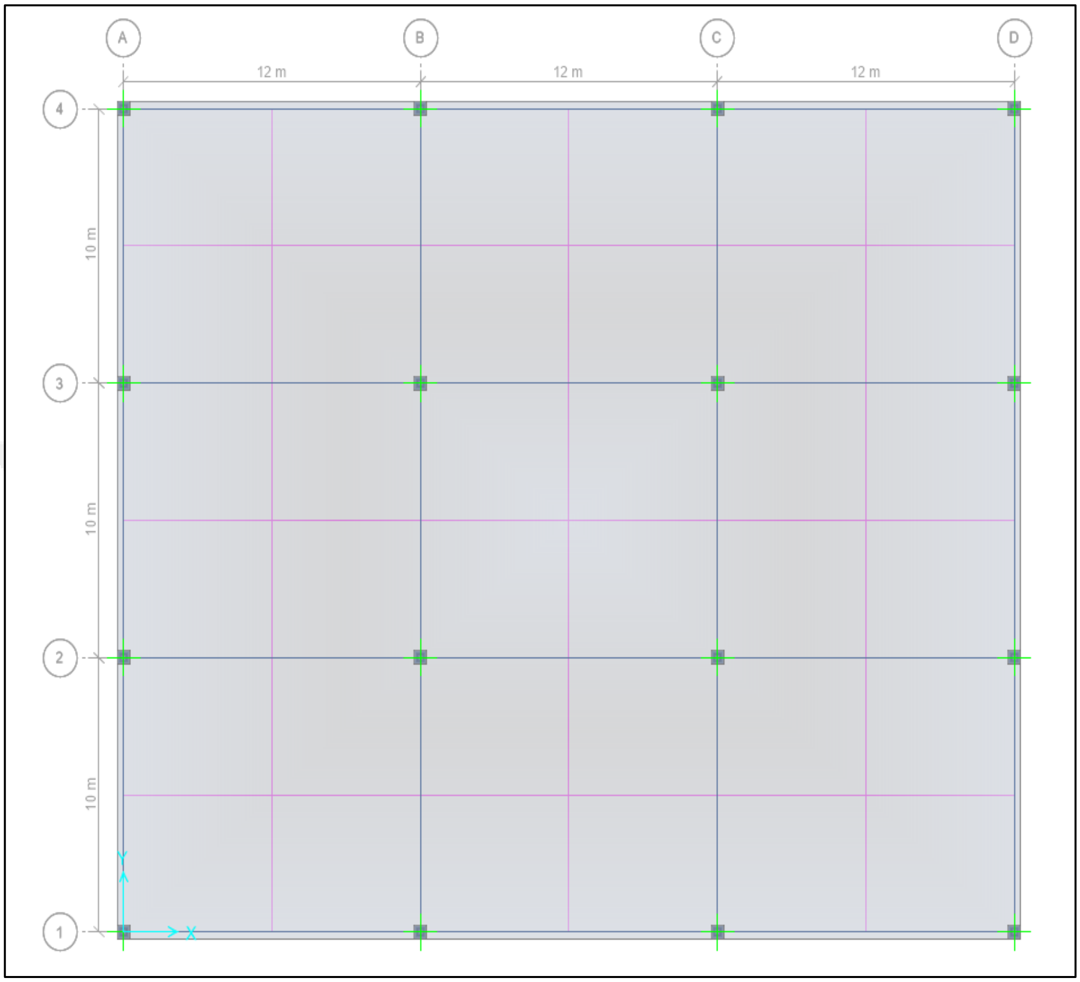

Figure 3.4: Meshing in waffle slab with beams.

It is worth mentioning that the meshing length was used as 0.5 m.

Further, Figure 3.5 represents the meshing process of the slab, considering the solid sections.

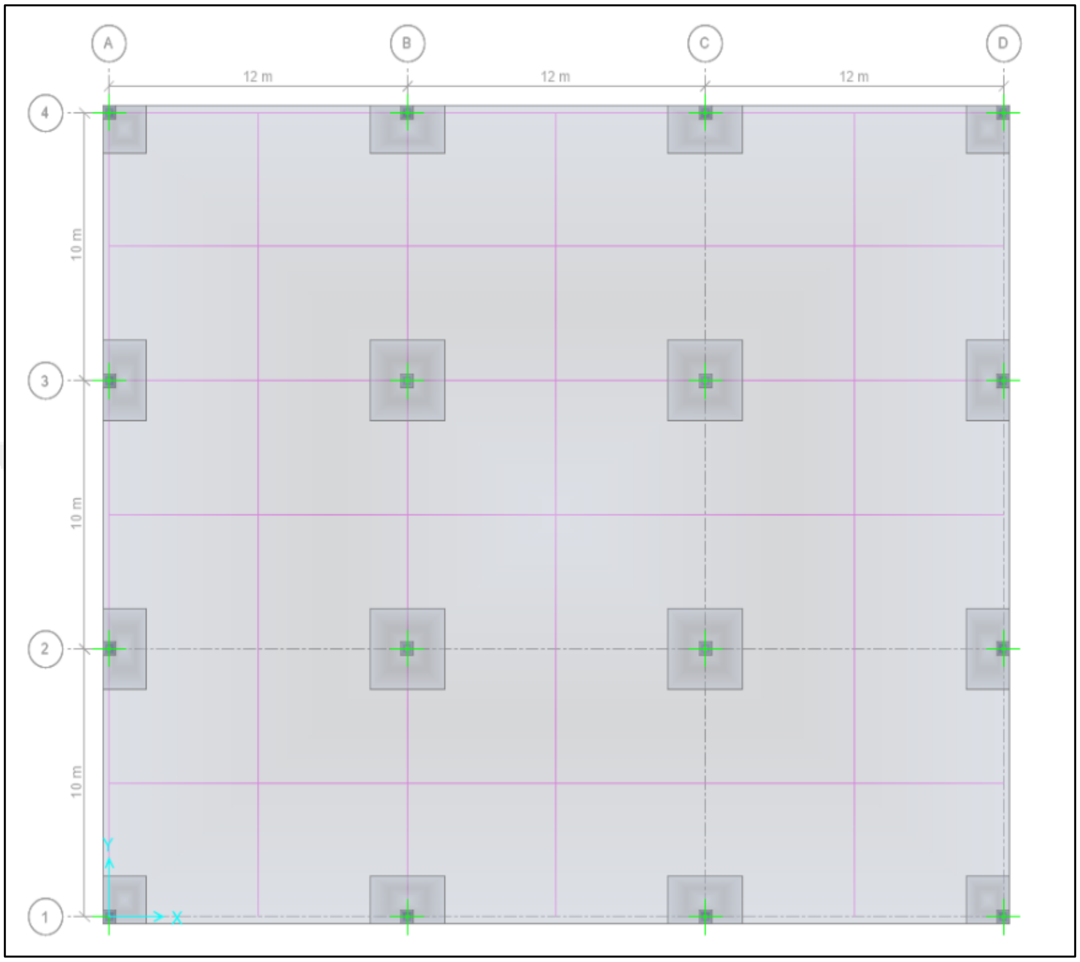

Figure 3.5: Meshing in waffle slab with solid sections.

3.6 DEFINITIONS OF RESEARCH MATERIALS

Figure 3.6 illustrates the definition of the boundary conditions, inputs, and constraints associated with conventional concrete properties.

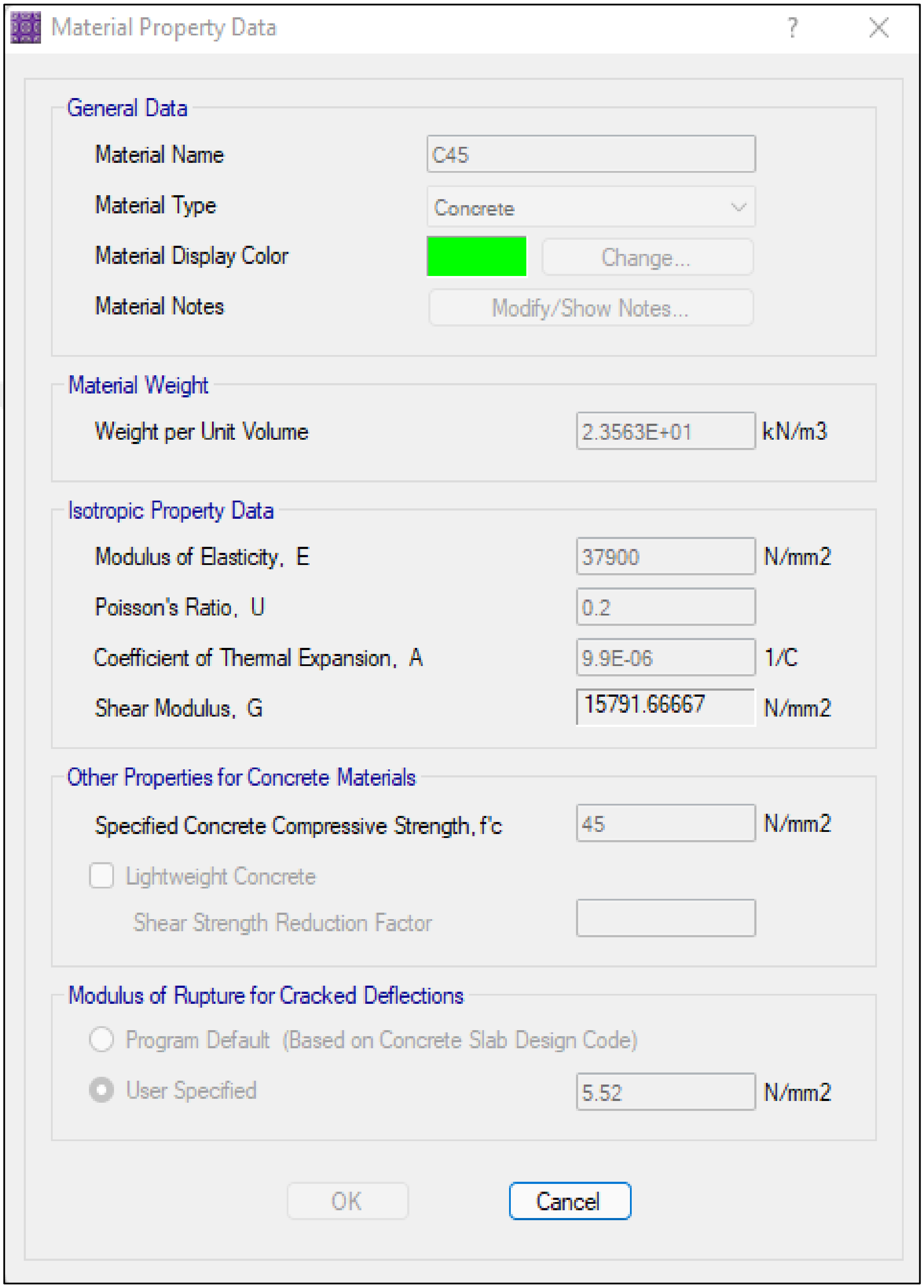

Figure 3.6: The definition of the boundary conditions, inputs, and constraints associated with conventional concrete properties.

In addition, Figure 3.7 illustrates the definition of the boundary conditions, inputs, and constraints associated with the SSC properties, which employ steel fibers.

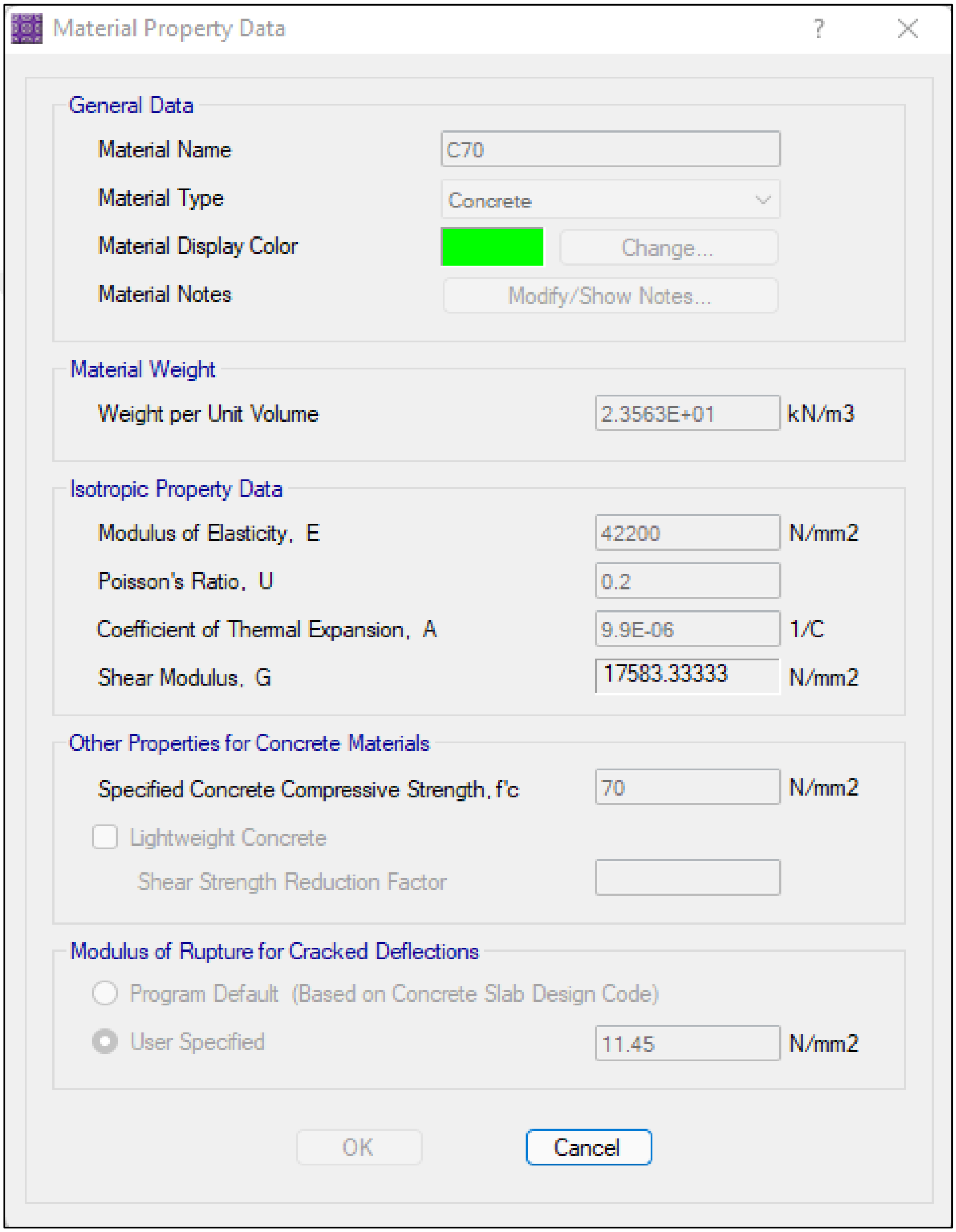

Figure 3.7: The definition of the boundary conditions, inputs, and constraints associated with the SSC properties, which employ steel fibers.

Also, Figure 3.8 illustrates the definition of the boundary conditions, inputs, and constraints associated with flexural reinforcement properties.

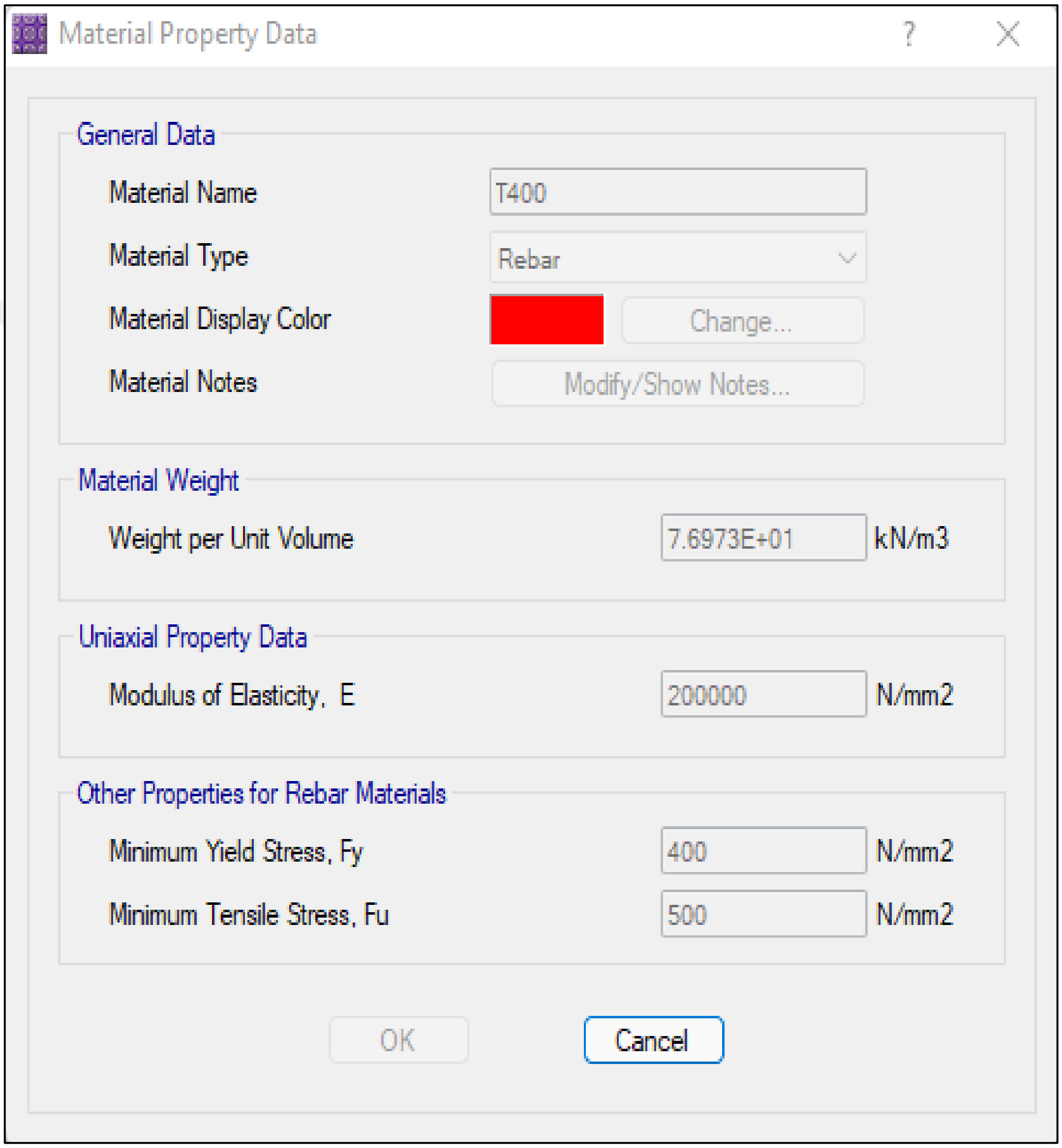

Figure 3.8: The definition of the boundary conditions, inputs, and constraints associated with flexural reinforcement properties.

Moreover, Figure 3.9 illustrates the definition of the boundary conditions, inputs, and constraints associated with shear reinforcement properties.

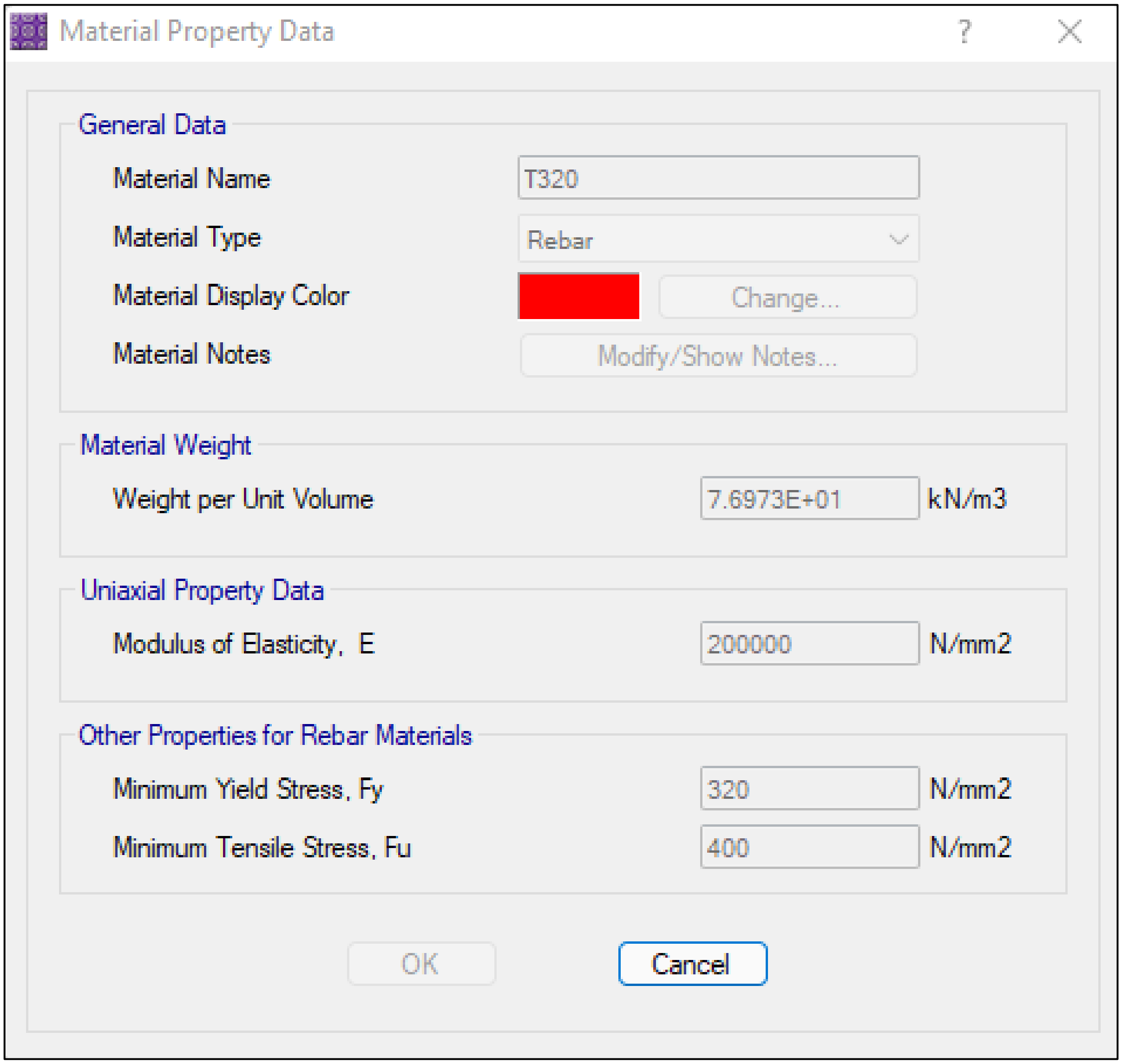

Figure 3.9: The definition of the boundary conditions, inputs, and constraints associated with shear reinforcement properties.

3.7 SECTIONS INPUTS

In addition to the definition of the previous variables, the numerical analysis requires defining the boundary conditions, inputs, and constraints associated with sections. Figure 3.10 represents the definition of the boundary conditions, inputs, and constraints related to sections.

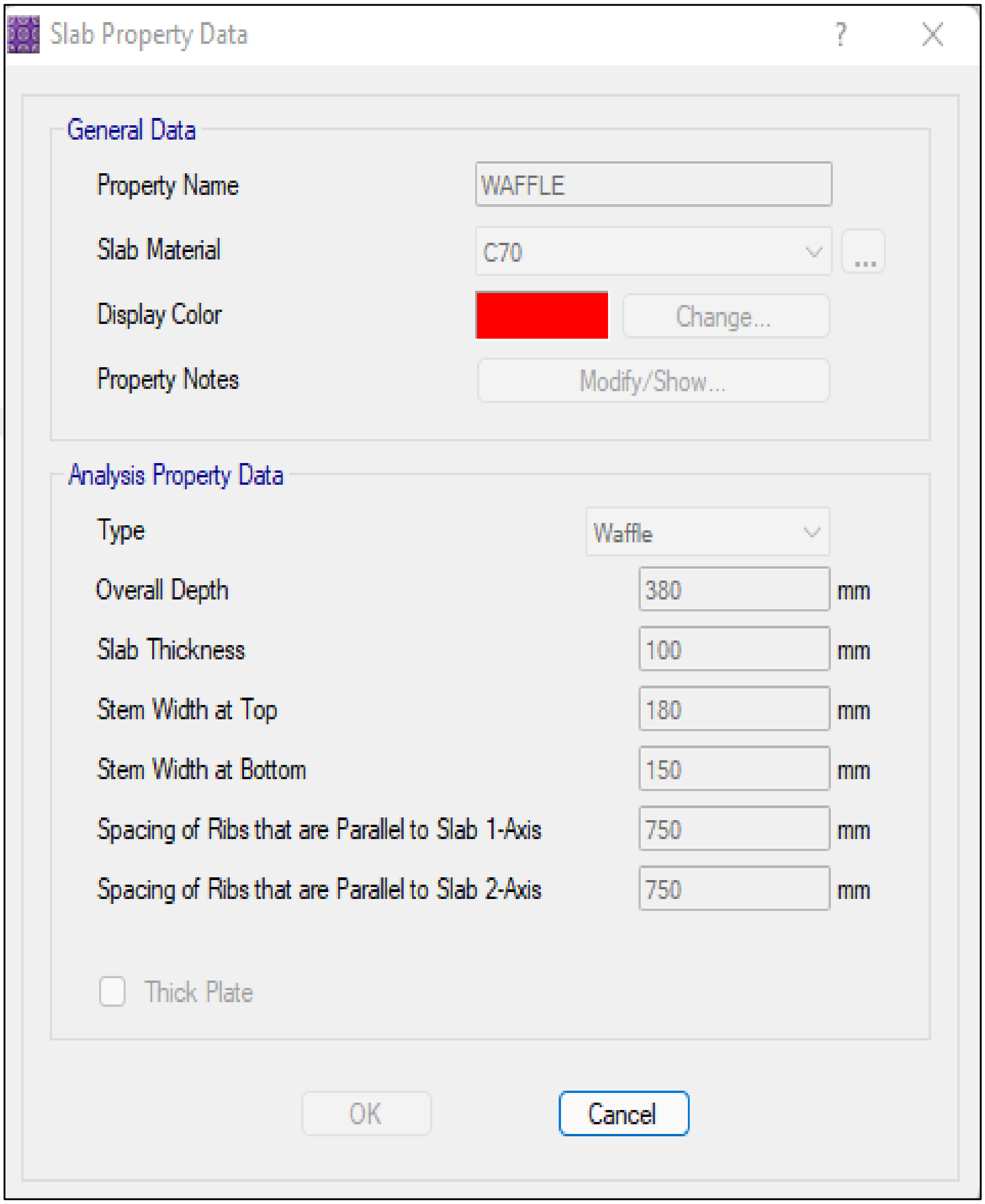

Figure 3.10: The definition of the boundary conditions, inputs, and constraints related to sections.

Further, Figure 3.11 describes the definition process of the boundary conditions, inputs, and constraints related to sections when the steel fibers are added.

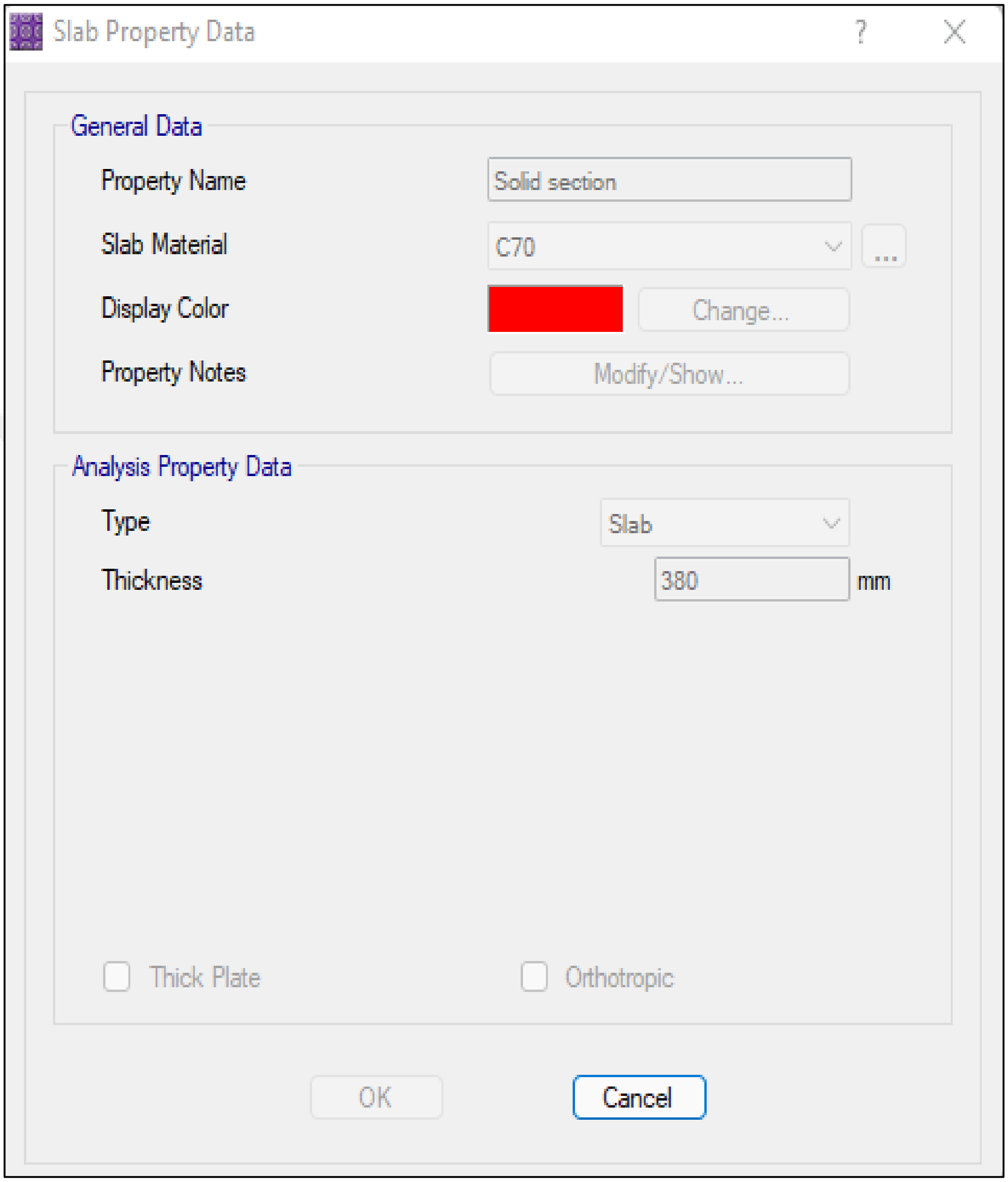

Figure 3.11: The definition process of the boundary conditions, inputs, and constraints related to sections when the steel fibers are added.

Moreover, Figure 3.12 describes the definition process of the boundary conditions, inputs, and constraints related to flat panel slab properties.

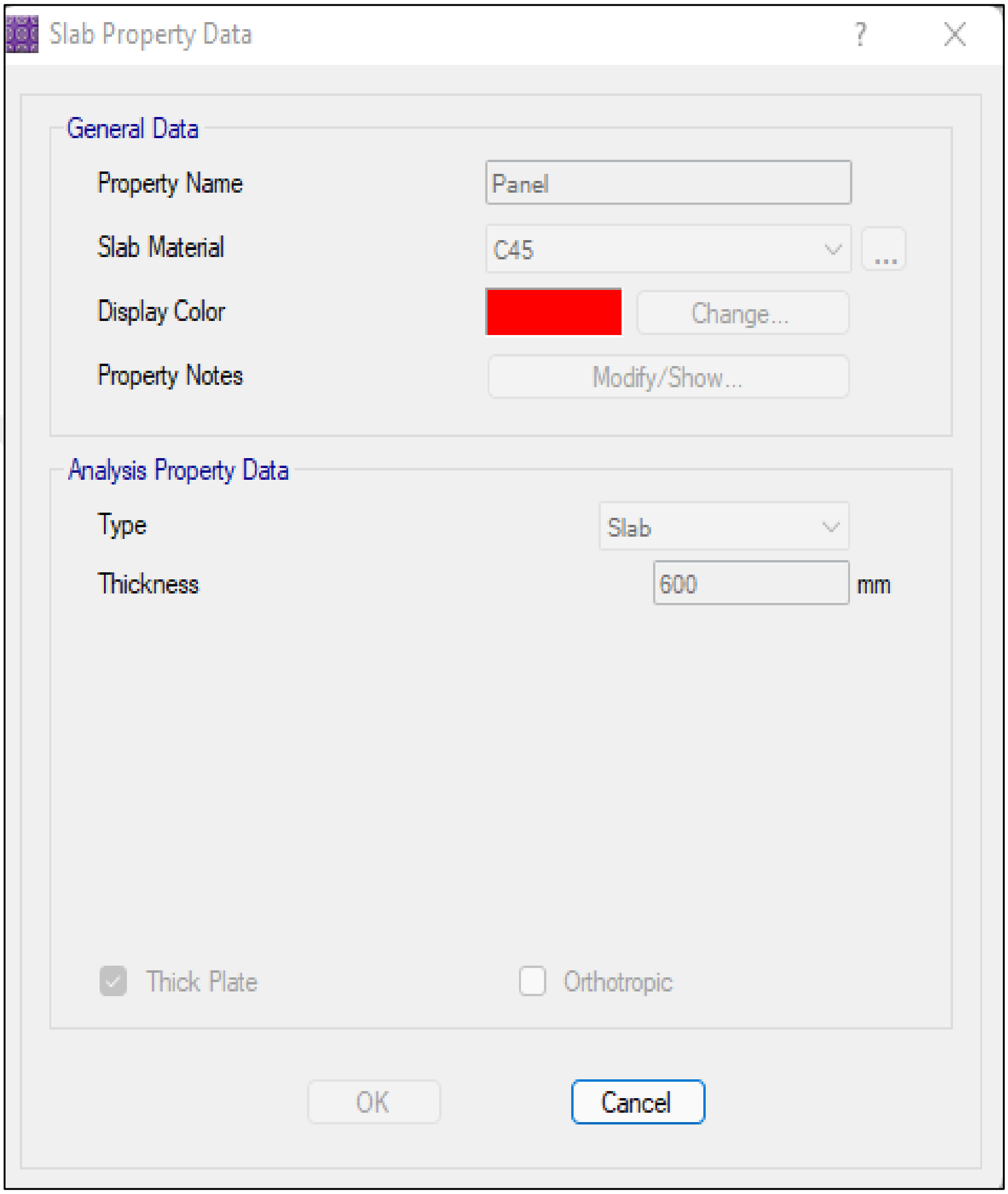

Figure 3.12: The definition process of the boundary conditions, inputs, and constraints related to flat panel slab properties.

In addition, Figure 3.13 describes the definition process of the boundary conditions, inputs, and constraints related to beam sections properties.

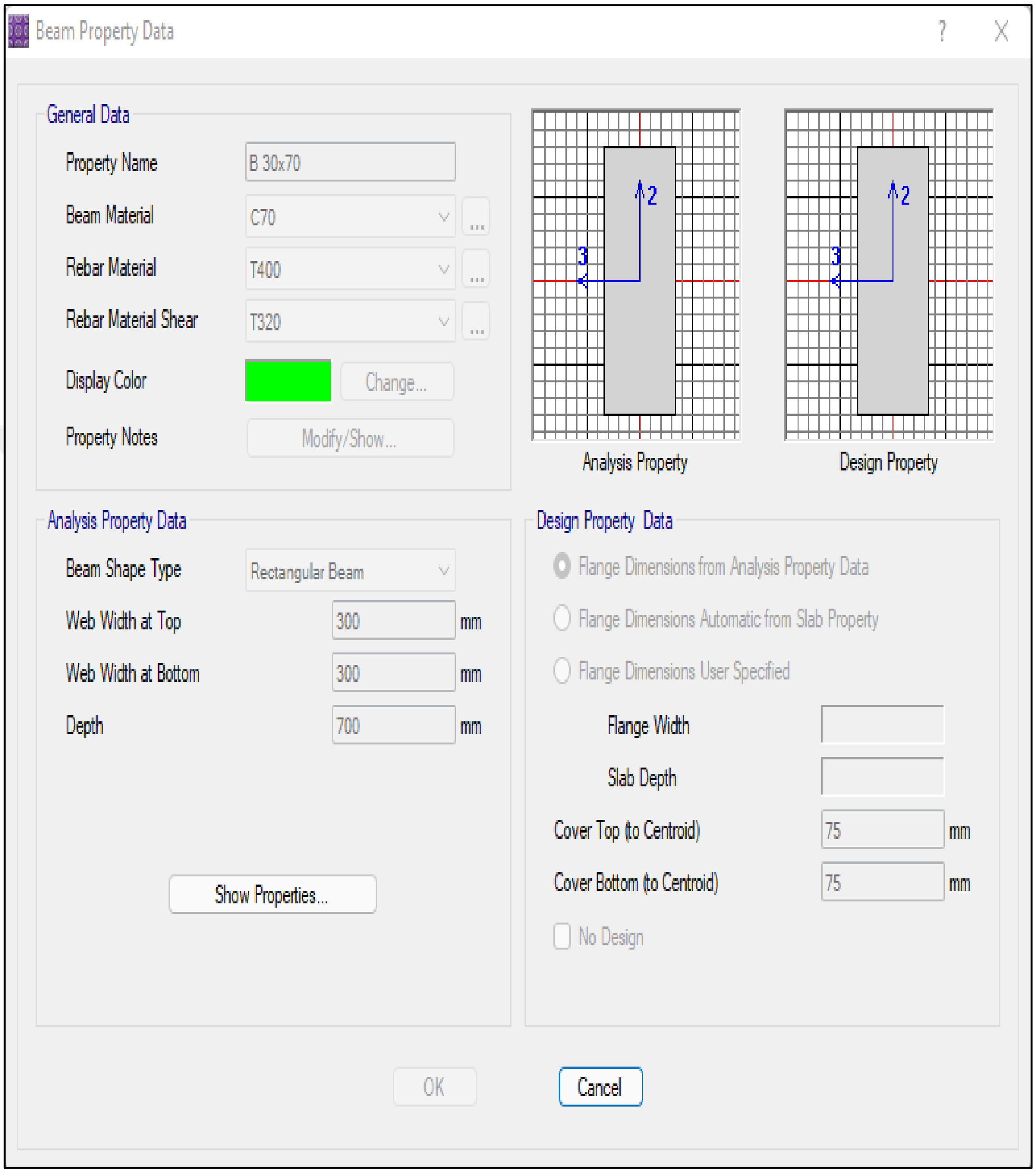

Figure 3.13: The definition process of the boundary conditions, inputs, and constraints related to beam section properties.

In addition, Figure 3.14 describes the definition process of the boundary conditions, inputs, and constraints related to column section properties.

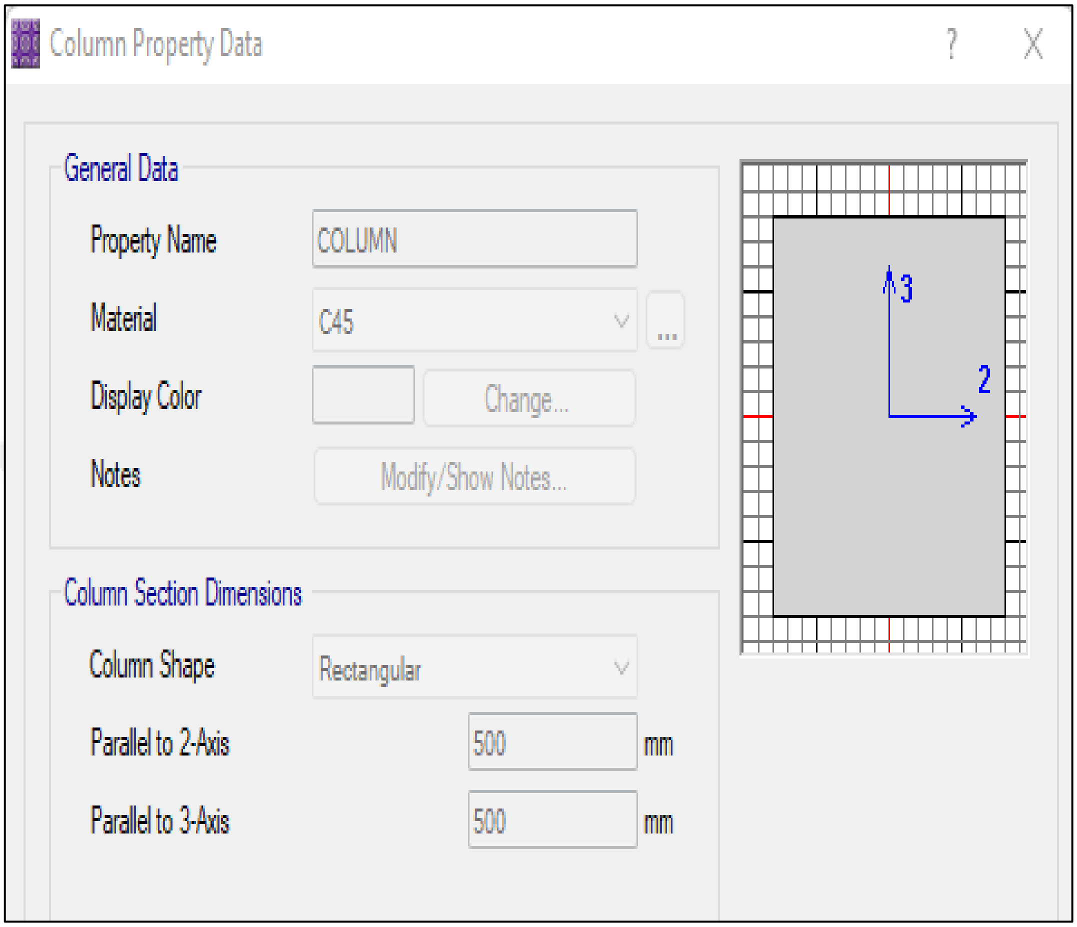

Figure 3.14: The definition process of the boundary conditions, inputs, and constraints related to column section properties.

3.8 LOADS AND COMBINATIONS

In this section, the definition of the dead load, superimposed dead load, live loads, and deflection control combinations are illustrated.

3.8.1 Dead Load

Dead load refers to loads relatively resulting from the self-weight of permanent components of the building, such as slabs, walls, beams, and columns.

The calculations are done by SAFE software package depending on an automatic manner. The dead loads are calculated using the member sections and their estimated material densities by the following equations:

i. Slab self-weight calculated as a planar load:

$$Q\ (kN/m^2) = \gamma c \times \text{Slab thickness}$$

ii. Beam self-weight calculated as a linear load:

$$W\ (kN/m) = \gamma c \times \text{beam height} \times \text{beam width}$$

iii. Column self-weight calculated as a concentrated load:

$$P\ (kN) = \gamma c \times \text{col. Height} \times \text{col. Length} \times \text{col. Width}$$

3.8.2 Super-Lmposed Dead Load (SDL)

Superimposed dead loads are the additional loads applied on a structure, by adding finishing, fault ceiling, plastering, and nonstructural elements to the building's structural elements' weight. It was assumed to be 5 kN/m^2.

3.8.3 Live Loads

Live loads include any temporary forces that act on a building or structural element. Typically, they include people, furniture, and almost everything else that can be moved throughout a building.

The live load (LL) is determined from ASCE 7-16/Table 4.1 [59]. The live load estimated value is 3 kN/m^2 for residential buildings. The definition of the inputs and boundary conditions linked to all live loads is illustrated in Figure 3.15.

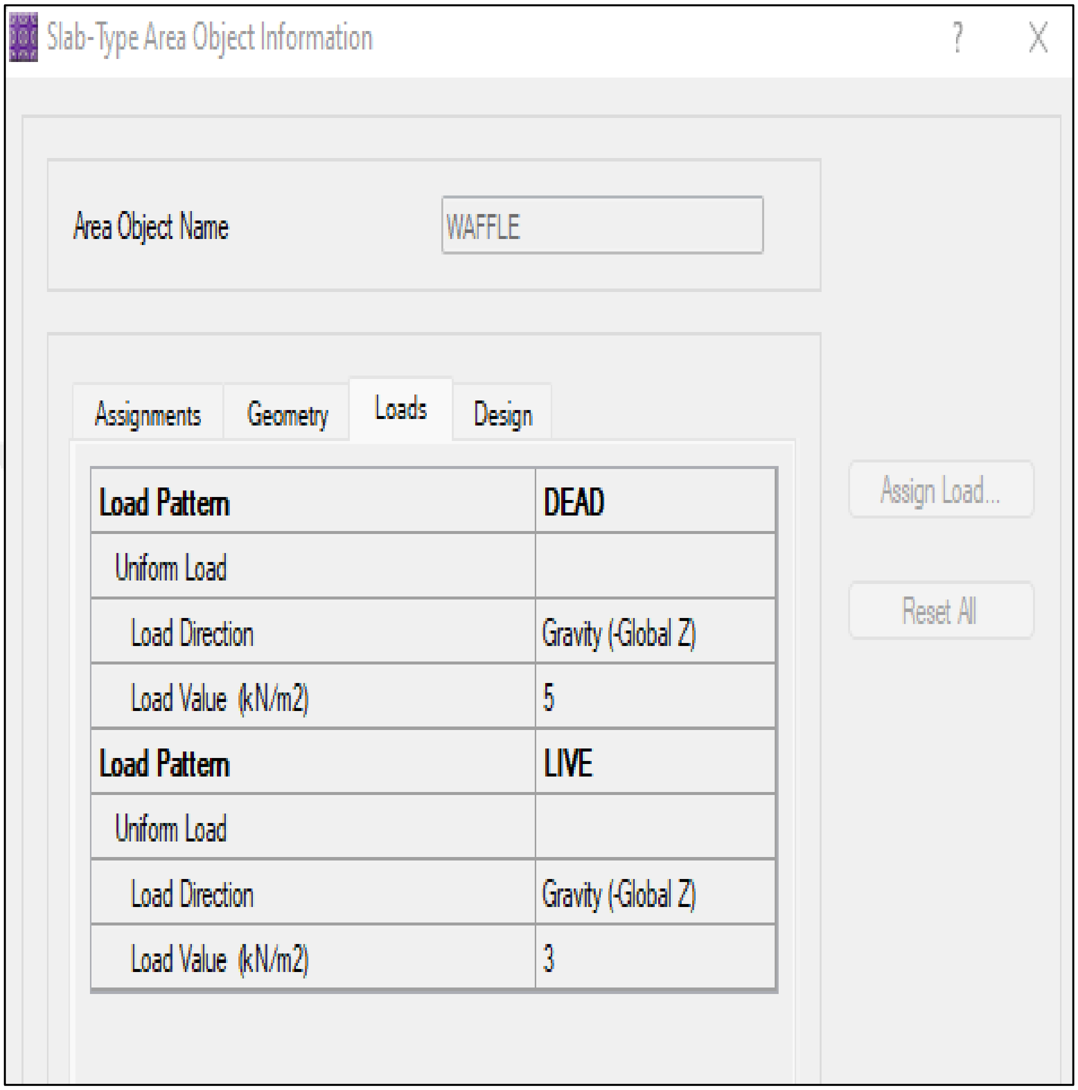

Figure 3.15: The definition of the inputs and boundary conditions linked to the live loads.

In addition, Figure 3.16 represents the selection and determination of the ultimate combination 1.

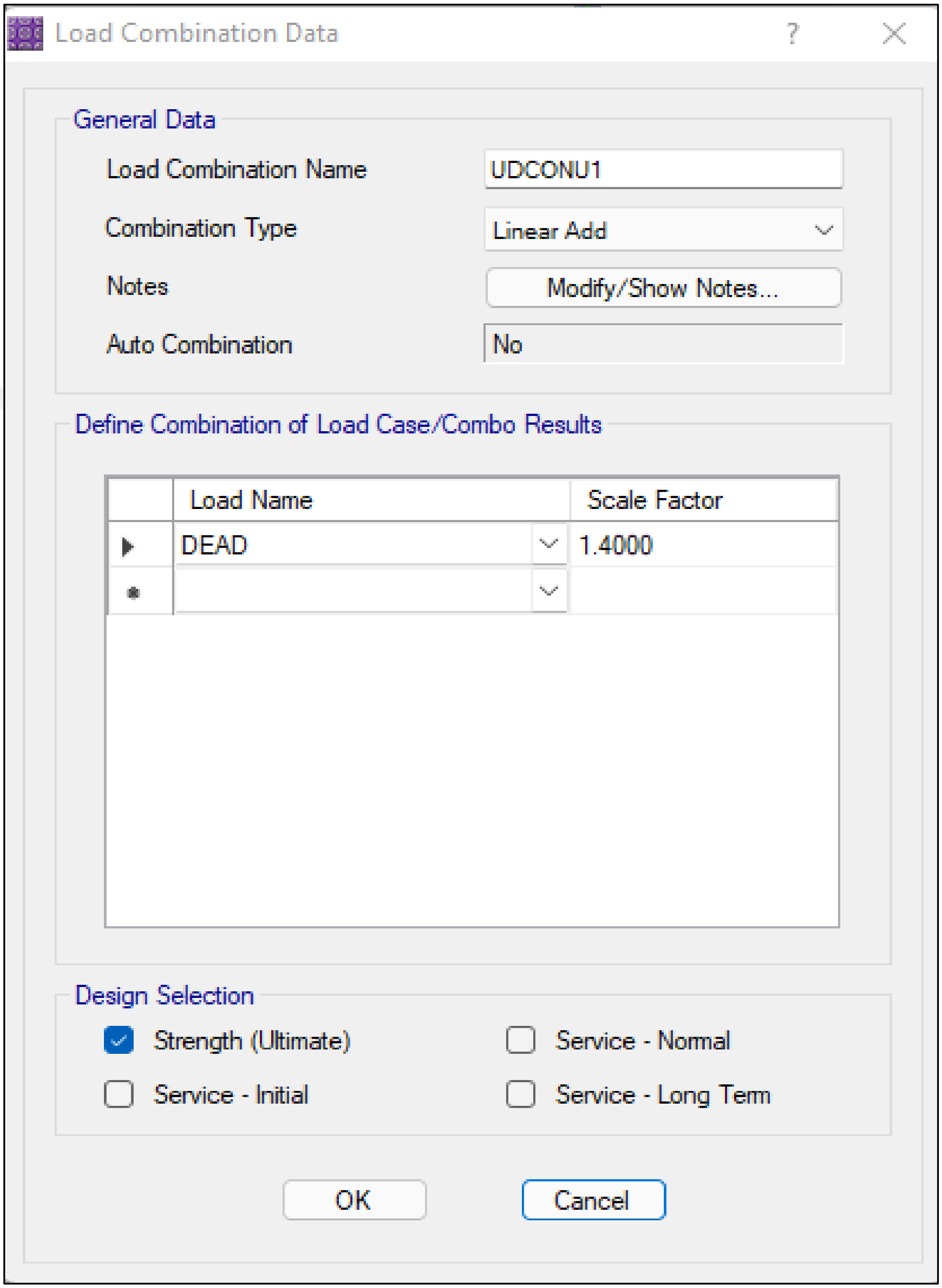

Figure 3.16: The selection and determination of the ultimate combination 1.

Moreover, Figure 3.17 represents the selection and determination of the ultimate combination 2.

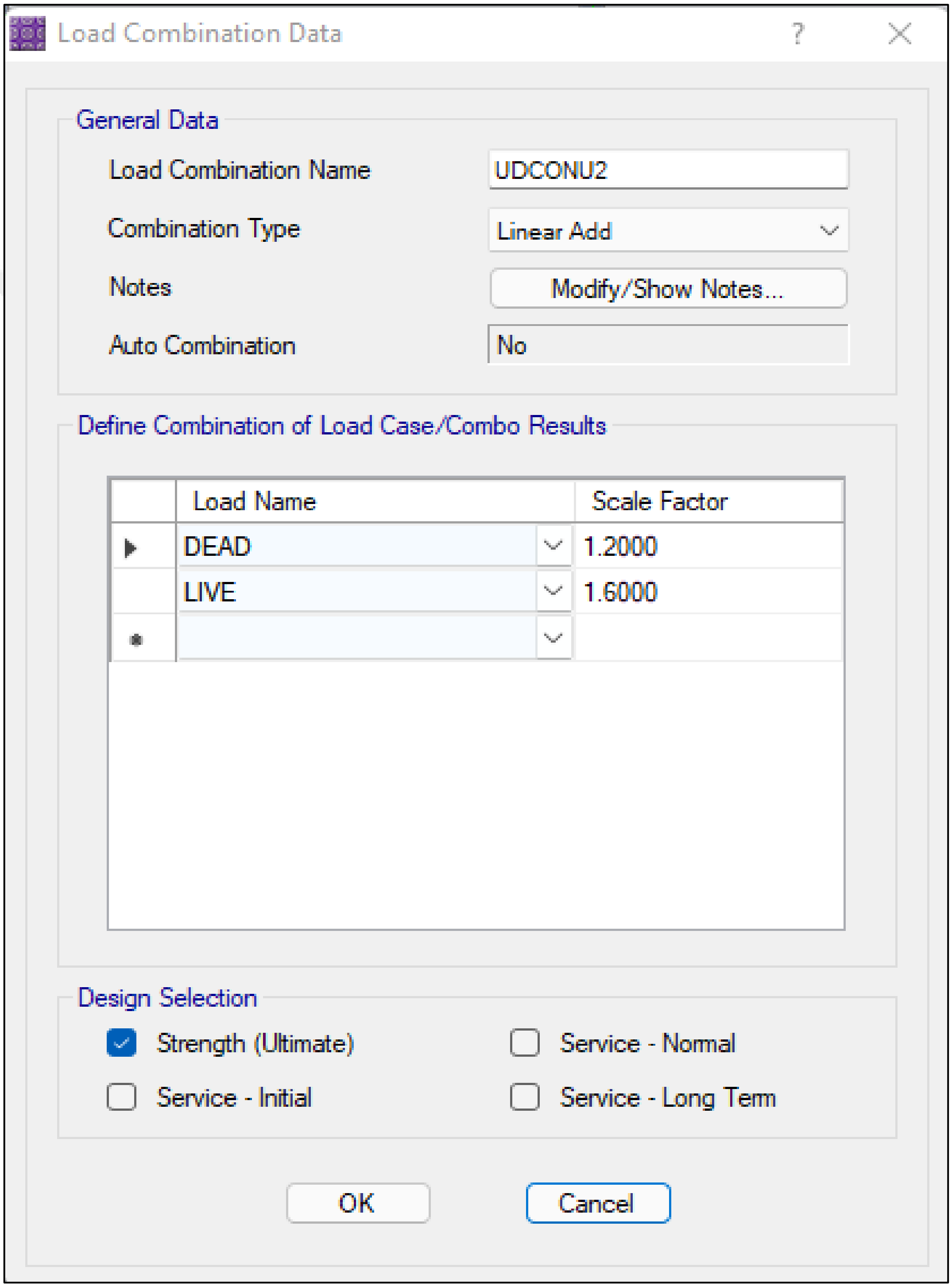

Figure 3.17: The selection and determination of the ultimate combination 2.

It can be indicated from Figures 3.16 and 3.17 that two different ultimate load combinations can be considered, including:

i. Ultimate Combination 1: 1.4 DL

ii. Ultimate Combination 2: 1.2 DL + 1.6 LL

3.8.4 Deflection Control Combinations

Long-term deflection in slabs refers to the deflection or deformation that happens over time as a result of shrinkage and temperature. According to ACI 318-14 [60], long-term deflection is defined as the sum of instantaneous deflection for 75% of the live load and a long-term effect of 25% LL.

In this work, three cases of control combinations were considered to help conduct the numerical analysis of the two-way ribbed slab, including:

i. Case-1 represents (DL+SDL+0.25LL), taking into consideration creep and shrinkage.
ii. Case-2 refers to (DL+SDL+LL) for short-term deflection
iii. Case-3 represents (DL+SDL + 0.25LL) for short term deflection

Long Term deflection = Acase1+Acase2-Acase3

Figure 3.18 presents the considerations and boundary conditions related to the long-term combination of Case 1.

These definitions are vital to helping calculate the long-term deflection

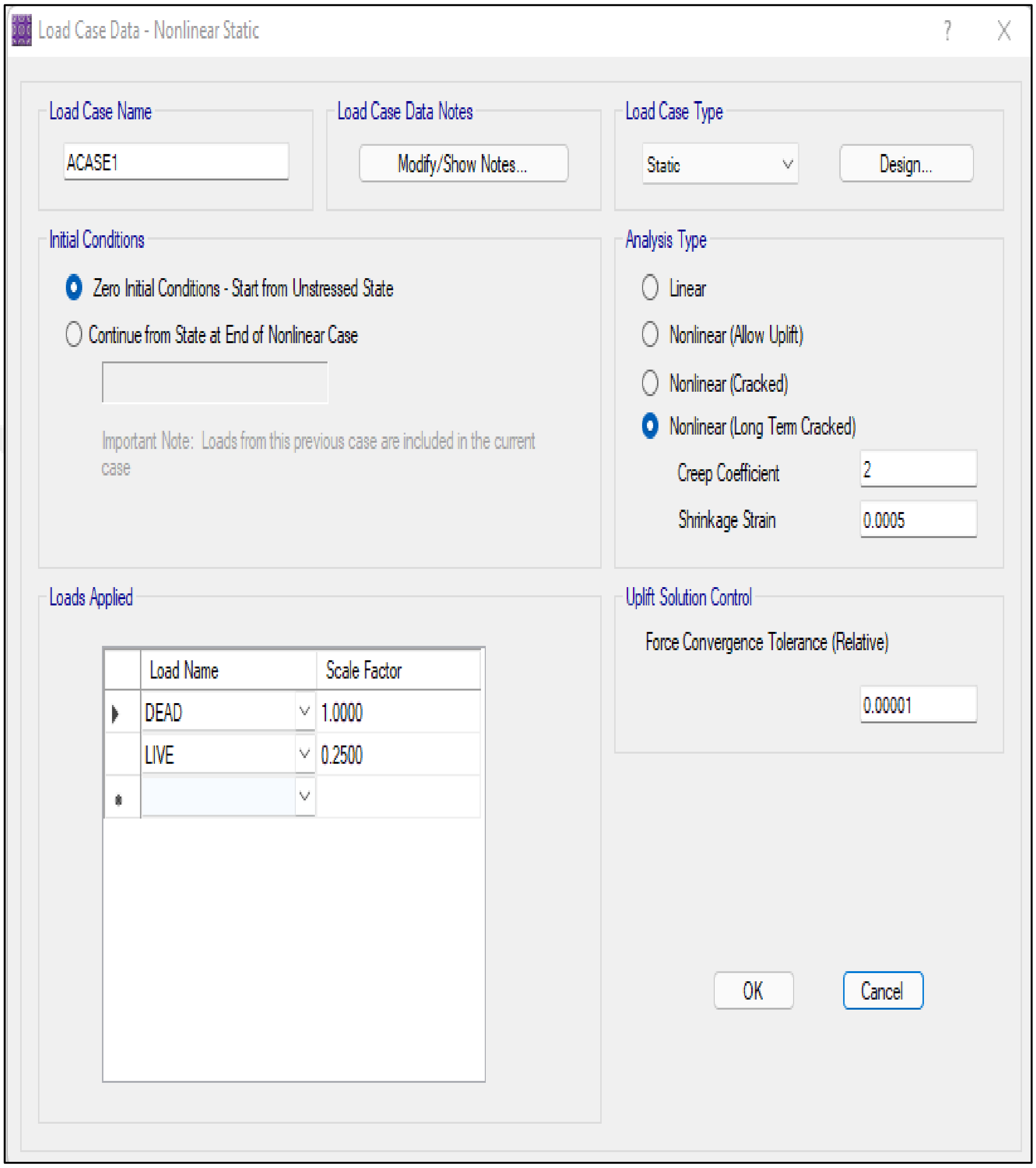

Figure 3.18: Considerations and boundary conditions related to the long-term combination Case 1.

Figure 3.19 presents the considerations and boundary conditions related to the short-term effect case.

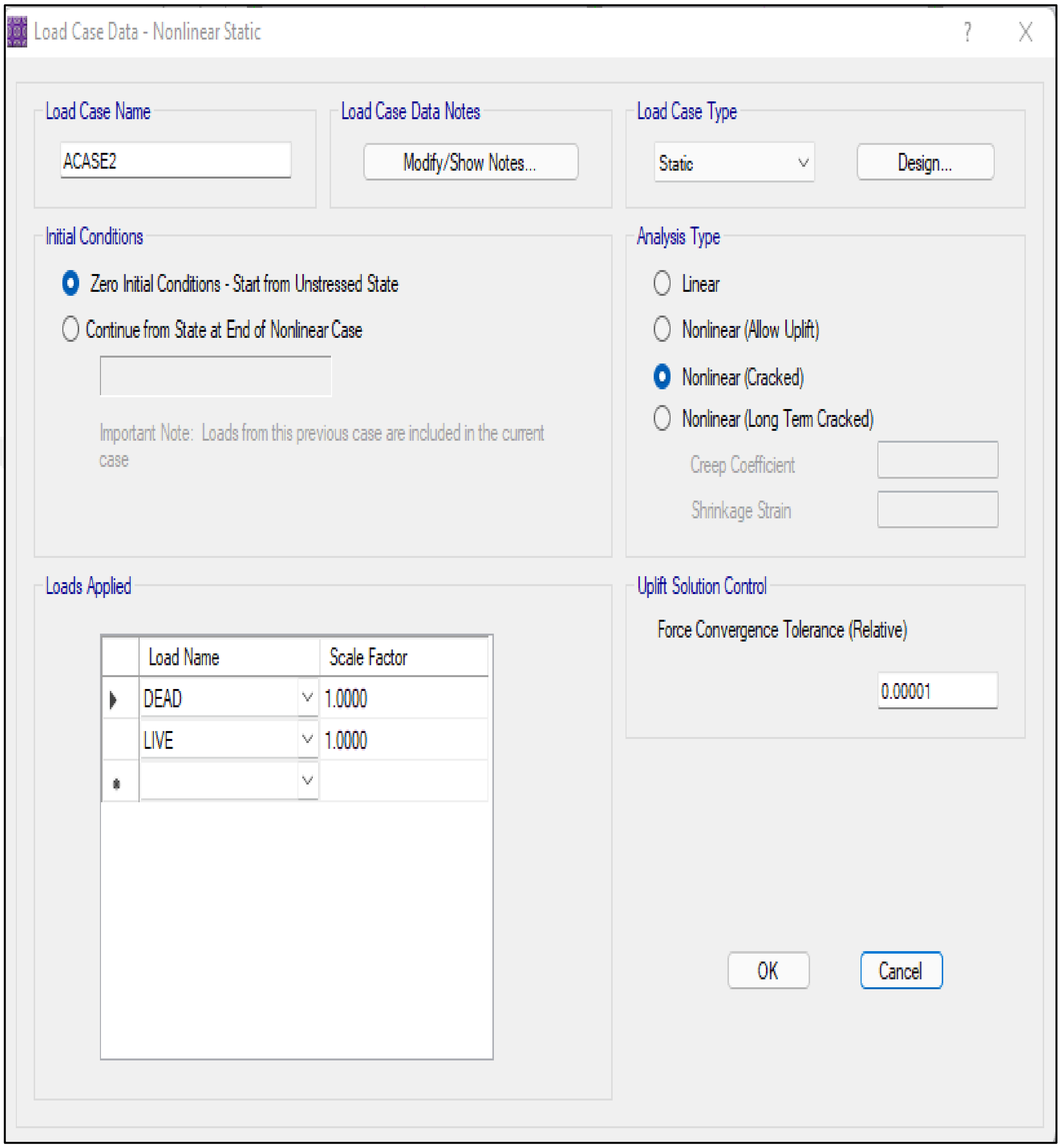

Figure 3.19: Short-term effect case.

Figure 3.20 presents the considerations and boundary conditions related to the short-term 25 % LL case.

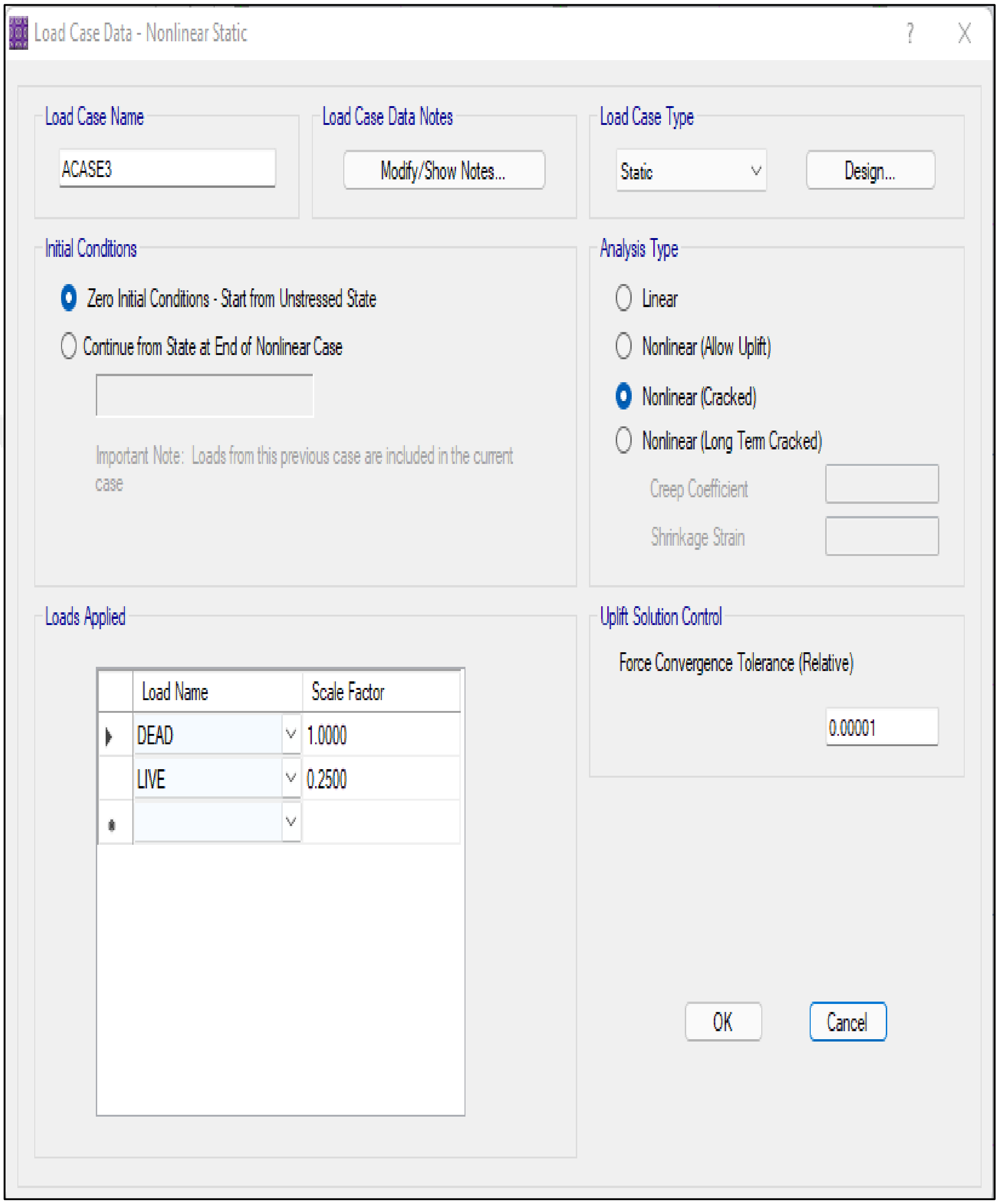

Figure 3.20: Short-Term 25 % LL case.

Figure 3.21 presents the considerations and boundary conditions related to the long-term deflection combination.

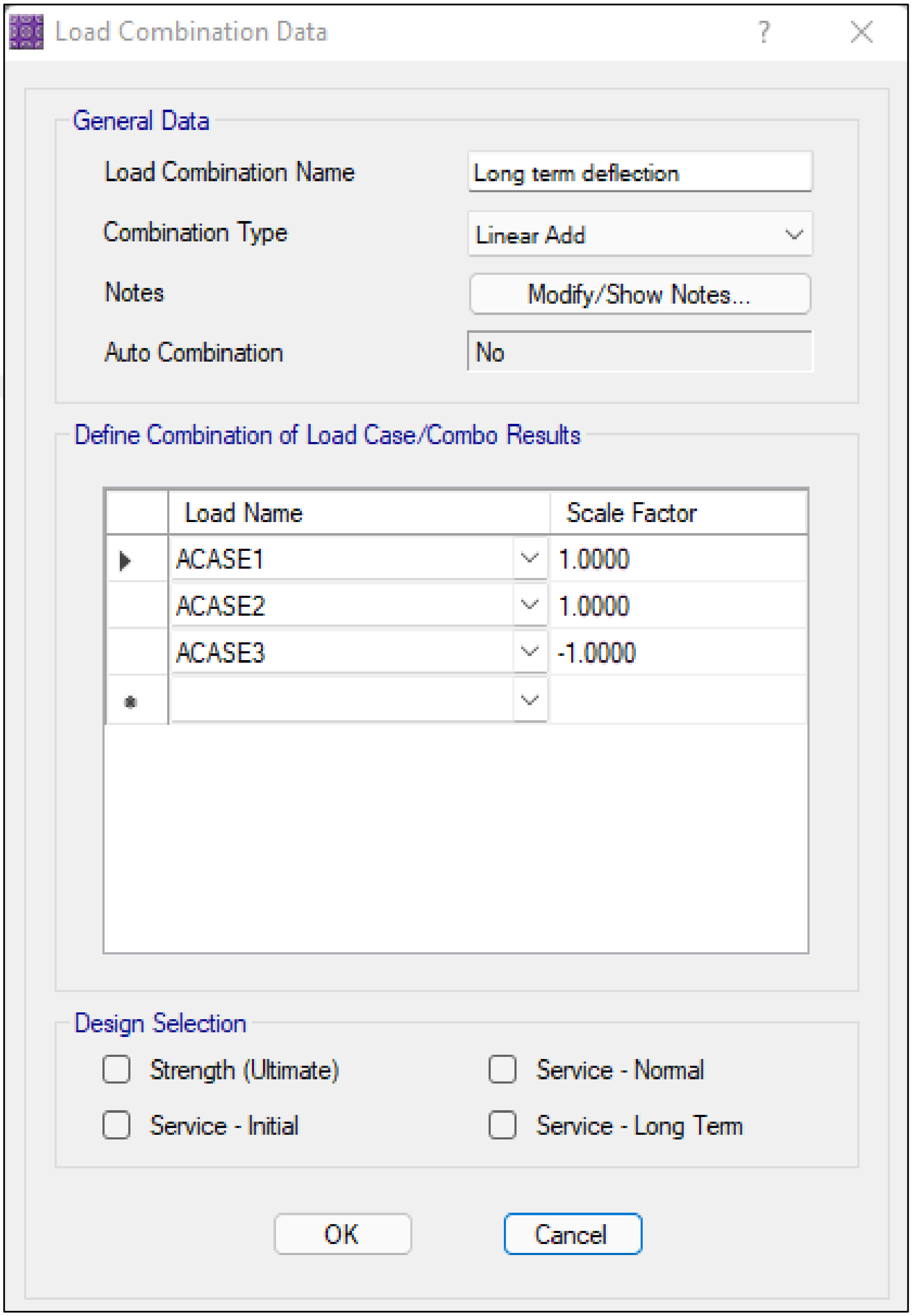

Figure 3.21: Long-Term deflection combination.

It can be indicated from Figure 3.21 that the long-term deflection can be defined as the sum of instantaneous deflection for 75% of the live load and a long-term effect of 25% LL, depending on ACI 318-14 recommendations and standards.

3.9 CHAPTER SUMMARY

After conducting the analysis and preparation of the research methodology, it can be inferred that a numerical approach is implemented. Seven case studies were taken into account using this technique. The seven cases considered the presence of beams along support lines, the existence of solid sections in columns, and the addition of fibers to concrete. The target of mathematical simulations and numerical modeling of these cases associated with the two-way ribbed slabs includes the assessment of the influence of the integration of steel fibers into the SCC on its structural behavior related to the waffle slabs. After the simulations and numerical analysis are carried out, the results will contain critical aspects associated with the impact of the waffle system adopted, the effect of adding steel fibers to concrete on a waffle slab with beams, the influence of adding steel fibers to concrete on a waffle slab with solid sections, and the effect of adding steel fibers to concrete on a waffle slab with both beams and solid sections. Conclusions and recommendations are drawn in chapter five to help scholars, students, and professionals conduct significant improvements and enhancements to the study outcomes.

4. RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter shows the main findings of the research work done in this thesis. Four main effects were discussed in this chapter: (1) the impact of the waffle system adopted, (2) the effect of adding steel fibers to concrete on a waffle slab system with beams, (3) the influence of adding steel fibers to concrete on a waffle slab system with solid sections, and (4) the effect of adding steel fibers to concrete on waffle slab system with both beams and solid sections. These outputs are essential for the final conclusions and recommendations extracted from this thesis

4.2 EFFECT OF THE WAFFLE SYSTEM ADOPTED

4.2.1 Maximum Deflection

In order to study the influence of the waffle slab system, four distinct scenarios were compared. The graph below (Figure 4.1) depicte the maximum deflection of cases C1, C2, C4, and C5. The beam-supported two-way waffle slab C1 has a maximum deflection of 47 mm. The maximum deflection for the conventional solid slab case C2 was 27.3 mm. According to the graph, the maximum deflection of the waffle slab with solid sections scenario C4 is 38.1 mm. The maximum deflection shown in the chart for case C5, covering the flat slab, is 29.8 mm.

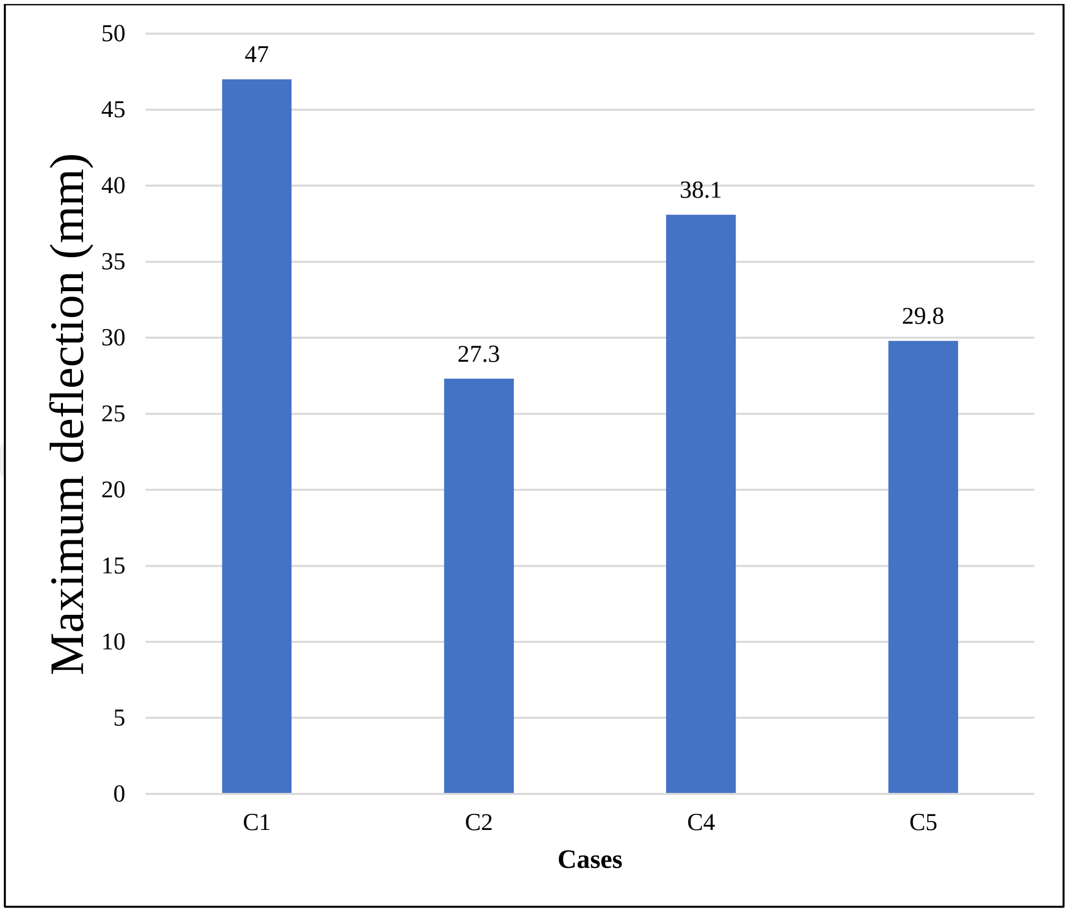

Figure 4.1: The results of the maximum deflection of cases C1, C2, C4, and C5.

The maximum deflection of a waffle slab with drop beams C1 was compared to that of a solid slab C2. The results demonstrate that a waffle slab with beams along support lines has a maximum deflection that is 72 percent greater than a solid slab. Waffle slab deflections are, in fact, greater than solid slab system deflections. These results can demonstrate how flexible waffle slab systems are in comparison to solid slab systems. The maximum slab deflections are clearly decreasing as the volume of concrete increases.

Moreover, the waffle slab with solid sections has a higher maximum deflection than the solid slab system by 28%. The reason remains the same as in Cases C1 and C2. The solid slab has more concrete volume than the waffle slab, making it stiffer. Finally, the results show that the maximum deflection of a two-way waffle slab with beams on support lines is 23% greater than that of a solid-section waffle slab.

The solid section at the columns with a depth of 60 cm stiffens the waffle slab C4 and reduces the maximum deflection by 23% compared to the waffle slab with drop beams.

4.2.2 Slab Reinforcement Results

Figures 4.2, 4.3, 4.4, and 4.5 depict a chart of the reinforcement area.

4.2.2.1 Interior Middle Strip in X-Direction

The reinforcement area per strip for the four scenarios C1, C2, C4, and C5 was the second significant output. The reinforcement area per interior middle strip-x of the four different slab systems is visualized in Figure 4.2. Case C1 has a top reinforcement area of 566 mm^2 and a bottom reinforcement area of 594 mm^2. Otherwise, the flat slab in Case C2 requires top reinforcement of 766 mm^2 and bottom reinforcement of 1044 mm^2. In the case of C4, the reinforcement area was 379 mm^2 for top reinforcement and 611 mm^2 for bottom reinforcement. The reinforcement area in the internal middle strip of the case C5 flat slab was 725 mm^2 for top reinforcement and 1144 mm^2 per strip for bottom reinforcement.

Several graphs are generated to present a visual comparison of reinforcement results across all slab types. In the case of C2, the top and bottom reinforcement areas are increased by 75% and 35%, respectively, when compared to the waffle slab with beams. Furthermore, when compared to the waffle slab with solid sections at columns, the reinforcement area per middle strip for Case C5 solid slab increased by 87 percent and 91 percent, respectively, for top and bottom reinforcement.

In comparison to the previous results, it is clear that as the volume of concrete increases, the self-weight also increases, resulting in more loads. When the two waffle systems are analyzed, the waffle slab with beams C1 has 49% more top reinforcement than the waffle slab with solid sections C4.

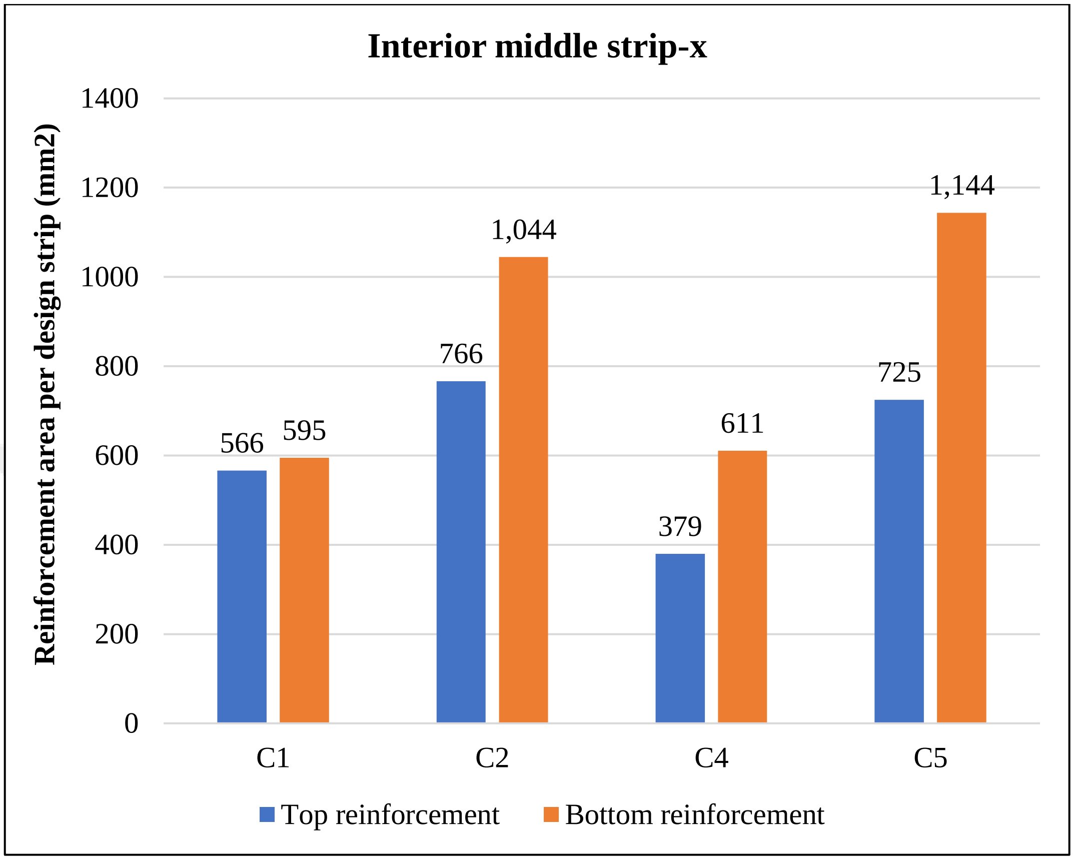

Figure 4.2: Interior middle strip-x reinforcement cases of C1, C2, C4, and C5.

4.2.2.2 Exterior Middle Strip in X-Direction

A graph illustrating the four slab systems is shown in Figure 4.3 for the exterior middle strip-x. Case C1 features a 476 mm^2 top reinforcement area and a 593 mm^2 bottom reinforcement area. However, the flat slab in Case C2 provides 545 mm^2 of top reinforcement and 971 mm^2 of bottom reinforcement.

The reinforcement area in scenario C4 was 222 mm^2 for top reinforcement and 554 mm^2 for bottom reinforcement. The reinforcement area in the case of the C5 flat slab's outside middle strip was 531 mm^2 for top reinforcement and 1,097 mm^2 per strip for bottom reinforcement.

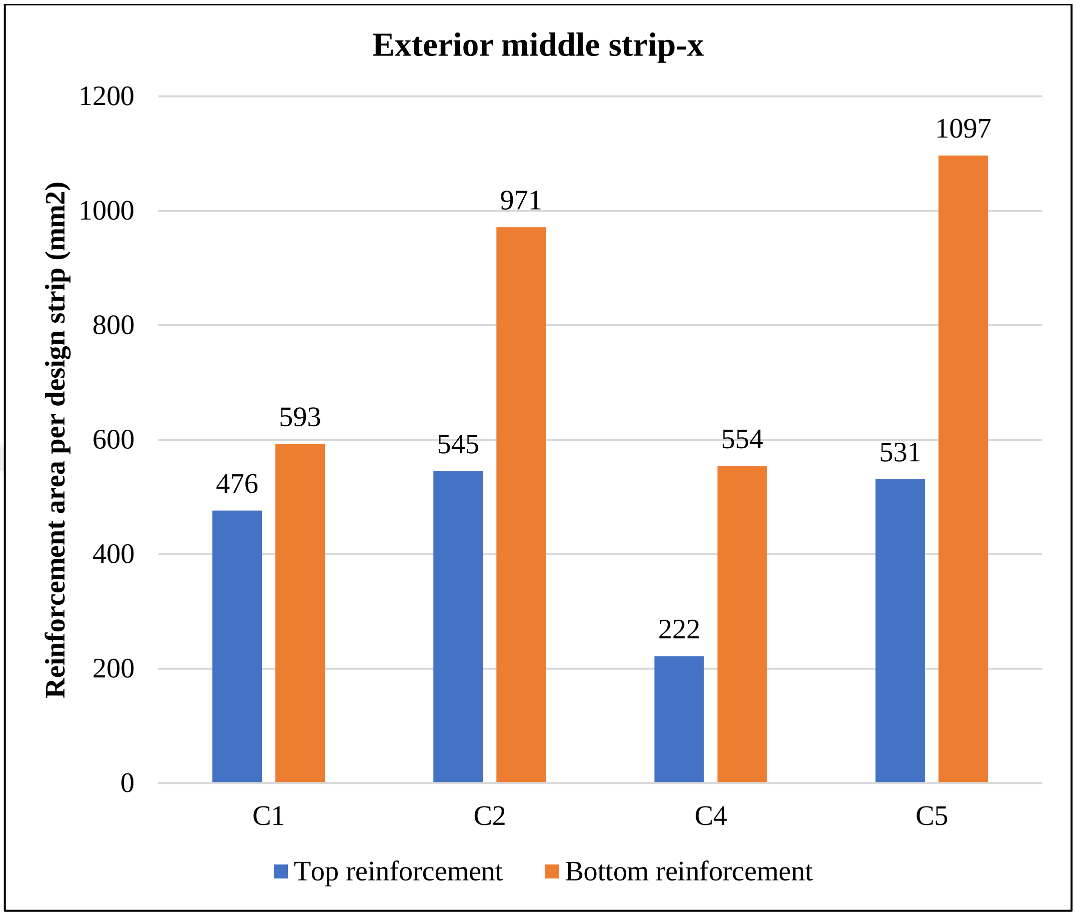

Figure 4.3: Exterior middle strip-x cases C1, C2, C4, and C5.

As compared to the waffle slab with beams, the bottom and top reinforcement areas in case C2 are increased by 64% and 14%, respectively. Additionally, when compared to the waffle slab with solid sections at columns, the reinforcement area per middle strip for Case C5 solid slab increased by 98 and 139 percent for the bottom and top reinforcement, respectively. According to the results, the waffle system C1 has 114% more top reinforcement area than the waffle slab with solid panels C4.

Figure 4.4 illustrates the reinforcement area for the four cases, C1, C2, C3, and C4, in the interior middle strip in the y-direction, respectively. The graphs represent the same trend as the strips in the x-direction.

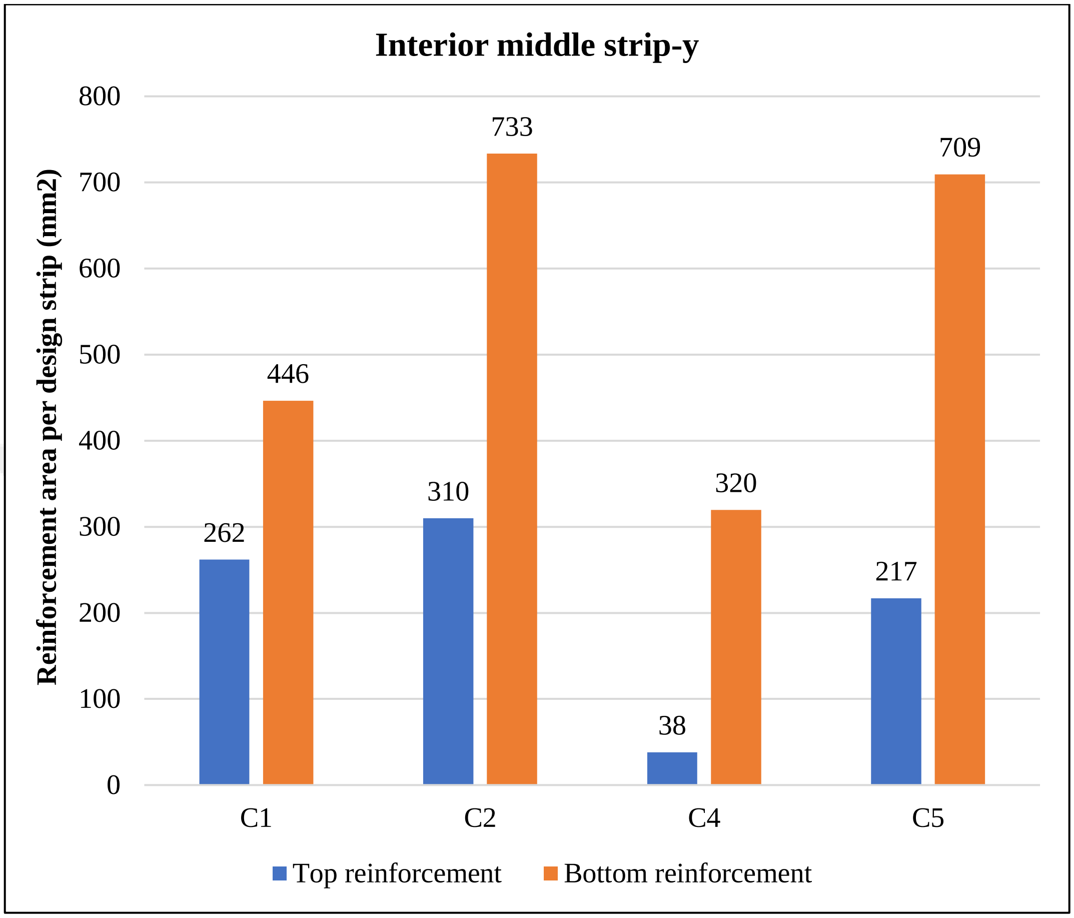

Figure 4.4: Interior middle strip-y cases C1, C2, C4, and C5.

Furthermore, the numerical analysis and mathematical simulation results provided data regarding the reinforcement area for the four cases, C1, C2, C3, and C4, in the exterior middle strip in the y-direction, respectively. The graphs represent the same trend as the strips in the x-direction. These results are shown in Figure 4.5.

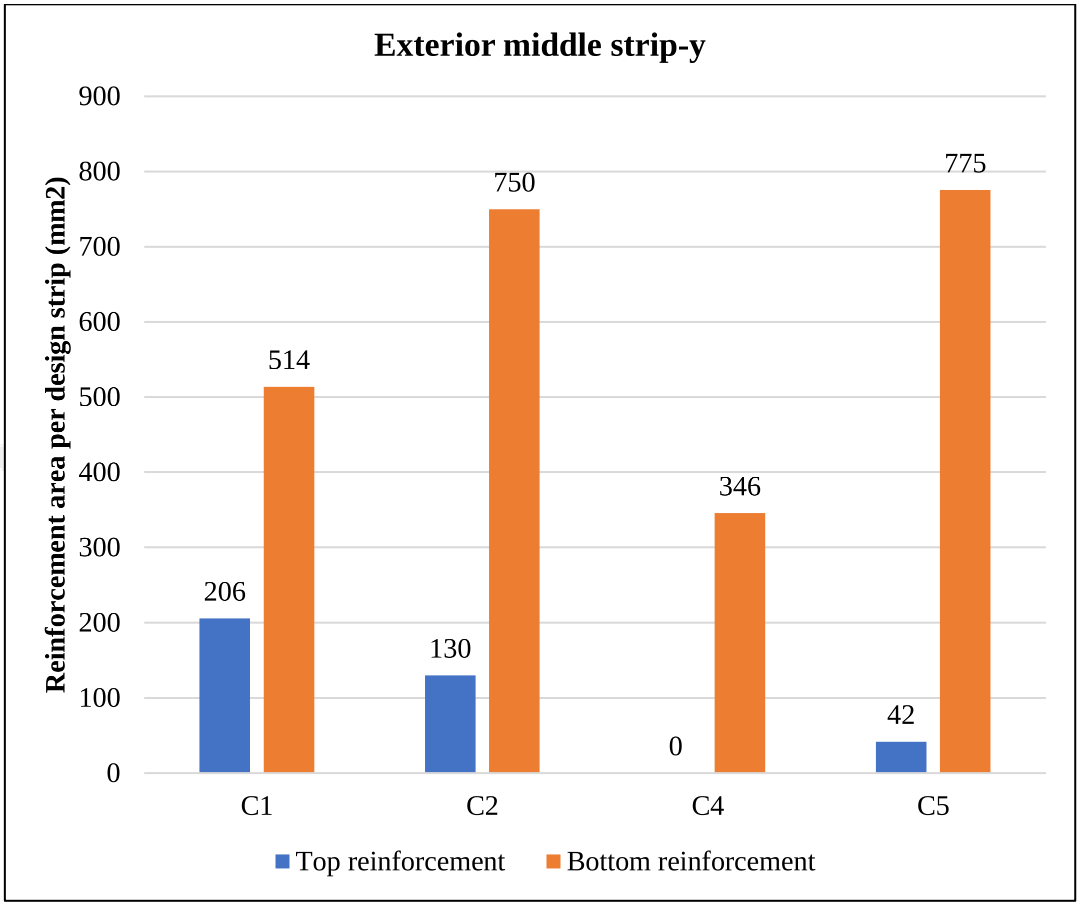

Figure 4.5: The results of exterior middle strip-y cases C1, C2, C4, and C5.

4.3 EFFECT OF ADDING STEEL FIBERS TO CONCRETE ON WAFFLE SLAB SYSTEM WITH BEAMS

4.3.1 Maximum Deflection

This section discusses the maximum deflection findings for Cases C1, C2, and C3. C1 shows the waffle slab with beams, C2 the solid slab, and C3 the waffle slab with beams and steel fibers. This comparison demonstrates the influence of incorporating steel fibers into concrete on a waffle slab system with beams.

Figure 4.6 depicts a graph showing the maximum deflection of the various situations. As previously stated, the maximum deflection of Case C1 and Case C2 is 47 mm and 27.3 mm, respectively. Meanwhile, the maximum deflection of the waffle slab system with beams and steel fibers is 39.9 mm. In the case of C3, the addition of steel fibers decreases the maximum deflection of a waffle slab with beams by 18%. Otherwise, the maximum deflection of a waffle slab with beams is 46% more than that of a solid slab.

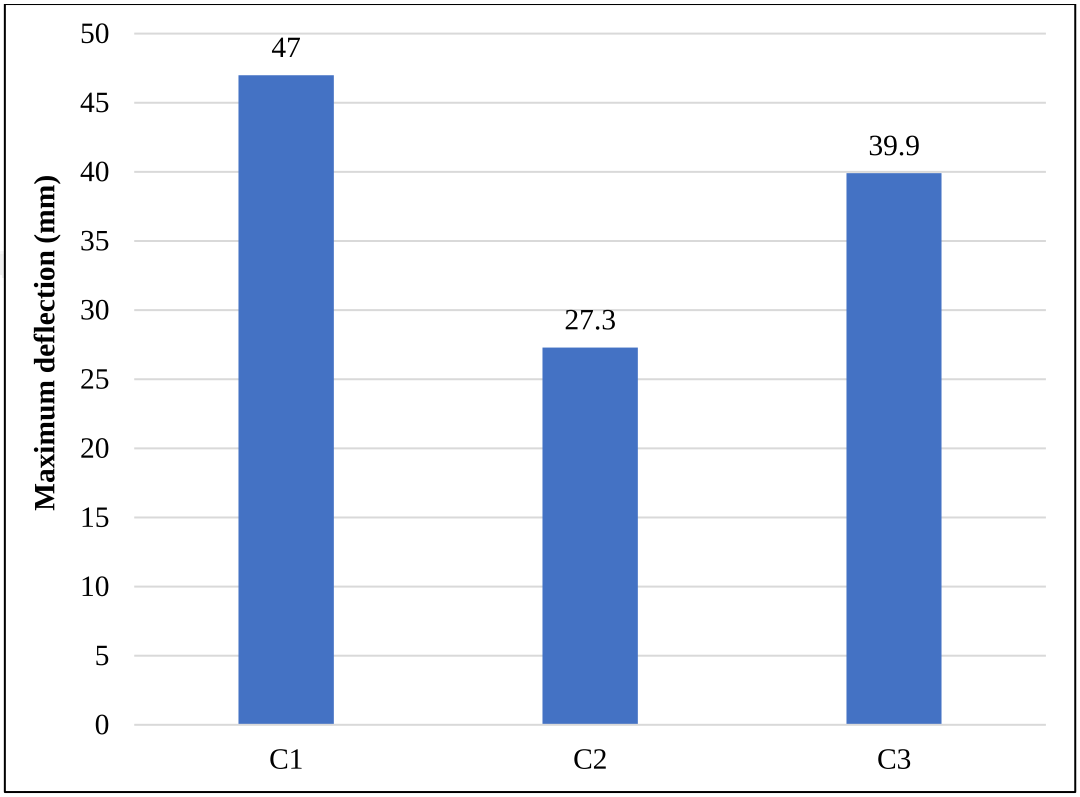

Figure 4.6: The results of the maximum deflection of C1, C2, and C3 compared.

Further study was undertaken to investigate the optimum slab thickness to achieve a maximum deflection of 47 mm in Case C3. According to Figure7, the slab thickness of case C3 with steel fibers must be 34 cm in order to obtain the maximum deflection of the typical waffle slab C1. The addition of steel fibers to a waffle slab system with beams decreases slab thickness by 11%, 4 cm.

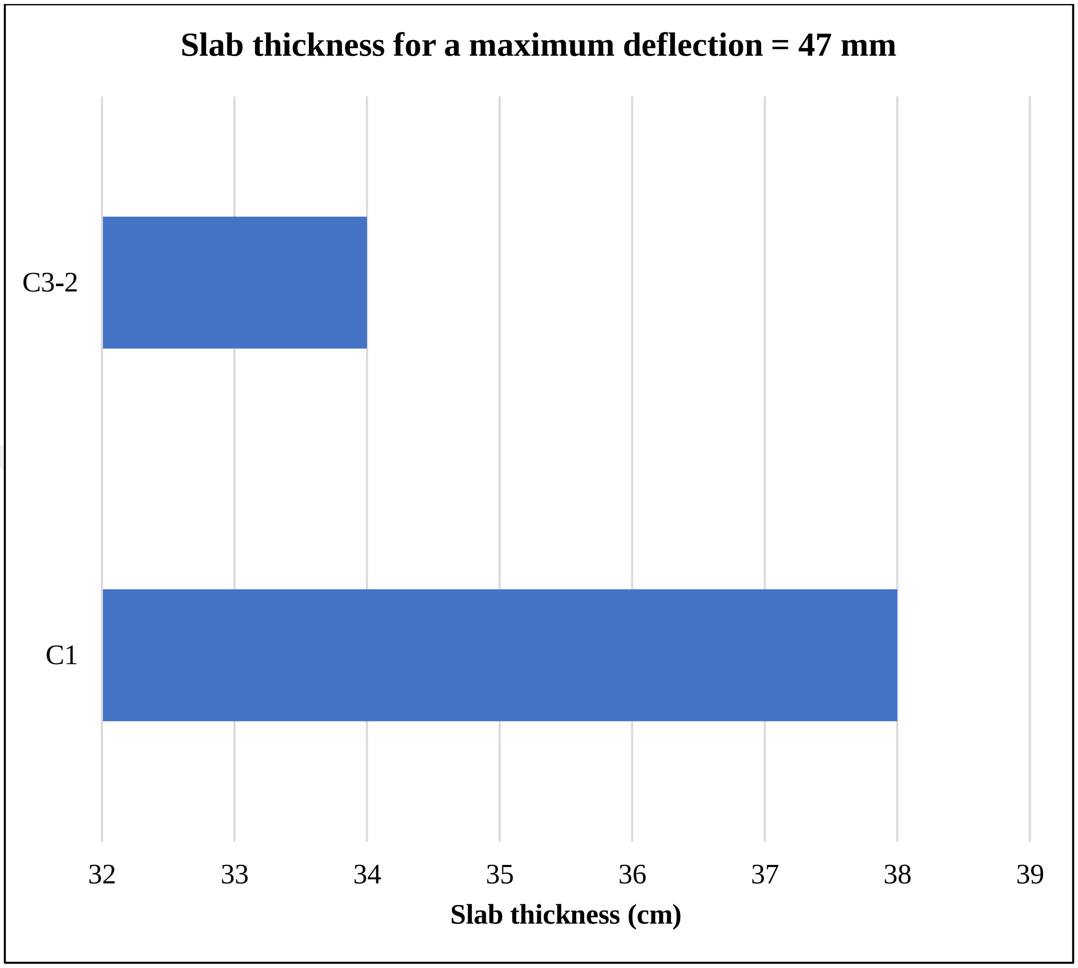

Figure 4.7: Slab thickness for a maximum deflection= 47mm Case C1 and C3.

4.3.2 Slab Reinforcement Results

4.3.2.1 Interior and Exterior Middle Strip in Both Directions

The slab reinforcement results for the interior and exterior middle strips in both directions are illustrated in Figures 4.8, 4.9, 4.10, and 4.11.

The same scenario is displayed in both directions. The study reveals that the top and bottom reinforcement areas per strip for waffle slabs C1 and C3 are almost identical, with no significant differences. Meanwhile, it demonstrates that in both situations, C1 and C3, less top and bottom reinforcement is required than in the solid slab.

Indeed, because the solid slab requires more concrete than the waffle slab, the dead load is more significant, resulting in higher reinforcing percentages.

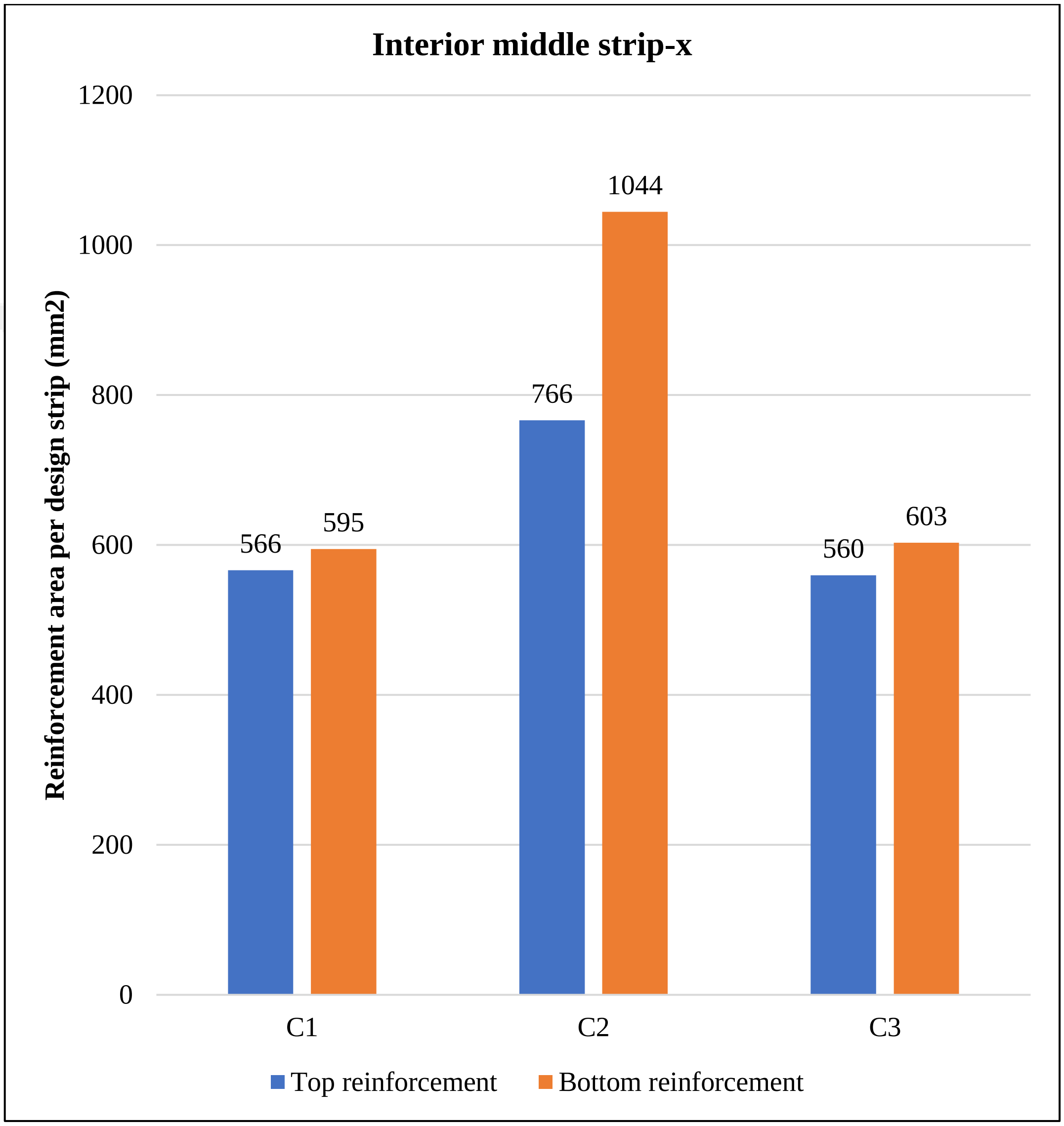

Figure 4.8: Interior middle strip-x reinforcement cases C1, C2, and C3.

Figure 4.9 represents the numerical research findings associated with the exterior middle strip-x reinforcement cases C1, C2, and C3.

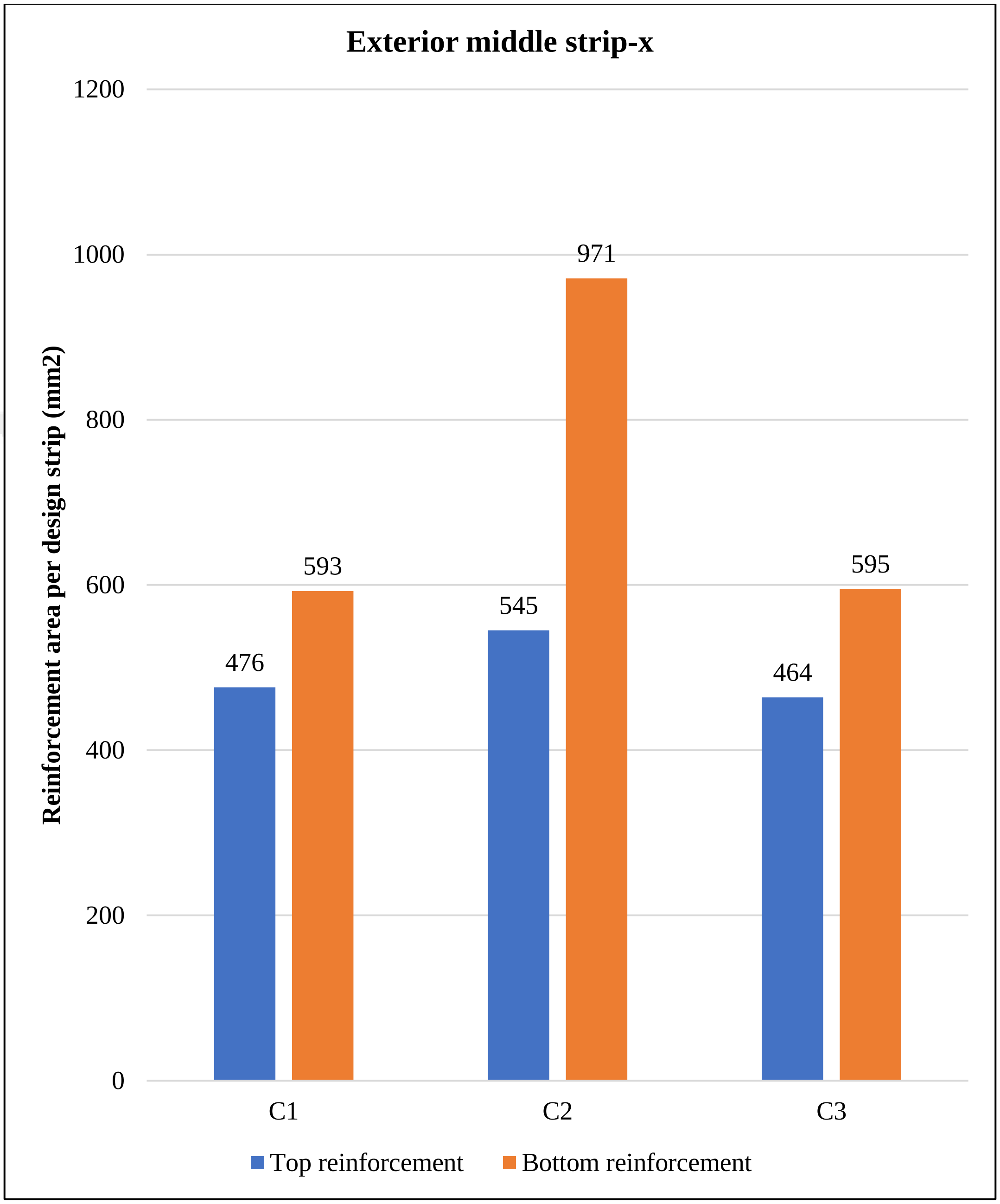

Figure 4.9: Exterior middle strip-x reinforcement cases C1, C2, and C3.

In addition, Figure 4.10 represents the numerical research findings associated with interior middle strip-y reinforcement cases C1, C2, and C3.

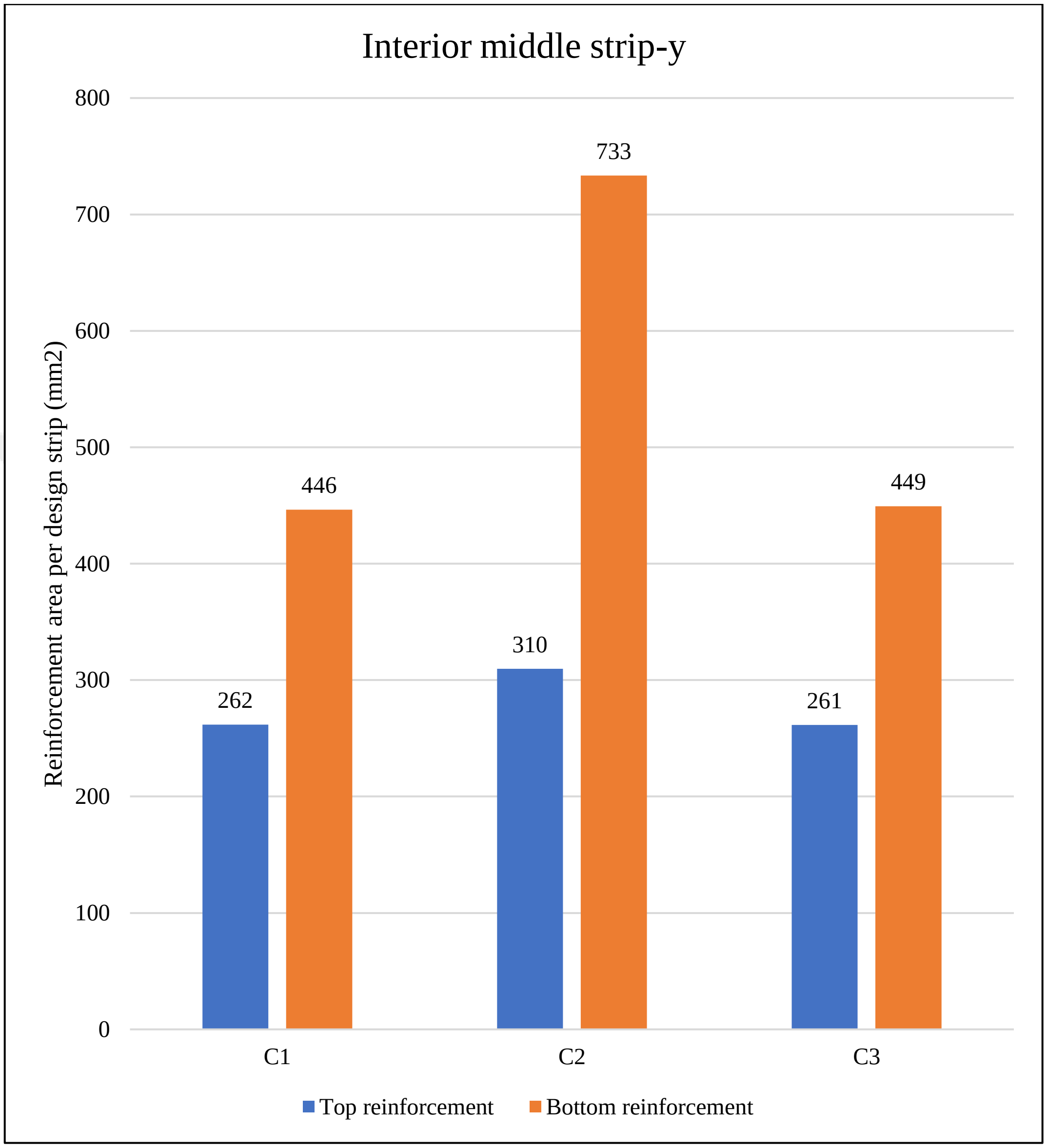

Figure 4.10: The numerical research findings associated with interior middle strip-y reinforcement cases C1, C2, and C3.

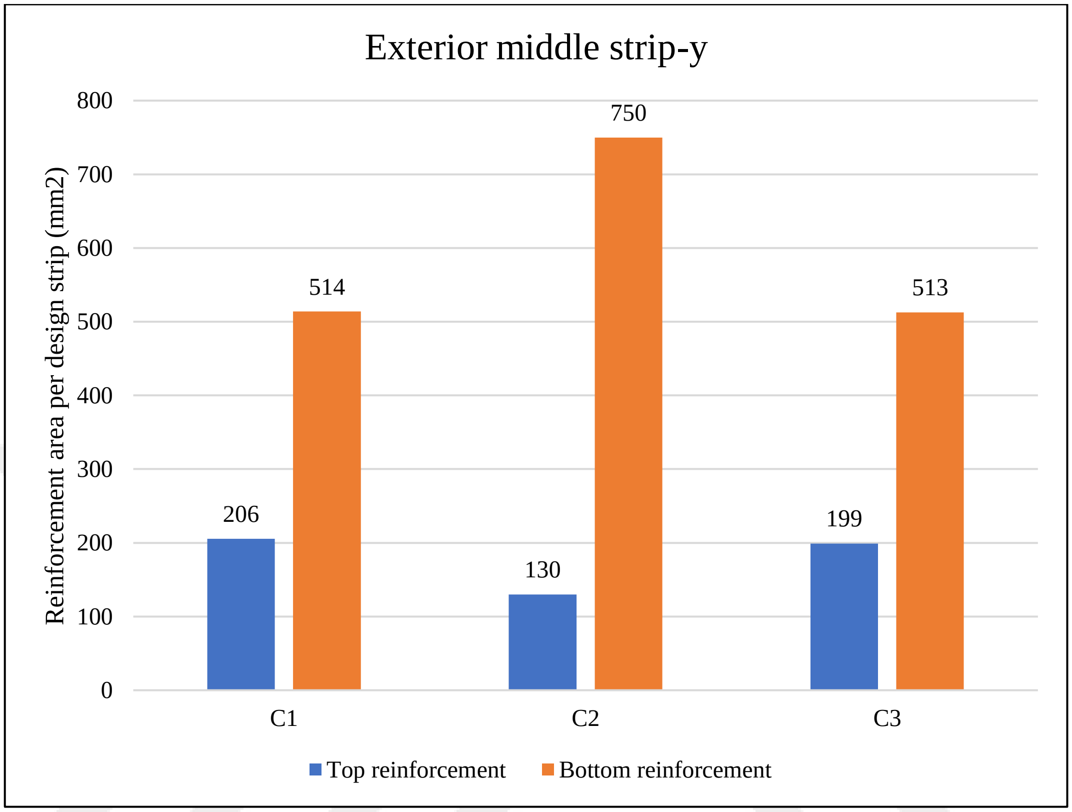

Figure 4.11: The numerical research findings associated with exterior middle strip-y reinforcement cases C1, C2, and C3.

4.3.3 Beam Reinforcement Results

For cases, C1, C2, and C3, the interior and exterior beam strips in both directions are evaluated.

Figure 4.12 demonstrates the interior beam reinforcement for the different cases. For Case C1, the top reinforcement in the interior beam is 4,509 mm^2, the bottom reinforcement is 2,454 mm^2, and the shear reinforcement is 2,588 mm^2/m.

Case C2 also has 2,952 mm^2 of top beam reinforcement, 1,558 mm^2 of bottom beam reinforcement, and 3,365 mm^2/m of shear reinforcement. When steel fibers are added, the top reinforcement of the interior beam is 4,247 mm^2, the bottom reinforcement is 2,419 mm^2, and the shear reinforcement is 2,401 mm^2/m.

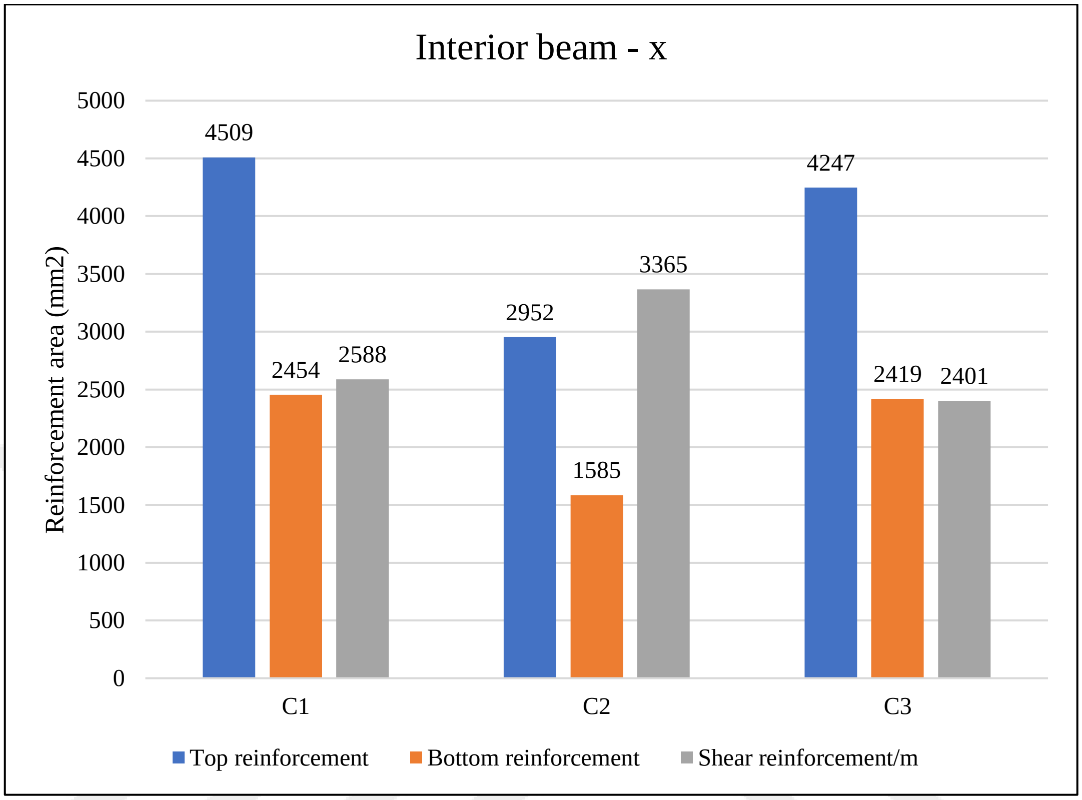

Figure 4.12: The numerical research findings associated with interior beam-x reinforcement Cases C1, C2, and C3.

The findings indicate that the amount of top reinforcement for the interior beam is much more in the case of C1 than in the case of C3. Case C1 has slightly more bottom and top reinforcement of the interior beam than Case C3. In flexural reinforcement, C1 and C3 are both greater than C2, whereas C2 is lower in shear reinforcement.

Figure 4.13, Figure 4.14, and Figure 4.15 show how other beams behave similarly.

Figure 4.13 indicates the numerical research findings associated with exterior beam-x reinforcement Cases C1, C2, and C3.

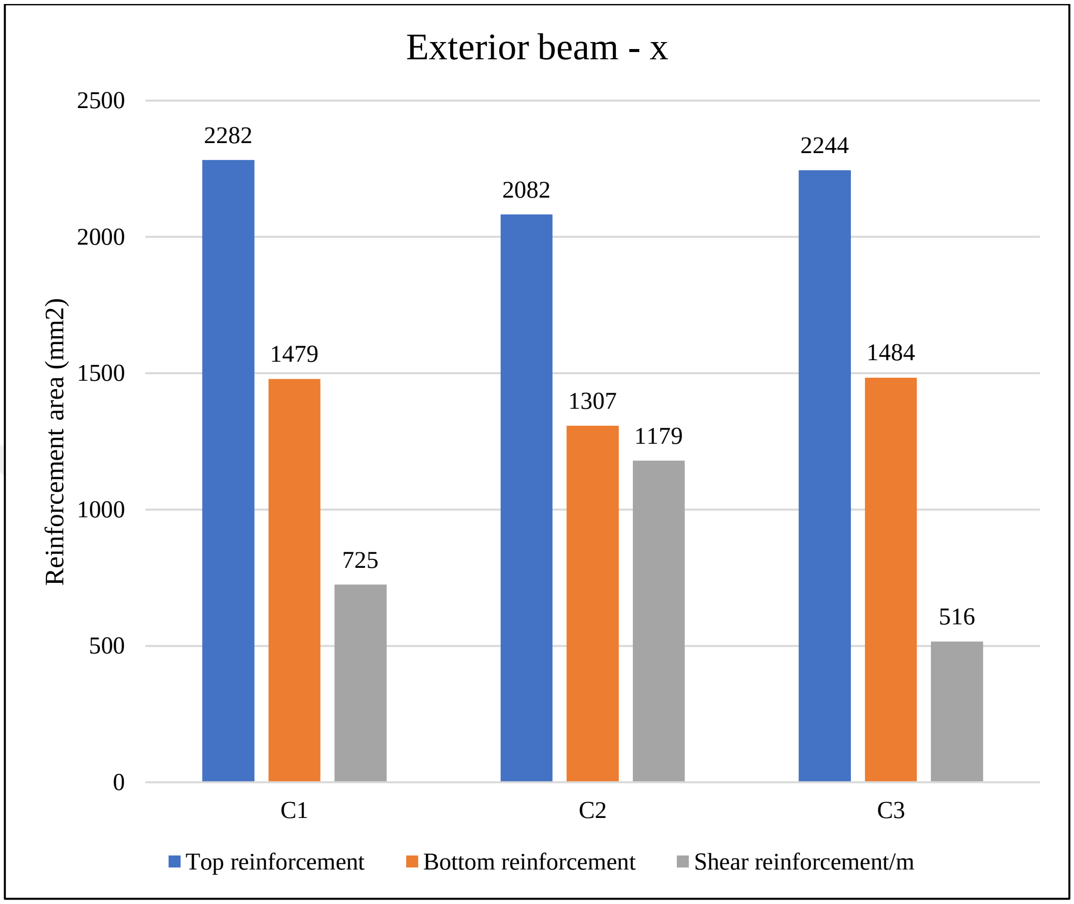

Figure 4.13: The numerical research findings associated with exterior beam-x reinforcement Cases C1, C2, and C3.

Furthermore, the research modeling, mathematical simulations, and numerical analysis indicated the numerical research findings associated with interior beam-y reinforcement Cases C1, C2, and C3. Figure 4.14 expresses these results.

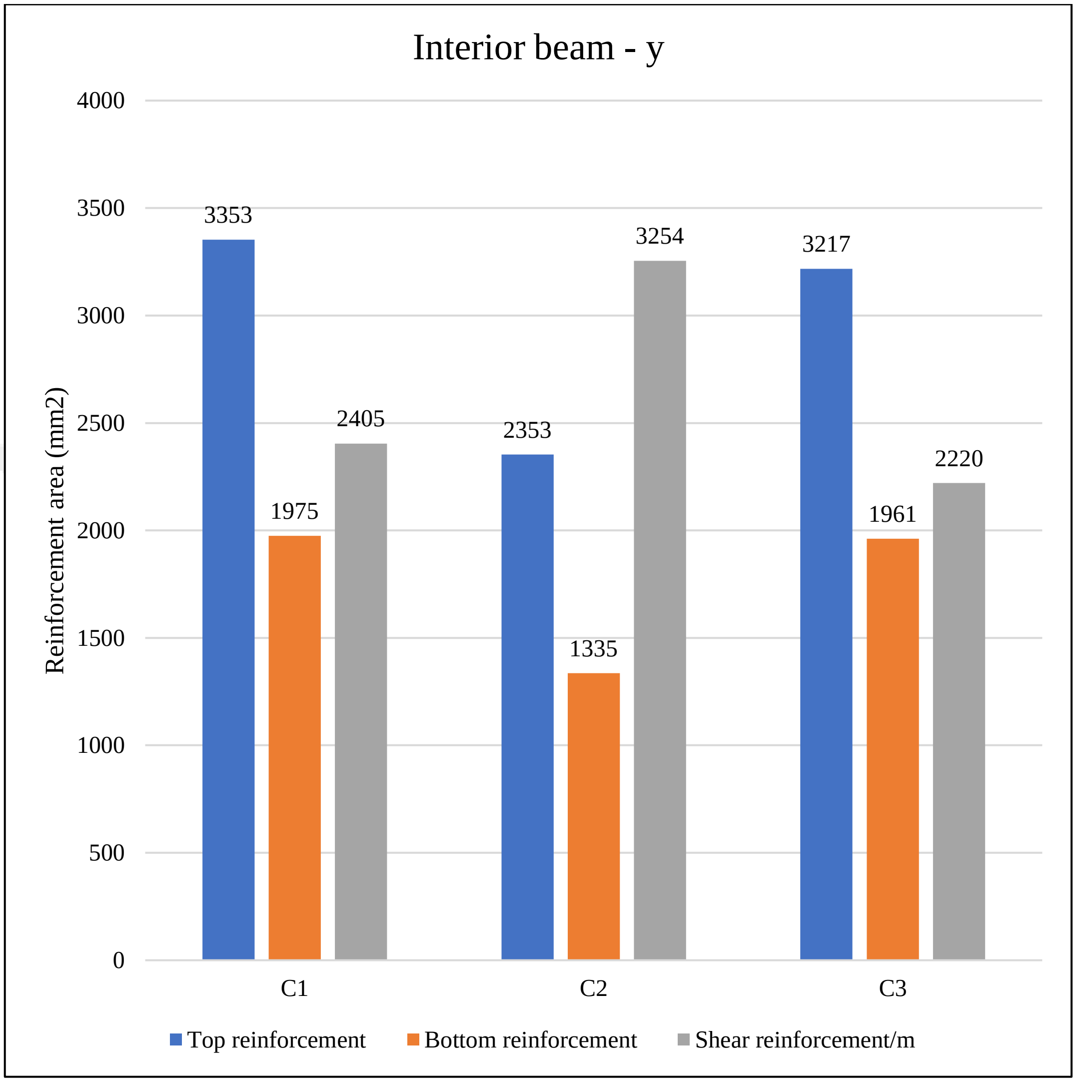

Figure 4.14: The numerical research findings associated with interior beam-y reinforcement Cases C1, C2, and C3.

Moreover, the research modeling, mathematical simulations, and numerical analysis indicated the numerical research findings associated with exterior beam-y reinforcement Cases C1, C2 and C3. Figure 4.15 shows these results.

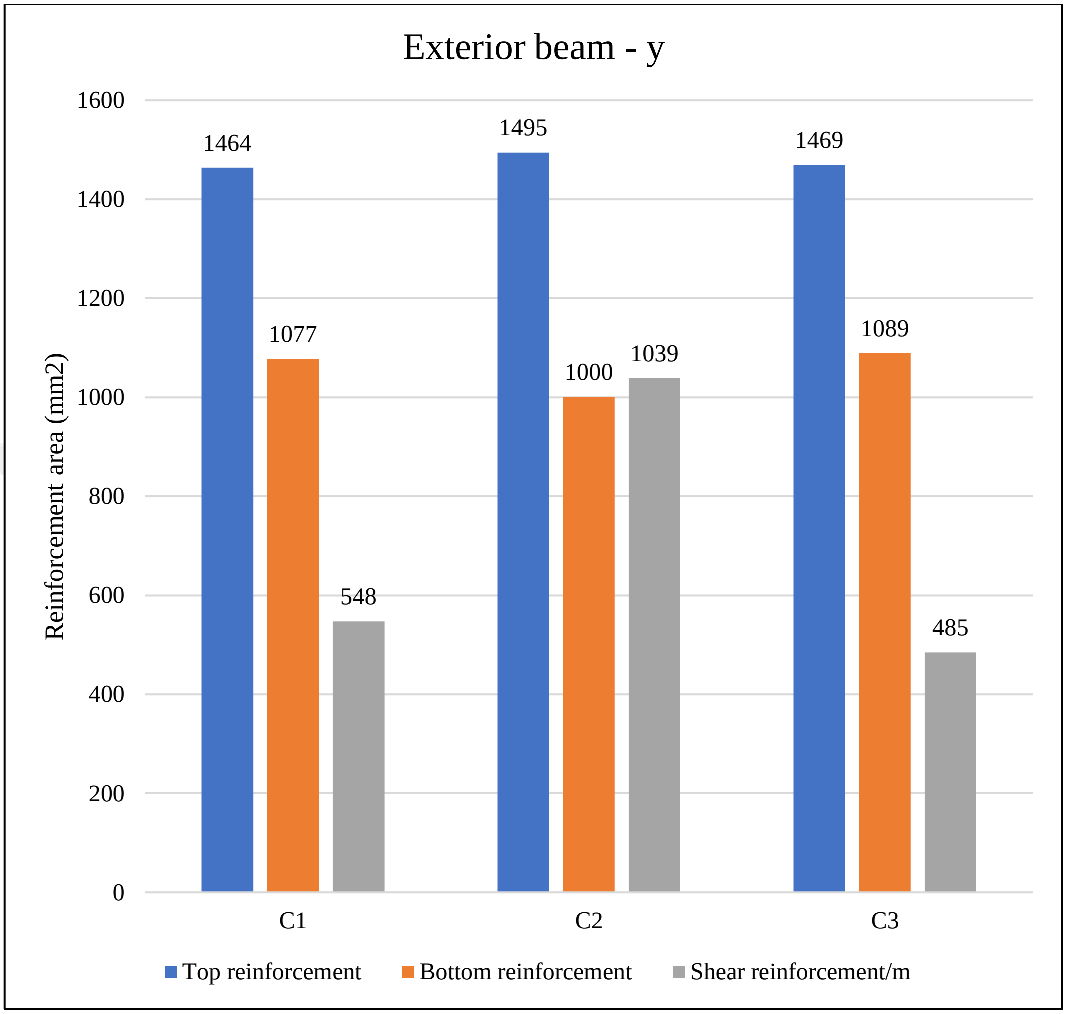

Figure 4.15: The numerical research findings associated with exterior beam-y reinforcement Cases C1, C2 and C3.

4.4 EFFECT OF ADDING STEEL FIBERS TO CONCRETE ON WAFFLE SLAB SYSTEM WITH SOLID SECTIONS

4.4.1 Maximum Deflection

The maximum deflection findings for Cases C4, C5, and C6 are discussed in this section. The waffle slab with solid panels is shown in C4, the flat slab in C5, and the waffle slab with solid sections and steel fibers in C6. This comparison shows how inserting steel fibers into concrete improves a waffle slab system with solid sections.

The graph in Figure 4.16 displays the maximum deflection of the various scenarios. The maximum deflection of Case C4 and Case C5 is 38.1 mm and 29.8 mm, respectively. Meanwhile, the waffle slab system with solid panels at the columns and steel fibers C6 has a maximum deflection of 34.7 mm. In the case of C6, adding steel fibers reduces the maximum deflection of a waffle slab with solid panels by 10%. However, a waffle slab with a solid section has a maximum deflection that is 28% greater than a flat slab. Both cases, C4 and C6, have a larger maximum deflection of concrete than flat slabs because flat slabs are stiffer than waffle slabs.

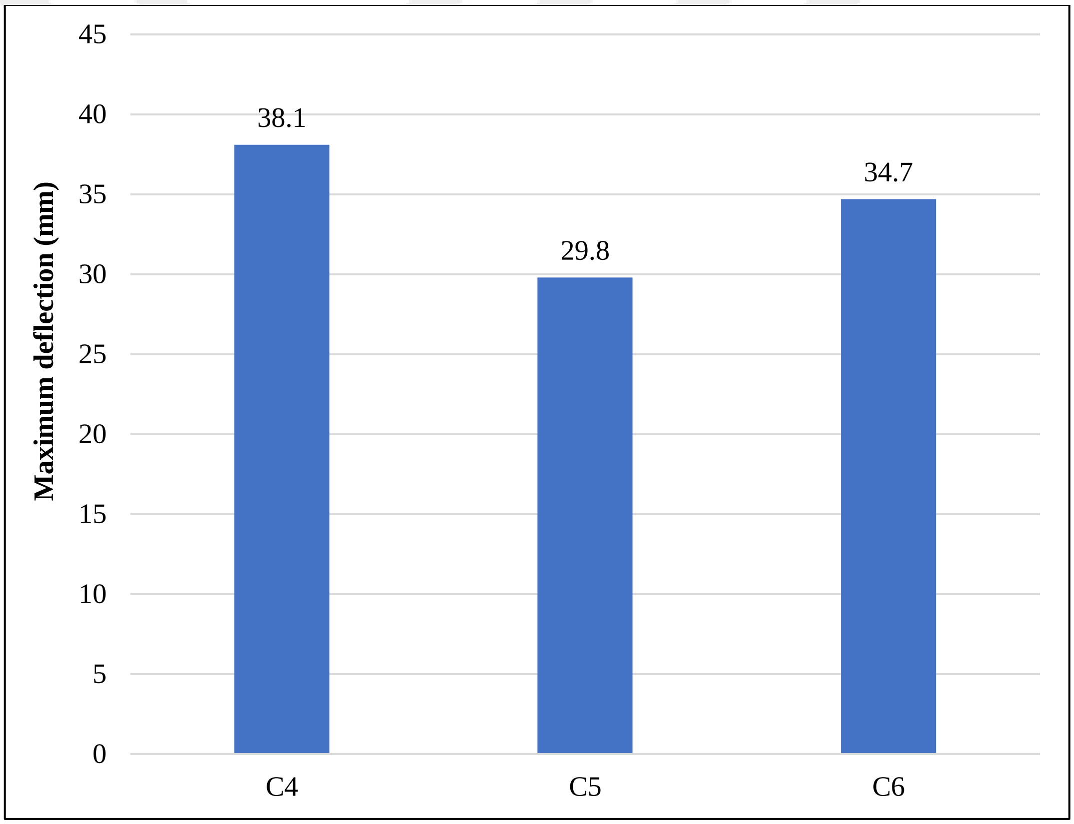

Figure 4.16: Maximum deflection of cases C4, C5, and C6 in mm.

In Case C6, more research was conducted to determine the optimal slab thickness to produce a maximum deflection of 38 mm. Figure 4.17 shows that the slab thickness of case C6 with steel fibers must be 36 cm to achieve the maximum deflection of the conventional waffle slab C4. Steel fibers added to a waffle slab system with solid sections reduce slab thickness by 5%, about 2 cm.

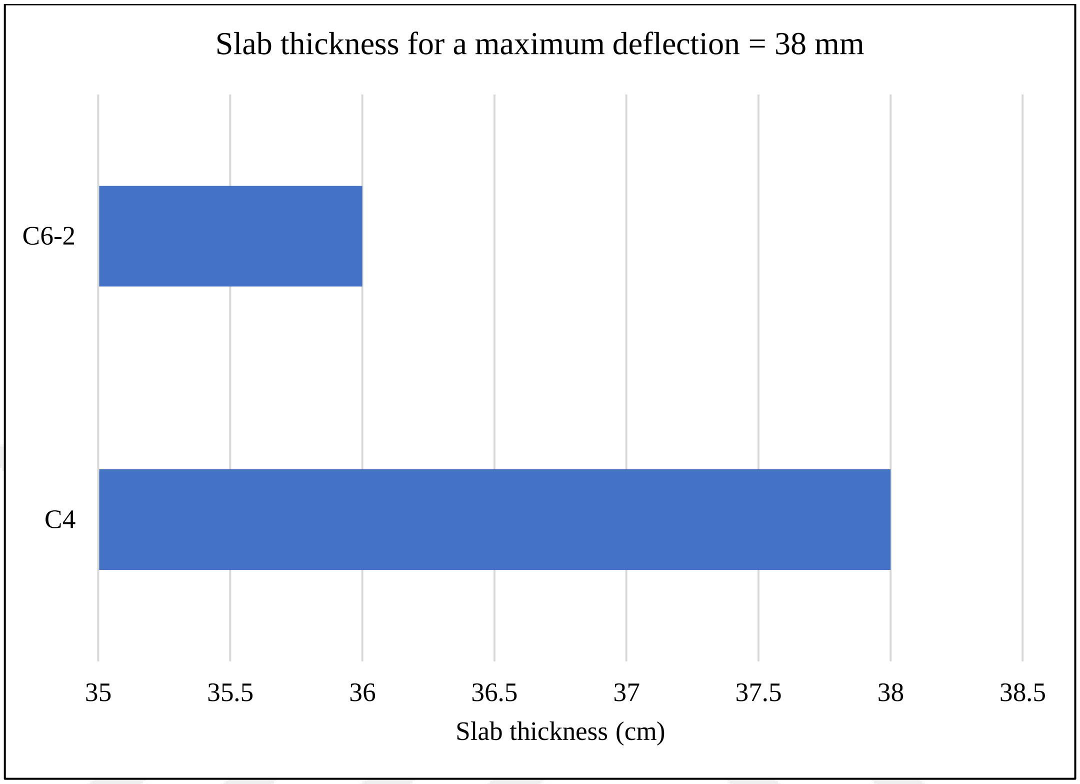

Figure 4.17: Slab thickness for a maximum deflection 38 mm case C6.

4.4.2 Slab Reinforcement Results

4.4.2.1 Middle Strips

In both directions, the reinforcement area per design strip is indicated for the internal middle strip and the external, middle strip. The values were shown for cases C4, C5, and C6. The outcomes of reinforcement in cases C4 and C5 were previously represented. Meanwhile, the reinforcement area for case C6, which indicates a waffle slab with solid sections and steel fibers, was 381 mm2 for top reinforcement and 658 m2 for bottom reinforcement in the x direction of the internal strip.

As a result, cases C4 and C6 have equal reinforcement areas per design strip and require less reinforcement at the top and bottom than case C5. A similar situation is applied to the exterior and interior strip in both directions.

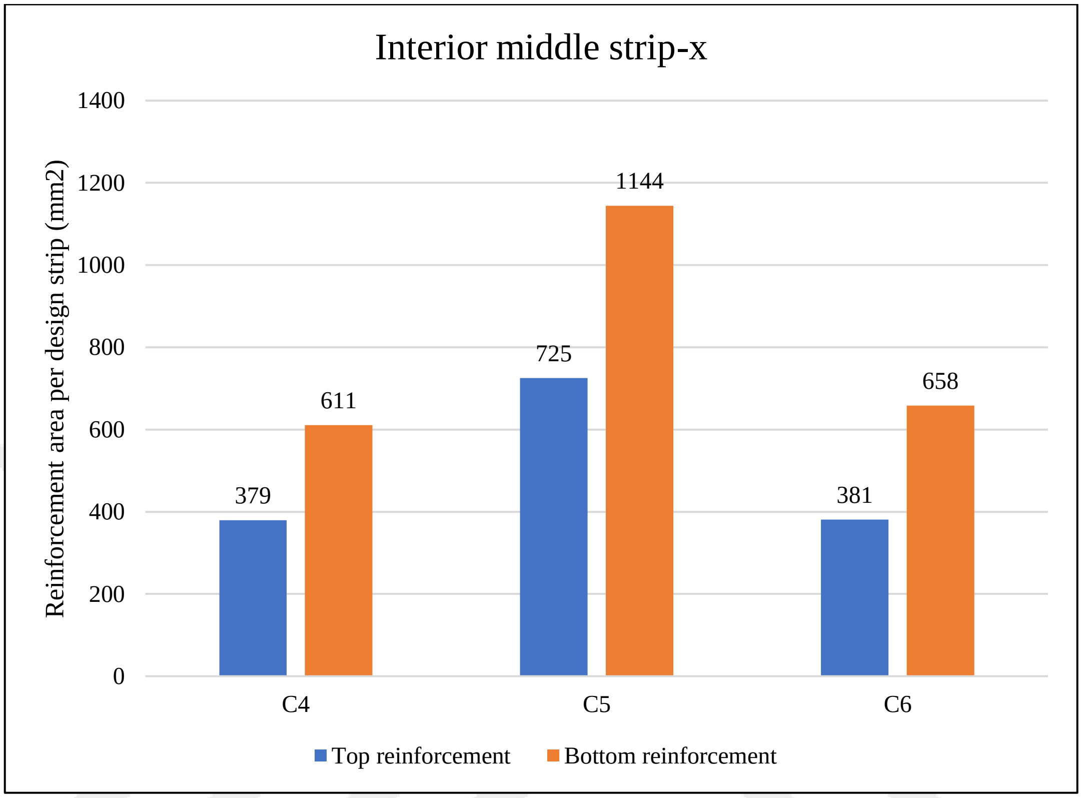

Figure 4.18: Interior middle strip-x reinforcement of cases C4, C5, and C6.

Additionally, the research modeling, mathematical simulations, and numerical analysis indicated the numerical research findings associated with exterior middle strip-x reinforcement for cases C4, C5, and C6. Figure 4.19 indicates these findings.

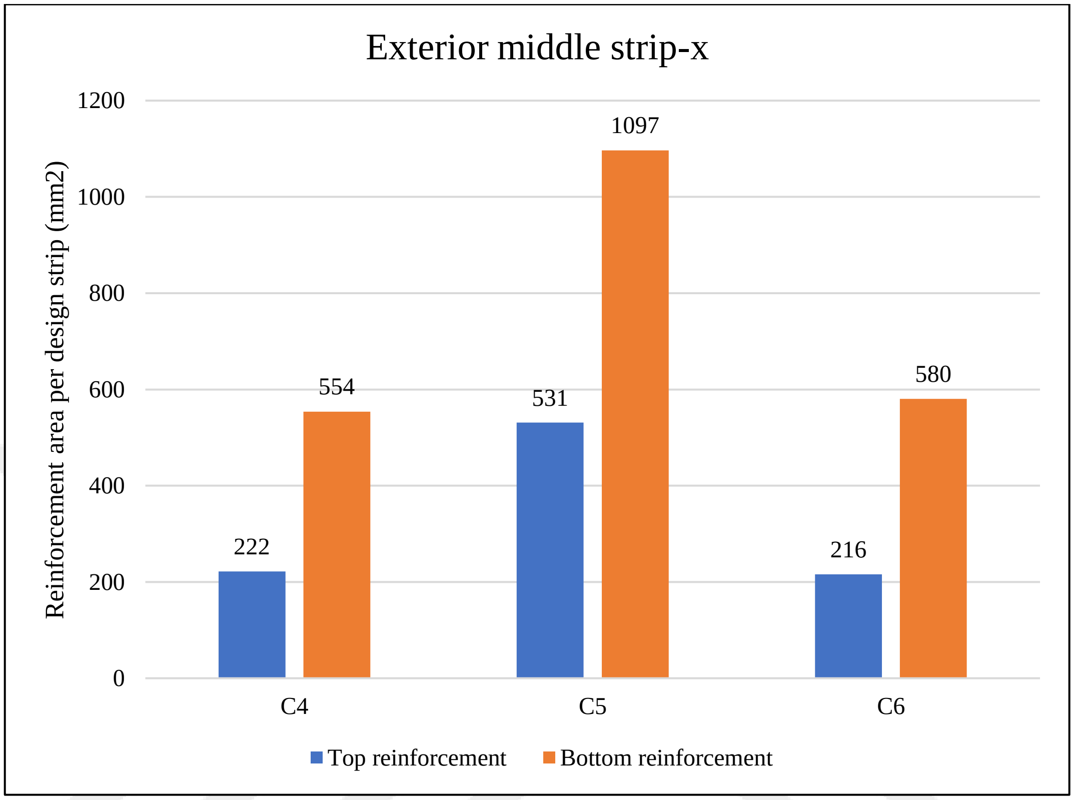

Figure 4.19: The numerical research findings associated with exterior middle strip-x reinforcement for cases C4, C5, and C6.

Besides, the research modeling, mathematical simulations, and numerical analysis indicated the numerical research findings associated with interior middle strip-y reinforcement for cases C4, C5, and C6. Figure 4.20 expresses these results.

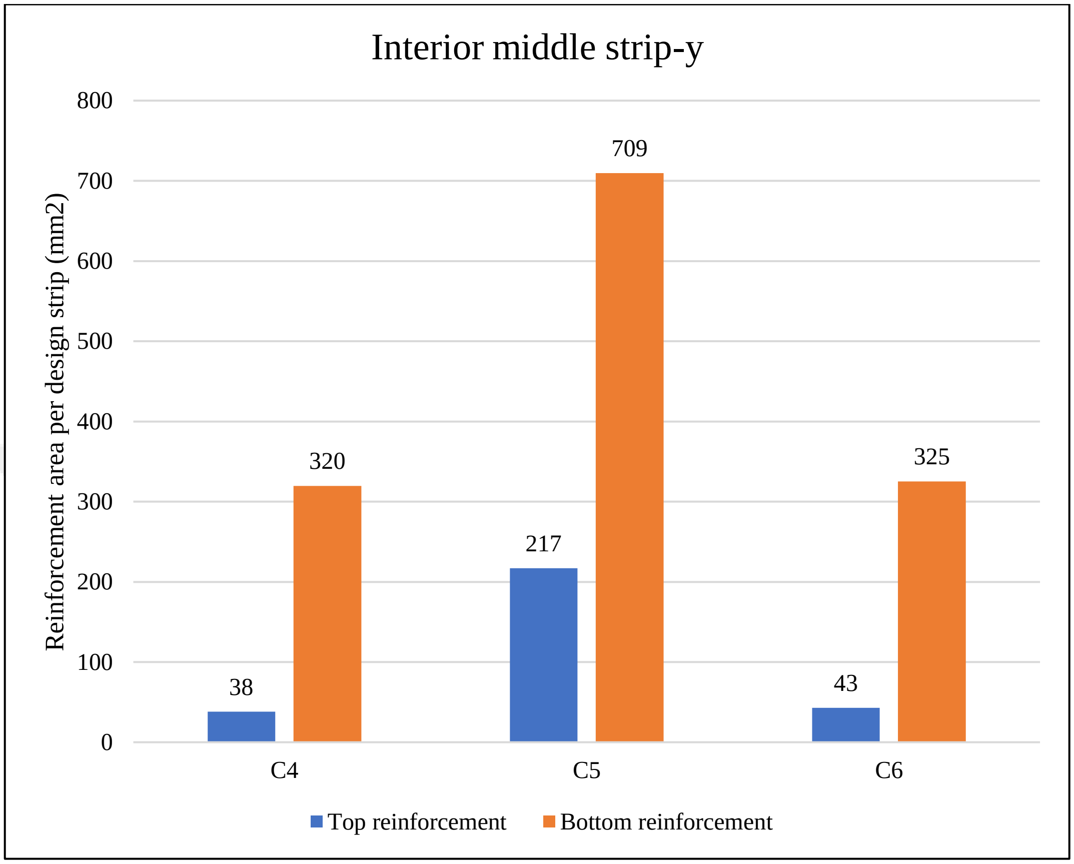

Figure 4.20: The numerical research findings associated with interior middle strip-y reinforcement for cases C4, C5, and C6.

Also, the research modeling, mathematical simulations, and numerical analysis indicated the numerical research findings associated with the exterior middle strip-y reinforcement for cases C4, C5, and C6. Figure 4.21 expresses these results.

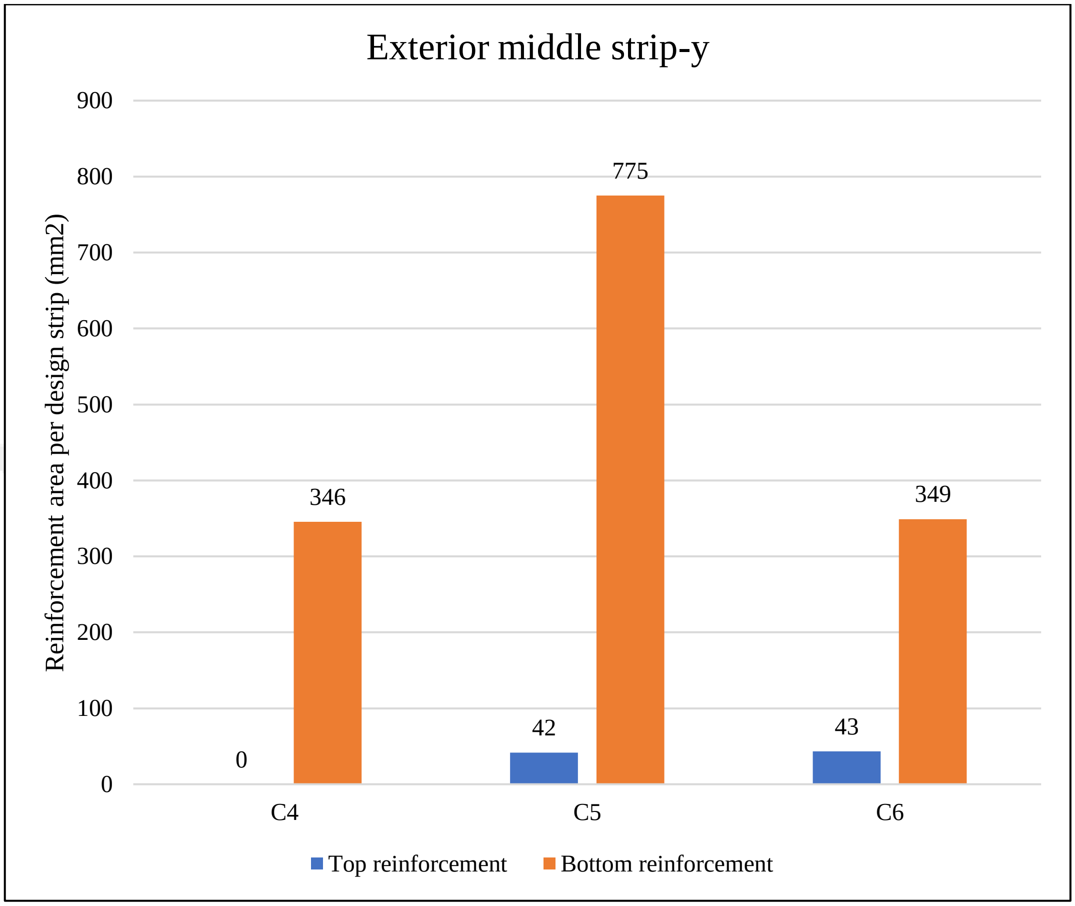

Figure 4.21: The numerical research findings associated with the exterior middle strip-y reinforcement for cases C4, C5, and C6.

4.4.2.2 Columns Strips

Figure 4.22, Figure 4.23, Figure 4.24, and Figure 4.25 display the reinforcement area values for column strips for cases C4, C5, and C6. The results of interior column reinforcement in the x direction in case C4 are 6,376 mm^2 for top reinforcement and 924 mm^2 for bottom reinforcement. For a flat slab, the reinforcement area per interior column in the x direction is 6,244 mm^2 top reinforcement and 1,354 mm^2 bottom reinforcement. Meanwhile, the interior column strip reinforcement area for case C6, which represents a waffle slab with solid sections and steel fibers, is 6,021 mm^2 for top reinforcement and 931 m^2 for bottom reinforcement in the x direction.

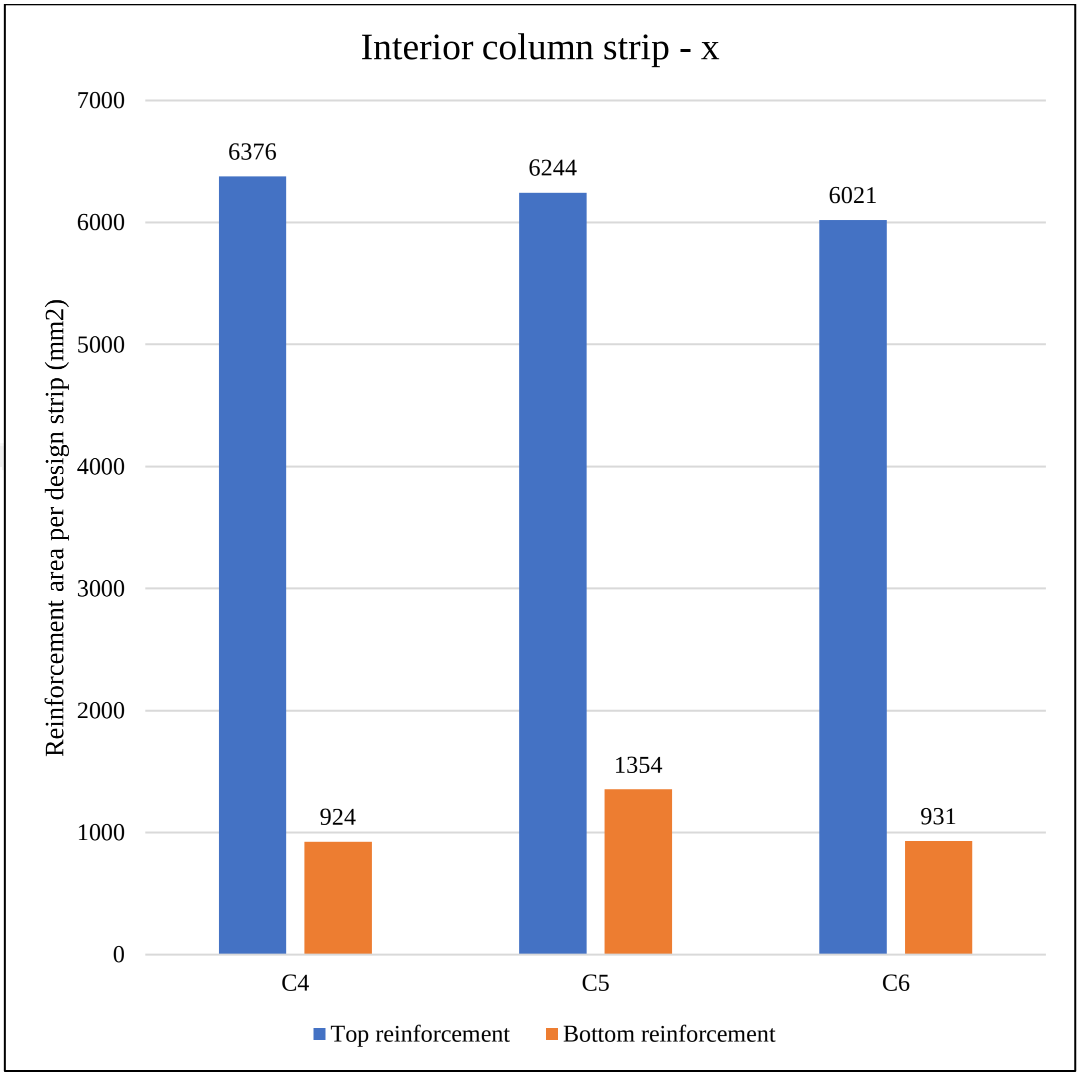

Figure 4.22: Interior column strip-x reinforcement for cases C4, C5, and C6.

Further, the numerical analysis, research modeling, and mathematical simulations indicated the numerical research findings related to exterior column strip-x reinforcement for cases C4, C5, and C6. Figure 4.23 expresses these results.

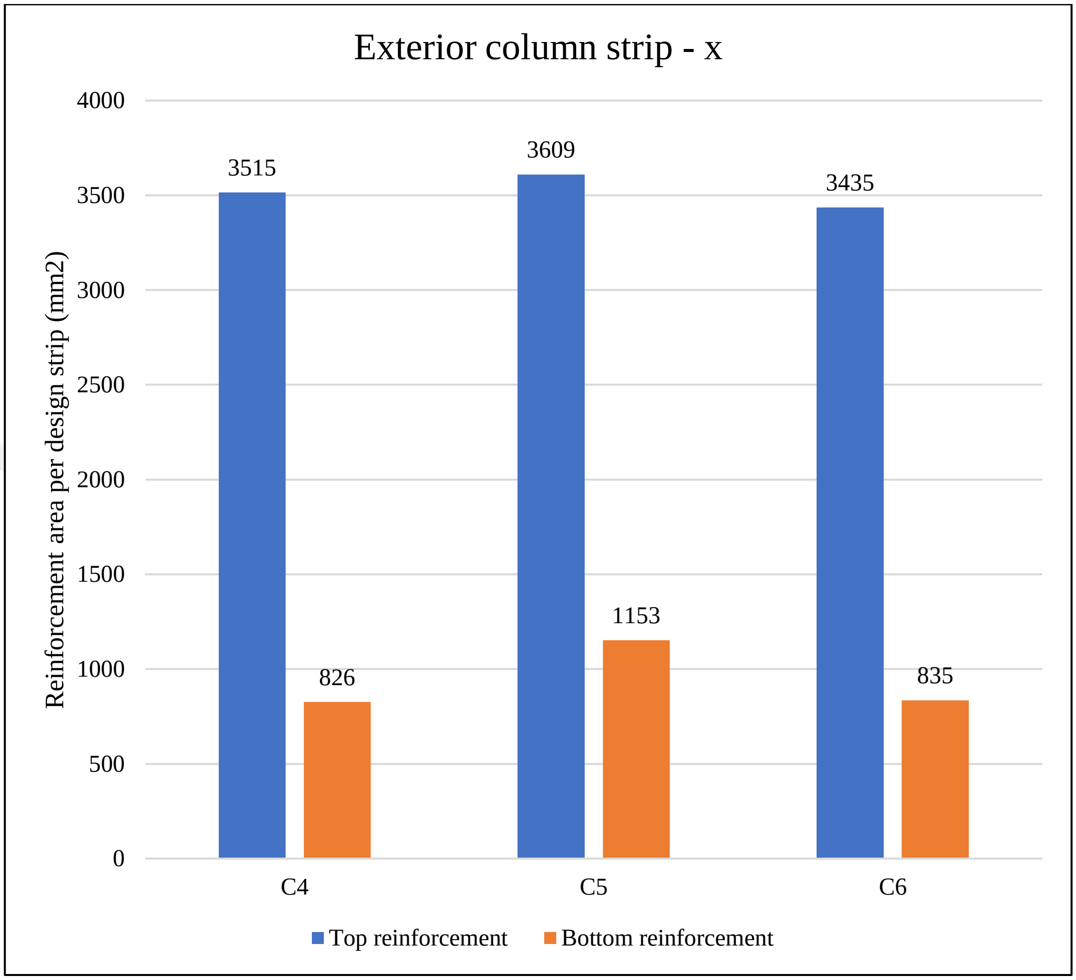

Figure 4.23: The numerical research findings related to exterior column strip-x reinforcement for cases C4, C5, and C6.

Besides, the numerical analysis, research modeling, and mathematical simulations indicated the numerical research findings related to interior column strip-y reinforcement for cases C4, C5, and C6. Figure 4.24 expresses these results.

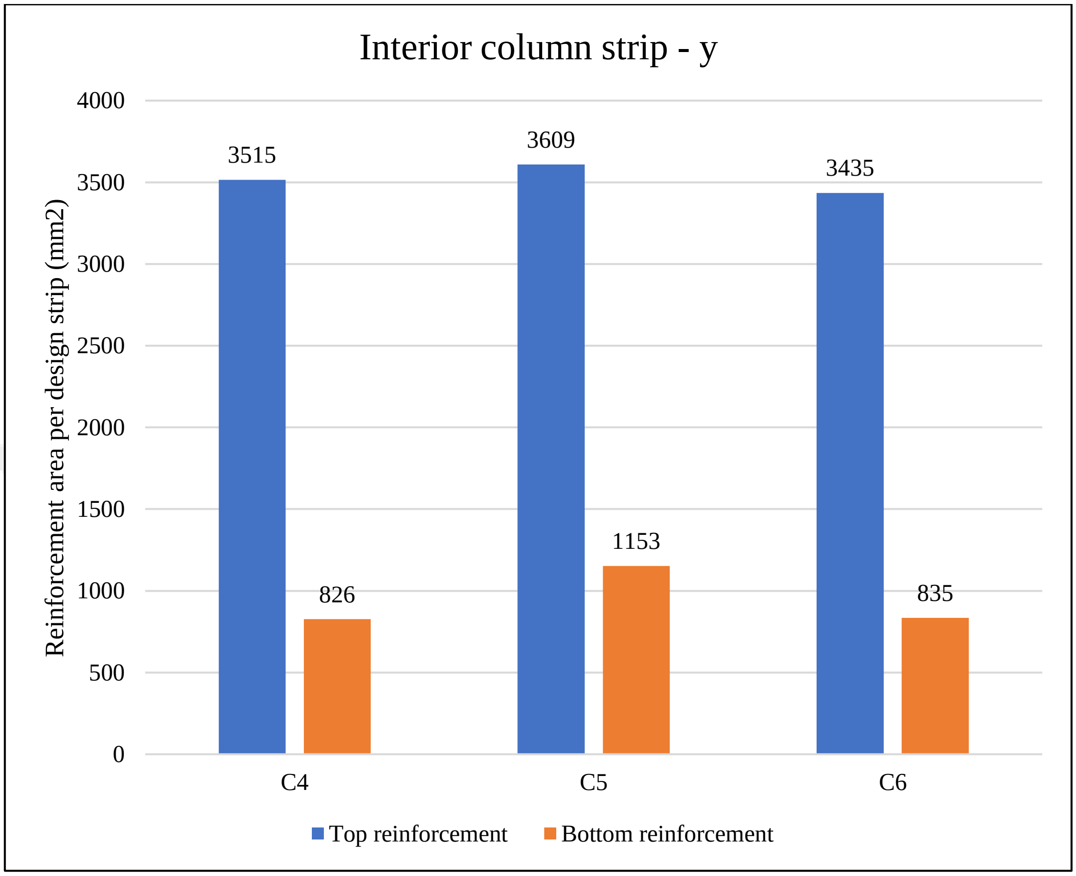

Figure 4.24: The numerical research findings related to interior column strip-y reinforcement for cases C4, C5, and C6. Figure 4.24 expresses these results.

Additionally, the numerical analysis, research modeling, and mathematical simulations indicated the numerical research findings related to exterior column strip-y reinforcement for cases C4, C5, and C6. Figure 4.25 expresses these results.

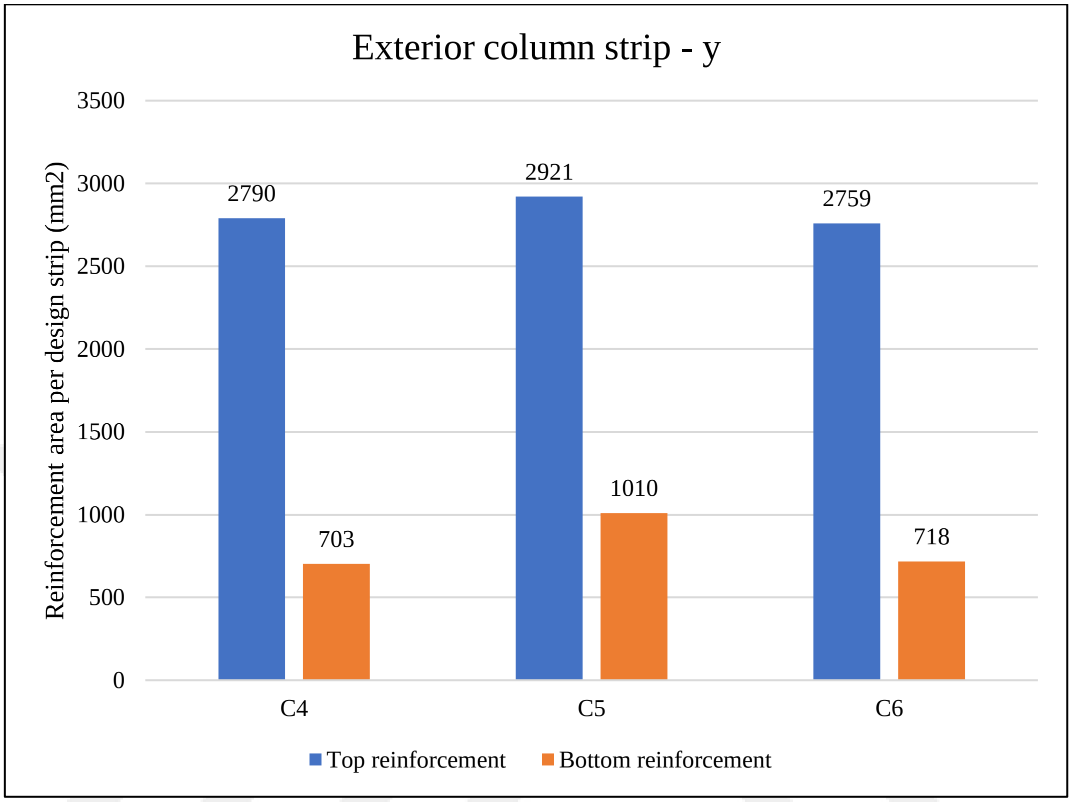

Figure 4.25: The numerical research findings related to exterior column strip-y reinforcement for cases C4, C5, and C6.

In conclusion, cases C4 and C6 have equal reinforcement areas per design strip (column strip) and require less reinforcement at the top and bottom than case C5. In both directions, a similar scenario happened to the exterior and interior column strips.

4.4.2.3 Punching Shear Results

A punching shear failure can occur in a waffle slab, just as it does in a flat slab. Cases C4, C5, and C6 were subjected to parametric analysis to demonstrate the punching shear. The punching shear for waffle slab C4 was 0.73, 0.78, and 0.96 at the interior, edge, and corner, as shown in Figure 26. Otherwise, the pushing shear for flat slab C5 was 0.87, 0.73, and 0.82 towards the interior, edge, and corner. The punching values in concrete Case C6 dropped after the addition of steel fibers, as shown in the graph of Figure 4.26, 0.59, 0.61, and 0.79 near the interior, edge, and corner, accordingly.

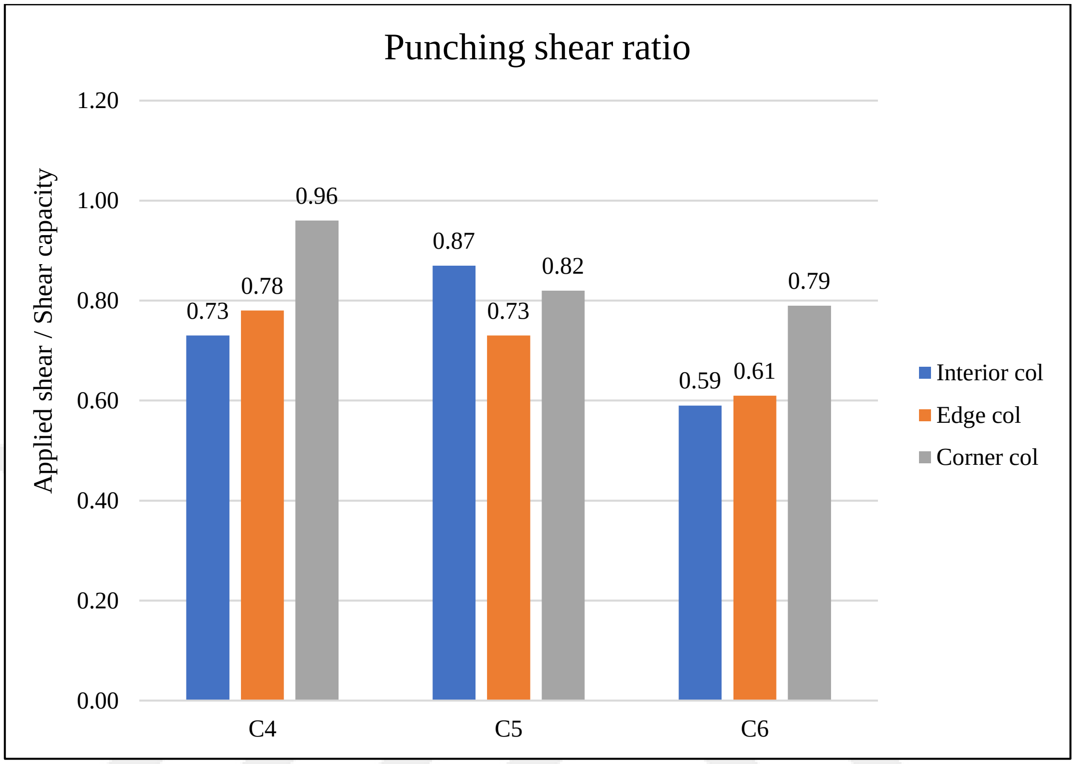

Figure 4.26: The punching shear ratio for Cases C4, C5, and C6.

Eventually, steel fibers in Case C6 reduced the punching shear for the interior, edge, and exterior columns by 24% in a waffle slab system with the solid panel at columns. The three cases represent punching shear of less than 1%.

4.5 EFFECT OF ADDING STEEL FIBERS TO CONCRETE ON WAFFLE SLAB SYSTEM WITH BOTH BEAMS AND SOLID SECTIONS

4.5.1 Maximum Deflection

In this section, the maximum deflection of a waffle slab with beams and fibers C3, a waffle slab with solid sections at columns and steel fibers C6, and a combined waffle system of cases C3 and C6 are compared. Figure 27 shows that the maximum deflection of the combined waffle system with steel fibers is 31 mm.

The results indicate that a waffle slab with beams along support lines and fibers C3 has a 15% greater maximum deflection than a waffle slab with solid sections and fibers C6. Furthermore, the C7 mixed waffle slab with solid sections, beams, and steel fibers has a 28% lower maximum deflection than the Case C3 system.

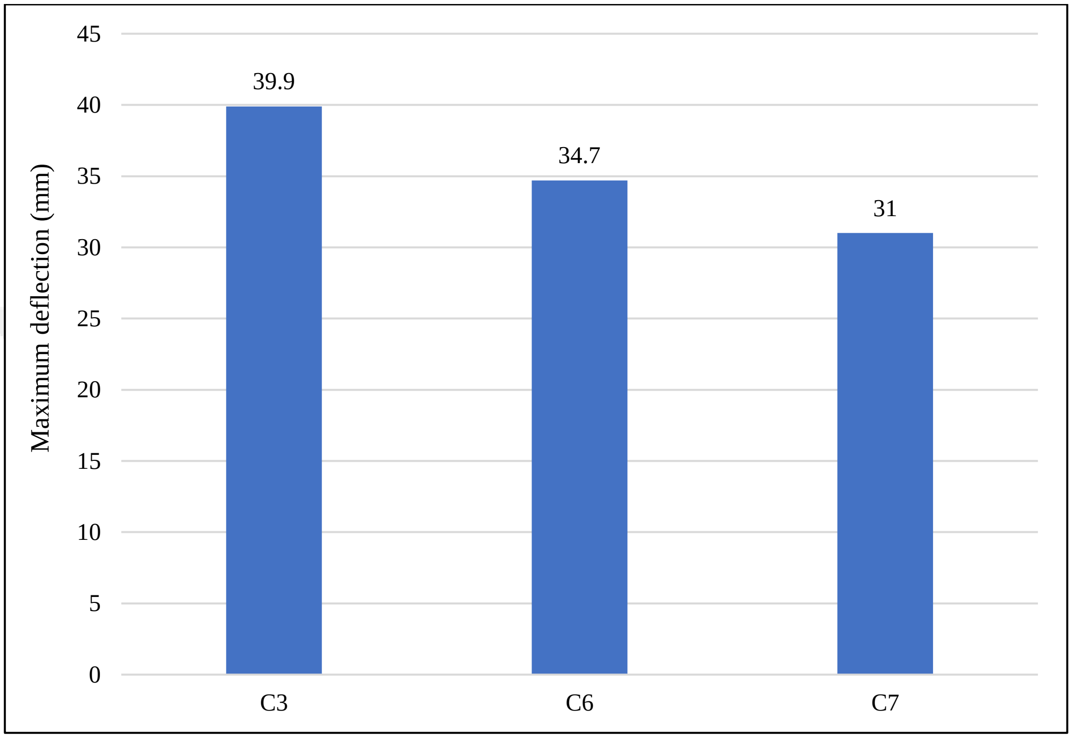

Figure 4.27: Maximum deflection in mm for Cases C3, C6, and C7.

More investigation was undertaken in Case C7 to establish the appropriate slab thickness to achieve a maximum deflection of 38 mm. Figure 4.28 indicates that in the case of C7, the slab thickness can be 33 cm in order to obtain the maximum deflection of the standard waffle slab C4. Steel fibers added to a waffle slab system with solid sections and beams reduce slab thickness by 13% or around 5 cm.

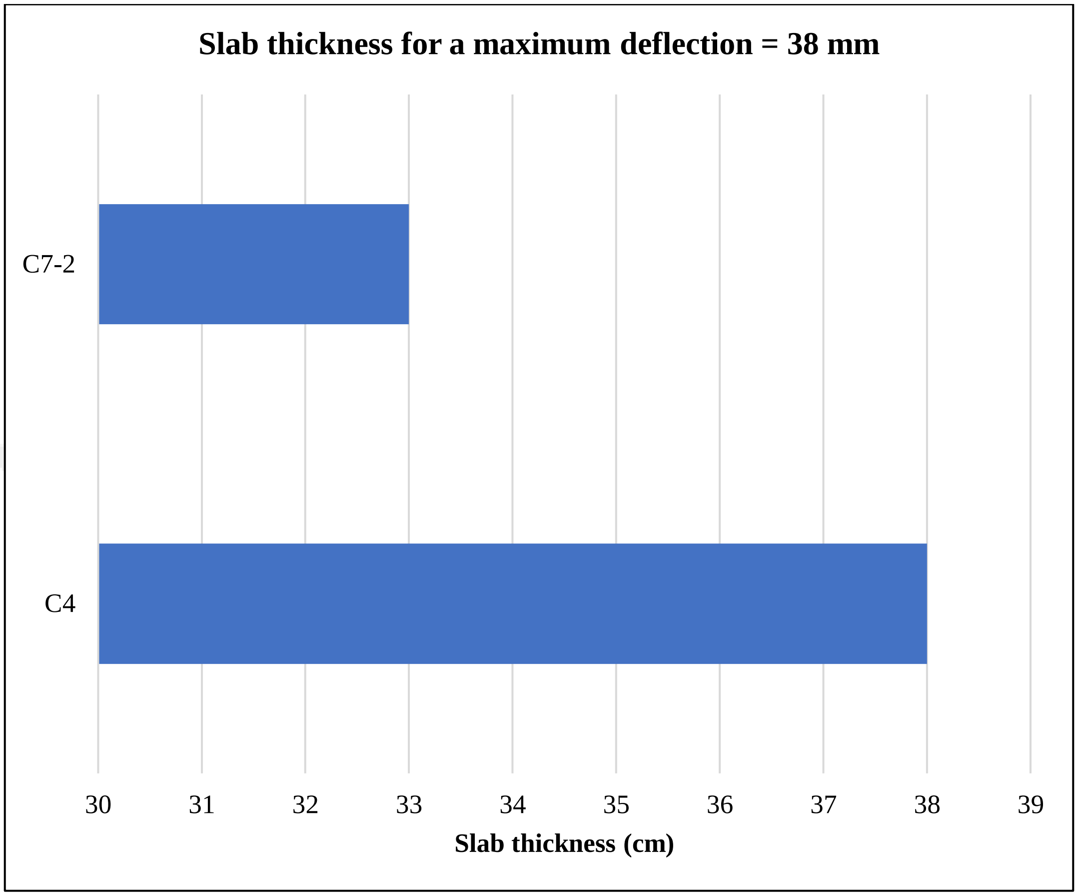

Figure 4.28: Slab thickness for a maximum deflection 38 mm for case C7.

4.5.2 Slab Reinforcement Results

Figure 4.29, Figure 4.30, Figure 4.31, and Figure 4.32 show the reinforcing area per strip for the three cases, C3, C6, and C7. Figure 4.29 below shows the reinforcing area per interior middle strip in x direction of the three distinct slab systems. The top reinforcement area of Case C3 is 560 mm^2, and the bottom reinforcement area is 603 mm^2.

Otherwise, the waffle slab with solid sections and fibers in Case C6 requires 381 mm^2 of top reinforcement and 658 mm^2 of bottom reinforcement. The reinforced area in Case C7 is 574 mm^2 for top reinforcement and 592 mm^2 for bottom reinforcement. Both cases C3 and C7 have identical reinforcement areas in the interior middle strip that remain higher than the reinforcement in Case C6. The same trend may be seen in both directions for interior and exterior strips.

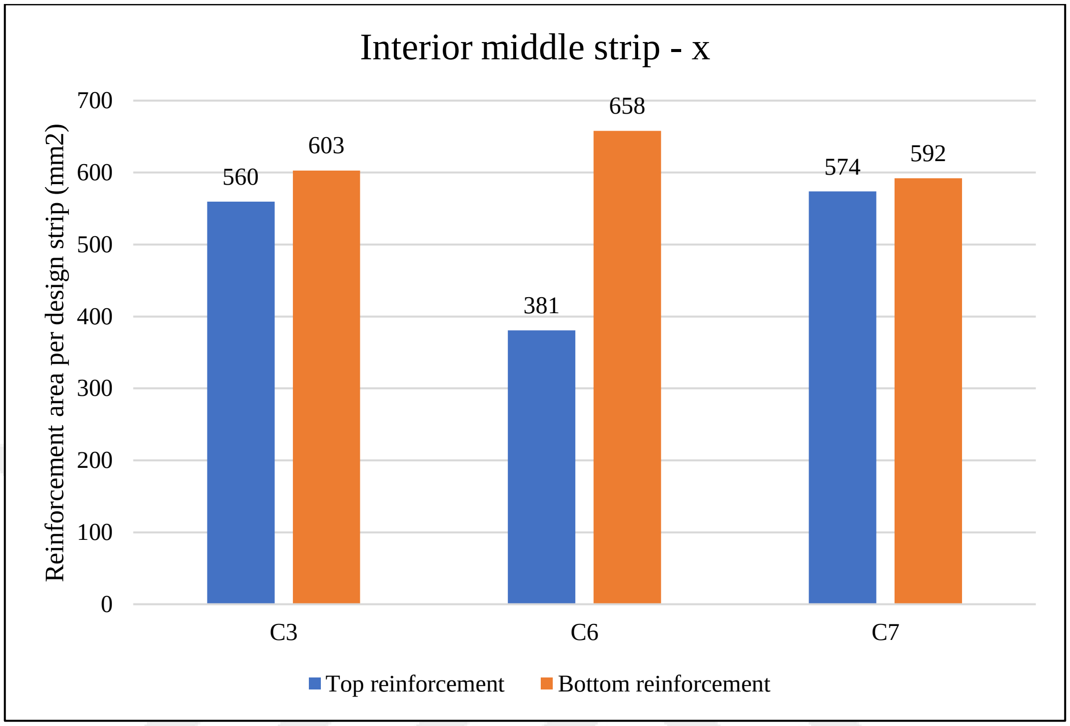

Figure 4.29: Interior middle strip-x reinforcement for cases C3, C6, and C7.

At the same time, the numerical analysis, research modeling, and mathematical simulations indicated the numerical research findings related to exterior middle strip-x reinforcement for cases C3, C6, and C7. Figure 4.30 expresses these results.

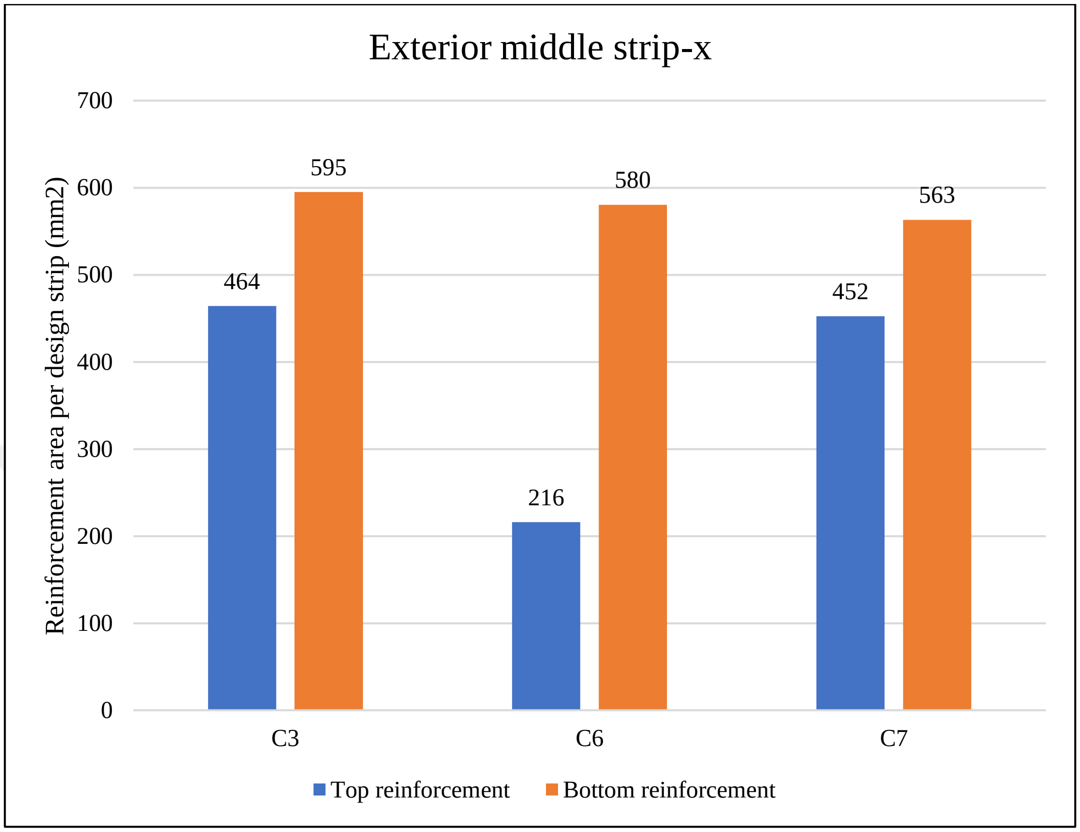

Figure 4.30: Exterior middle strip-x reinforcement for cases C3, C6, and C7.

Also, the numerical analysis, research modeling, and mathematical simulations indicated the numerical research findings related to interior middle strip-y reinforcement for cases C3, C6, and C7. Figure 4.31 expresses these results.

Moreover, the numerical analysis, research modeling, and mathematical simulations indicated the numerical research findings related to exterior middle strip-y reinforcement for cases C3, C6, and C7. Figure 4.32 expresses these results.

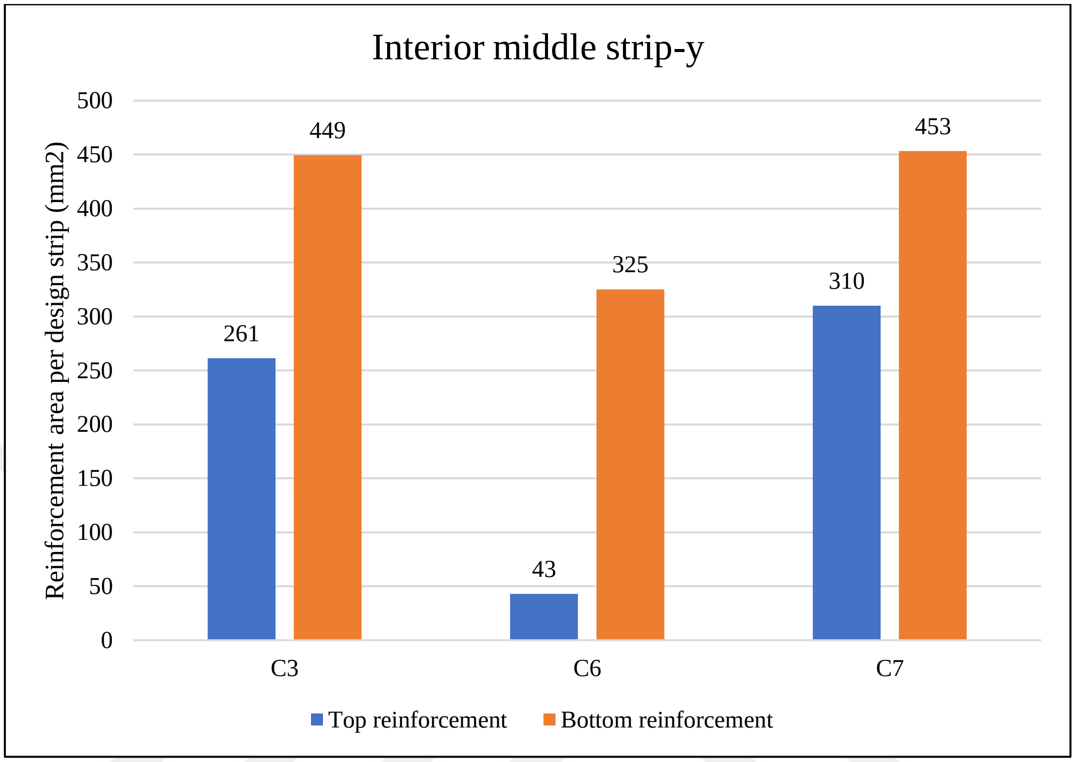

Figure 4.31: Interior middle strip-y reinforcement for cases C3, C6, and C7.

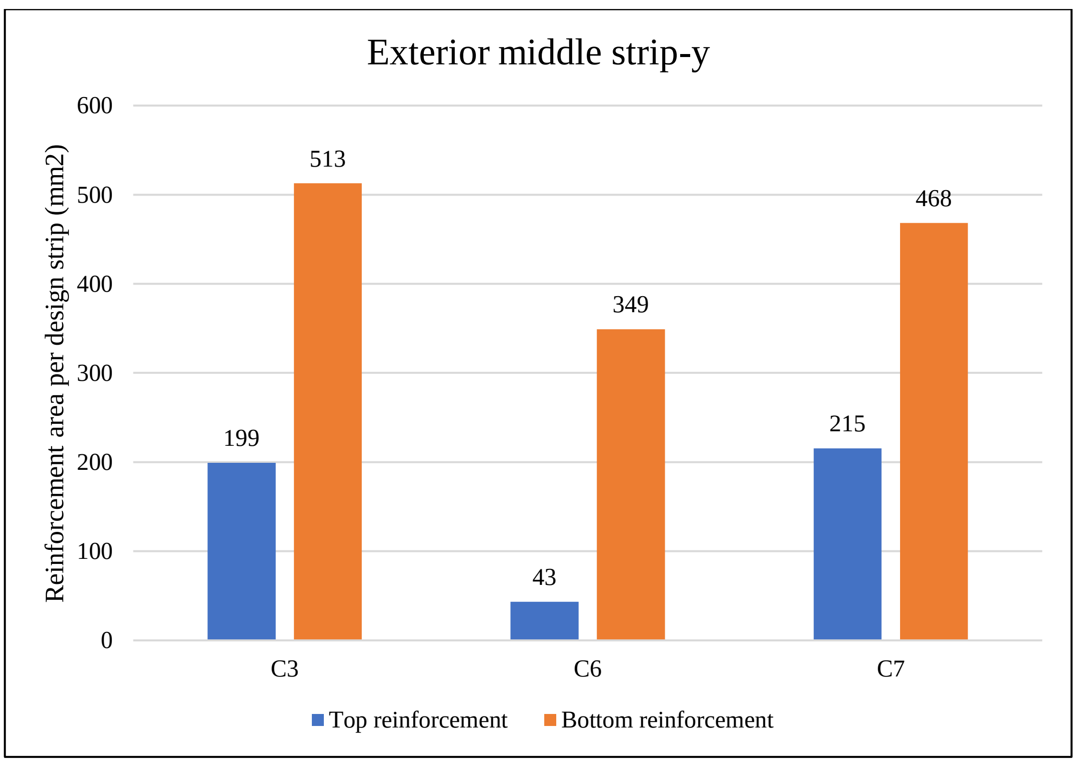

Figure 4.32: Exterior middle strip-y reinforcement for cases C3, C6, and C7.

4.5.3 Beam Reinforcement Results

For cases, C3 and C7, the interior and exterior beam strips in both directions are evaluated.

4.5.3.1 Interior Beam-X

Figure 4.33 indicates the interior beam reinforcement for the different cases in the x direction. Case C3 has 4,247 mm^2 of top reinforcement in the interior beam, 2,419 mm^2 of bottom reinforcement, and 2,401 mm^2/m of shear reinforcement. Case C7 includes top beam reinforcement of 2,568 mm^2, bottom beam reinforcement of 2,260 mm^2, and shear reinforcement of 2,485 mm^2/m. A combined waffle slab system with steel fibers resulted in less top reinforcement than a waffle slab with beams and fibers C3. Meanwhile, it appears that both bottom and shear reinforcement are unaffected.

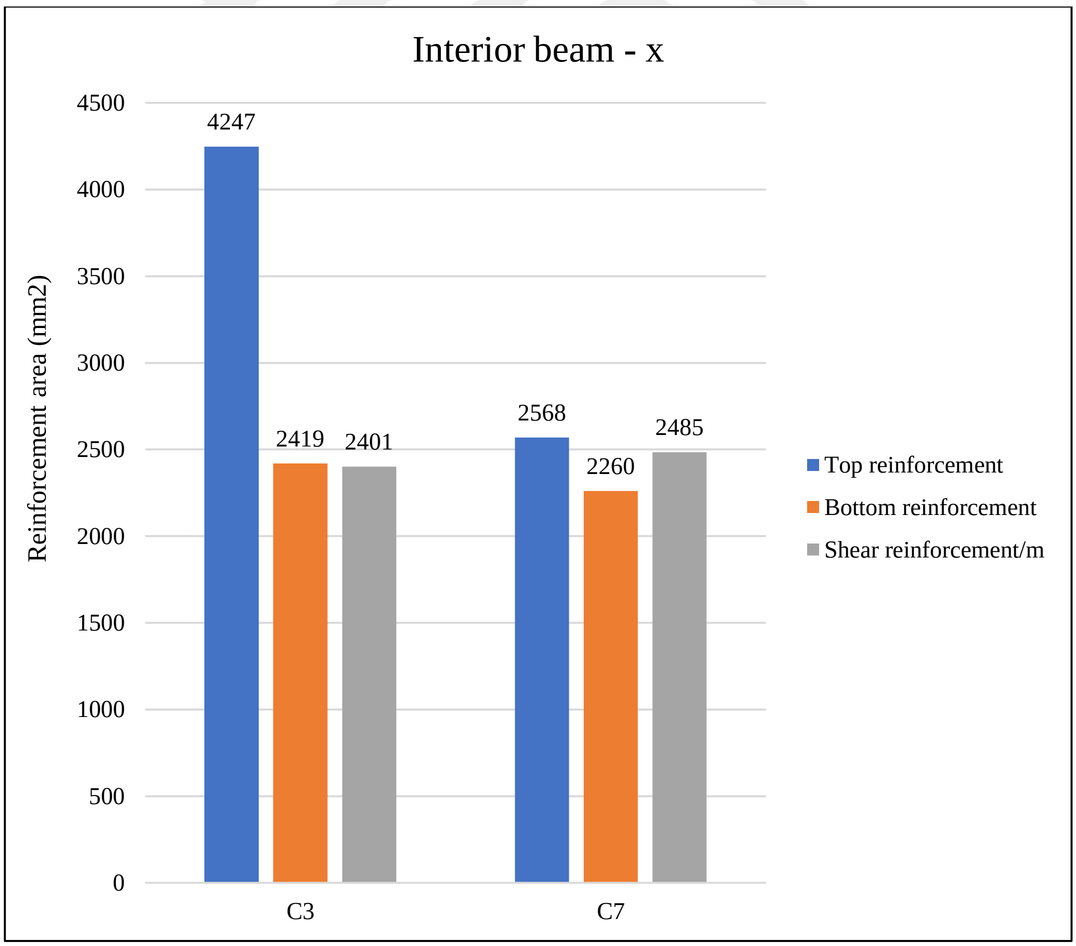

Figure 4.33: Interior beam-x reinforcement for Cases C3 and C7.

4.5.3.2 Exterior Beam-X

As illustrated in Figure 4.34, case C3 requires higher top reinforcement than a mixed waffle slab system C7 by 25%. In addition, the bottom and shear reinforcement stay the same.

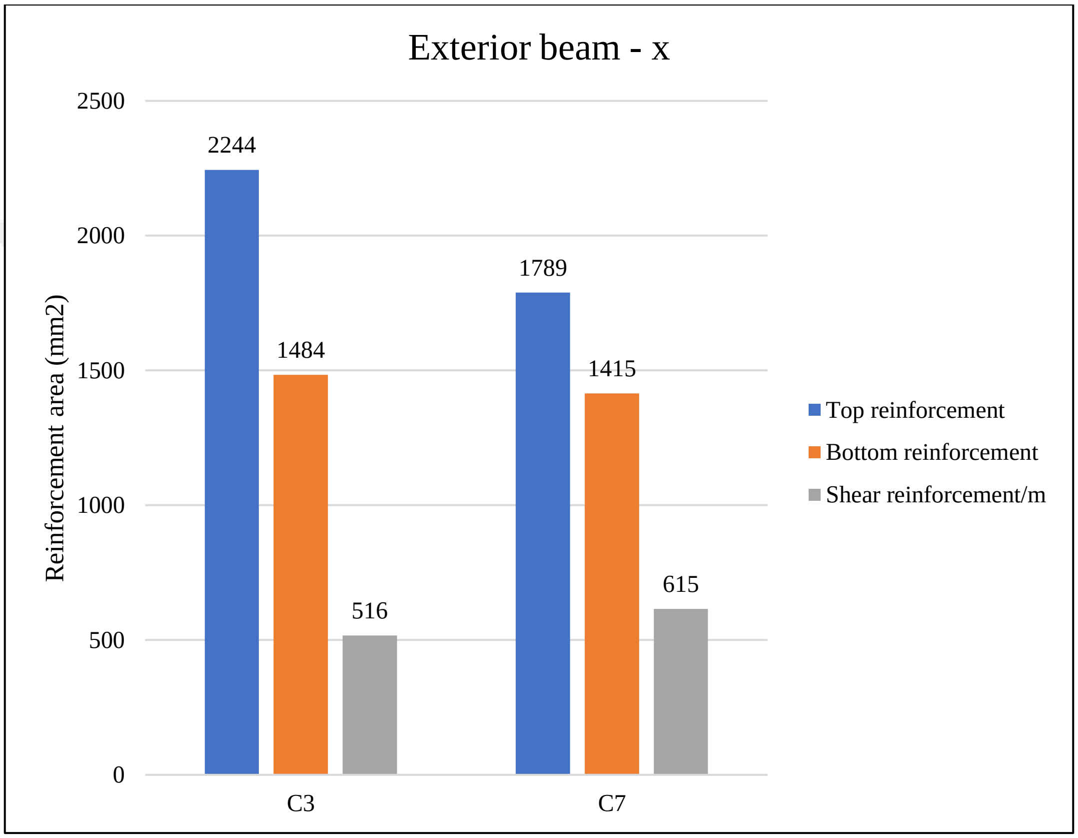

Figure 4.34: Exterior beam-x reinforcement for Cases C3 and C7.

4.5.3.3 Interior Beam-Y

Figure 4.35 presents the reinforcement areas per interior beam in the y direction. It demonstrates that a mixed system of waffle slab including fibers in concrete C7 results in lower top reinforcement than cases C3 by 49%. Meanwhile, both bottom and shear reinforcement are similar in the two cases.

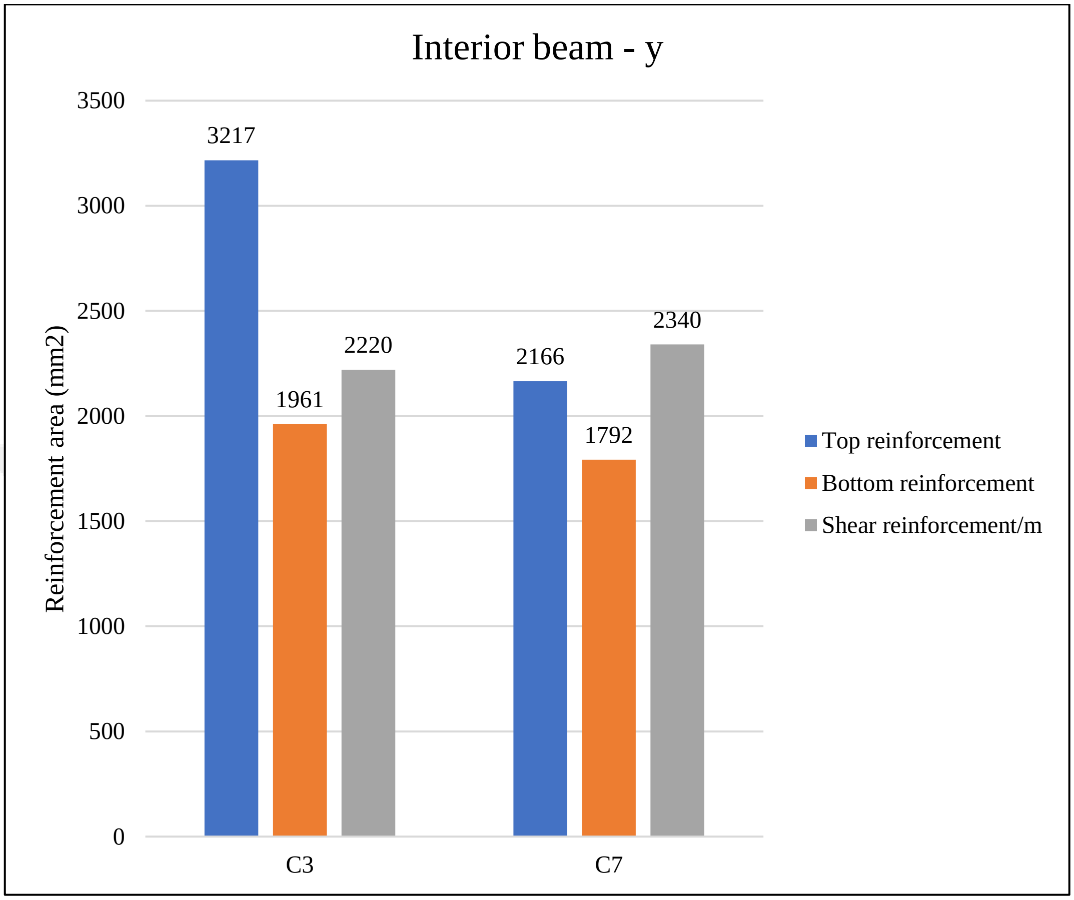

Figure 4.35: Interior beam-y reinforcement for Cases C3 and C7.

4.5.3.4 Exterior Beam-Y

The illustration in Figure 4.36 depicts the reinforcing areas per exterior beam in the y direction. It reveals that a combined system of waffle slab with fibers in concrete C7 results in 21% less top reinforcement than case C3. Meanwhile, the bottom and shear reinforcement are the same in both scenarios.

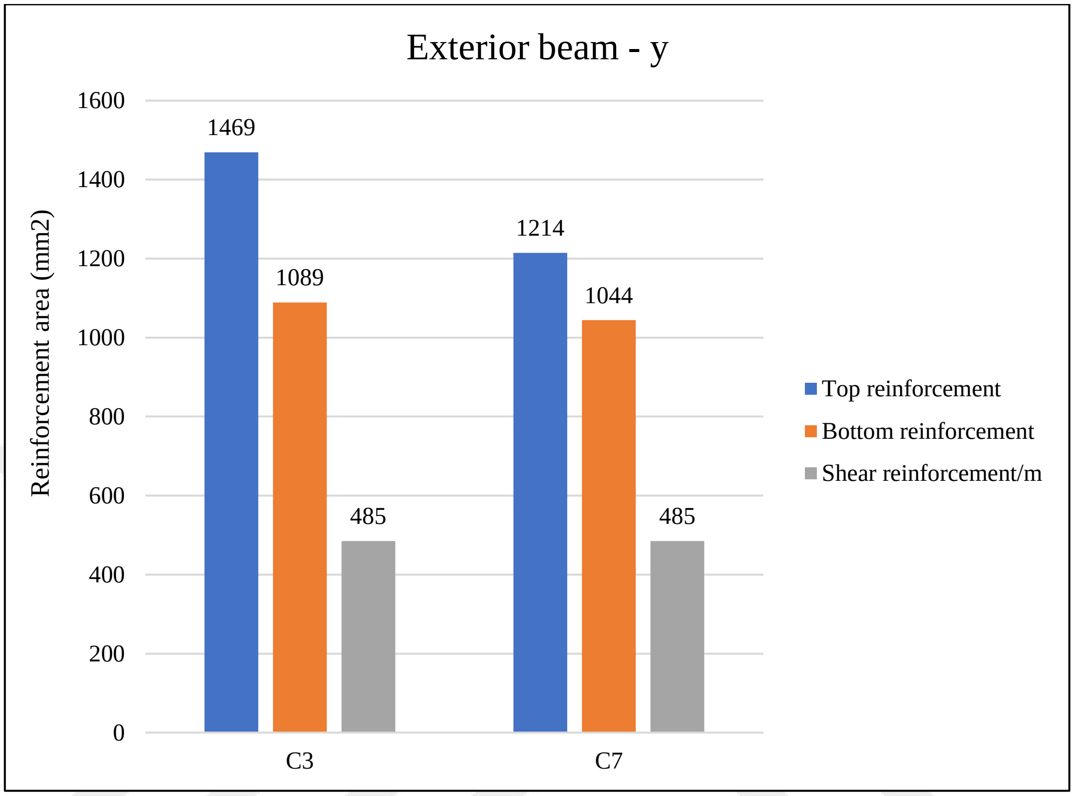

Figure 4.36: Exterior beam-y reinforcement for Cases C3 and C7.

4.6 DISCUSSIONS

The results of this work indicated that adding steel fibers to the waffle slab would decrease the maximum deflection of a waffle slab. Also, the results revealed that the deflections in the waffle slabs are more significant than that in the solid slab. In addition, the research findings confirmed that punching shear values in concrete Case C6 dropped after the addition of steel fibers. These results are consistent with the results of [13], who conducted an analysis examining the impact of adding steel fibers to concrete slabs on the punching shear resistance and found that integrating steel fibers into concrete would reduce the punching shear and increase the slabs' punching shear resistance. In addition, [13] found that the concrete slab with steel fibers had significant enhancements in the cracking behavior and higher integrity and homogeneity of slabs connected to steel fibers. The results of this study are also consistent with the results of [16],[18],[49],[50],[53], who carried out research examining the critical role of steel fibers integration into the concrete slabs on their punching shear resistance.

Their experimental work revealed that adding steel fibers could significantly increase the punching shear resistance of the concrete slabs. Also, the results of this work are consistent with the findings of [14], [15], [50], who executed research analyzing the integration of steel fibers into slabs and found that adding steel fibers to the slabs would reduce the deflection amount and minimize the cracking growth. Besides, the results of this work are compatible with the findings of [51], who studied the impact of adding steel fibers into concrete slabs and found that integrating these fibers into concrete slabs would improve the cyclic and flexural performance related to the bridge deck slabs and reduce deflection and increase its stiffness.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CHAPTER GOAL

This chapter aims to address the major conclusions of this thesis. In addition, it aims to represent critical conclusions and recommendations that help construction companies and researchers adopt steel fiber in SCC to improve its effectiveness, robustness, workability, and mechanical properties.

5.2 CONCLUSIONS

This work is carried out to examine and evaluate the contribution of adding steel fibers to concrete to improve its strength and performance. A comparative analysis is conducted to achieve the study goal, considering seven case studies through which the relevance and critical benefits of integrating steel fibers into concrete are assessed and identified. The SAFE® software package was employed to numerically model and simulate the waffle slab and other slabs in the seven cases. Significant parameters are taken into account to evaluate the beneficial impact of adding steel to concrete, namely reinforcement ratios in slabs and beams, long-term deflection, and punching shear. Furthermore, the influence of some factors on the waffle slabs' behavior is examined. These factors include the impact of steel fiber integration into concrete, the effect of drop beams as a supporting system, and the influence of solid sections at columns. Based on the numerical analysis executed via the SAFE® program, the research findings can be classified in the following paragraphs:

i. Waffle slab deflections are, in fact, greater than solid slab system deflections. This aspect proves how flexible waffle slab systems are compared with solid slab systems.

ii. As the volume of concrete increases, the self-weight also increases, resulting in more loads. When the two waffle systems are analyzed, the waffle slab with beams C1 has 49% more top reinforcement than the waffle slab with solid sections C4.

iii. The waffle system C1 has 114% more top reinforcement area than the waffle slab with solid panels C4.

iv. The addition of steel fibers decreases the maximum deflection of a waffle slab with beams by 18%. Also, the maximum deflection of a waffle slab with beams is 46% more than that of a solid slab.

v. The top and bottom reinforcement areas per strip for waffle slabs C1 and C3 are almost identical, with no significant differences. Meanwhile, in both situations, C1 and C3, less top and bottom reinforcement is required than in the solid slab.

vi. The amount of top reinforcement for the interior beam is much more significant in case C1 than in case C3. Case C1 has slightly more bottom and top reinforcement of the interior beam than Case C3. In flexural reinforcement, C1 and C3 are both greater than C2, whereas C2 is lower in shear reinforcement.

vii. Inserting steel fibers into concrete improves a waffle slab system with solid sections.

viii. Cases C4 and C6 have a more significant maximum deflection of concrete than flat slabs because flat slabs are stiffer than waffle slabs.

ix. Steel fibers added to a waffle slab system with solid sections reduce slab thickness by 5%, about 2 cm.

x. The punching values in concrete Case C6 dropped after the addition of steel fibers.

xi. The C7 mixed waffle slab with solid sections, beams, and steel fibers has a 28% lower maximum deflection than the case C3 system.

xii. Steel fibers added to a waffle slab system with solid sections and beams reduce slab thickness by 13% or around 5 cm.

xiii. A combined waffle slab system with steel fibers resulted in less top reinforcement than a waffle slab with beams and fibers. Also, it appears that both bottom and shear reinforcement are unaffected.

xiv. A mixed system of waffle slab including fibers in concrete C7 results in lower top reinforcement than case C3 by 49%.

xv. A combined system of waffle slab with fibers in concrete C7 results in 21% less top reinforcement than case C3.

5.3 RECOMMENDATIONS

Based on the numerical research findings and mathematical simulation outcomes, the researchers suggest a number of critical recommendations that can help improve the adoption of steel fiber in the construction industry, which includes:

i. Carrying out additional tests and validations of the beneficial role and advantageous impact of integrating steel fiber into the SCC.

ii. Increasing the support of top management.

iii. Conducting plenty of educational sessions, workshops, and training courses that help engineers and project managers understand the importance and benefits of steel fibers addition into the SCC.

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