NUMERICAL STUDY ON VARIOUS STEEL STIFFENER ANGLES TO REINFORCE HALF-LOADED FLAT SLABS

RUBAANANTAN A/L RAJOO

A project report submitted in partial fulfilment of the requirements for the award of Master of Engineering (Civil)

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

September 2023

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature :

Name : Rubaanantan Rajoo

ID No. : 23UEM00502

Date : 7/12/2023

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"NUMERICAL STUDY ON VARIOUS STEEL STIFFENER ANGLES TO REINFORCE HALF-LOADED FLAT SLABS"** was prepared by **RUBAANANTAN A/L RAJOO** has met the required standard for submission in partial fulfilment of the requirements for the award of Master of Engineering (Civil) at Universiti Tunku Abdul Rahman.

Approved by,

Signature : ______________________

Supervisor : Dr. Woon Kai Siong

Date : 7/12/2023

Signature : ______________________

Co-Supervisor : ______________________

Date : ______________________

ACKNOWLEDGEMENTS

I am extremely thankful for Dr.Woon Kai Siong's guidance and support as I worked to finish my project. In addition to enriching my project, his wise criticism, commitment, and depth of knowledge motivated me to strive for academic excellence. I am incredibly grateful that I was able to work under his direction.

I would also like to thank my family for their unwavering faith in my capabilities, their patience during challenging moments, and their enthusiasm for my academic jorney have been the cornorstones of my accomplishments.. Their sacrifices and confidence in my potential have ignited my drive to excel. A significant part of this achievement is owed to them, and I eagerly anticipate the opportunity to bring them pride through the application of the knowledge and skills I've gained from this project. My family's support and Dr.Woon Kai Siong's guidance have made a tremendous difference to me both in terms of studying and my personal development, which I am very grateful for.

ABSTRACT

The study addresses the challenges in creating an accurate ABAQUS model for estimating punching shear capacity, highlighting the lack of necessary historical data and a gap in research on the impact of varying steel stiffener angles in half-loaded flat slabs. With a predominant focus on a 45-degree angle in previous studies, there is a compelling need for clear guidelines in determining optimal dimensions for steel stiffeners, prompting a comprehensive exploration. To tackle this problem, this study includes developing a numerical model based on historical results, evaluating the influence of different steel stiffener angles using ABAQUS simulations, and identifying suitable dimensions. The methodology involves modeling two control flat slabs (1600mm x 1600mm x 100mm) from historical work to serve as a reference. Additionally, five specimens, each featuring stiffeners with various vertical plate angles, are modeled. Each stiffener maintains a constant length and thickness of 200mm and 6mm, respectively, with varying height to accommodate different angles. The study assesses the influence of stiffeners with various angles on ultimate punching load, deflection, cracking pattern, stress, and damage. The findings indicate that variations among different stiffener plate angles have a less significant impact on deflection, ranging between 20mm and 23mm, and ultimate punching load, ranging between 163.5kN and 165kN. The nearly significant results may be attributed to variances in material properties, boundary conditions, modeling simplifications, and interactions between structural elements. Acknowledging limitations, the study notes the absence of detailed information in historical works, leading to assumptions about material properties that may introduce uncertainties. The chosen tie constraint technique for stiffener installation, preferred for ease of analysis and result interpretation due to material constraints, may deviate from the effectiveness demonstrated by steel bolts in prior research. The study refrains from exploring site-specific considerations such as soil conditions and seismic factors, recognizing their importance in practical applications but acknowledging that these aspects fall beyond the scope of the current research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

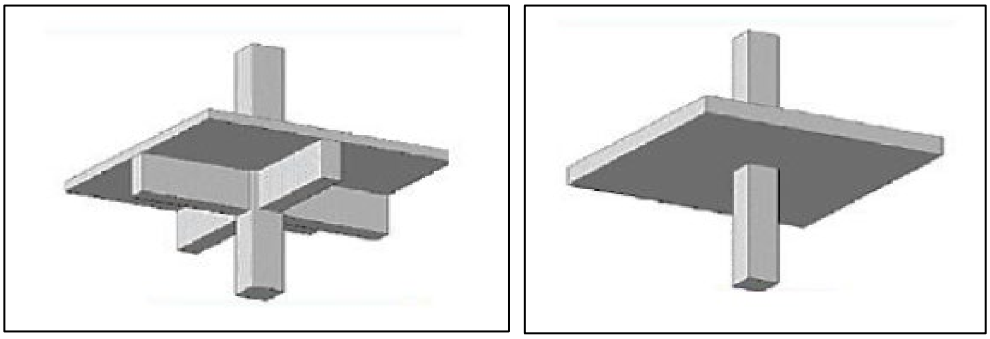
CHAPTER 1

INTRODUCTION

1.1 General Introduction

In the late 19th century, flat slab systems emerged independently in Europe and North America. Engineers recognized the advantages of eliminating beams between columns to simplify construction and reduce overall story heights without sacrificing structural volume. The first flat slab system, designed by George M. H., was completed in the USA in 1901. Turner C.A. further popularized the concept from 1905 to 1909, while simultaneously, Swiss engineer Robert M. developed a similar system. Between 1900 and 1908, Robert M. conducted experimental studies leading to a patent in 1909. In 1910, his design was applied in Zurich to a warehouse with columns supporting a reinforced concrete plate directly. During the same period, engineer Arthur F. implemented concrete plate-supported structures in Russia, contributing to the development of such systems. Despite some design variations, large columns were commonly used to efficiently transmit loads from concrete plates. Notably, there was little consideration for specific reinforcement to resist punching failure in these early systems (Sagban et al., 2019).

In recent decades, the flat slab structural system has become increasingly popular due to its numerous advantages despite the notable risk of punching shear. Unlike traditional structures where beams support the slab and transfer loads, including the self-weight of the slab, to the columns, flat slabs present an aesthetically pleasing perspective marked by the absence of beams between columns. In this specific design, the slab efficiently distributes its weight and self-weight directly to the columns, eliminating the necessity for beams between columns. Flat slabs are widely utilized in various structures, such as commercial buildings, hotels, and parking spaces, where there is minimal reliance on beam support, setting them apart from conventional slab structures (Salehuddin et al., 2020) as shown in Figure 1.1.



a) Conventional Slab b) Flat Slab

Figure 1.1: Slab Structures (Salehuddin et al,. 2020)

1.2 Importance of the Study

This research has broad implications for structural engineers and the construction sector. It increases global resilience of structures by optimizing steel stiffeners, which are critical for supporting these frequently utilized flat slabs. The study also promises cost-saving benefits, allowing informed judgments that reduce construction costs. The study, which emphasizes sustainability, leads exact designs, eliminating material waste. It improves building safety standards and informs risk reduction measures, which contributes to safety. It fills a void academically, paving the door for future studies. In essence, this research has a significant impact on structural integrity, cost-effectiveness, sustainability, safety, and academic advancement in the construction business.

1.3 Problem Statement

The structural integrity of flat slabs under punching shear is a critical concern in civil engineering, necessitating innovative approaches to reinforce and enhance their performance. Researchers has made several studies in understanding the reinforcement of flat slabs, however there remain a notable gap in the investigation of steel stiffener angles. Through this exploration, the study seeks to contribute valuable insights to the field, ultimately informing the design and construction practices for more robust and resilient structures.

Saib Kadhim and Ammash (2019) introduced an innovative method for fortifying flat plates through the application of steel stiffeners. Their study focused on evaluating the effectiveness of steel stiffeners with varying arrangements and quantities in enhancing punching shear strength. The strengthening steel plates were strategically extended from the column to the slab, essentially functioning as a column capital equivalent to a concrete column capital. The investigation comprised two phases: an experimental study involving the molding of three reinforced concrete flat slabs, each strengthened with different size and quantities of steel stiffeners, and a subsequent numerical modeling phase conducted using the ABAQUS finite element program. The research explored the impact of size of stiffener and the column's shape on both experimental and numerical fronts, yielding noteworthy agreement between the two sets of results.

Building on their previous work, the same authors proposed a repair system for flat slabs subjected to punching shear stresses, particularly those loaded to only half their capacities. This repair system centered on retrofitting damaged concrete by incorporating steel stiffeners with varying sizes and quantities. Experimental results served as the foundation for calibrating a nonlinear finite element model developed using ABAQUS. This model was then employed for a parametric study to assess the effects of altering compressive strength and flexural reinforcement on shear capacity. The numerical test results highlighted and confirmed the effectiveness of the proposed system in repairing damaged flat slabs, specifically in addressing punching shear concerns (Ammash, Kadhim and Dhahir, 2022).

In a separate study, Rasoul, Mohamed and Taher (2019) focused on evaluating the accuracy of predicting normal concrete behavior in simulating punching shear strength of flat slabs using finite element modeling in ABAQUS. Adopting Eurocode and FIB standards, the researchers predicted concrete curves for compressive and tensile stresses, incorporating two models based on prior experimental studies. The punching shear strength of two selected flat slab specimens, one with studs and the other without, was simulated in ABAQUS to validate punching shear force against vertical midspan displacement in accordance with the adopted experimental work. Simulation results demonstrated a high degree of concordance with finite element analysis (FEA) curves, affirming the reliability of the proposed modeling approach in predicting punching shear strength in flat slabs.

In conclusion, the identified problems underscore the need for focused attention in this research area. First, previous study confirms ABAQUS reliability, yet the challenge lies in the absence of data needed to create nearly significant model for estimating punching shear capacity based on historical results. Second, the lack of research on how different angles of steel stiffeners affect the strength of half-loaded flat slabs using ABAQUS simulations. Notably, previous study exclusively utilized stiffeners with only 45-degree angle. Lastly, lack of clear guidelines for figuring out the best dimensions for steel stiffeners emphasizing the need for more comprehensive exploration.

1.4 Aim and Objectives

The aim of this study is to discover the numerical study on various steel stiffener angles to reinforce half-loaded flat slabs. Therefore, the objectives needed to be achieved are:

a) To develop a numerical model that can estimate the ultimate punching shear capacity as per the experimental historical result.
b) To evaluate the effect of different steel stiffener angles on the punching shear strength of half-loaded flat slabs using numerical simulation with ABAQUS.
c) To identify a suitable dimension for steel stiffeners based on the numerical simulation results.

1.5 Scope and Limitation of the Study

The scope of study thoroughly explores a variety of steel stiffener angles for reinforcing half-loaded flat slabs, encompassing a spectrum to ensure a comprehensive analysis. Besides that, the structural examination focuses on key factors such as load-carrying capacity and deflection concerning the stiffener angles. The primary methodology employed is finite element analysis (FEA) using ABAQUS, enabling a detailed assessment of how different stiffener angles impact the performance of flat slabs. Overall, the main aim is to provide practical applications applicable to real-world construction scenarios, offering valuable insights for structural engineers and designers by identifying an suitable dimension for the steel stiffener The study also does not consider the effect of welding between angle stiffener with the plate.

Nevertheless, it's important to consider certain limitations in this study such as material properties and site factor respectively. Due to the absence of detailed information in the historical work, certain material properties may be assumed in the study. These assumptions, while necessary for analysis, may introduce uncertainties and variations that could impact the accuracy of the results. Additionally, the application of the tie constraint technique for the direct installation of stiffeners onto the flat slab introduces the potential for variations in structural behavior compared to the established effectiveness demonstrated by steel bolts in previous research. However, this approach is considered to facilitate easier analysis and result interpretation compared to a steel bolt connection, where unnecessary complexity could be added. Material constraints further contribute to the preference for the tie constraint method, particularly in situations where implementing the bolt method for the model in the analysis is more challenging. Furthermore, the study does not delve into site-specific considerations such as soil conditions and seismic considerations. While these factors are crucial in practical applications, they are beyond the scope of this research.

1.6 Outline of the Report

The structure of the report is broken down into 5 chapters. This structured outline provides a clear and logical flow to the research report, making it easy for the readers to follow the research process, understand the findings, and appreciate the implications and recommendations arising from this study.

In the opening Chapter 1, the report begins by providing a comprehensive introduction to the study's context and significance. It presents the background and motivation behind the research, including the challenges faced in half-loaded flat slab designs. The problem statement is clearly articulated, followed by a delineation of the study’s objectives. The chapter also discusses the importance of the study in enhancing the structural integrity and safety of such slabs, as well as its contribution to the field of structural engineering.

Chapter 2 delves into the existing body of knowledge on the subject matter. It reviews and analyzes relevant literature, including prior research on steel stiffener angles and punching shear in flat slabs. The chapter identifies gaps in the existing knowledge, highlighting areas where the current study can make a significant contribution. It provides a foundation for understanding the context in which the research was conducted and offers a critical perspective on prior research findings.

Followed by Chapter 3, this chapter details the methodology employed in the study, outlining how the research was carried out. It describes the tools and techniques used, with a focus on the use of finite element analysis (FEA) through Abaqus. The chapter provides insights into the numerical models, simulation setup, and the specific range of steel stiffener angles considered for analysis. It offers a transparent view of the study's methodology, ensuring the reproducibility of the research.

The next Chapter 4 presents the findings of the study, which include the results of numerical analyses with a focus on punching shear behavior and mid-span deflection. It uses figures, tables, and charts to visually represent the data. The chapter discusses the implications of these findings in the context of the research objectives, comparing them with prior research and related literature. It also addresses any limitations encountered during the study.

In the final Chapter 5, the report concludes by summarizing the key findings and their broader significance. It emphasizes the contribution of the study to the field of structural engineering and its practical applications. The chapter also offers recommendations for structural engineers and designers regarding the selection of steel stiffener angles to enhance punching shear resistance in half-loaded flat slabs. It considers the study's limitations and suggests directions for future research, ensuring the study's results are effectively integrated into the industry.

CHAPTER 2

LITERATURE REVIEW

2.1 Punching Shear

Punching shear failure in concrete flat slabs poses a significant risk, often occurring suddenly with minimal warning and potential for devastating losses (Deifalla, 2020). This vulnerability has been a focal point of extensive investigations encompassing experimental, theoretical, and analytical studies since the 1960s. The phenomenon is localized and stems from concentrated stresses near supporting columns (Izs and Gwt, 2019), as shown in Figure 2.1.

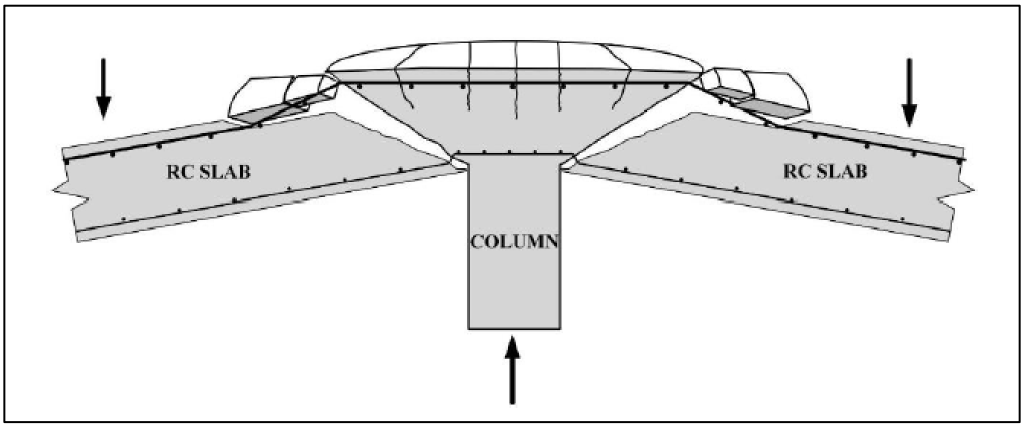


Figure 2.1: Concentrated Loading of Structure (Sagban et al., 2019)

The punching shear capacity of flat slab under static loads depends on various factors. These include slab thickness, column shape,concrete strength, and the presence of shear reinforcement (Bashandy et al., 2022).

For instance, increasing flat slab thickness tends to boost punching shear strength but may compromise flexural capacity and shear stress at a specific distance from the column. Thicker flat slabs, while exhibiting reduced overall deformations, are more susceptible to punching shear failure (Bashandy et al., 2022).

Concerning column shape, rectangular and square columns are more prone to failure, with rectangular columns potentially having lower punching shear strength than their square counterparts due to shear force concentration along the control perimeter. The use of High-Strength Concrete (HSC) enhances punching shear resistance, allowing for the transmission of larger forces through the slab-column connection (Bashandy et al., 2022).

Shear reinforcement plays a crucial role in preventing the spread of punched shear cracks. Typically in the form of bars, shear reinforcement crosses inclined fissures to avert punching shear failure. For effective prevention, the reinforcement should possess sufficient tension strength, ductility, and anchoring. Various types of shear reinforcements are available for this purpose (Bashandy et al., 2022).

The strength of punching shear is measured at the critical perimeter zone, a specified distance from the column face. Different codes, such as ACI, fib model code, and Eurocodes, provide methodologies for calculating punching force, contributing to a comprehensive understanding of this critical structural behavior (Sagban et al., 2019.).

2.2 Finite Element Analysis (FEA)

The abstracts of several papers highlight a concentration on using ABAQUS for the analysis of flat slabs.

Savaris, Andrew and Liberati (2022) demonstrated that the studies encompass the modeling of slabs, the alignment of numerical simulations with experimental findings, and the comparison of results with established code values. Through these simulations, insights into punching shear capacity, crack patterns, and slab behavior under various loads are gained cheaper and faster. The application of ABAQUS and finite element analysis proves crucial in understanding the structural dynamics of flat slabs, thereby aiding in the optimization of their design.

Al Hasani and Abdulraeg (2021) revealed that the utilization of ABAQUS software involves incorporating a plastic damage behavior model. The proposed modeling approach has undergone validation against experimental findings available in the existing literature. The results indicate a favorable agreement between the modeled and experimental outcomes, specifically regarding the displacement associated with the ultimate load and the failure load.

2.3 Concrete Damage Plasticity (CDP)

The accuracy of the Finite Element Analysis (FEA) model in ABAQUS relies on the information concerning the constitutive model of the material. Widely acknowledged for its precision and practicality, the Concrete Damage Plasticity (CDP) model is utilized (Savaris, Andrew and Liberati, 2022). It focuses on failure mechanisms characteristic of quasi-brittle materials, particularly concrete (Izs and Gwt, 2019). This characteristic is manifested through parameters that define the yield surface as shown in Figure 2.2 and Table 2.1, and the nonlinear relationship of stress-strain in cases of compression and tension (Rasoul, Mohamed and Taher, 2019).

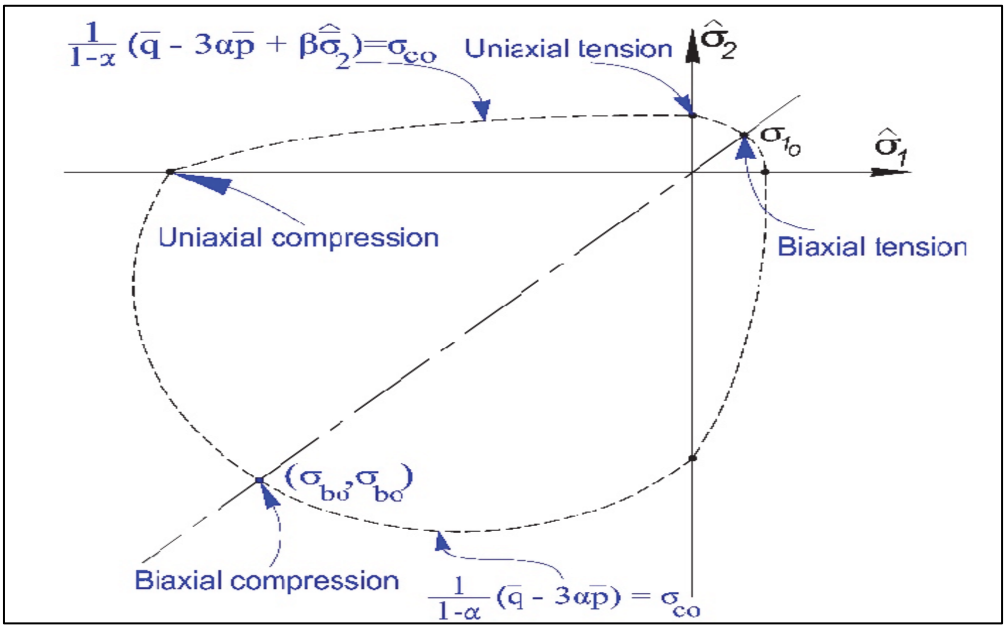


Figure 2.2: Yield Surface (Cuong-Le, Minh and Sang-To, 2021)

Table 2.1: CDP Model Parameter (Cuong-Le, Minh and Sang-To, 2021)

Dilation angle	Eccentricity (ε)	σ_{b0} / σ_{c0}	Kc
30° ~ 40°	0.1	1.16	0.667

2.3.1 Uniaxial Loading in Compression

In the context of uniaxial loading conditions in compression, two distinct components can be identified.

Cuong-Le, Minh and Sang-To (2021) discovered that the first part involves the behavior exhibited during compression, which unfolds in three phases. The initial phase is characterized by a linear stress-strain relationship, defined by the modulus of elasticity and Poisson's ratio. Phases 2 and 3 encompass inelastic strain-stress data specific to compression as shown in Figure 2.3. Moving to the second part, the focus is on the compression damage variable (dc), a crucial element for specifying compressive stiffness degradation. This variable is determined through plastic strain, and its relationship with inelastic strain is visually depicted in Figure 2.4

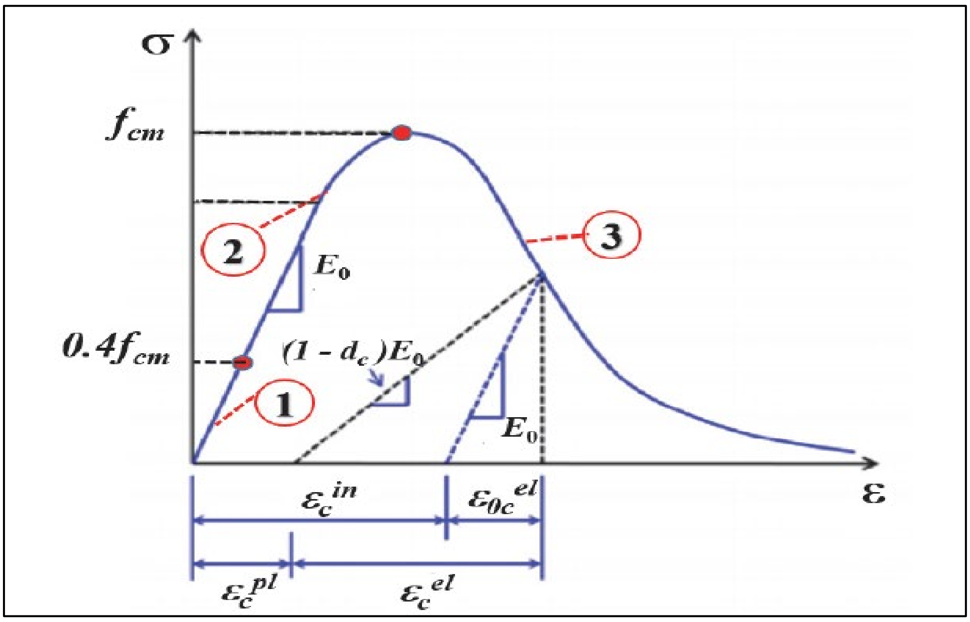


Figure 2.3: Compression Behaviour (Cuong-Le, Minh and Sang-To, 2021)

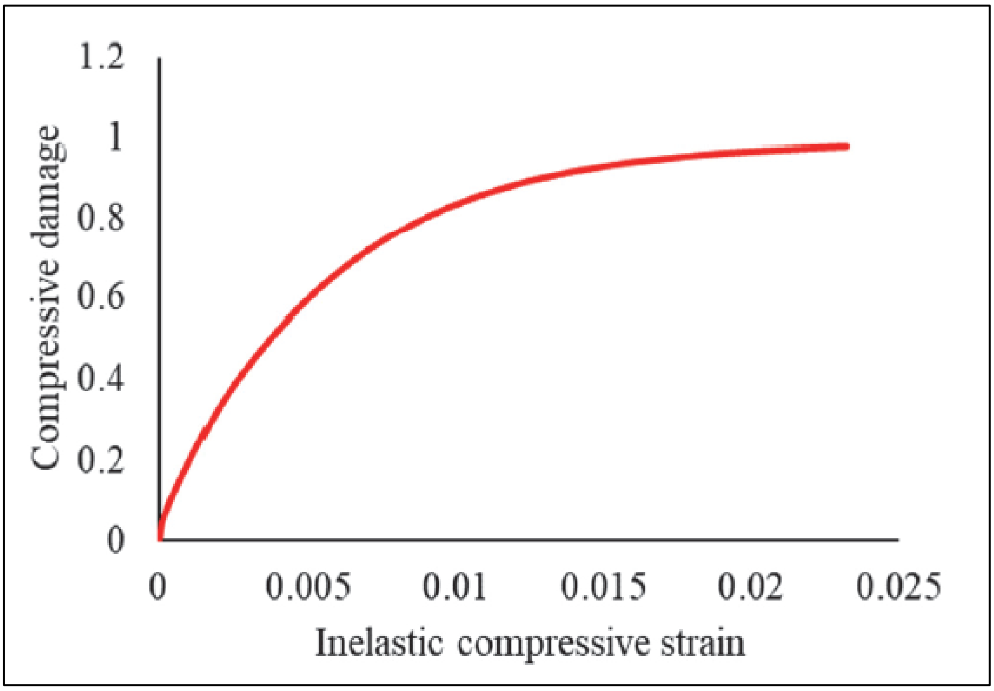


Figure 2.4: Relationship of Compressive Damage and Inelastic Strain (Cuong-Le, Minh and Sang-To, 2021)

2.3.2 Uniaxial Loading in Tension

Similar to compression, in the context of uniaxial loading condition in tension, two dinstict components can be identified.

Cuong-Le, Minh and Sang-To (2021) discovered that the tensile nonlinear behavior of concrete is represented by a curve illustrating the relationship between cracking strain and stress under tension as shown in Figure 2.5. Notably, the characteristic of this curve remains independent of the element meshing in the Finite Element Method (FEM) model. Furthermore, the shape of the curve does not impact the results, provided the fracture energy (GF), which corresponds to the area under the graph, remains consistent. The examination of damaged parameters in tension, the focus is on establishing the relationship between tensile damage and crack opening shown in Figure 2.6

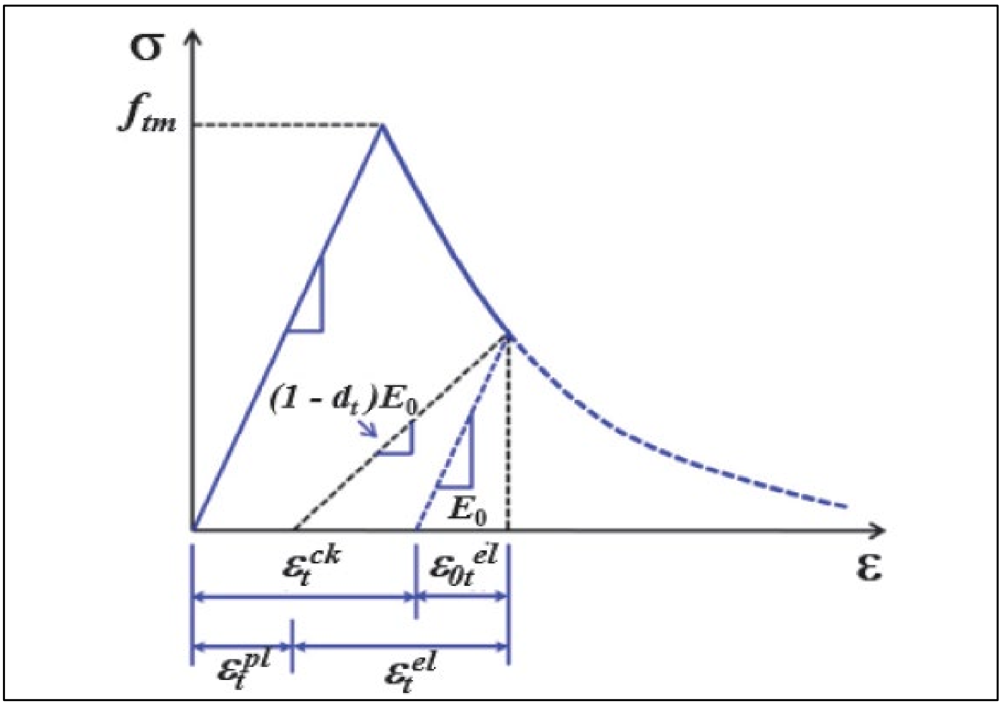


Figure 2.5: Tension Behaviour (Cuong-Le, Minh and Sang-To, 2021)

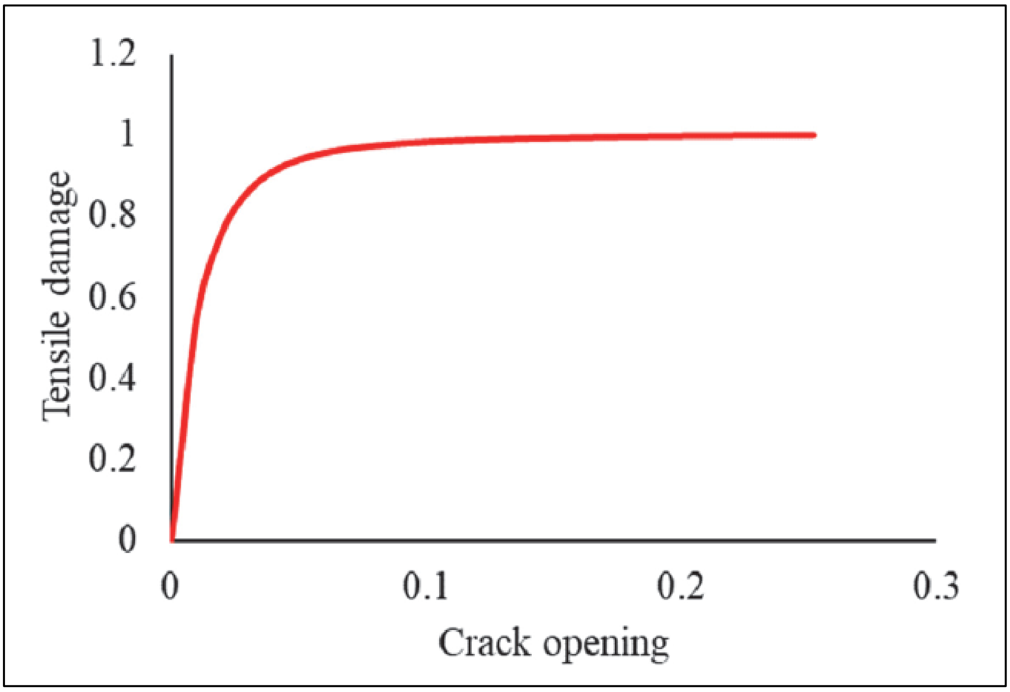


Figure 2.6: Relationship of Tensile Damage and Crack Opening (Cuong-Le, Minh and Sang-To, 2021)

2.3.3 Simulation Tool to Generate CDP

In the work by Elkady (2023), a notable contribution was the introduction of a generating tool called "ABAQUS – CDP Generator" as shown in Figure 2.7. This tool proves particularly valuable in situations where either the Concrete Damage Plasticity (CDP) model is not provided or complete stress-strain data is unavailable. In such instances, the generator tool becomes instrumental, facilitating the acquisition of values for the parameters needed for analysis. By employing this tool, researchers and practitioners can overcome the absence of specific model details or data, ensuring a more comprehensive and adaptable approach to the application of the CDP model in various scenarios. The generator tool thus emerges as a practical solution to address uncertainties or gaps in information related to the CDP model, enhancing the flexibility and accessibility of the modeling process.

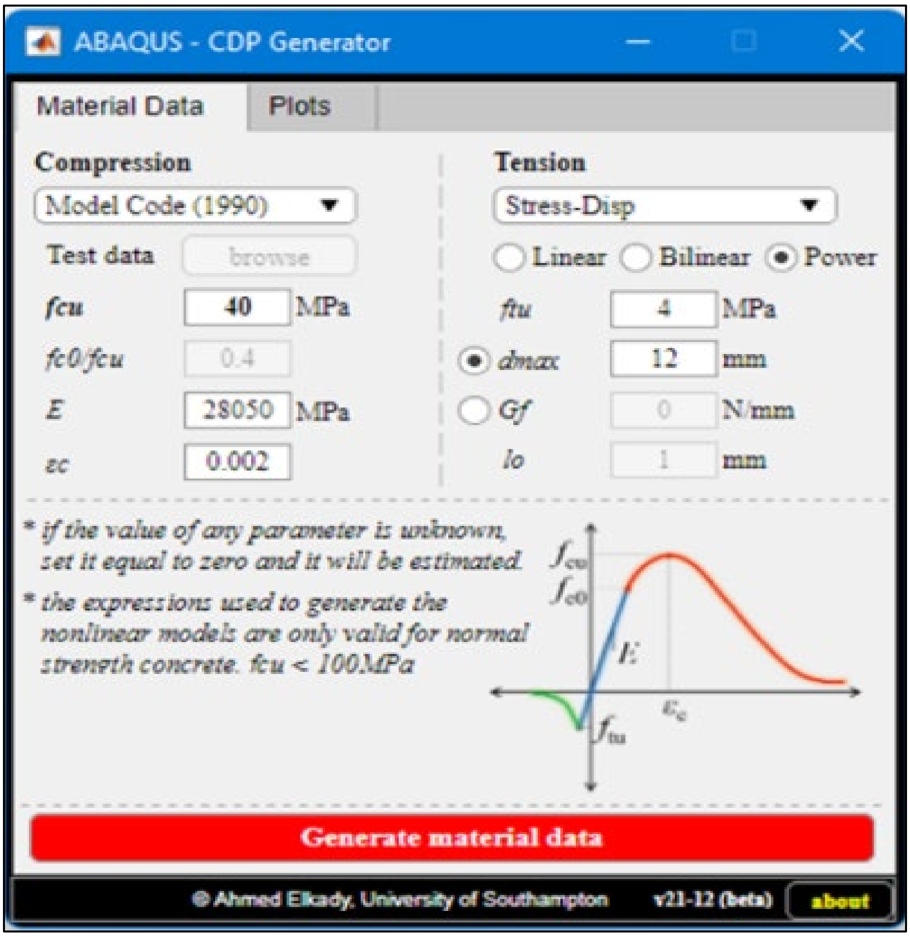


Figure 2.7: ABAQUS-CDP Generator (Elkady, A., 2023)

2.4 Strengthening Method

This subtopic presents various approaches to strengthening existing flat slabs against punching shear. The objective is to provide a reading key capable of adapting to different strengthening techniques and offering a comprehensive understanding of the problem. The research conducted by various authors from 2019 to 2023 has provided valuable insights into enhancing the punching shear resistance of flat slabs through different techniques and materials.

Rasoul, Mohamed and Taher (2019) utilized EC2 and FIB90 models, revealing that code models consistently underestimated punching shear resistance. The finite element simulation demonstrated favorable results compared to experimental models. Saib, Kadhim and Ammash (2019) explored the impact of steel stiffeners on failure perimeter, revealing that increasing their size and number significantly enhanced load capacity. Circular columns were found to increase ultimate load, with good agreement between experimental and theoretical results. Both focused on capturing stress-strain behavior and enhancing punching shear capacity using ABAQUS.

Inácio, Lapi and Pinho Ramos (2020) investigated the use of high-strength concrete (HSC) for punching strength enhancement. The rational use of HSC, particularly in a thin layer near the column, was deemed efficient in achieving almost equal punching strength as slabs entirely casted in HSC. The proposed analytical approach for failure load prediction showed promising results, with recommendations for further tests to validate the method.

Abdulhussein and Al-Sherrawi (2021) introduced a steel collar strengthening technique, effectively enhancing punching shear resistance. Results indicated a significant increase in punching shear resistance, ranging from 41% to 77%, and the technique changed the mode of failure to flexural punching shear. The presence of steel collars increased cracking load and stiffness, demonstrating good agreement between experimental and numerical results using ABAQUS.

In the same year, Taresh, Yatim and Azmi (2021) proposed a technique that shifted the failure mode from pure punching shear to flexure-induced punching deformation. Strengthened slabs showed substantial improvements in failure load, deformation capacity, stiffness, and energy absorption. Confinement pressure on the concrete mass near the column led to an enlarged critical section. The ACI design code was found to underestimate punching shear strength, while a simple approach based on yield line theory accurately estimated flexural strength.

Neamah and Al-Ramahee (2021) work focused on enhancing the slab-column connection using steel plates and stiffeners. The strengthened connection exhibited increased stiffness, ductility, ultimate load, and reduced crack width. However, the presence of three instead two stiffeners had no significant effect on ultimate load and behaviour.

The following year, researcher explored different materials for enhancement. Mohammed et al., (2022) investigated the use of steel fiber, reporting a 21.8% increase in punching shear capacity compared to slabs without steel fiber. Notably, slabs with steel fiber exhibited significant ductile behavior and improved energy absorption. Shatarat and Salman (2022), in the same year, evaluated the effectiveness of circular and continuous rectangular spiral reinforcement in enhancing punching shear carrying capacity. Both ACI 318-19 and Eurocode 2 were considered conservative in determining punching shear strength, with Eurocode 2 providing a closer prediction. In addition, Ammash, Kadhim and Dhahir (2022) emphasized the positive impact of increasing the size and number of steel stiffeners on failure perimeter and punching shear capacity. Repaired slabs were stiffer, with improved crack propagation, and punching shear capacity increased by 41.7%, 58.8%, and 74.4%. Additionally, higher concrete compressive strength and flexural reinforcement ratio positively affected punching shear capacity.

Makhlouf et al., (2023) work demonstrated the effectiveness of CFRP stirrups in increasing punching shear resistance. Experimental results indicated a significant increase in punching shear resistance, and the novel scheme of variable width stirrups yielded the highest punching capacity. Finite element analysis closely matched experimental results, and theoretical equations were verified on the experimental specimens. The novel scheme and CFRP stirrups were recommended for enhancing punching shear resistance.

2.5 Summary

The crucial lesson gleaned from these chapters is the understanding of punching shear failure. Through thorough inspection and subsequent strengthening interventions, such collapses could have been averted with the use of tools to identify failure in a cheaper and faster manner. These findings provide valuable insights into the effectiveness of various steel stiffener angles in reinforcing half-loaded flat slabs and offer a comprehensive understanding of the factors influencing their structural performance.

CHAPTER 3

METHODOLOGY

3.1 Introduction

A detailed step-by-step procedure, illustrated in the accompanying flowchart as in Figure 3.1, guides the systematic execution of simulations. The research methodology begins with an extensive literature review to establish a foundation and understand existing knowledge in the domain of "Numerical Study On Various Steel Stiffener Angle To Reinforce Half Loaded Flat Slabs". A pivotal reference point for this study is the historical work conducted by Ammash, Kadhim, and Dhahir in 2022.

Following by, a control flat slab is meticulously modeled with suitable specifications, incorporating dimensions and material properties. Subsequent to the modeling phase, the control flat slab undergoes comprehensive analysis and testing to understand its structural behavior. Numerical results is then obtained. To validate the precision of the model, a thorough comparison is made between numerical and experimental results, considering scenarios without stiffeners and with stiffeners at a 45° angle. This dual verification underscores the reliability of the software, both with and without the steel stiffener. In the event of dissatisfaction with the results, adjustments are made, and the modeling process is iterated.

Upon achieving nearly significant alignment with experimental results, the validated model serves as the foundation for investigating the retrofitting of steel stiffeners with various angles (25°, 35°, 45°, 55°, 65°). The subsequent phase involves generating numerical results. Finally, a comprehensive comparison of the results across all angles is conducted to identify the most suitable dimension for the steel stiffener.

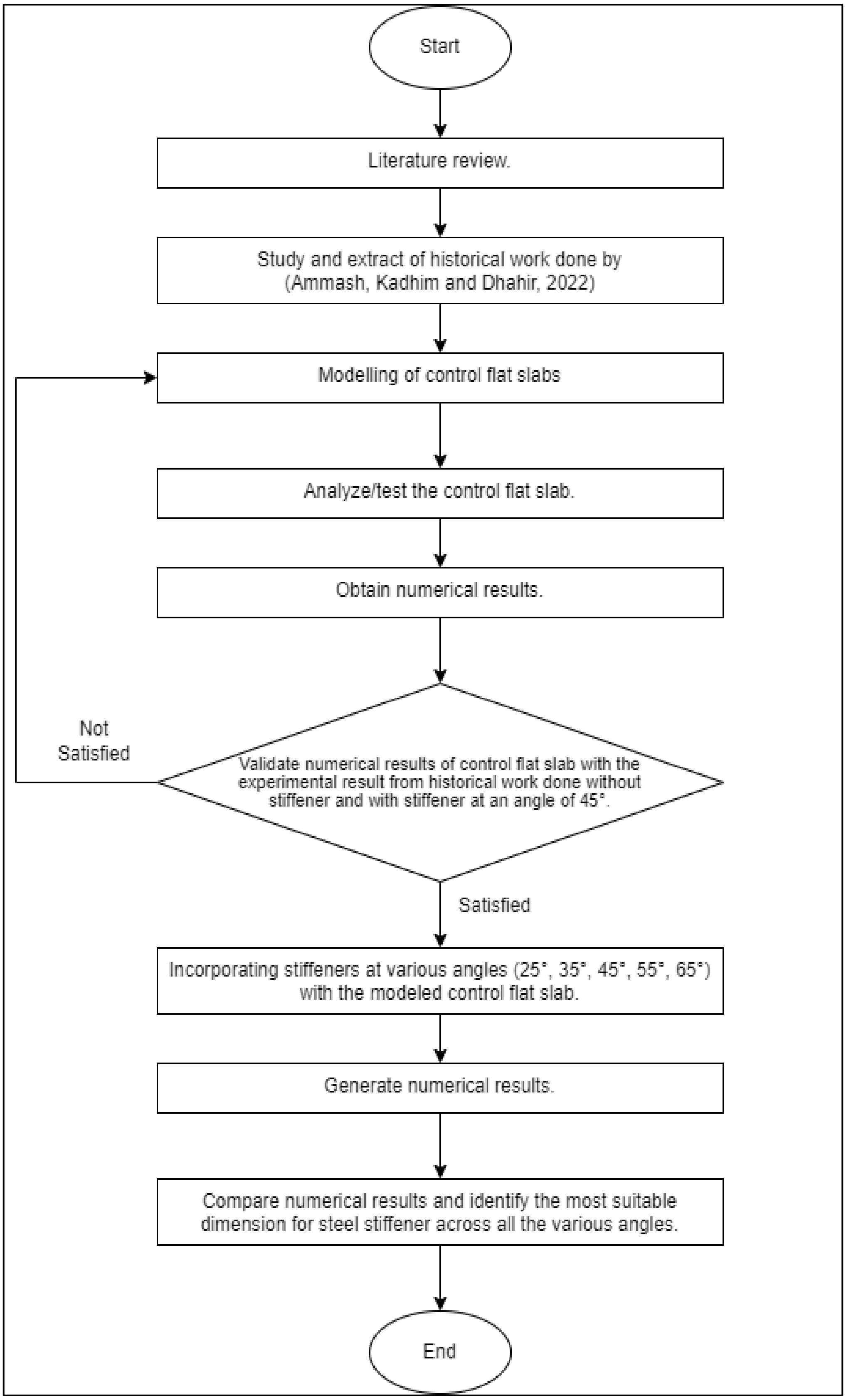


Figure 3.1: Flowchart

3.2 Historical Work Done

3.2.1 Experimental Flat Slab

The experimental program involved testing specimens without stiffener application and with stiffener at an 45° angled. Stiffener testing occurred after loading the slabs up to 50% of their ultimate load. The stiffener installation included using a hammer drill to create holes in both the slabs and steel plates, followed by thorough surface cleaning with a vacuum cleaner. Subsequently, four L-shaped steel plates were securely affixed to the slab using Fisher bolts, and triangular-shaped steel stiffeners were welded to these plates. In the case of the stiffener specimen, the steel stiffeners had dimensions of 200 × 200 with a width of 200mm, and each specimen was equipped with two steel stiffeners per side.

Both specimens underwent testing in an inverted configuration as shown in Figure 3.2, utilizing a hydraulic testing machine with a 900 kN capacity. The slab supported on all four edges, were subjected to concentrated loads during the test. To ensure a uniform stress distribution and a flat column surface, each specimen was cleared of protrusions. The static load was incrementally applied in 10 kN steps until failure, with continuous observation to identify the initial crack location and corresponding load.

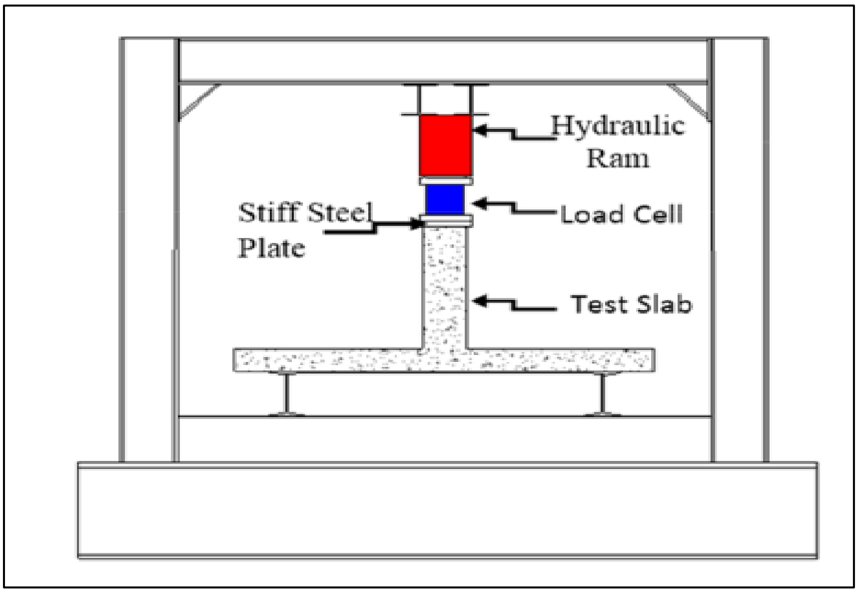


Figure 3.2: Experimental Test Set-Up (Ammash, Kadhim and Dhahir, 2022)

3.2.2 Load-Displacement Graph

Figure 3.3 meticulously presents a comprehensive comparison between experimental and numerical data, drawing upon the prior work of Ammash, Kadhim and Dhahir, (2022), both before and after the reinforcement of stiffeners. The ultimate displacement and punching load values are methodically outlined, offering a clear overview of the structural behavior under different conditions. In the experimental set (E), recorded values for ultimate displacement and punching load were 16.00mm and 128kN, respectively, while the numerical set exhibited 17.25mm and 134.46kN. Furthermore, with the introduction of stiffeners, identified as EA-45 for the experimental set and numerical for the numerical set, distinctive values emerged 23.11mm with 203.00kN and 21.32mm with 210.64kN, respectively.

Figure 3.3: Load – Displacement of Historical Work Done - Experimental and Numerical (Ammash, Kadhim and Dhahir, 2022)

3.3 Control Flat Slab

The "control flat slab" serves as a reference in the experimental framework of this study, representing a standardized test flat slab that will undergo rigorous testing using various angles of steel stiffeners. Information crucial to this investigation is derived from comprehensive historical research.

In Figure 3.4, a Finite Element Analysis (FEA) sample of the control flat slab is presented. This visual representation illustrates the intricacies of the numerical simulation during the modeling process, showcasing the underlying structural elements. Figure 3.5(a) and Figure 3.5(b) further delves into the detailing of the control flat slab, providing a closer look at the specific components and features that contribute to its overall structural integrity. Figure 3.4 shows the experimental set-up

Additionally, Figure 3.6 highlights the uniaxial loading applied to the control flat slab in both compressive and tensile modes, contributing valuable insights into its property behavior. However only for the tensile damage, it is produced using the generator tool. For a comprehensive understanding of the materials involved, Tables 3.1 and 3.2 present the concrete material and steel reinforcement parameters of the control flat slab. The tables present a thorough summary of the characteristics of the utilized materials, thereby establishing a basis for the subsequent stage of the numerical simulation analysis.

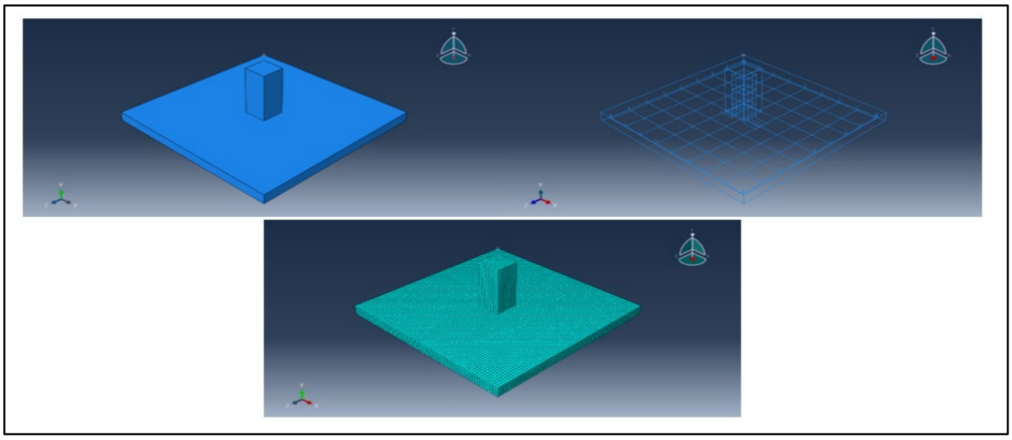


Figure 3.4: FEA Modelling of Control Flat Slab

The flat slabs in focus have a square shape with dimensions of 1600mm and a thickness of 100mm. Reinforcement includes Ø10mm bars spaced at 187.50mm c/c with a 25mm concrete cover, resulting in a measured depth of 75mm. The accompanying square column is 200mm in dimension and 500mm in height, reinforced with 8 Ø10mm bars and 3 Ø10mm stirrups. The attachment of reinforcement in both the column and flat slab enhances their strength and stability. This connection ensures effective load distribution, reinforces against various forces, and contributes to the overall durability of the structure.

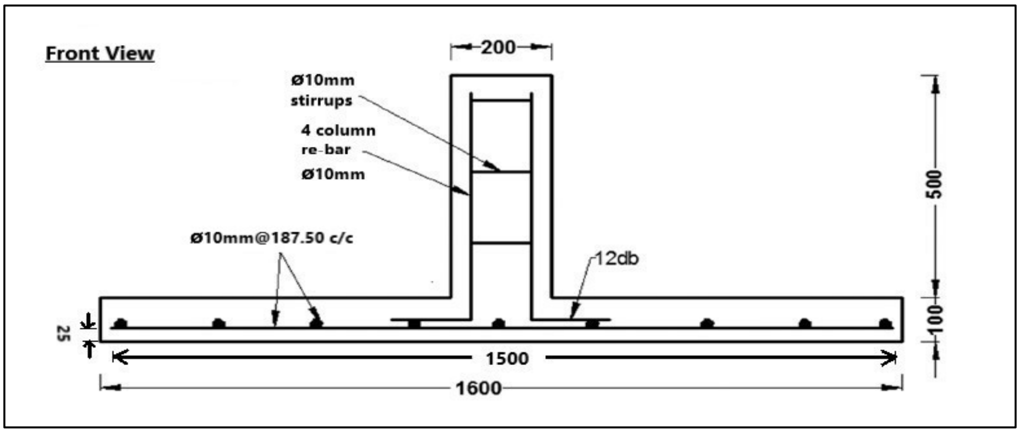


Figure 3.5(a): Detailing of Control Flat Slab (Front View) (Ammash, Kadhim and Dhahir, 2022).

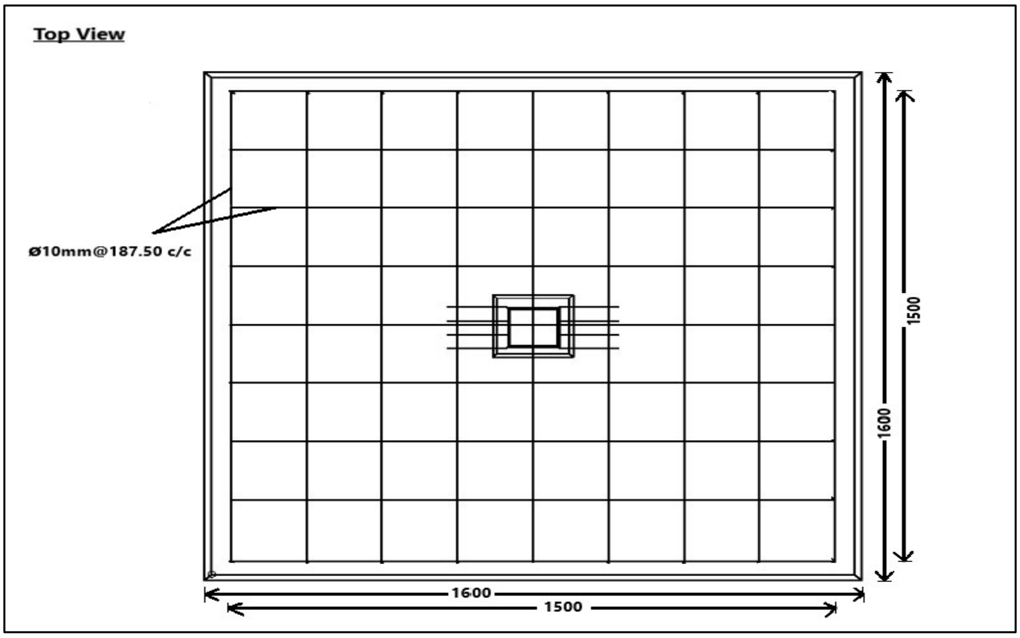


Figure 3.6(b): Detailing of Control Flat Slab (Top View) (Ammash, Kadhim and Dhahir, 2022).

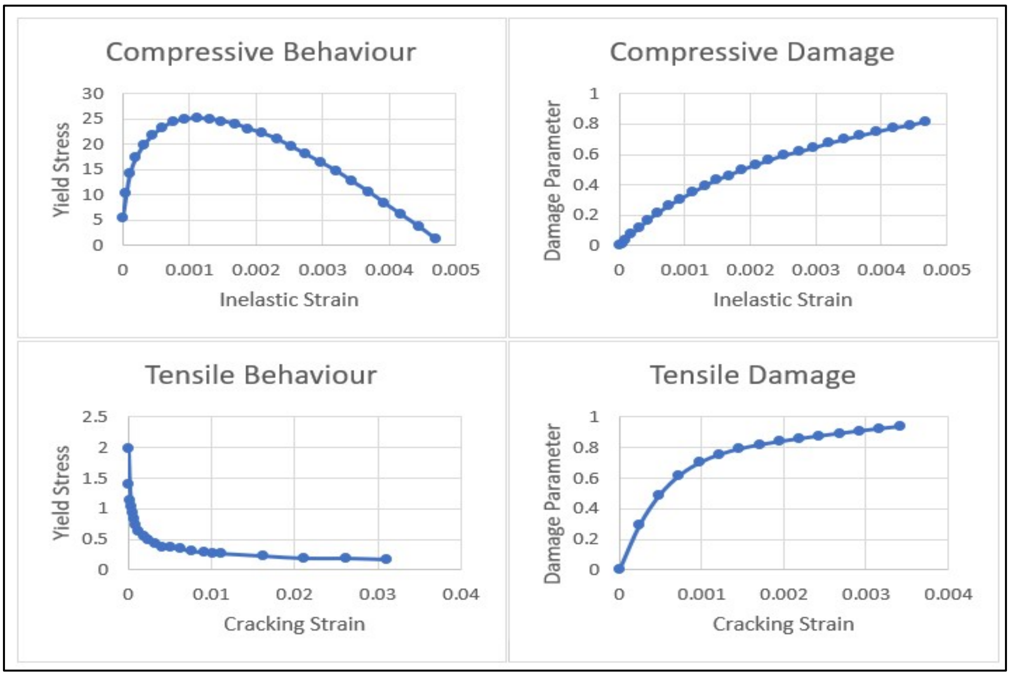


Figure 3.7: Uniaxial Loading Applied in Both Compressive and Tensile (Rasoul et al, 2019).

Table 3.1: Concrete Material Parameter (Rasoul et al, 2019)

Parameter	Value
Compressive Strength	25 Mpa
Young's Modolus (E)	28,000
Poisson's Ratio	0.18
Dilation Angle	36
Eccentricity	0.1
fb0/fc0	1.16
K	0.667
Viscoscity Parameter	0.001

Table 3.2: Steel Reinforcement Parameter (Rasoul et al, 2019)

Parameter	Value
Young's Modolus (E)	200,000
Poisson's Ratio	0.3
Yield Strength	635 Mpa
Ultimate Tensile Strength	713 Mpa

3.4 Test Flat Slab

This research undertakes an experimental program to examine five standardized test flat slab specimens. These specimens are intricately configured with stiffener arrangements at various angles, achieved by manipulating the height dimension as shown in Figure 3.7. The specimens, hereafter refers to NA-25, NA-35, NA-45, NA-55 and NA-65 that correspond to stiffener angles of 25°, 35°, 45°, 55°, & 65° respectively.

The study employs a combination of steel plates and stiffeners to thoroughly evaluate the structural behavior, focusing on the ultimate load and the deflection of these specimens. Each specimen is characterized by two triangular-shaped stiffeners, expertly welded with L-shaped steel plates and attached to all sides of the column. This plates meticulously fabricated and positioned to act as a rigid region at the critical points of maximum shear and flexural stress.

The length of both the plate and stiffener is maintained as a constant variable at 200mm, featuring a thickness of 6mm. Additionally, the width of the plate remains fixed at 200mm. The distinguishing factor lies in the height dimension, which varies according to the specified angle ranging from 25 to 65 degrees.

In this study, the application of the tie constraint technique is employed for the direct installation of stiffeners onto the flat slab and column. This method introduces a potential variation in structural behavior compared to the conventional steel bolt connection, as demonstrated in prior research. However, the tie constraint approach is chosen for its ease of analysis and result interpretation, offering a more straightforward alternative to the complex steel bolt connection. Additionally, material constraints further support the preference for the tie constraint method, particularly in situations where implementing the bolt method proves more challenging during the numerical simulation analysis.

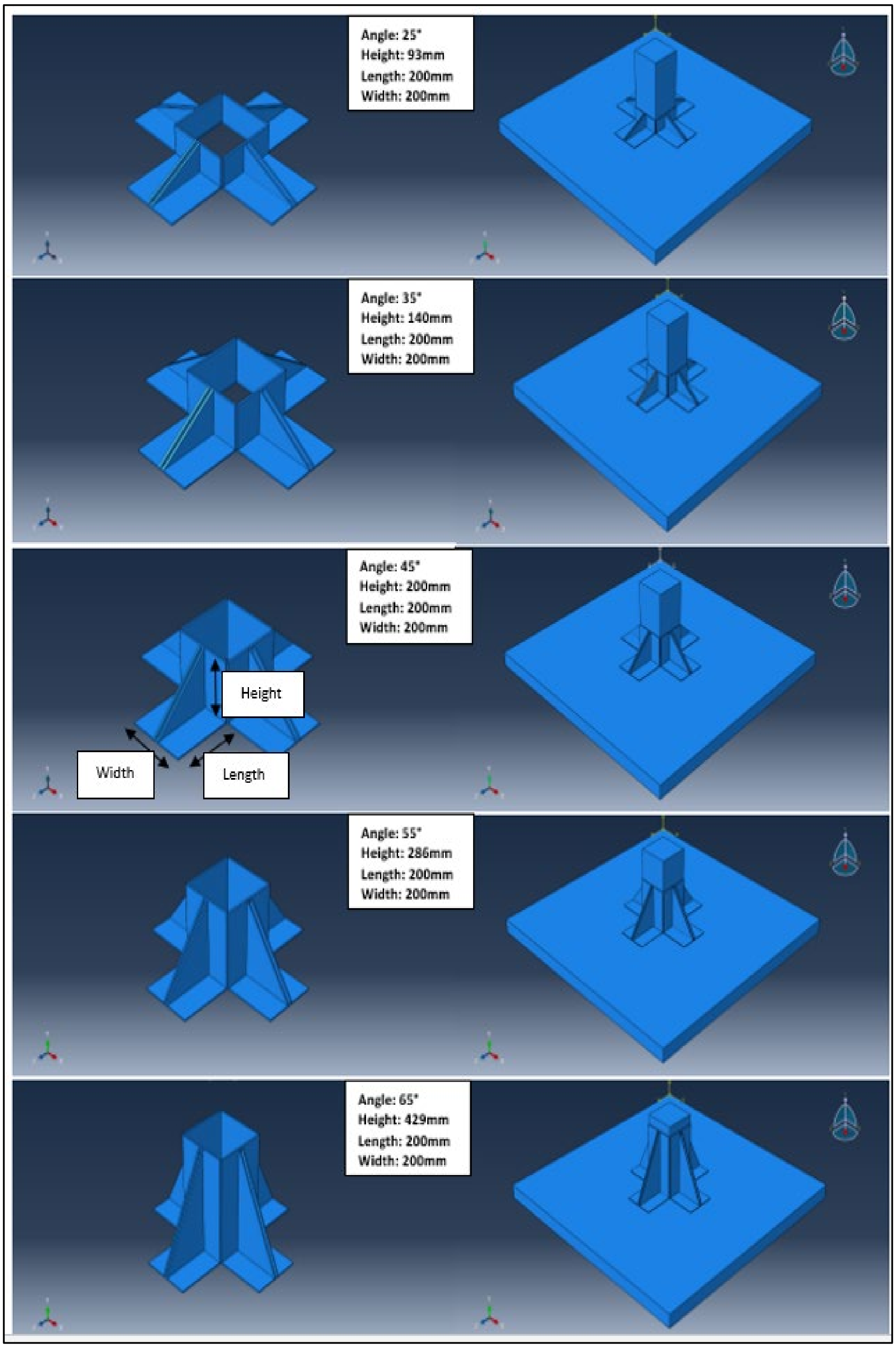


Figure 3.8: Steel Stiffener Incorporating with Flat Slab

3.5 Numerical Modelling & Analysis

The analysis utilized ABAQUS / Standard 2014 CAE 6.14 for a nonlinear finite element numerical examination of the test specimens. With the ensured reliability and accuracy of the chosen FEA software, considerations were made regarding element types, material modeling, and convergence studies. The primary objective was to compare the numerical simulation results with the historical experimental work. The model represented flat slab with a compressive strength of 25MPa, both without and with steel stiffener, where the column was subjected to loading.

To simulate various components, brick elements (solid elements) were employed for concrete, support plate, steel plate, and stiffeners, using the C3D8 type (8 nodes linear brick, full integration). Truss elements were employed for reinforcement steel, using T3D2 type (linear two-node displacement), embedded within solid elements to establish a full contact model between reinforcement and concrete. The interaction between reinforcement and concrete involved an embedded region approach, while stiffeners were modeled with a tie connection approach. The interface between the two supporting plates and the concrete was modeled as a normal hard contact with additional tangential contact ('penalty') and a friction coefficient of 0.2. The plates were simply supported for both edges of the slab along the z-axis.

Concrete behavior was characterized using damaged plasticity, while steel reinforcement behavior was characterized using yield and ultimate tensile strengths. Total force distribution load until failure was applied with a magnitude of 250kN for the flat slab with stiffener and approximately 50% less than (128kN) flat slab without stiffener. A linear hexahedral mesh with a size of 25mm was used in the simulation, resulting in a total of 30,379 nodes and 23,069 elements.

3.6 Result Validity

The numerical simulation analysis result was concluded with the extraction of data, where two key steps were undertaken.

Initially, plotting XY data to illustrate punching load against mid-span deflection where a comparison was made between numerical and experimental data for specimens with and without a stiffener, confirming the model's accuracy in replicating observed structural behavior. The validation process extended to by the comparison of the cracking partern of the experimental with the numerical simulation of the flat slab.These further confirms validation steps collectively ensured the reliability of the numerical simulation results across various conditions and scenarios.

Lastly, a comprehensive comparison among all test specimens was conducted to identify the most suitable dimension for the steel stiffener, offering insights for optimizing its design.

3.7 Summary

The primary aim is to contribute insights into optimal steel stiffener angles for enhancing the punching shear strength of flat slabs. Building on prior research, the methodology encompasses a comprehensive evaluation of different angles' effects through numerical simulations using ABAQUS. The chapter outlines specific objectives, such as developing numerical punching shear capacity and identifying most suitable dimension for steel stiffener designs. By leveraging the reliability of finite element analysis, this research seeks to refine design practices for more resilient flat slab structures.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In Chapter 4 of the study, the focus shifts towards crucible effort addresses the attainment of our three primary objectives with a focus on validation, evaluation and identifying .

The validation process involves comparing numerical simulation results obtained from the Finite Element Analysis (FEA) software Abaqus with experimental data from historical studies. The initial phase involves designing specimens to closely replicate the significant values of ultimate punching load and deflection observed in historical experiments. The creation of a graph illustrating the relationship between punching load and mid-span displacement serves as a tangible measure of the alignment between simulated and experimental data. Concurrently, a visual inspection of crack patterns exhibited in both sets of specimens is conducted. The comparative analysis of these crack patterns offers an additional layer of assurance and insight into the fidelity of the specimens.

Upon the successful validation of the data, our attention moved to the next focal point. Evaluating the influence of different stiffener angles on the overall structural behavior using the Abaqus software. The results obtained from these simulations, which are presented comprehensively, are evaluated in graphical terms. This deeper exploration unravels intricate details related to concrete tension damage, reinforcement tension stress, and steel stiffener tension stress.

Finally, the discussion section serves as a platform to distill our observations derived from the results, focusing on key patterns and insights. This critical analysis extends to achieving our third objective, pinpointing the most suitable dimensions for future research endeavors. By scrutinizing the data, we aim to draw conclusive findings and contribute to the broader understanding of the subject matter, paving the way for informed decisions in the field of flat slab structures.

4.2 Validity of Control Flat Slab

Table 4.1 meticulously lays out the comparison between experimental and numerical data, both before and after the reinforcement of stiffeners. The values for ultimate displacement and ultimate punching load are systematically detailed, providing a clear snapshot of the structural behavior under different conditions.. In the experimental set (E), an ultimate displacement of 16.00mm and punching load of 128kN were recorded, while the numerical set (N) exhibited 17.56mm and 108.30kN, respectively. Furthermore, the introduction of stiffeners, denoted as EA-45 and NA-45, showcases distinctive values of 23.11mm with 203.00kN and 22.39mm with 164.87kN, respectively.

To augment these numerical representations, Figures 4.1 and 4.2 offer visual insights. Figure 4.1 presents a comparative graph of load-displacement between experimental and numerical scenarios. Meanwhile, Figure 4.2 delves into the cracking patterns, drawing a visual parallel between the experimental and numerical realms.Together, these data sets and visual representations constitute a comprehensive examination.

Table 4.1: Ultimate Punching Load & Deflection of Numerical and Experimental.

Model (Specimen Designation)	Ultimate Deflection (mm)	Ultimate Punching Load (kN)
Experimental (E)	16.00	128.00
Numerical (N)	17.56	108.30
EA-45	23.11	203.00
NA-45	22.39	164.87

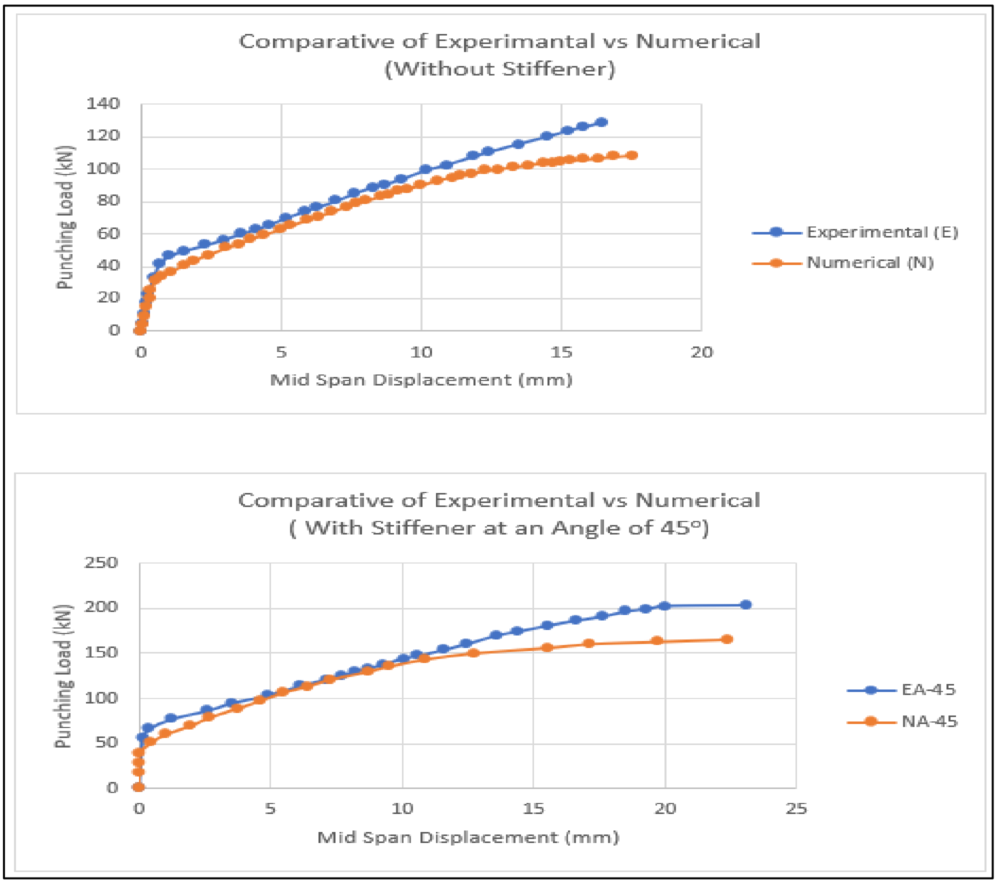


Figure 4.1: Load-Displacment of Experimental and Numerical Without Stiffner and With Stiffener at an Angle of 45°

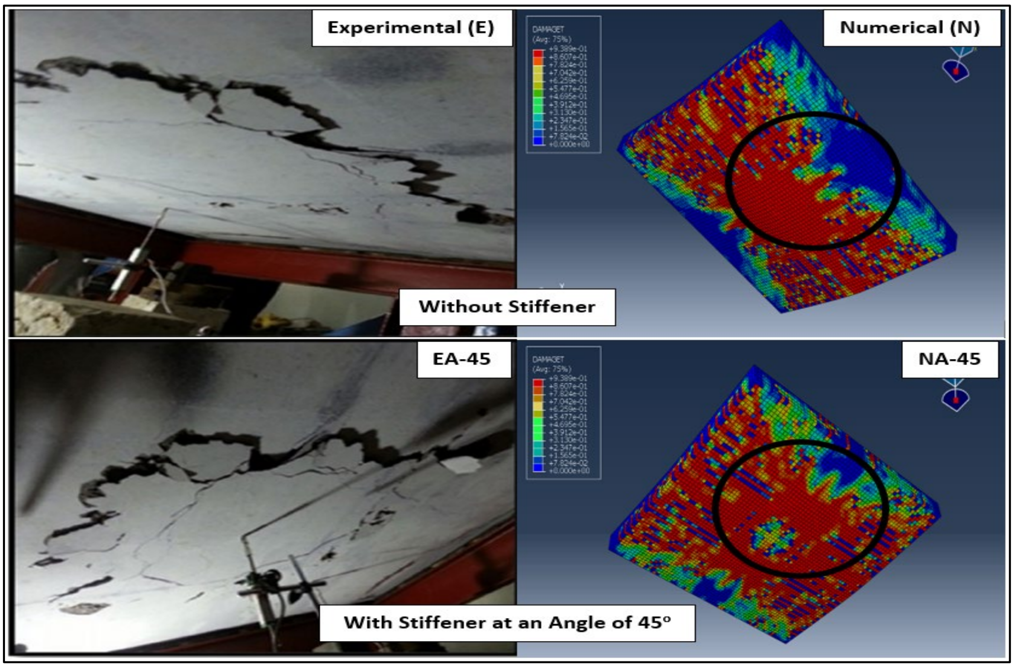


Figure 4.2: Comparitve Cracking Pattern of Experimental and Numerical Without Stiffner and With Stiffener at an Angle of 45°

4.3 Result Evaluation in Numerical Simulation Analysis

4.3.1 Ultimate Punching Load vs Deflection

Table 4.2 outlines the ultimate deflection and ultimate load of flat slabs with stiffeners at various angles. The specimens, identified by their respective angles (NA-25, NA-35, NA-45, NA-55, and NA-65), present corresponding values of 21.58mm with 163.92kN, 21.33mm with 164.60kN, 22.39mm with 164.87, 21.14mm with 163.61kN, and 20.09mm with 163.29kN respectively.

Complementing this tabulated data, Figure 4.3 provides a comparative representation of load-displacement for the different stiffener angles, offering a visual understanding of their performance distinctions. Additionally, Figure 4.4 zooms in on flat slab displacement, presenting a focused visual exploration. Together, these elements contribute to a comprehensive analysis of the impact of stiffener angles on the structural behavior of flat slabs.

Table 4.2: Ultimate Punching Load & Deflection of Flat Slab with Stiffeners Various Angle.

Model (Specimen Designation)	Ultimate Deflection (mm)	Ultimate Punching Load (kN)
NA-25	21.58	163.92
NA-35	21.33	164.60
NA-45	22.39	164.87
NA-55	21.14	163.61
NA-65	20.09	163.29

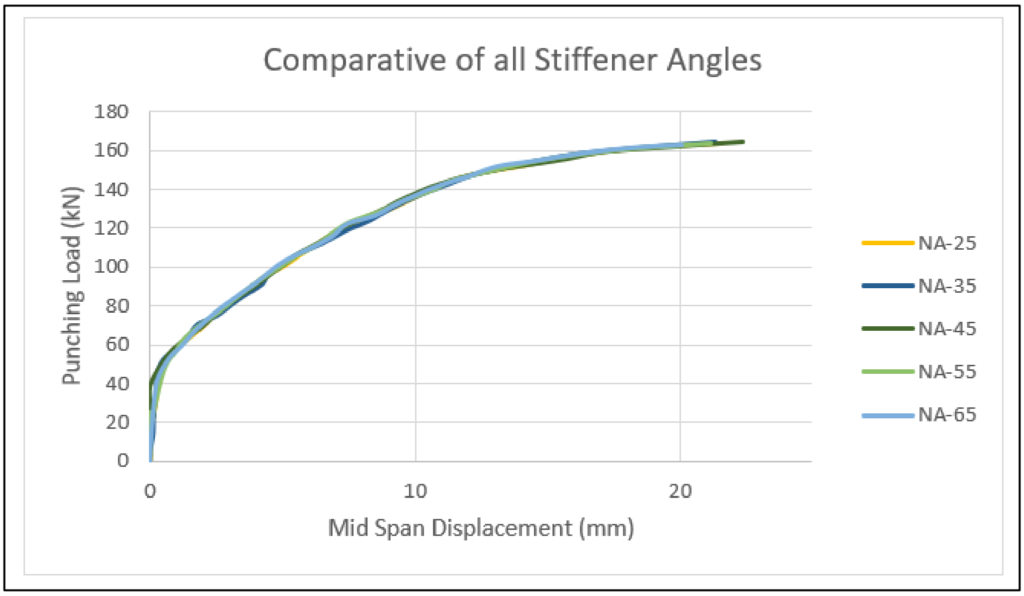


Figure 4.3:Comparitive Load-Displacment of Stiffener Angles

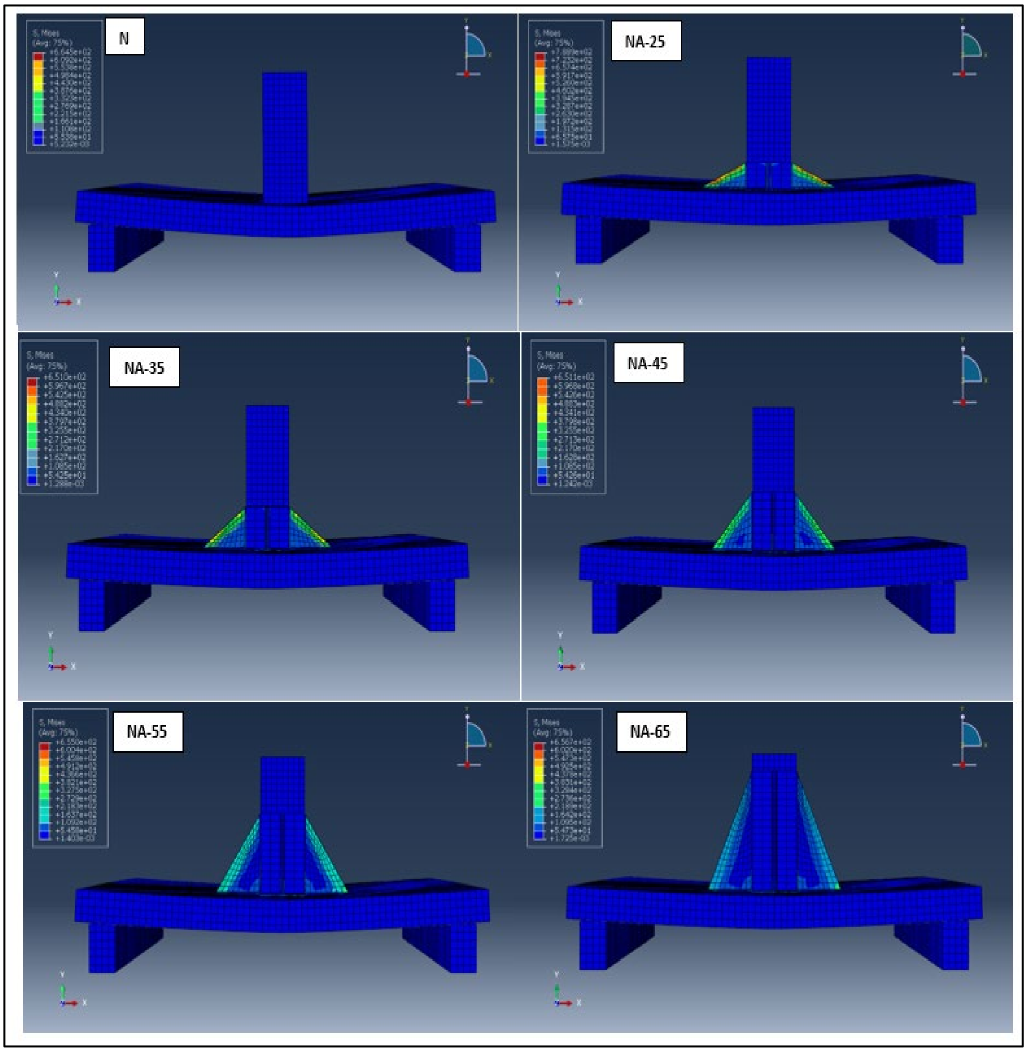


Figure 4.4: Flat Slab Displacement

4.3.2 Analysis of Numerical Flat Slab

In Figures 4.5, 4.6, and 4.7, a clear representation of concrete tension damage, reinforced and stiffener tension stressis presented respectively in a 3D view, employing a contour color gradient that transitions from red to blue. This representation offers a detailed perspective on the manifestation of tension damage within the concrete structure. It serves as a valuable tool for localizing potential weak points and gaining insights into the overall integrity of the concrete. This visual exploration significantly enhances our understanding of the structural behavior, laying a foundation for informed conclusions regarding the influence of different parameters on concrete tension damage. The transition in color, shifting from warmer hues like red (indicating higher damage intensity) to cooler tones like blue (signifying lower damage intensity), provides a visual spectrum that aids in pinpointing areas of concern and gauging the overall impact on structural integrity.

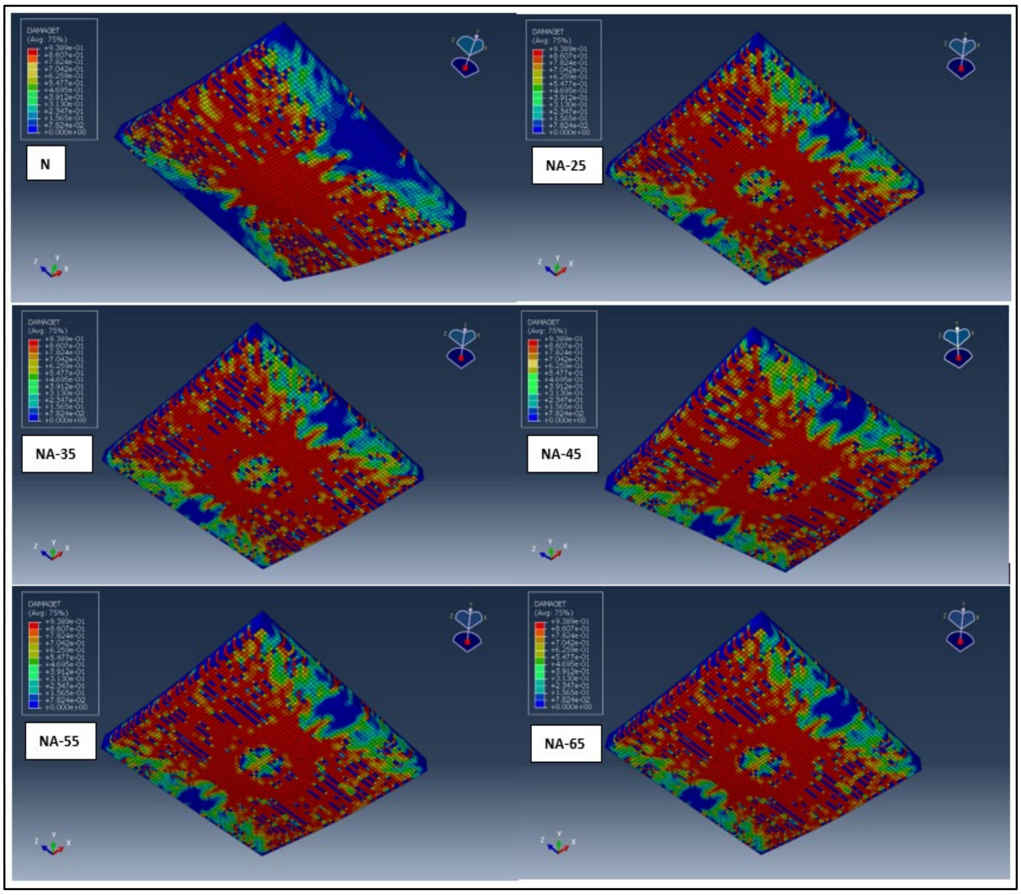


Figure 4.5: Concrete Tension Damage

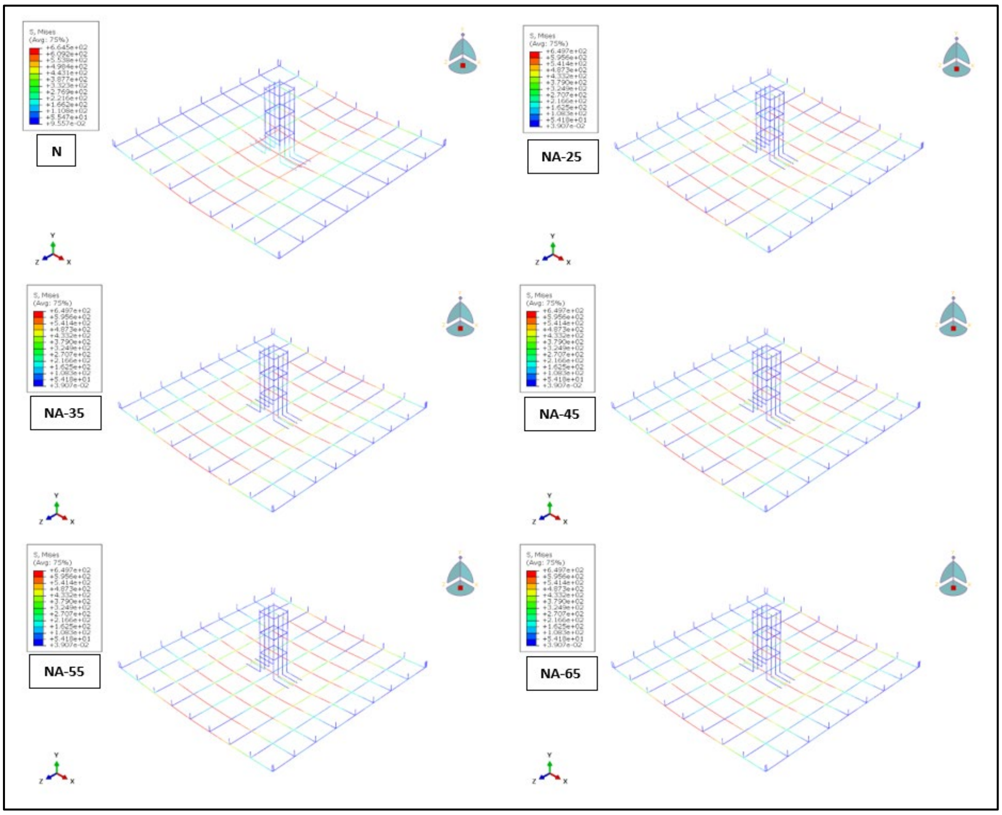


Figure 4.6: Reinforced Bar Tension Stress

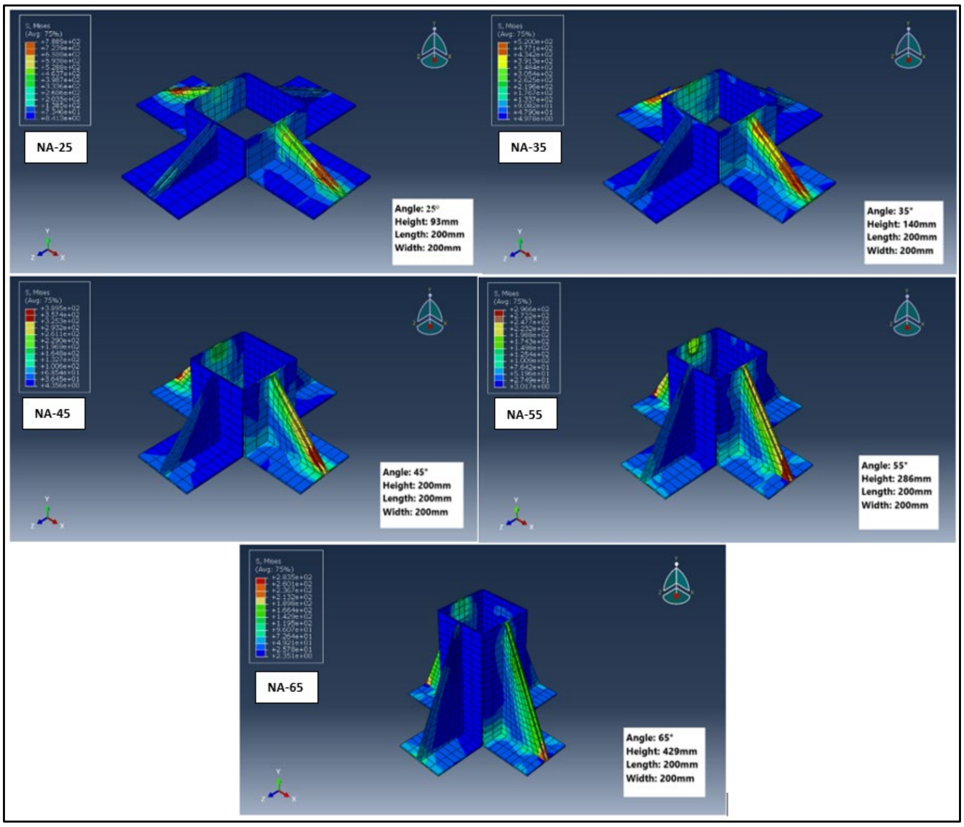


Figure 4.7: Steel Stiffener Tension Stress

4.4 Discussion

a) Accuracy of cases without stiffeners and with stiffeners at an angle of 45° are 84.61% and 81.22% for respectively.

b) Although the result show less significant, can be seen in Table 4.2 that model NA-45 has slightly better result in term of ultimate deflection and ultimate load compared to all other models. The corresponding values are 22.39mm with 164.87 respectively.

c) Results revealed less significant in these parameters between the steel stiffener angles. May be due to material properties, boundary conditions, and modeling simplifications. These assumptions play a crucial role in influencing the outcomes of the simulations. Additionally, the interactions between structural elements, like the slab and stiffeners, act to alleviate the impact of variations in stiffener angles.

d) The crack pattern observed in the support area of the numerical model compared to the experimental model reveals more damage, attributable to the utilization of rectangular beams instead of an I-beam, aligning with the experimental setup.

4.5 Summary

The study focuses on validating, evaluating, and identifying key aspects related to the structural behavior of flat slabs. The validation process involves comparing numerical simulations with historical experimental data, ensuring alignment in ultimate punching load and deflection. The evaluation delves into the influence of different stiffener angles on structural behavior, revealing nuanced details in concrete tension damage and stress distribution. The discussion section critically analyzes these results, pinpointing suitable dimensions for future research.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In conclusion, this study successfully conducted a comprehensive numerical analysis and achieved its three primary objectives.

Initially, two numerical models were developed and demonstrated the capability to generate results that closely align with historical experimental data. The accuracy of our numerical simulations was confirmed through alignment with experimental data, achieving accuracies of 84.61% and 81.22% for cases without stiffeners and with stiffeners, respectively.

Subsequently, five numerical models were developed using the control flat slab with incorporating still stiffener at an angle of 25^o, 35^o, 45^o, 55^o and 65^o. The results revealed was nearly significant ma be due to variance of material properties, boundary condition, modelling simplification and interaction between structural element.

Ultimately, prartical considerations favor the 45° stiffener (NA-45) as the suitable stiffener. Beyond competitive performance, this angle offers practicality and ease of construction, contributing to potential cost-effectiveness and overall feasibility. Its versatility is further underscored by historical usage in diverse scenarios and loading conditions in prior research.

While this study acknowledges certain limitations, the collective findings effectively addressed a significant gap in existing research. Moreover, this investigation has broadened our comprehension of the repercussions of steel stiffener angles, offering valuable insights for future research endeavors aimed at refining the design of half-loaded flat slabs to enhance their punching shear capacity.

5.2 Recommendations

For the purpose of future research orientations, it is advisable to expand the scope beyond the manipulation of stiffener angles. Instead investigate into the consequences of modifying the quantity and thickness of stiffeners which could provide nuanced insights into their impact on the structural performance of half-loaded flat slabs.

Additonally, it is advised to investigate alternative boundary conditions. Specifically, consider modeling the support for numerical specimens as an I-beam rather than utilizing two rectangular support beams. This adjustment would make the numerical setup more closely resemble the actual experimental configuration.

Lastly, future research endeavors may consider a comparative analysis between tie constraints and steel bolts to further understand the nuanced implications of different attachment techniques on structural behavior Consequently, this would contribute to the resilience and adaptability of the suggested stiffener configurations.

REFERENCES

Abdulhussein, A.A. and Al-Sherrawi, M.H., 2021. Experimental and Numerical Analysis of the Punching Shear Resistance Strengthening of Concrete Flat Plates by Steel Collars. Engineering Technology & Applied Science Research, [online] 11(6), 7853–7860. https://doi.org/10.48084/etasr.4497.

Ammash, H.K., Kadhim, S.S. and Dhahir, M.K., 2022. Repairing Half-Loaded Flat Slabs Against Punching Shear Using Steel Stiffeners. Case Studies in Construction Materials, [online]16. https://doi.org/10.1016/j.cscm.2022.e01032.

Bashandy, A.A., Mohamed Eid, F., Abd El-salam Arab, M., Elkassas, A. and Bashandy, A., 2022. Resisting Punching Shear of Flat Slab. International Journal of Advanced Research in Science, Engineering and Technology, [online] 9(2). Available at: <www.ijarset.com>.

Cuong-Le, T., Minh, H. Le and Sang-To, T., 2021. A Nonlinear Concrete Damaged Plasticity Model for Simulation Reinforced Concrete Structures Using ABAQUS. Frattura ed Integrita Strutturale, [online] 16(59), pp.232–242. https://doi.org/10.3221/IGF-ESIS.59.17.

Deifalla, A., 2020. Strength and Ductility of Lightweight Reinforced Concrete Slabs Under Punching Shear. Structures, [online] 27, pp.2329–2345. https://doi.org/10.1016/j.istruc.2020.08.002.

Al Hasani, S., A, N.H. and Abdulraeg, A.A., 2021. Numerical Study of Reinforced Concrete Beam by Using ABAQUS Software. International Journal of Innovative Technology and Interdisciplinary Sciences, [online] 4(3), pp.733–741. https://doi.org/10.15157/IJITIS.2021.4.3.733-741.

Inácio, M.M.G., Lapi, M. and Pinho Ramos, A., 2020. Punching of Reinforced Concrete Flat Slabs – Rational Use of High Strength Concrete. Engineering Structures, [online] 206. https://doi.org/10.1016/j.engstruct.2020.110194.

Izs, A. and Gwt, J., 2019. Punching Shear Failure of Reinforced Concrete Flat Slab System-A Review. European Journal of Advances in Engineering and Technology, https://doi.org/10.13140/RG.2.2.21115.5712.

Makhlouf, M.H., Ismail, G., Abdel Kreem, A.H. and Badawi, M.I., 2023. Investigation of Transverse Reinforcement for R.C Flat Slabs Against Punching Shear and Comparison with Innovative Strengthening Technique Using FRP Ropes. Case Studies in Construction Materials, [online] 18. https://doi.org/10.1016/j.cscm.2023.e01935.

Mohammed, A.H., Mubarak, H.M., Hussein, A.K., Abulghafour, T.Z. and Nassani, D.E., 2022. Punching Shear Characterization of Steel Fiber-Reinforced Concrete Flat Slabs. HighTech and Innovation Journal, [online] 3(4), pp.483–490. https://doi.org/10.28991/HIJ-2022-03-04-08.

Neamah, Z.A. and Al-Ramahee, M.A., 2021. Strengthening of Bi-Axially Loaded RC Slab-Column Connection Using Steel Plates and Stiffeners. Scientific Review Engineering and Environmental Sciences, [online] 30(1), pp.29–37. https://doi.org/10.22630/PNIKS.2021.30.1.3.

Rasoul, Z.M.R.A., Mohamed, H. and Taher, A.M., 2019. Accuracy of Concrete Strength Prediction Behavior in Simulating Punching Shear Behavior of Flat Slab Using Finite Element Approach in ABAQUS. [online] 7(4), pp.1933–1949. https://doi.org/10.21533/pen.v7i4.943.

Sagban, A., Al-Jafar, M., Hussain, H.K., Bremani, A., Abdulnasser, S. and Abbas, M., 2019. A Review on Flat Slab Punching Shear Reinforcement. [online] Available at: <https://www.researchgate.net/publication/336748683>.

Saib Kadhim, Safa and Ammash, H., 2019. Steel Stiffeners for Enhancement of Slab-Column Connections. Al-Qadisiyah Journal for Engineering Sciences. https://doi.org/10.30772/qjes.v12i4.621.

Salehuddin, S., Zaini, S.S., Nik Azizan, N.Z., Rahim, N.L., Mohamad Ibrahim, N., Abdul Rahim, M. and Mamat Ghani, A., 2020. Assessment on the Performance of Flat Slab Under Service Load and Ultimate Load Using ABAQUS. Earth and Environmental Science. Institute of Physics Publishing. https://doi.org/10.1088/1755-1315/476/1/012059.

Savaris, G., Andrew, E. and Liberati, P., 2022. Numerical Analysis of Punching Shear in Reinforced Concrete Flat Slab Using Damaged Plasticity Model. [online] Available at: <https://www.researchgate.net/publication/366066468>.

Shatarat, N. and Salman, D., 2022. Investigation of Punching Shear Behavior of Flat Slabs with Different Types and Arrangements of Shear Reinforcement. Case Studies in Construction Materials, [online] 16. https://doi.org/10.1016/j.cscm.2022.e01028.

Taresh, H.R., Yatim, M.Y.M. and Azmi, M.R., 2021. Punching Shear Behaviour of Interior Slab-Column Connections Strengthened by Steel Angle Plates. Engineering Structures, [online] 238. https://doi.org/10.1016/j.engstruct.2021.112246.

Elkady, A. 2023. ABAQUS CDP Generator: A Tool for Generating Concrete Damage Parameters for ABAQUS, Zenodo, [online] Version v23.04. https://doi.org/10.5281/zenodo.7755926