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ERBIL POLYTECHNIC UNIVERSITY

# Aspect Ratio and Relative Beam-Slab Stiffness Effects on the Long-term Deflection of Slabs

A Thesis

Submitted to the Council of the Erbil Technical Engineering College at Erbil Polytechnic University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering


By

**Karwan Khalid Ismael**

B.Sc. in Civil Engineering

Supervised by

**Dr. Sarkawt Asaad Hasan**


ERBIL KURDISTAN

JUN 2022

# DECLARATION

I declare that the Master Thesis entitled: "Aspect Ratio and Relative Beam-Slab Stiffness Effects on the Long-term Deflection of Slabs" is my own original work, and hereby I certify that unless stated, all work contained within this thesis is my own independent research and has not been submitted for the award of any other degree at any institution.

Signature:

Student Name: Karwan Khalid Ismael

Date: 4/10/2022

# SUPERVISOR CERTIVICATE

This thesis has been written under my supervision and has been submitted for the award of the degree of Master of Science in Civil Engineering with my approval as supervisor.

Signature:

Name: Dr. Sarkawt Asaad Hasan

Date: 4/10/2022

**I confirm that all requirements have been fulfilled.**

Signature:

Name: Asst. Prof. Dr. Bahman Omar Taha

Head of the Department of Civil Engineering Techniques

Date: 4/10/2022

**I confirm that all requirements have been fulfilled.**

Signature:

Name: Asst. Lecture. Bayad Abdulqadr Ahmed

Postgraduate Office

Date: 4-10-2022

# EXAMING COMMITTEE CERTIFICATION

We certify that we have read this thesis: Aspect Ratio and Relative Beam-Slab Stiffness Effects on the Long-term Deflection of Slabs and as an examining committee examined the student (**Karwan Khalid Ismael**) in its content and what related to it. We approve that it meets the standards of a thesis in terms of scope and quality for the degree of Master in Civil Engineering.

Signature:
Name: Asst. Prof. Dr. Faris Rashied Ahmed
Member
Date: 2.10.2022

Signature:
Name: Asst. Prof. Dr. Muhammad Ali Ehsan
Member
Date: 4/10/2022

Signature:
Name: Dr. Sarkawt Asaad Hasan
Supervisor
Date: 4/10/2022

Signature:
Name: Prof. Dr. Mereen Hasan Fahmi
Chairman
Date: 4.10.2022

Signature:
Name: Prof. Dr. Ayad Zeki Saber Agha
Dean of Erbil Technical Engineering College
Date: 04-10-2022

# DEDICATION

To my beloved and first teachers, my parents, whose affections, love, encouragements, faithful prayers have given us the drive and discipline to tackle a task with enthusiast and determination, without their love and support this project would not have been made possible.

To my wife, my siblings, whose support, understanding and trust make me be proud for the works which I do in my life.

My friend who encourages and supports me,
All the people in my life who touch my heart, I dedicate this research.

I am forever thankful.

# LINGUESTIC REVIEW

I confirm that I have reviewed the thesis titled Aspect Ratio and Relative Beam-Slab Stiffness Effects on the Long-term Deflection of Slabs from the English linguistic point of view, and I confirmed that its free of grammatical and spelling errors.

University of Raparin Language and Development Center

Signature:

Name of reviewer: Sardar A. Hussein

Date: May 2022

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Karwan Khalid Ismael

2022

## ABSTRACT

This study investigates the deflection in reinforced concrete slabs aiming to have a better understanding for the effects of the aspect ratio and the relative beam-slab stiffness parameters and to assess the ACI318 provisions for slab deflection control. The investigations included both long-term deflection for the evaluation of the mentioned parameters and the short-term deflection for the assessment of the deflection calculation methods (Finite Element SAFE software, ANSYS software and the ACI crossing beam approach).

As ACI318-19 does not include the aspect ratio (long span/short span) within the span affecting the determination of the flat plate thickness; an evaluation for this variable, a parametric long-term deflection (LTD) analysis has been done using SAFE for variable long span length (5m, 7.5m, 10m) and different aspect ratio at different panel locations (interior, edge, and corner). The results showed there is a noticeable effect for the aspect on the LTD (long span) and that the ACI318-19 recommended thicknesses met partially the ℓ/240 LTD limit in panels of long spans up to 7.5 m with aspect ratio range 1 to 2, in panels of long spans up 10 m with aspect ratio 1. For the ℓ/480 deflection limit, apart from rectangular 5 m long spans panels, the provisions were inadequate to satisfy the ℓ/480 limit in all other cases. For larger aspect ratio of 3, the current research suggests the use of the same ACI318-19 two-way flat plate recommended thickness taking the long span as the active span for aspect ratio of 2 to 3. For the non-satisfied cases, the current study proposed minimum thickness for corner, edge and interior flat plate slabs to satisfy both the deflection limit of ℓ/240 and ℓ/480.

For the effect of the relative beam-slab stiffness on the LTD of interior, edge and corner panel two-way beam-slabs system, the LDT deflection (both long span and mid panel deflection), the parametric study showed that the ACI318-19 provisions are adequate for interior slab panels; however, the provisions are inadequate for edge and corner panels of relative beam-slab equal to 0.2.

For the effects of the relative beam-slab stiffness of one-way slabs, (10x4.9 m, 7.5x3.6 m and 6.1x3 m slab panels) with aspect ratio greater than 2, the current study showed that with using the ACI318-19 recommended slab thickness it is required to have a minimum relative beam-slab stiffness of 5 to satisfy the LTD limit of ℓ /240, and 20 to satisfy the LTD limit of ℓ /480 along the supporting beams. For lower relative-beam stiffness, the current study proposes revised minimum thicknesses to ensure having the LTD under the long direction beam to be within the allowable deflection of ℓ /240 and ℓ /480.

Moreover, the Bondy's approach has been evaluated considering the LTD of interior, edge and corner panel flat plates for different aspect ratios. In all cases studied, Bondy's approach has been shown to be adequate for the ℓ/240 deflection limits. With respect to the deflection limit of ℓ/480, Bondy's approach produced satisfactory results (deflections) at the interior panels only.

The current study also showed that the ACI crossing beam approach for long span deflection calculation in flat plate slabs at different panel locations (interior, edge, and corner) are not accurate even at the elastic short-term deflection in rectangular slab panels (aspect ratio of 2) when compared with the SAFE and ANSYS deflection results, which showed closer results between them.

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# LIST OF SYMBOLS

| Symbols | Meaning |
|---|---|
| bw | Beam width |
| $b_c$ | Width of the column strip |
| $b_m$ | Width of the middle strip |
| C1 | Width of column |
| C2 | Length of column |
| Ct | Modification factor for moment inertia of beam |
| $COF_{AB}$ | Carry over factor |
| $DF$ | Slab-beam joint distribution factors |
| $E_C$ | Modulus of elasticity |
| $FEM$ | Fixed end moment coefficient |
| $f'_c$ | Compressive strength of concrete |
| FEM | Finite element method |
| $f_y$ | Yield strength of reinforcement |
| H | Height of column |
| h | Thickness of slab |
| Hb | Height of beam |
| Hc | clear height of column |
| $I_b$ | Moment inertia of the beam |
| $I_e$ | Effective moment of inertia of the slab |
| $I_s$ | Moment of inertia of the slab |
| $K_{ec}$ | Equivalent stiffness of column |
| $K_{AB}$ | Stiffness factor |
| $K_c$ | Flexural stiffness of column members |

| | |
|---|---|
| $K_{ec}$ | Equivalent column stiffness |
| $K_{sb}$ | Flexural stiffness of slab-beams |
| $K_t$ | Flexural stiffness of column torsion |
| L1 | Long span length |
| L2 | Short span length |
| Ld | Diagonal span length |
| Ldc | Clear diagonal length |
| $LF_c$ | Load factor of the column strip |
| $LF_m$ | Load factor of the middle strip |
| LTD | Long term deflection |
| $\ell$ | Clear short span length in table (2-1) |
| $\ell_n$ | Clear long span length |
| $M_{AB}$ | Fixed end moment coefficient |
| $M_{net}$ | Difference in floor moments to left and right of column |
| w | Total load |
| $\Delta_{f,ref}$ | Deflection due to vertical displacement |
| $\Delta\theta_l$ | Deflection due to the left rotation |
| $\Delta\theta_r$ | Deflection due to the right rotation |
| $\alpha_{fm}$ | Average relative beam-slab stiffness |
| $\Delta$ | Mid panel deflection |
| $\Delta c$ | Deflection of the column strip |
| $\Delta m$ | Deflection of the middle strip |
| $\Delta\theta$ | Angle change |
| $\alpha$ | Relative beam-slab stiffness |
| $\beta$ | Clear long span length/clear short span length |

# LIST OF ABBREVIATIONS

| Abbreviation | Meaning |
|---|---|
| ACI | American Concrete Institute |
| DL | Dead Load |
| LL | Live Load |
| SDL | Super Imposed Dead Load |
| A1-10 | **A**: "**A**spect ratio", **1**: Aspect ratio value, **10**: long span length in meter |
| A2-10 | **A**: "**A**spect ratio", **2**: Aspect ratio value, **10**: long span length in meter |
| A1-7.5 | **A**: "**A**spect ratio", **1**: Aspect ratio value, **7.5**: long span length in meter |
| A2-7.5 | **A**: "**A**spect ratio", **2**: Aspect ratio value, **7.5**: long span length in meter |
| A1-5 | "**A**spect ratio", **1**: Aspect ratio value, **5**: long span length in meter |
| A2-5 | "**A**spect ratio", **2**: Aspect ratio value, **5**: long span length in meter |
| TA1-10* | TA: "**T**wo way", thickness as required by **A**CI318-19, **1**: Aspect ratio value, **10**: long span length in meter. |
| TA 1.5-10 | TA: "**T**wo way", thickness as required by **A**CI318-19, **1.5**: Aspect ratio value, **10**: long span length in meter. |
| TA 2-10 | TA: "**T**wo way", thickness as required by **A**CI318-19, **2**: Aspect ratio value, **10**: long span length in meter. |
| TA 2.5-10 | TA: "**T**wo way", thickness as required by **A**CI318-19, **2.5**: Aspect ratio value, **10**: long span length in meter. |

| | |
|---|---|
| TA 3-10 | TA: "**T**wo way", thickness as required by **A**CI318-19, **3**: Aspect ratio value, **10**: long span length in meter. |
| TA 1-7.5 | TA: "**T**wo way", thickness as required by **A**CI318-19, **1**: Aspect ratio value, **7.5**: long span length in meter. |
| TA 1.5-7.5 | TA: "**T**wo way", thickness as required by **A**CI318-19, **1.5**: Aspect ratio value, **7.5**: long span length in meter. |
| TA 2-7.5 | TA: "**T**wo way", thickness as required by **A**CI318-19, **2**: Aspect ratio value, **7.5**: long span length in meter. |
| TA 2.5-7.5 | TA: "**T**wo way", thickness as required by **A**CI318-19, **2.5**: Aspect ratio value, **7.5**: long span length in meter. |
| TA 3-7.5 | TA: "**T**wo way", thickness as required by **A**CI318-19, **3**: Aspect ratio value, **7.5**: long span length in meter. |
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| TA 1.5-5 | TA: "**T**wo way", thickness as required by **A**CI318-19, **1.5**: Aspect ratio value, **5**: long span length in meter. |
| TA 2-5 | TA: "**T**wo way", thickness as required by **A**CI318-19, 2: Aspect ratio value, **5**: long span length in meter. |
| TA 2.5-5 | TA: "**T**wo way", thickness as required by **A**CI318-19, **2.5**: Aspect ratio value, **5**: long span length in meter. |
| TA 3-5 | TA: "**T**wo way", thickness as required by **A**CI318-19, 3: Aspect ratio value, **5**: long span length in meter. |
| O4.9 | O: indicates "**O**ne-way slab", **4.9** indicates the short span length |
| O3.6 | O: indicates "**O**ne-way slab", **3.6** indicates the short span length |
| O3.1 | O: indicates "**O**ne-way slab", **3.1** indicates the short span length |

| | |
|---|---|
| SA1-10 | **SA**: "Relative **s**tiffness", **1**: **A**spect ratio value, **10**: long span length in meter |
| SA2-10 | **SA**: "Relative **s**tiffness", **2**: **A**spect ratio value, **10**: long span length in meter |
| SA1-7.5 | **SA**: "Relative **s**tiffness", **1**: **A**spect ratio value, **7.5**: long span length in meter |
| SA2-7.5 | **SA**: "Relative **s**tiffness", **2**: **A**spect ratio value, **7.5**: long span length in meter |
| SA1-5 | **SA**: "Relative **s**tiffness", **1**: **A**spect ratio value, **5**: long span length in meter |
| SA2-5 | **SA**: "Relative **s**tiffness", **2**: **A**spect ratio value, **5**: long span length in meter |
| B1-10 | **B**: "Bondy's approach", thickness as suggested by Bondy, **1**: Aspect ratio value, **10**: long span length in meter. |
| B2-10 | **B**: "Bondy's approach", thickness as suggested by Bondy, **2**: Aspect ratio value, **10**: long span length in meter. |
| B1-7.5 | **B**: "Bondy's approach", thickness as suggested by Bondy, **1**: Aspect ratio value, **7.5**: long span length in meter. |
| B2-7.5 | **B**: "Bondy's approach", thickness as suggested by Bondy, **2**: Aspect ratio value, **7.5**: long span length in meter. |
| B1-5 | **B**: "Bondy's approach", thickness as suggested by Bondy, **1**: Aspect ratio value, **5**: long span length in meter. |
| B2-5 | **B**: "Bondy's approach", thickness as suggested by Bondy, **2**: Aspect ratio value, **5**: long span length in meter. |

# CHAPTER ONE

## Introduction

### 1.1 Introduction

The deflection calculation is a necessary aspect of two-way flat plates, two-way beam-slabs and one-way slabs. The deflection calculation in the (ACI 318-19, 2019) code requirement provided in Table 8.3.1.1 and Table 7.3.1.1 of the (ACI 318-19, 2019) have been substantially unchanged since 1963. Several authors have suggested changes to the code provisions to reflect the current construction and design practices, including (Bondy, K. B, 2005) (Scanlon, A., and Lee, Y. H., 2006), (Bischoff, P.H. and Scanlon, A., 2007), (Scanlon, A. and Suprenant, B., 2011). Excessive deflections in the slab can result in damage to nonstructural elements such as windows, doors, and partitions, and adversely affect the operation of equipment.

A flat plate slab is a two-way reinforced concrete slab that generally does not have beams or drop panels or capitals, and the loads are transferred directly to the supporting concrete columns. In this type of slab system, it is recognized that the deflection is a critical aspect, where the slab might experience excessive deflection resulting in cracks in the supported partitions walls.

### 1.2 Background

In the two-way flat plat slabs, ACI318-19 provisions do not consider the aspect ratio (large span (L1)/short spans (L2)) as a parameter in the recommended minimum slab thickness. The slab thickness depends on the large span only, for example, for an exterior flat plat slab panel of both 10 x 10 m and 10 x 5 m as shown in Figure 1.1, ACI318-19 recommends the same slab thickness ($\ell n/30$, $\ell n$

is the clear long span length). This means as long as the long span is not changing, no matter how the short span length is changed, the recommended slab thickness is always the same.

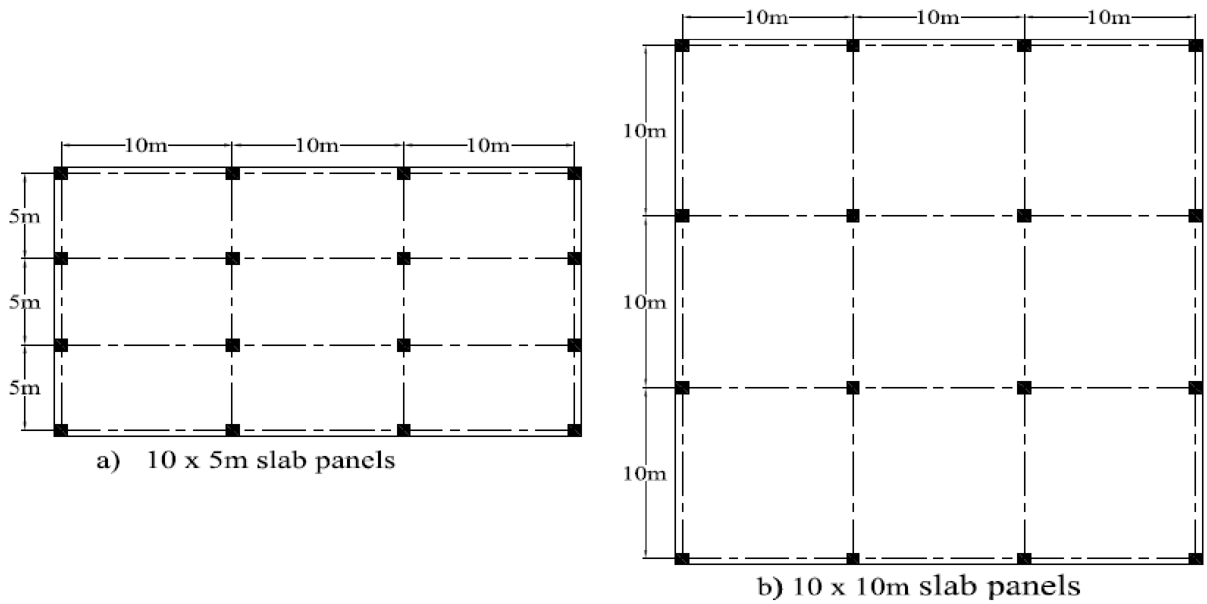


Figure 1.1: a) Flat plate slab with aspect ratio 2; b) Flat plate slab with aspect ratio 1

Further, with the flat plate aspect ratio exceeding 2 as shown in Figure 1.2, the situation becomes even more uncertain. As an attempt to apply the minimum thickness recommended by Table 8.3.1.1 (minimum thickness of two-way slabs without edge beam) of ACI318-19 to an exterior flat plat slab (for example) with aspect ratio greater than 2, below are the provisions that might be related to this task:

1- Table 8.3.1.1 (ACI 318-19, 2019) does not consider the aspect ratio as a factor affecting the thickness of two-way flat plate slabs.
2- Table 8.3.1.1 (ACI 318-19, 2019) provides “Minimum thickness for non-prestressed slabs without interior beams”. Moreover, in Section 8.3.1.1, it is clearly stated that Table 8.3.1.1 provisions are applicable “for non-prestressed slabs without interior beams spanning between supports on all sides, having a maximum ratio of long-to-short span of 2”,

For such a case under investigation (an exterior flat plat slab with aspect ratio greater than 2), as an effort to look for what ACI318-19 provisions would be applicable, the following issues will be faced:

1- Going with Table 8.3.1.1 (two-way flat slab thickness) will violate the requirement of having a maximum aspect ratio of 2.

2- If Table 7.3.1.1 is followed (one-way slab thickness), then the sub-issue would be which span to use:

A- if the short span is used, then this choice will not match with the direction of bending action, which is in the long span, as shown in Figure 1.2.

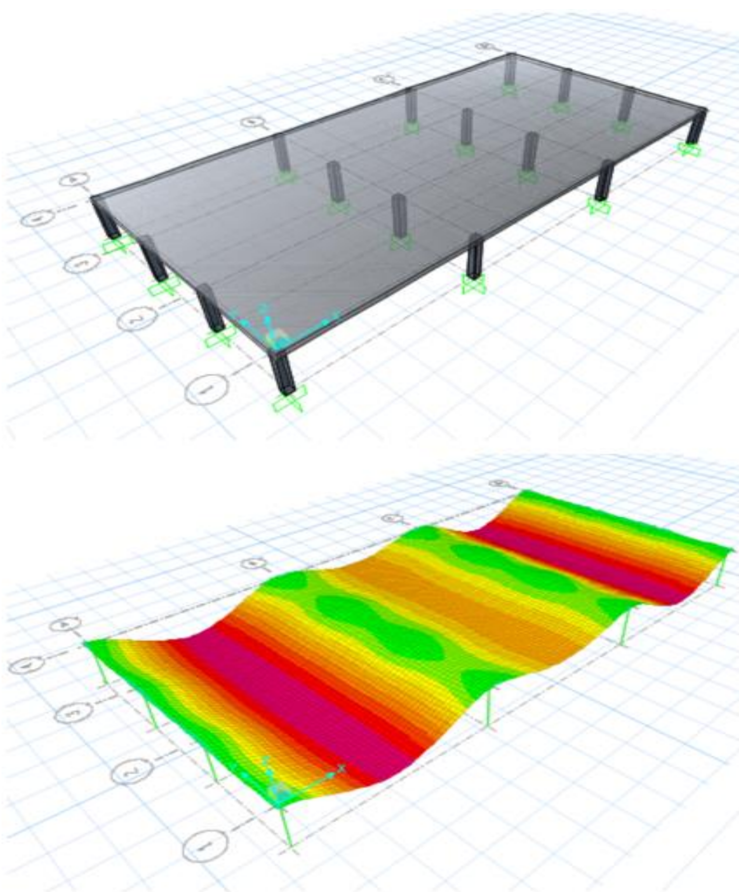

Figure 1.2: The deflected shape of flat plate slab with an aspect ratio greater than two

B- If the long span is used, then two sub-issues will come out:

- There is no clear article in ACI318-19 that would allow/recommend the use of the long span in one-way slabs.
- The recommended thickness would be (L2/28), which is 17.9 % larger than the thickness recommended for two-way flat plate of aspect ratio equal or less than 2. This would show an inconsistency in the ACI318-19 provisions. As for aspect ratio equal or less than 2, there is no consideration for the aspect ratio. However, for larger aspect ratio (less critical slabs), a larger slab thickness would be required.

The current study aims to remove the ambiguity related to thickness of flat plate slabs with aspect ratio greater than 2 as well as find and recommend changes in the ACI318-19 in this respect.

On the other hand, for flat plate slabs, if beams are provided at the long sides as shown in Figure 1.3, traditionally, the slab would be considered as one-way slabs spanning in the short direction, and the provisions of one-way slabs (Table 7.3.1.1 in ACI318-19) will be applied. This is done without having any restriction on the minimum requirements for the relative beam-slab stiffness of the provided beams recommended by the ACI 318-19. In such circumstances, if the beam stiffness is low, then there will be a deflection in the long span (beam span) might exceed the allowable $\ell/240$ or $\ell/480$ deflection, which is overlooked by the ACI318-19 provisions. Thus, the current study believes that there is a need to have a minimum limit for the provided relative beam-slab stiffness, beyond it, the slab could be considered as one-way slab in the short direction.

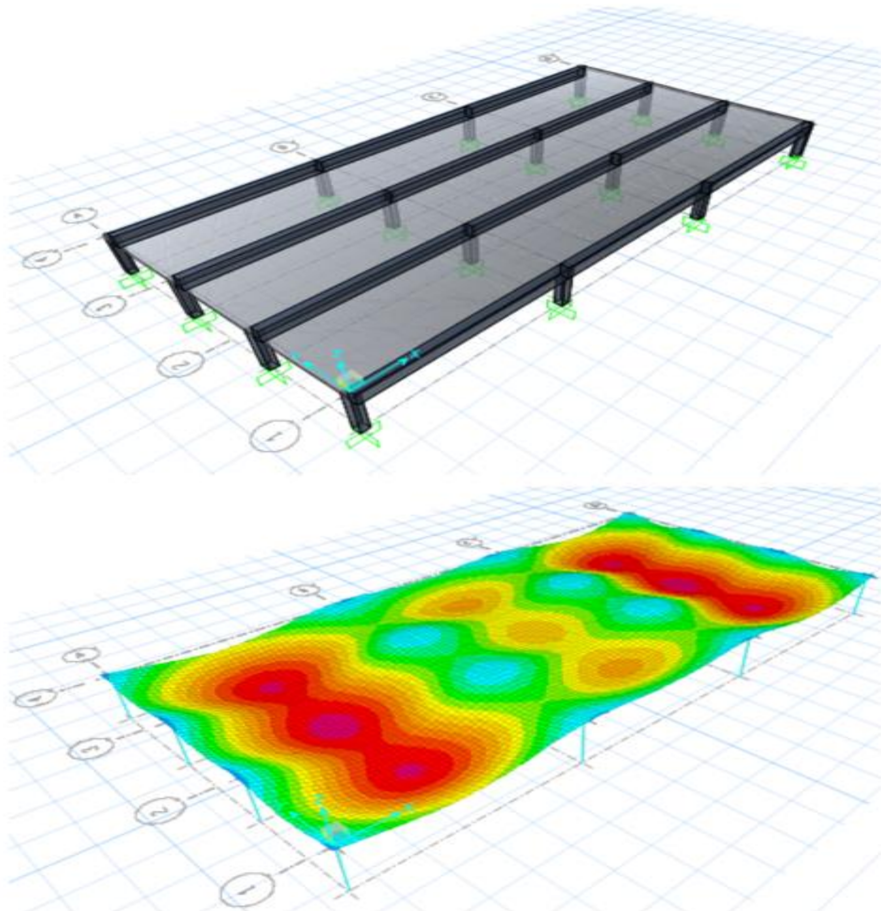

Figure 1.3: The deflected shape of one-way slab (with edge beam) with an aspect ratio greater than 2

In the current work, the reported deflections are long span deflection (point A), short span deflection (point B), mid panel deflection (point C) as illustrated in Figure 1.4, where

- L1 is the long span
- L2 is the short span
- Ld is the diagonal span

These long, short, mid panel deflections are evaluated by comparing them with the allowable permissible deflection calculated based on the corresponding active span of L1, L2, Ld, respectively.

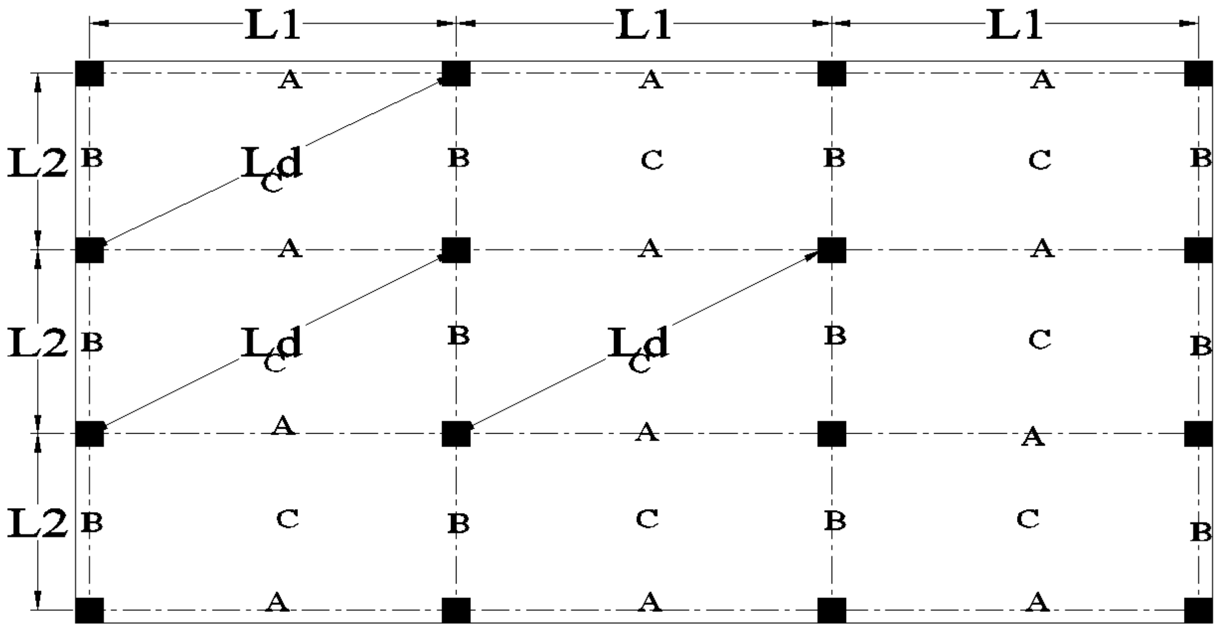


Figure 1.4: Position of the deflection calculation and its length in the permissible deflection calculation

## 1.3 Deflection calculation approaches

The deflection calculation could be done manually using ACI crossing beam approach (PCA Notes on ACI 318-11, 2013) or using Finite Element computer softwares [such as SAFE (CSI, 2016) and ANSYS (Thompson, M.K. and Thompson, J.M, 2017)]. In this study the SAFE software is used to analyze the two way and one-way slabs for deflection calculation. As a way to evaluate the accuracy of the SAFE results, a comparison has been made between the results of the SAFE with the results of the ACI crossing beam approach and ANSYS considering the deflection at the elastic stage.

## 1.4 Problem statement

- ACI 318-19 code provisions doesn't consider the effect of the aspect ratio on the flat plate slabs.

- ACI 318-19 code provisions for one-way slabs doesn't specify a minimum relative beam-slab stiffness
- ACI 318-19 code does not include clear provisions for flat plate slabs minimum thickness with aspect ratio greater than 2

## 1.5 Aims

The current study focuses on the slab deflection, at the elastic uncracked stage and elastic cracked stage aiming

1) To evaluate the ACI Crossing Beam approach in calculating the elastic uncracked deflection the against SAFE and ANSYS.
2) To evaluate the effects of the aspect ratio (3- 1) on the long-term deflection of flat plate slabs. and proposing new thickness equations.
3) To evaluate the effects of the aspect ratio (2- 1) on the slab-beam system slabs deflection.
4) To evaluate the effect of the beam-slab relative stiffness (0.2- 2) on the slab-beam system slabs deflection.
5) To evaluate the Bondy's approach for flat plate thickness of the aspect ratio (2-1)
6) To evaluate the effect of the beam-slab relative stiffness on the one-way slabs

## 1.6 Methodology

The current study uses the Finite Element SAFE software, ACI crossing beam approach and ANSYS to calculate the short-term deflection of flat plate slabs with the bellow variables:

- Different long span lengths (10, 7.5, and 5 m) for two-way flat plate slabs
- Different aspect ratios (1, 2,) for two-way flat plate slabs

The Finite Element SAFE software is used to calculate the LTD of flat plates, two-way beam slabs and one-way beam-slabs for different aspect ratios and relative beam-slab stiffness configurations, as detailed below:

- Different long span lengths (10, 7.5, and 5 m) for two-way flat plate slabs
- Different aspect ratios (1, 1.5, 2, 2.5 and 3) for two-way flat plate slabs
- Different short span lengths (3, 3.6, 4.9 m) for one-way slabs
- Different relative beam-slab stiffness for one-way slabs

## 1.6 Limitation of the study

The current study is limited to the following cases:

- Two types of slabs (flat plate slab and beam-slab) system
- One floor building
- For beam-slab system, the provided beam size is equal at all two/four sides.

## 1.7 The structure of the thesis

Five chapters are included in the current thesis. It is organized as follows:

- The first chapter gives a brief overview of the two-way slabs and one-way slabs.
- The second chapter comprises literature review about the deflection of the slab and the minimum thickness of the slabs. It presents the ACI318-19 Code provisions for slab deflection control. It includes the minimum thickness requirement of two types of slabs (one-way and two-way slabs). Additionally, the calculation method of the slab deflections is briefly presented for flat plate slabs, by different methods (ACI crossing beam approach, ANSYS, SAFE)
- In the third chapter, a brief overview of the parametric study cases is presented.

- The fourth chapter demonstrates the results and discussion of the calculated slab deflection (long term deflections and short-term deflections).
- The fifth chapter presents the conclusions and recommendations.
- The last part of this study is the appendix which covers the calculation samples of the deflection of the flat plate slab using ACI crossing method, the relative stiffness calculation of the beam-slab (appendix A). The (appendix B) includes the table of the results.

# CHAPTER TWO

## Review of literature

### 2.1 Introduction

ACI 318-19 provides two alternative approaches for deflection control. First approach; specifying minimum thickness for controlling the deflection as a ratio of the long span of the slab (maximum span-to-depth ratio). This recommendation is attractive as a mean of deflection control due to its simplicity; however, many researchers ( (Hwang, S.J. and Chang, K.Y., 1996), (Scanlon, A. and Lee, Y. H, 2010), (Bondy, K. B, 2005), (Gilbert, R. I, 1985)) have criticized it for not providing the concrete strength, actual load level, desired deflection limit, and the steel quantities. Second approach; the calculated deflection of the slab panel is compared to the allowable permissible deflection.

The minimum slab thickness or maximum span/depth ratio approach was the focus of many researches for decades. Different forms for the maximum allowable span/depth ratio for slabs have been suggested by several studies such as (Gilbert, R. I, 1985), (Scanlon, A., and Lee, Y. H., 2006), (Hümme, J., von der Haar, C., Lohaus, L. and Marx, S., 2016), (Ahmat, K.A., 2017) and (Fahmi, M.H. and Saber, A.Z., 2020) considering the effects of various factors such as reinforcement ratio, support condition, target maximum permissible incremental deflection, aspect ratio, long term deflection effects, sustained load and concrete modulus of elasticity.

The flexural stiffness (EI) of a flexural member is an important variable in the deflection calculation. For the reinforced concrete members, the cracked amount of the section impacts considerably the moment of inertia. This effect needs to be considered in the analysis of deflection (Setareh, M. and Darvas, R., 2016). In general, there are two methods that can be used to determine the cracking effect. One method is the effective moment of inertia (Ashraf, S.M., 2017), and the other is the mean curvature method (Gilbert, R.I., 2011).

In addition, creep and shrinkage have significant effects on the LTD, and thus literature gives many ways for the purpose of considering this effect. For example, ACI 318-19 method is the most famous one. Using a range of refined methods (Pack, L., 2017) for the deflection analysis, like a FEM analysis (Tošić, N., Pecić, N., Poliotti, M., Marí, A., Torres, L. and Dragaš, J., 2021) or non-linear analysis.

(Hasan S. and Taha B, 2020) conducted a nonlinear cracked analysis to obtain the LTD using finite element SAFE software for 600 flat plate corner panel cases with variable long span length, aspect ratio, thickness as recommended by ACI 318-14, concrete grade and live load. The study concluded that: (1) Aspect ratio has an effect on the LTD of flat plate without beam especially at large long direction spans; (2)ACI provisions, for $\ell/240$ are adequate for most case (long spans up to 7.0 m); (3) ACI provisions, for $\ell/480$ are not adequate in most of the studied cases (Long spans of 5 m to 10 m); (4) The large span in considered as the “reference span”, along which, all the deflection calculations and checks are required to be performed. They have emphasized that the effect of the aspect ratio that hasn’t been mentioned in five Standards (ACI 318-14 (ACI 318-14, 2014) , CSA A23.3-14 (CSA A23.3-14, 2014), AS 3600 (AS 3600-18, 2018), BS8110 (BS EN 8110-1-1997, 1997), Euro code 2 (BS EN 1992-1-1, 2004) ) provision for the calculation of the minimum allowable thickness.

(Cohen, L.C., 2012) suggested that the (ACI 318-11, 2011) Code provisions are inadequate to design two-way slab systems for serviceability. He listed issues on more than one level: (1) The slabs that designed following the ACI 318-19 provisions might exceed the defined deflection limits; (2) The minimum thickness requirements should be changed to include the parameters of the aspect ratio of a panel and the applied load.

Moreover, (Bondy, K. B, 2005) identified two problems in ACI 318 Provisions; 1) The thickness calculation of Two-way slabs is designed in accordance with the long span length in Table 8.3.1.1 as per ACI 318-19 provisions; 2) Since, as already mentioned, the required minimum thickness is completely independent of the loads, Table 8.3.1.1 of ACI 318 may not provide sufficient guidance for properly designing heavily loaded slabs. The paper worked on the aspect ratio considerations in the slab thickness calculation, and the term “span” used in the ACI318-19 provisions was suggested by Bondy to be taken as the diagonal slab panel length instead of the long span length. The paper suggested that to evaluate the mid panel deflection, it needs to be compared with the deflection limit calculated based on the same diagonal length.

(Thompson & Scanlon, 1988) conducted a Finite Analysis of 300 slabs; many variables were taken into consideration, including the slab aspect ratio; Scanlon recommended that “for square slab panels, the required ACI minimum thickness should be increased by 10 %.”

(Gullapalli, A., 2009) recommended “increasing the slab thickness by %10 (above those recommended by ACI318) for a flat plate in the following conditions: 1) longer clear-span not greater than 20 ft; 2) superimposed dead load not greater than 20 psf; 3) live load not greater than 70 psf, 4) concrete compressive strength not less than 3000 psi”. For flat plate conditions falling outside the above range, the slab thickness was recommended to be determined based on the Scanlon, and Lee (2006) equation.

(Al-Numan, B. S. and Abdullah, C. S., 2018) have developed a simulation model that considering the materials and loads uncertainties. The results showed that the

ACI 318-14 provisions for the allowable minimum thickness are appropriate for 4m spans and less for flat plate.

(Scanlon, A. and Choi, B.S., 1999) recommended an alternative method to determine minimum the allowable slab thicknesses for one-way construction, including effects of span length, time-dependent deflection, design loads and loading.

(Scanlon, A. and Lee, Y. H, 2010) have compared the minimum thickness for one-way and two-way slabs by several design provisions such (ACI 318-08, 2008), (BS EN 8110-1-1997, 1997), (BS EN 1992-1-1, 2004), (AS 3600-2001, 2001) and the unified equation proposed by (Scanlon, A. and Lee, Y. H, 2010). The effects of various design parameters are evaluated such as (support conditions, span length, and applied loads). According to the results, ACI 318-08 provisions need to be revised to cover the range of design parameters. Additional using instructions need to be included in ACI 318-08; however, the ACI provisions for flat plates appear adequate for deflection limits of ℓ/240 for typical spans and loads, but may not satisfy the permissible deflection limits of l/480 in many cases.

## 2.2 Minimum thickness requirement

For two-way flat plate slabs and one-way slabs, (ACI 318-19, 2019), (BS EN 1992-1-1, 2004), (AS 3600-18, 2018) and (CSA A23.3-14, 2014) provide two approaches for the deflection control. In the first approach, a minimum thickness given as a function primarily of the span length and the span boundary conditions, in which case, the deflection calculation is not required. Alternatively, as the $2^{nd}$ approach, smaller thickness could be used if deflection calculations are made and shown to satisfy the deflection limits given in the ACI318-19 Code.

The minimum thickness of solid non-prestressed one-way slabs could be found in ACI318-19 Code, Table 7.3.1.1. The minimum thickness depends mainly on the clear span in the short direction ($\ell$), as illustrated in Table 2.1.

Table 2.1: ACI318-19, Table 7.3.1.1 Minimum thickness of solid non-prestressed one-way slabs.

| **Support condition** | **Minimum *h*#** |
|---|---|
| Simply supported | $\ell$/20 |
| One end continuous | $\ell$/24 |
| Both ends continuous | $\ell$/28 |
| Cantilever | $\ell$/10 |

# Expression applicable for normal weight concrete and *fy* = 420 MPa. For other cases, minimum *h* shall be modified in accordance with 7.3.1.1.1 through 7.3.1.1.3, as appropriate.

The minimum thickness requirements for two-way flat plate slabs could be found in ACI318-19 Code Table 8.3.1.1. The minimum thickness depends mainly on the clear span in the long direction ($\ell_n$), as shown in Table 2.2.

Table 2.2: ACI318-19, Table 8.3.1.1- Minimum thickness of nonprestressed two-way slabs without interior beams(mm) #

| fy, MPa* | Without drop panels& | | | With drop panels& | | |
|---|---|---|---|---|---|---|
| | Exterior panels | | Interior panels | Exterior panels | | Interior panels |
| | Without edge beams | With edge beams@ | | Without edge beams | With edge beams@ | |
| 280 | ℓn/33 | ℓn/36 | ℓn/36 | ℓn/36 | ℓn/40 | ℓn/40 |
| 420 | ℓn/30 | ℓn/33 | ℓn/33 | ℓn/33 | ℓn/36 | ℓn/36 |
| 550 | ℓn/27 | ℓn/30 | ℓn/30 | ℓn/30 | ℓn/33 | ℓn/33 |

# *ℓn* is the clear span in the long direction, measured face-to-face of supports (mm).

***** For *fy* between the values given in the Table, minimum thickness shall be calculated by linear interpolation.

& Drop panels as given in Section 8.2.4, ACI318-19

@ Slabs with beams between columns along exterior edges. Exterior panels shall be considered to be without edge beams if $\alpha f$ is less than 0.8.

The minimum thickness requirements for two-way beam-slabs can be calculated in ACI318-19 Code, Table 8.3.1.2. The minimum thickness depends on the clear span in the long direction ($\ell_n$), relative stiffness and the aspect ratio, as shown in Table 2.3.

Table 2.3: Minimum thickness of non-prestressed two-way slabs with beams spanning between supports on all sides, (Table 8.3.1.2 from ACI 318-19).

| α_fm# | | | |
|---|---|---|---|
| $\alpha_{fm} \leq 0.2$ | 8.3.1.1 applies | | (a) |
| $0.2 \leq \alpha_{fm} \leq 2$ | Greater of; | $\dfrac{\ell_n\left(0.8 + \dfrac{f_y}{1400}\right)}{36 + 5\beta(\alpha_{fm} - 0.2)}$ | (b)#,* |
| | | 125 | (c) |
| $\alpha_{fm} > 2$ | Greater of; | $\dfrac{\ell_n\left(0.8 + \dfrac{f_y}{1400}\right)}{36 + 9\beta^{\&}}$ | (d) |
| | | 90 | (e) |

# $\alpha_{fm}$ is the average value of αf for all beams on edges of a panel.
* $\ell_n$ is the clear span in the long direction, measured face-to-face of beams
& β is the ratio of clear spans in long to short directions of slab.

On the other hand, according to ACI318-19, slab thickness less than those recommended in Table 2.1, Table 2.2 and Table 2.3 could be used. In these cases, the maximum permissible deflection should not be exceeded. In the current study, the used slab thicknesses are as required by Table 2.1, Table 2.2 and Table 2.3; However, as a way for the evaluation of these thicknesses, the calculated LTD have been compared with the $\ell/240$ and $\ell/480$ deflection limits as shown in the Table 2.4

Table 2.4: ACI318-19, Table 24.2.2- Maximum permissible calculated deflections

<table>
<tr><th>Member</th><th colspan="2">Condition</th><th>Deflection to be considered</th><th>Deflection limitation</th></tr>
<tr><td>Flat roofs</td><td colspan="2" rowspan="2">Not supporting or attached to nonstructural elements likely to be damaged by large deflections Immediate deflection due to L</td><td>Immediate deflection due to maximum of Lr, S, and R</td><td>$\ell/180$</td></tr>
<tr><td>Floors</td><td>Immediate deflection due to L</td><td>$\ell/360$</td></tr>
<tr><td rowspan="2">Roof or floors</td><td rowspan="2">Supporting or attached to nonstructural elements</td><td>Likely to be damaged by large deflections</td><td rowspan="2">That part of the total deflection occurring after the attachment of nonstructural elements, which is the sum of the time dependent deflection due to all sustained loads and the immediate deflection due to any additional live load.</td><td>$\ell/480$</td></tr>
<tr><td>Not likely to be damaged by large deflections</td><td>$\ell/240$</td></tr>
</table>

## 2.3 Deflection Calculation Methods

Various methods are available to calculate the deflections of one-way slabs and two-way slabs. Each of them needs accounting for cracking, which decreases the flexural stiffness.

Several methods are given by (ACI Committee 435, 1991) for computing of the immediate deflections of two-way slabs:

- Classical method, utilizing the elastic thin-plate theory equations
- ACI crossing beam approach, in which the slab is divided in a system of orthogonal middle and column strips
- Finite Element method

### 2.3.1 Classical Method

The classical method clearly needs difficult computations with assumptions on the boundary conditions and solution of differential equations; this method is long and not simple to implement on slabs with different spans and support conditions.

### 2.3.2 ACI Crossing Beam Approach

The ACI crossing method is a simplified calculation method to calculate one-way and two-way slabs deflections. This method considers two orthogonal one-way slabs, and each slab direction is separated into middle and column strips; the mid panel deflection of two-way slabs can be determined by “the sum of the midspan deflection of the column strip in one direction and that of the middle strip in the other direction”, as stated in in (Nilson, A., Darwin, D., Dolan, C., 2016)

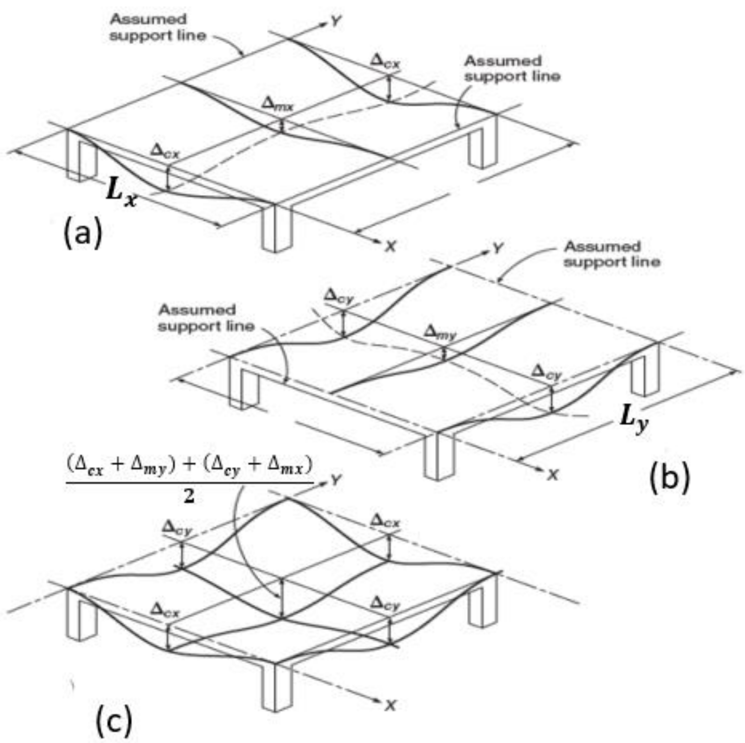


Figure 2.1: Basis of equivalent frame method for deflection analysis: (a) X direction bending;(b) Y direction bending; and (c) combined bending

In the computations of the deflection of the slab panels (interior, edge and corner panel) in both directions, it is suitable first to suppose that it deforms within a cylindrical surface, as it would if the bending moment were distributed uniformly at all sections across the panel width and if lateral bending of the panel were suppressed.

Considering the supports to be fully fixed preventing both rotation and vertical displacement.

Then the deflection $\Delta_{f,ref}$ is calculated as

$$\Delta_{f,ref} = \frac{wL^4}{384E_C I_s}$$

When the rotation at each end being known, the associated midspan deflection of the equivalent frame can be computed. It is easily confirmed that the midspan deflection of a member encountering an end rotation of $\theta$ rad, the far end being fixed, is

$$\Delta\theta = \theta \times \left(\frac{L}{8}\right)\left(\frac{I_s}{I_e}\right)$$

$$\theta = \frac{M_{net}}{K_{ec}}$$

Where:

- $M_{net}$ , is the difference in floor moments to left and right of column
- $K_{ec}$ , is the equivalent stiffness of column
- $\theta$, is the angle change

Thus, the total deflection at the midspan of the middle strip or column strip is the summation of the three parts, as below, where

$$\Delta c = LF \times \Delta_{f,ref} \times \frac{I_s}{I_c} + \Delta\theta_l + \Delta\theta_r$$

$$\Delta m = LF \times \ \Delta_{f,ref} \times \frac{I_s}{I_m} + \Delta\theta_l + \Delta\theta_r$$

Where

- $\Delta c$ and $\Delta m$ is the deflection of the column strip and middle strip, respectively
- The subscripts $r$ and $l$ refer to the right and left end of the span, respectively.

The load factor ($LF$) of column strip for (both end span and interior span) can be found from Table 2.5 as stated in from (ACI 318-14, 2014) section 8-10.

Load factor of column strip for end span as stated in Table 2.6 from (ACI 318-14, 2014) section 8-10.

ACI 318-19 code, these tables (Table 2.5 and Table 2.6) are omitted maybe in a recognition to use software in the calculation of slab deflection

$$LF_c = \frac{0.60 + \frac{1+0.75}{2}}{2} = 0.7375$$

Load factor of middle strip for end span

$$LF_m = 1 - LF_c = 0.2625$$

Load factor of column strip for interior span as stated in Table 2.6.

$$LF_c = \frac{0.75 + 0.6}{2} = 0.675$$

Load factor of middle strip for interior span

$$LF_m = 1 - LF_c = 0.325$$

Where:

- $LF_c$ is the load factor of column strip
- $LF_m$ is the load factor of middle strip

Table 2.5: Column-strip moment, portion of total moment at critical section,[ (ACI 318-14, 2014) section 8-10].

| | | $\ell_2/\ell_1$ | | |
|---|---|---|---|---|
| | | 0.5 | 1 | 2 |
| Interior negative moment<br>$\propto \ell_2/\ell_1 = 0$<br>$\propto \ell_2/\ell_1 \geq 1.0$ | | 0.75<br>0.90 | 0.75<br>0.75 | 0.75<br>0.45 |
| Exterior negative moment<br>$\propto \ell_2/\ell_1 = 0$ | $\beta_t = 0$<br>$\beta_t \geq 1.0$ | 1.0<br>0.75 | 1.0<br>0.75 | 1.0<br>0.75 |
| $\propto \ell_2/\ell_1 \geq 0$ | $\beta_t = 0$<br>$\beta_t \geq 1.0$ | 1.0<br>0.9 | 1.0<br>0.75 | 1.0<br>0.45 |
| positive moment<br>$\propto \ell_2/\ell_1 = 0$<br>$\propto \ell_2/\ell_1 \geq 1.0$ | | 0.6<br>0.9 | 0.6<br>0.75 | 0.6<br>0.45 |

Table 2.6: Percentage of moment and load factor $(LF)$ of column strip and middle strip [ (ACI 318-14, 2014) section 8-10]

| | | Percentage of moment | | Load factor $(LF)$ | |
|---|---|---|---|---|---|
| Slab location | Moment | Column strip | Middle strip | Column strip (LFc) | Middle strip (LFm) |
| End span | Exterior Negative | 100 | 0 | 0.7375 | 0.2625 |
| | Positive | 60 | 40 | | |
| | Interior negative | 75 | 25 | | |
| Interior span | Negative | 75 | 25 | 0.675 | 0.325 |
| | Positive | 60 | 40 | | |

The Moment of inertia of the column strip ($I_c$) and middle strip ($I_m$) can be found by:

$$I_c = \frac{b_c \times h^3}{12} \qquad I_m = \frac{b_m \times h^3}{12}$$

Where, as illustrated in Figure 2.2:

- $b_c$; is the width of the column strip
- $b_m$; is the width of the middle strip
- $h$; is the thickness of the slab

The moment inertia of the slab ($I_{frame}$) is;

$$I_{frame} = \frac{L_2 h^3}{12}$$

- Where: L2 is the width of span and h is the thickness of the flat plate slab as shown in Figure 2.2.

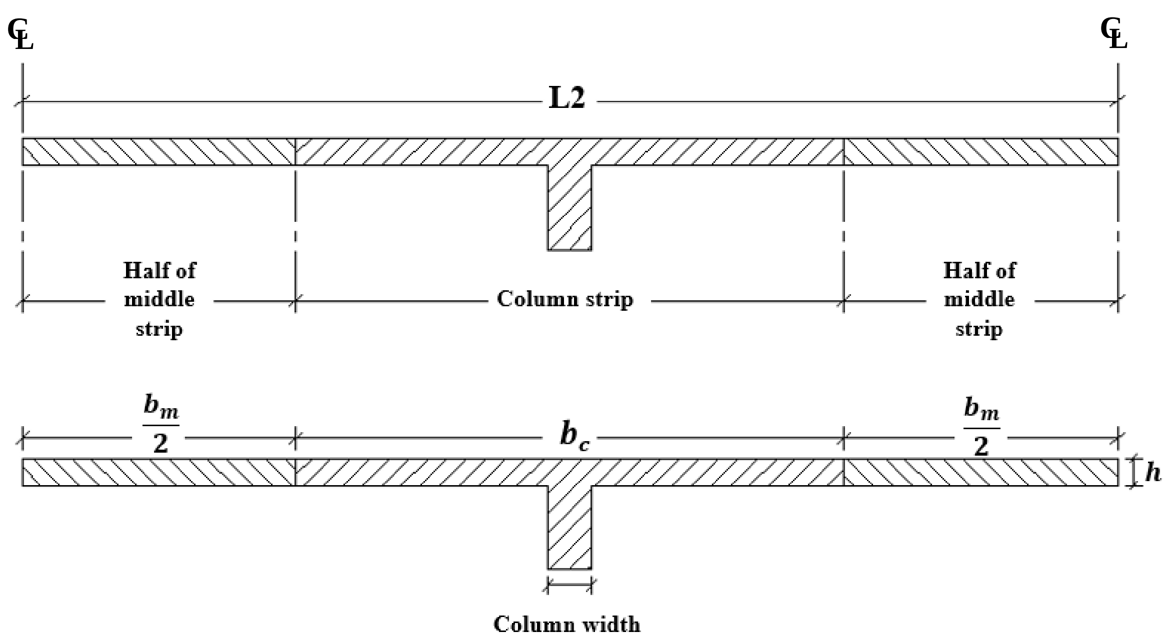


Figure 2.2: Column strip and middle strip in flat plat slab.

The finding of the $FEM$, $COF$ and $DF$ which are needed for the calculation of the moments in the method of moment distribution is detailed below:

Fixed end moment, ($FEM$) is;

$$FEM = M_{AB} * q_u * L2 * L1^2$$

$M_{AB}$ and $COF_{AB}$ can be found in the (Table A14) from (MacGregor, J G. and Wight, J K., 2012).

$M_{AB}$ is the fixed end moment coefficient,

$COF_{AB}$ is the carry over factor

Slab-beam joint distribution factors, *DF* at interior joint is;

$$DF = \frac{K_{sb}}{K_{sb} + K_{ec}}$$

Slab-beam joint distribution factors, *DF* at exterior joint is;

$$DF = \frac{K_{sb}}{K_{sb} + K_{sb} + K_{ec}}$$

Flexural stiffness of slab-beams at both ends ($K_{sb}$) is;

$$K_{sb} = K_{AB} \frac{E_{cs} I_s}{L1}$$

($K_{AB}$) is the stiffness factor, (Table A14) from (MacGregor, J G. and Wight, J K., 2012).

Flexural stiffness ($Kc$) of column members at both ends is;

$$K_c = \frac{k * E_{CS} * I_c}{H}$$

Column stiffness ($Kt$) due to the Effect of column torsion is:

$$K_t = \frac{9E_{cs}C}{\left[L_2 \left(1 - \frac{C_2}{L_2}\right)\right]}$$

Equivalent column stiffness ($K_{ec}$) due to the Flexural stiffness of column members at both ends and Column stiffness due to the Effect of column torsion:

$$K_{ec} = \frac{\sum K_c \times \sum K_t}{\sum K_c \times \sum K_t}$$

Where:

- $LF$ is the load distribution factor
- $I_c$ is the moment of inertia the column strip
- $I_m$ is the moment inertia of the middle strip
- $I_{frame}$ is the moment inertia of the slab.

The above calculation steps are for the deflections in one direction, in the perpendicular direction of the slab, the same calculation steps of the deflection are repeated using the ACI crossing beam method. The total deflection at the mid-panel is determined by summing up the middle-strip deflection in one direction and the column-strip deflection in the perpendicular direction.

The deflection of the mid panel in each panel (interior, edge and corner) can be found as;

$$\Delta = \frac{(\Delta c\ long\ direction + \Delta m\ Shortdirection) + (\Delta c\ short\ direction + \Delta m\ longdirection)}{2}$$

In the current study, the ACI crossing beam approach has been used to compute the slab deflection at the elastic uncracked stage. The deflections have been compared with those obtained using ANSYS and SAFE. The purpose of this was to evaluate the principals of the ACI crossing beam approach (excluding the long-term deflection effects).

### 2.3.3 Finite Element Method

The Finite Element Method (FEM) is a technique used for simulating physical phenomena using numerical calculations. for structural analysis purposes as well as deflection calculations. This technique is used to reduce the number of physical prototypes and experiments and to devise perfect components during the design phase to achieve better results faster while saving on costs. The current study uses FEM software such as SAFE 2016 and ANSYS.

### 2.3.3.1 SAFE 2016

SAFE is a software developed by (CSI, 2016); it is primarily used for analyzing and designing concrete slab systems. It includes all aspects of the engineering design process, from creating a design layout to analysis, design, and drawing production. Figure 2.3.

In this study, SAFE is used for calculating the long-term deflection and short-term deflection of the slabs

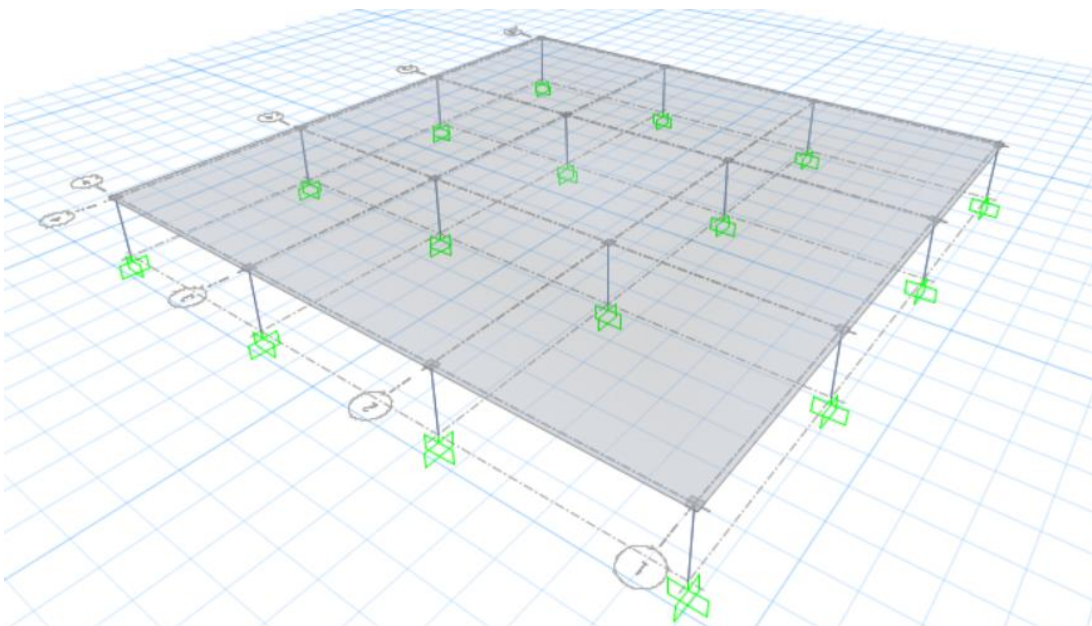

Figure 2.3: Shell elements and beam elements in SAFE model

#### 2.3.3.1.1 Finite Element SAFE modeling

The slabs are modelled using thick shell elements (include the transverse shear deformation); each element has 4 node; each node has six degrees of freedom (three translations and three rotation about the local axes) as shown in the Figure 2.4 ; the material property within each element is constant; the element includes shear deformation, and the element moments and shears are calculated at the nodes of the element (CSI, 2016).

The beams and columns are modelled using beam elements as shown in the Figure 2.5. Each beam element has two nodes with six degree of freedom at each node (three translations and three rotation about the local axes); the Biaxial bending, torsion, axial deformation, and biaxial shear are all accounted for, which are calculated at the two ends of each element, corresponding to each mesh point. Beam elements are prismatic (CSI, 2016).

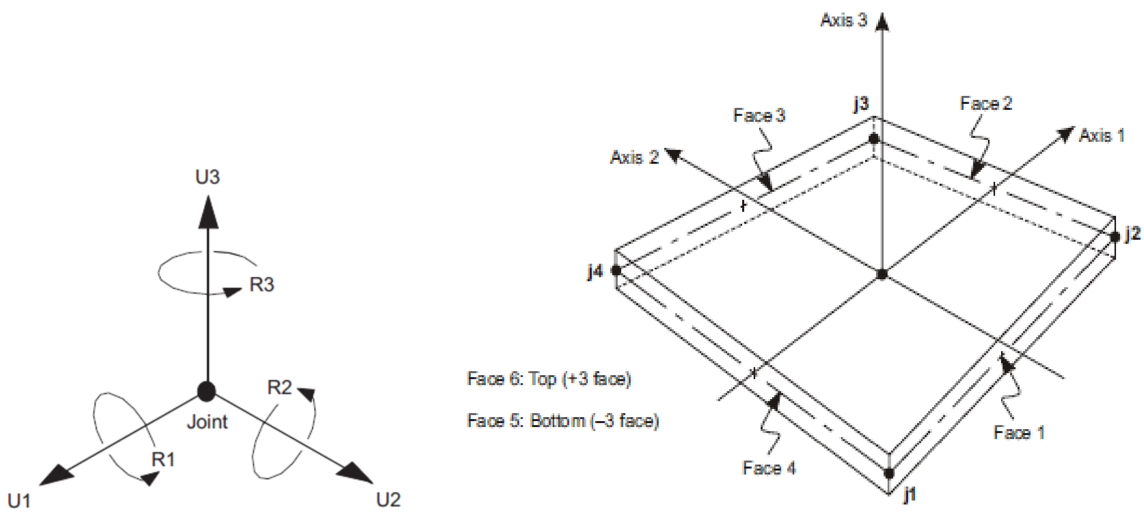


Figure 2.4: 4node quadratic shell element

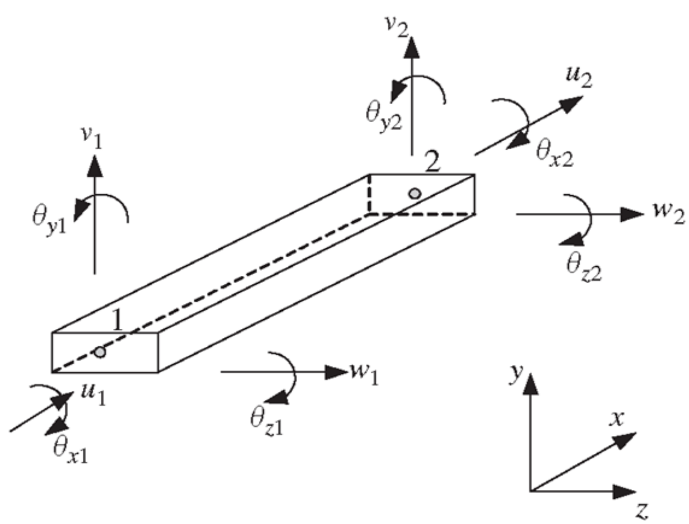


Figure 2.5: 6 degree of freedom beam element

#### 2.3.3.1.2 Finite Element SAFE nonlinear analyzing

The non-linear behavior of the slab shell elements is accounted for in the SAFE FE analysis by reducing the member stiffnesses due to the cracking of the concrete and performing a nonlinear cracking analysis. For the estimation of true deflections, which is a complex task, the effective stiffness is calculated to obtain cracked deflections with further application of modification factors to account for long-term deflections (due to creep and shrinkage). The Calculation of the long-term deflection was done according to the procedure shown in (PCA Notes on ACI 318-11, 2013).The following three cases are included in this procedure:

- Case 1: Immediate deflection under the DL + SDL + LL using nonlinear cracked analysis,
- Case 2: Immediate deflection under the DL + SDL + ΨLL using nonlinear cracked analysis,
- Case 3: Long-term deflection under the sustained loads of DL + SDL + ΨLL.

Where:

- DL is the self-weight of the slab,
- SDL is the superimposed dead load,
- LL is the live load,
- Ψ indicates the pesentage of sustained live load= 0.25

In order to calculate the long-term deflection value, a linear combination has been used resulted by adding case 3 to case 1 minus case 2, and the difference between these cases 1 and 2 is the incremental deflection (without creep and shrinkage) resulting from the non-sustained loading on cracked slabs.

### 2.3.3.2 ANSYS software Approach

The finite-element modeling software ANSYS solves mechanical problems numerically for a variety of purposes. Static/dynamic, structural analysis, etc., as well as acoustic and electromagnetic problems are included. ANSYS can implement the technology to a level that is appropriate to the scope of the problem. According to Figure 2.6 of the current study

In this study the method is used to determine the short-term deflection of flat plate slabs with different panel locations (interior, edge, corner) in order to compare it with the deflections of obtained from the SAFE method and the ACI crossing beam method.

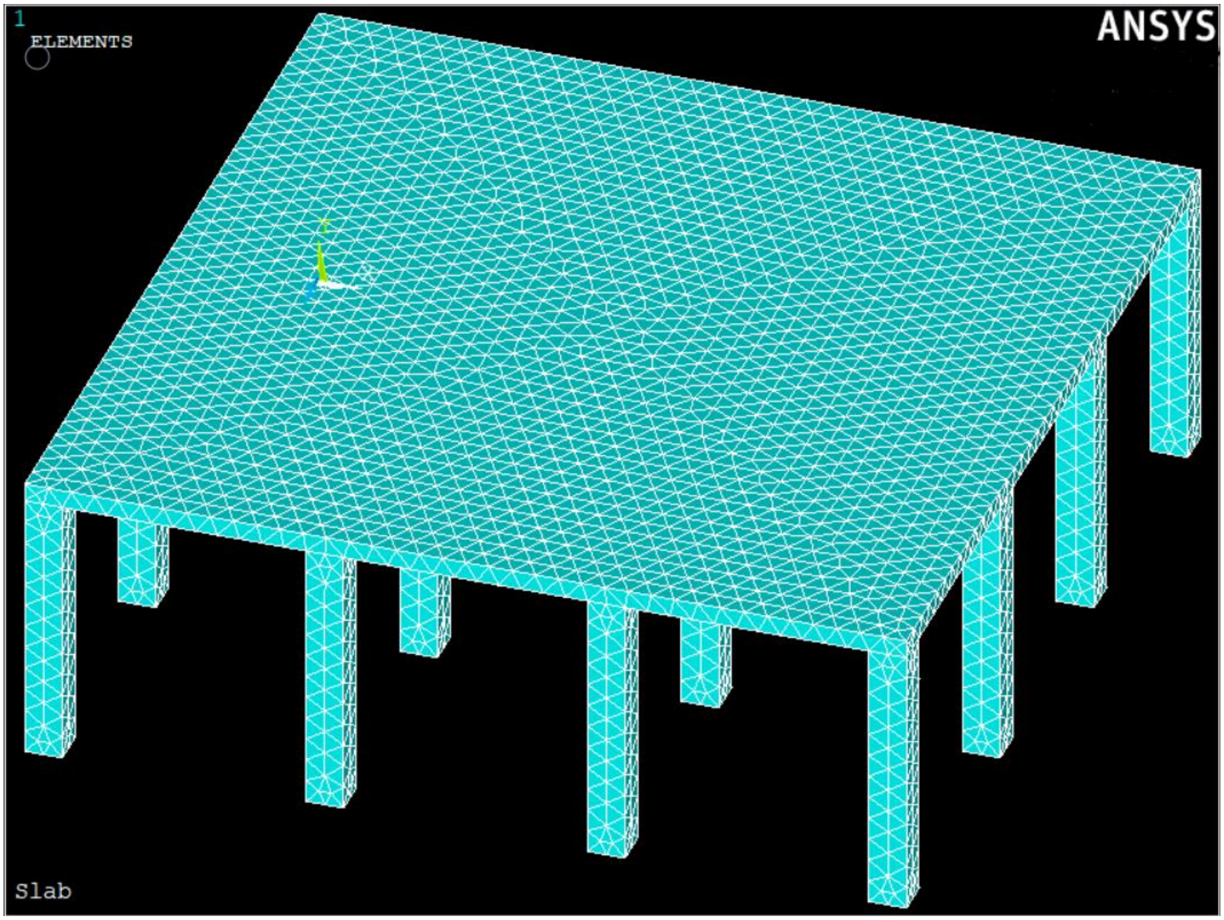


Figure 2.6: Tetrahedra elements in ANSYS model

### 2.3.3.2.1 Finite Element ANSYS modeling

The slabs, beams and columns are modelled using the 10 nodes tetrahedra elements (include the transverse shear deformation); each element has 10 nodes; each node has six degrees of freedom (three translations and three rotation about the local axes) (Thompson, M.K. and Thompson, J.M, 2017). The geometry, node locations, and the coordinate system for this element are shown in Figure 2.7.

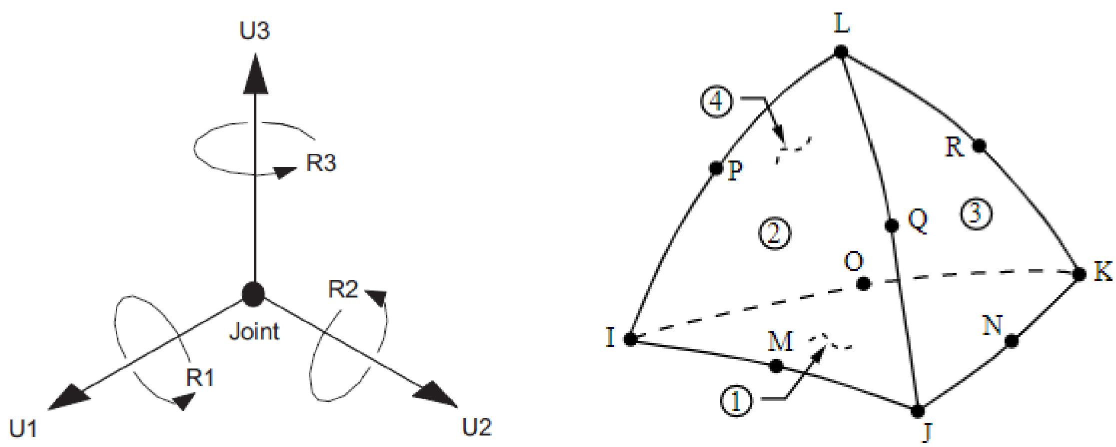


Figure 2.7: 10 nodes tetrahedra element

## 2.4 Relative beam-slab stiffness

The relative beam-slab stiffness is defined as the ratio of the beam stiffness to the slab stiffness meeting at a joint. This formula is used in two-way beam-slabs system Figure 2.8 for calculating the minimum thickness as shown in Table 2.3. In the current research, the relative beam-slab stiffness is also used in one-way slabs to obtain the minimum relative beam-slab stiffness that satisfy the ACI permissible deflection under the supporting beams.

The relative beam-slab stiffness is calculated for all the slab sides that have beams, see Figure 2.8, it is calculated by dividing the moment of inertia of the beam by the moment of inertia of the slab at each side (corner, interior and edge panel), then taking the average of all the four stiffness in one panel to obtain the average relative beam-slab stiffness for that slab panel;

$$\alpha = \frac{EI_b}{EI_s}$$

$$I_b = Ct\frac{bw(Hb)^3}{12}$$

Where:

- $\alpha$ is the relative beam-slab stiffness
- Ct is the modification factor as illustrated in Figure 2.9
- $I_b$ is the moment inertia of beam

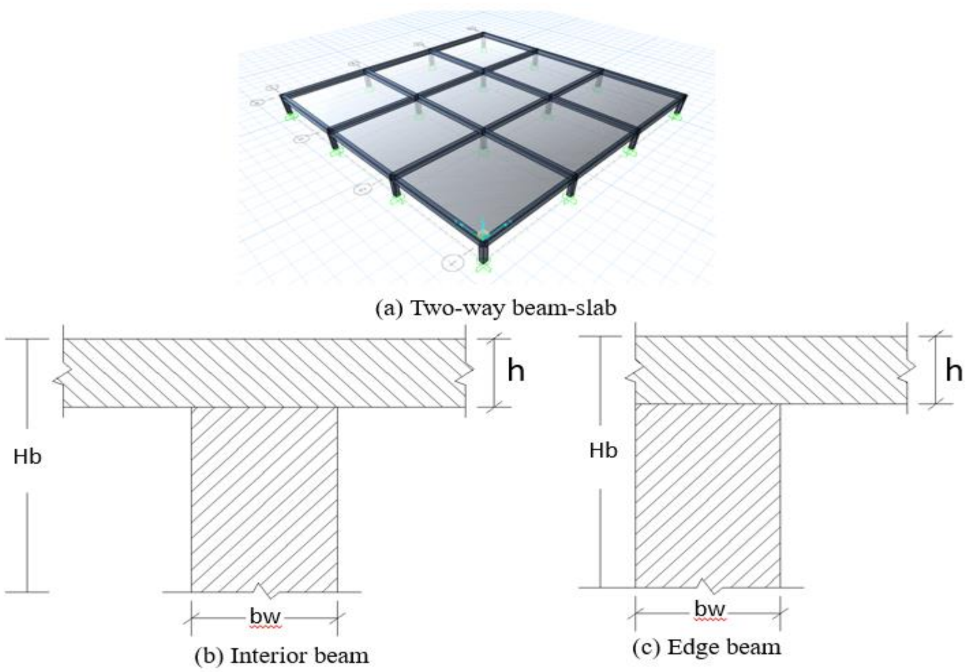


Figure 2.8: (a) Two-way beam-slab type; (b) Interior beam; (c) Edge beam

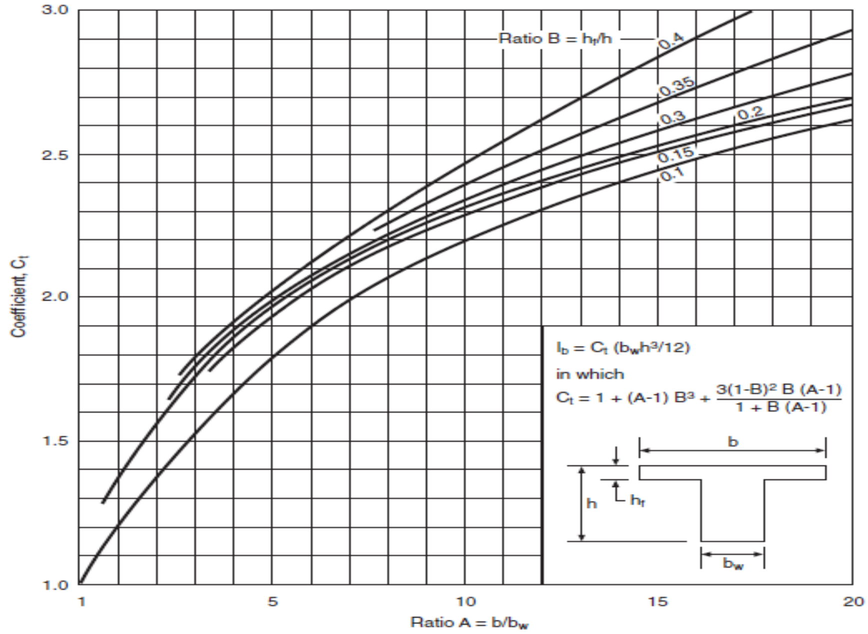


Figure 2.9: Figure 20-21 Coefficient Ct for Gross Moment of Inertia of Flanged Sections from (PCA Notes on ACI 318-11, 2013)

# CHAPTER THREE

## Parametric study

### 3.1 Introduction

This chapter includes the details of the parametric study performed in the current study. aiming to develop an understanding for the effects of the slab aspect ratio and the relative beam-slab stiffness on the deflection of flat plates, two-way beam-slabs, one-way slab, having the same number of spans and span lengths, designed according to ACI 318-19, the parametric study of this thesis is divided into five sections:

- The first section presents a comparison between SAFE, ANSYS and ACI crossing beam approaches for the deflection calculation results at the elastic uncracked stage.
- The second section evaluates the ACI 318-19 provisions for flat plate slabs with different aspect ratios.
- The third section evaluates the two-way slabs with different relative beam-slab stiffness.
- In the fourth section, the Bondy's approach for using the diagonal span instead of the long span in determining the flat plat slab thickness is evaluated.
- In the fifth section, the parametric study aims to determine the minimum relative stiffness beam-slab required to consider the slab as one-way slab supported on stiff beams.

In all parametric study parts, the following parameters were kept constant in all cases:

- Column dimension 400 x 400 mm ,3 m height, fixed at bottom

- 3 x 3 span building
- *fc'*=20 MPa
- The modulus of elasticity of concrete= 4700 $\sqrt{fc'}$ (ACI 318-19, section 19.2.2.1);
- Service load = DL (self-weight) +LL+SDL
- SDL=2.5 kN/m$^2$
- LL=1.92 kN/m$^2$
- Combined creep and shrinkage time-dependent factor = 2 (ACI 318-19, section 24.2.4.1.3)
- Element size: 0.25m
- Modulus of rupture is based on ACI-specified value of 0.62 $\sqrt{fc'}$ (ACI 318-19, section 19.2.3.1) (for nonlinear cracked analysis)
- Ratio of slab tension reinforcement for cracking analysis was 0.0018
- Yield strength of reinforcement was 420 MPa
- Beam width = 400 mm (for non-flat plate slab cases)

## 3.2 Parametric study for the comparison of deflection calculation approaches.

In the first section, the details of the case studies are presented aiming to compare the elastic deflections for interior, edge and corner panel flat plate slabs obtained using SAFE software with those obtained using the ACI crossing beam approach and ANSYS. The details of these case studies are shown in Table *3.1*, where the cases are grouped into six groups taking the following parameters as variables:

- Different Span length (10, 7.5, 5 m)
- Different Aspect ratio of slab (1, 2)

In each group, the slab thickness required for the corner panel according to ACI 318-19 requirements has been used for the 3x3 slab panels. For each case, three models have been created (ANSYS, SAFE, ACI Crossing Beam Approaches) making the total model studies equal to 18 models presenting data for 54 slab panels.

Table 3.1:Parametric study details for flat plat slabs under liner uncracked case for comparison of ACI Crossing Beam Approaches ANSYS and SAFE.

| Group | Cases, Slab Thickness, mm | | | Long span, L1, m | Short Span, L2, m | Aspect ratio, L1/L2 |
|---|---|---|---|---|---|---|
| | Interior | Edge | Corner | | | |
| A1-10* | 320 | 320 | 320 | 10 | 10 | 1 |
| A2-10 | 320 | 320 | 320 | 10 | 5 | 2 |
| A1-7.5 | 237 | 237 | 237 | 7.5 | 7.5 | 1 |
| A2-7.5 | 237 | 237 | 237 | 7.5 | 3.75 | 2 |
| A1-5 | 154 | 154 | 154 | 5 | 5 | 1 |
| A2-5 | 154 | 154 | 154 | 5 | 2.5 | 2 |
| *, A: "**A**spect ratio", **1**: Aspect ratio value, 10: long span length in meter. | | | | | | |

### 3.3 Parametric study for ACI 318-19 deflection control provisions for flat plate slabs with different aspect ratios

In the second parametric study part, the tested flat plate slab panels are divided into fifteen groups as detailed in Table 3.2 using the slab thicknesses based on the long span length and following Table 8.3.1.1 (ACI318-19) for two-way flat plate. Each group consists of 2 different cases (making the total number of case as 30): i) one case for using the thickness of the interior slab panel (ℓn/33) for the whole 3x3 slab panels; ii) another case for using the thickness of the exterior slab panel (ℓn/30) for the whole 3x3 slab panels. The aspect ratios have been obtained by keeping the long span length constant and varying the short span length aiming to evaluate the effect of the aspect ratio on the LTD of flat plate slabs along the long span. The resulted LTD was compared with the ACI deflection limits of ℓ /240 and ℓ/480.

The studied slab panels labeling has been done according to the location as interior, edge and corner as shown in Figure 3.1.

The parametric study including the following as variables:

- Different long Span length (10, 7.5, 5 m)
- Different Aspect ratio of slab (1, 2,3)

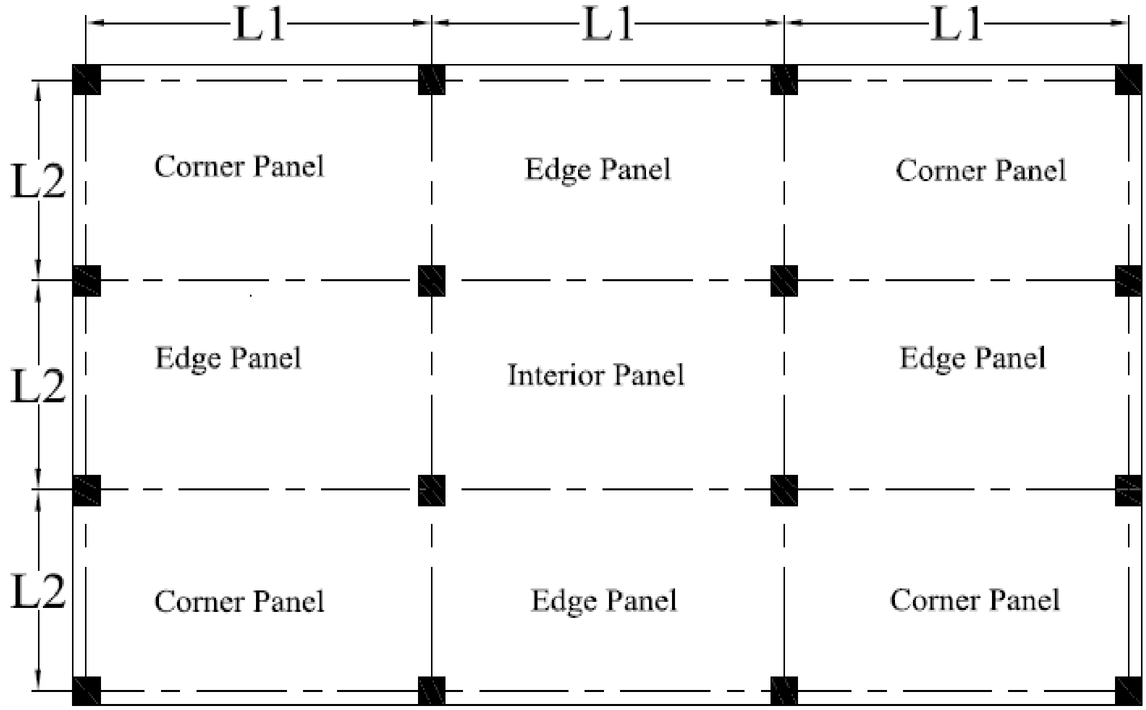


Figure 3.1: Two-way flat plate slab panel labelling according to the location

Table 3.2: Parametric Study details (flat plate slabs of aspect ratio of 1,2 and 3)

| Group | Slab Thickness, mm | | Long span, L1, m | Short Span, L2, m | Aspect ratio, L1/L2 |
|---|---|---|---|---|---|
| | Interior (ℓn/33) | Edge and corner (ℓn/30) | | | |
| TA1-10* | 291 | 320 | 10 | 10 | 1 |
| TA 1.5-10 | 291 | 320 | 10 | 6.66 | 1.5 |
| TA 2-10 | 291 | 320 | 10 | 5 | 2 |
| TA 2.5-10 | 291 | 320 | 10 | 4 | 2.5 |
| TA 3-10 | 291 | 320 | 10 | 3.33 | 3 |
| TA 1-7.5 | 215 | 237 | 7.5 | 7.5 | 1 |
| TA 1.5-7.5 | 215 | 237 | 7.5 | 5 | 1.5 |
| TA 2-7.5 | 215 | 237 | 7.5 | 3.75 | 2 |
| TA 2.5-7.5 | 215 | 237 | 7.5 | 3 | 2.5 |
| TA 3-7.5 | 215 | 237 | 7.5 | 2.5 | 3 |
| TA 1-5 | 140 | 154 | 5 | 5 | 1 |
| TA 1.5-5 | 140 | 154 | 5 | 3.33 | 1.5 |
| TA 2-5 | 140 | 154 | 5 | 2.5 | 2 |
| TA 2.5-5 | 140 | 154 | 5 | 2 | 2.5 |
| TA 3-5 | 140 | 154 | 5 | 1.66 | 3 |

*, TA: "**T**wo way", thickness as required by **A**CI318-19, **1**: Aspect ratio value, 10: long span length in meter.

## 3.4 Parametric study for two-way slabs with different relative beam-slab stiffness

This section presents the parametric study details for the evaluation of the long-term deflection (LTD) of flat plate slabs without edge beams and beam-slabs with different relative beam-slab stiffness using SAFE software. It aims at investigating the effects of the following variables on the long-term deflection

- Different long span length (10, 7.5, 5 m)
- Different aspect ratio of slab (1, 2, 3)
- Different relative beam-slab stiffness (0.2, 1, 3)

The studied cases are divided into six groups as detailed in Table 3.3; each group consists of 9 different (slab panel cases), totaling as 54 SAFE models, using the slab thickness specified by ACI 318-19.

In the current study section, in addition to the constant parameters listed in Section 3.1.

Table 3.3: Parametric study details (flat plate slabs and slabs with beam)

| Group | | Cases, Slab Thickness, mm | | | relative beam Stiffness | Beam width, mm | Long span, L1, m | Short Span, L2, m | Aspect ratio, L1/L2 |
|---|---|---|---|---|---|---|---|---|---|
| | Type of slab | Interior | Edge | Corner | | | | | |
| SA1-10[&] | Flat plate slab | 291 | 320 | 320 | no beam | no beam | 10 | 10 | 1 |
| | Beam-slab | 293 | 290 | 290 | 0.2* | 400 | | | |
| | | 235 | 235 | 235 | 2# | 400 | | | |
| SA2-10 | Flat plate slab | 291 | 320 | 320 | no beam | no beam | 10 | 5 | 2 |
| | Beam-slab | 293 | 286 | 286 | 0.2* | 400 | | | |
| | | 193 | 193 | 193 | 2# | 400 | | | |
| SA1-7.5 | Flat plate slab | 215 | 236.6 | 236.6 | no beam | no beam | 7.5 | 7.5 | 1 |
| | Beam-slab | 217 | 215 | 215 | 0.2* | 400 | | | |
| | | 174 | 174 | 174 | 2# | 400 | | | |
| SA2-7.5 | Flat plate slab | 215 | 236.6 | 236.6 | no beam | no beam | 7.5 | 3.75 | 2 |
| | Beam-slab | 217 | 212 | 211 | 0.2* | 400 | | | |
| | | 142 | 142 | 142 | 2# | 400 | | | |
| SA1-5 | Flat plate slab | 140 | 153.3 | 153.3 | no beam | no beam | 5 | 5 | 1 |
| | Beam-slab | 141 | 139 | 139 | 0.2* | 400 | | | |
| | | 112 | 112 | 112 | 2# | 400 | | | |
| SA2-5 | Flat plate slab | 140 | 153.3 | 153.3 | no beam | no beam | 5 | 2.5 | 2 |
| | Beam-slab | 141 | 135 | 137 | 0.2* | 400 | | | |
| | | 91 | 91 | 91 | 2# | 400 | | | |

[&], S: “Relative **S**tiffness”, A: **A**spect ratio , 1: Aspect ratio value, 10: long span length in meter.

* Beam hanged part depth (the part under the slab) ranged between 80 mm for the cases of L1 = 5 m to 120 mm for the cases of L1=10 m.

# Beam hanged part depth (the part under the slab) ranged between 540 mm for the cases of L1 = 5 m to 1100 mm for the cases of L1=10 m.

### 3.5 Parametric study for using Bondy's approach in determining flat plate thickness

This section demonstrates the parametric study details for the use of Bondy's approach in selecting the diagonal span as the one used with the ACI thickness provisions. In the study, the approach has been investigated taking the following as variables:

- Different long span length (10, 7.5, 5 m)
- Different aspect ratio of slab (1, 2)

The studied cases divided into six groups as detailed in Table 3.4; each group consist of 3 different slab panel cases, making the total cases of 18.

Table 3.4: Parametric study details for flat plate slab using Bondy's approach for thickness calculation

| Group | Slab Thickness, mm | | | Long span, L1, m | Short Span, L2, m | Diagonal length, LD, m | Aspect ratio, L1/L2 |
|---|---|---|---|---|---|---|---|
| | Interior | Edge | Corner | | | | |
| B1-10* | 411.4 | 452.5 | 452.5 | 10 | 10 | 14.14 | 1 |
| B2-10 | 321.7 | 353.8 | 353.8 | 10 | 5 | 11.18 | 2 |
| B1-7.5 | 304.3 | 334.7 | 334.7 | 7.5 | 7.5 | 10.61 | 1 |
| B2-7.5 | 237 | 260.7 | 260.7 | 7.5 | 3.75 | 8.39 | 2 |
| B1-5 | 197.1 | 216.8 | 216.8 | 5 | 5 | 7.07 | 1 |
| B2-5 | 152.3 | 167.5 | 167.5 | 5 | 2.5 | 5.59 | 2 |

*, B: "Bondy's approach", thickness as suggested by Bondy, 1: Aspect ratio value, 10: long span length in meter.

## 3.6 Parametric study for One-way slabs

The parametric study for the one-way slabs has been performed to evaluate the effects of the relative beam-slab stiffness on the LTD of the supporting beam and suggesting a minimum relative beam slab stiffness. In addition, the parametric study aims to suggest minimum one-way slab thicknesses for case of low relative beam-slab thickness that verify ACI limitation (Case A: ℓ/240, Case B: ℓ/480).

### 3.6.1 Parametric study for determining the minimum relative beam-slab stiffness of one-way slabs

In the fifth parametric study part, three different span panel configurations of L1xL2 as 10x4.9m, 7.5x3.6 m and 6x3.1 m (aspect ratio just above 2) with beams provided at the two long spans of the slab panel were analyzed to obtain the LTD, as detailed in Table 3.5 and Figure 3.2. The investigation was conducted by taking the relative beam-slab stiffness as variable aiming to determine the relative stiffness that would ensure that the LDT deflection under the supporting beams will be within the ACI limitation (Case A: ℓ/240, Case B: ℓ/480). The studied slab panels labelling has been done according to the location as interior, exterior, interior edge, exterior edge as shown in Figure 3.2.

Each group in Table 3.5 consists of 2 different slab configuration cases (where the same thickness for the whole 3x3 panel): 1) using the slab thickness required for the internal panel L2/28; 2) using the slab thickness required for the external panel L2/24

The slabs thickness was calculated as one-way according to ACI318-19 provisions (L2/24 for exterior spans, L2/28 for interior spans, where L2 is the short span). For the calculation of the relative beam-slab stiffness, refers to section 2.3

For each beam-slab configuration case, the SAFE long-term deflection analysis has been made, many iterations (14 – 17 iterations) have been used to find out the relative beam-slab stiffness (by increasing the beam depth while the slab thickness unchanged) that would restrict the deflection in the long span (under the supporting beams) to satisfy the deflection limit (Case A: ℓ/240, Case B: ℓ/480). This means that up to 100 SAFE analysis models have been created to obtain the data of the one-way beam-slab cases of Table 3.5.

Table 3.5: Parametric study details on one-way slabs supported on beams with different relative beam-slab stiffness.

| Group | Slab Thickness, mm as per ACI 318-19[&] | | | | Range of the tested relative beam-slab stiffness | | | | Long span, L1, m | Short Span, L2, m | Aspect ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Interior edge ℓ/28 | Exterior edge ℓ/24 | Interior ℓ/28 | Exterior ℓ/24 | Interior edge | Exterior edge | Interior | Exterior | | | |
| O4.9[#] | 161 | 188 | 161 | 188 | 1 -20 | 1[*] – 17[@] | 1 -10 | 1 - 8 | 10 | 4.9 | 2.04 |
| O3.6 | 114 | 134 | 114 | 134 | 1 -13 | 1 - 11 | 1-10 | 1 -8 | 7.5 | 3.6 | 2.08 |
| O3 | 93 | 109 | 93 | 109 | 1 -9 | 1 - 7 | 1 -9 | 1 - 4 | 6.1 | 3 | 2.03 |

[#]: O: Indicates "**O**ne-way slab", the number indicates the short span length

[&]: The thickness is taken as ratio of the short span (one-way action in the short span), Table 7.3.1.1 in ACI318-19

*: As an illustration, for this case, the relative stiffness of 1 occurred with beam dimension of 188x360 mm (width x depth)

[@]: The relative stiffness of 17 occurred with beam dimension of 188x844 mm with the moment inertia for interior beam= 0.036102 m^4, the moment inertia for interior span= 0.002692m^4, the moment inertia for edge beam = 0.03012m^4 and the moment inertia for end span= 0.001456m^4. The relative stiffness= $\left(\frac{0.036102}{0.002692}+\frac{0.03012}{0.001456}\right)/2=17$

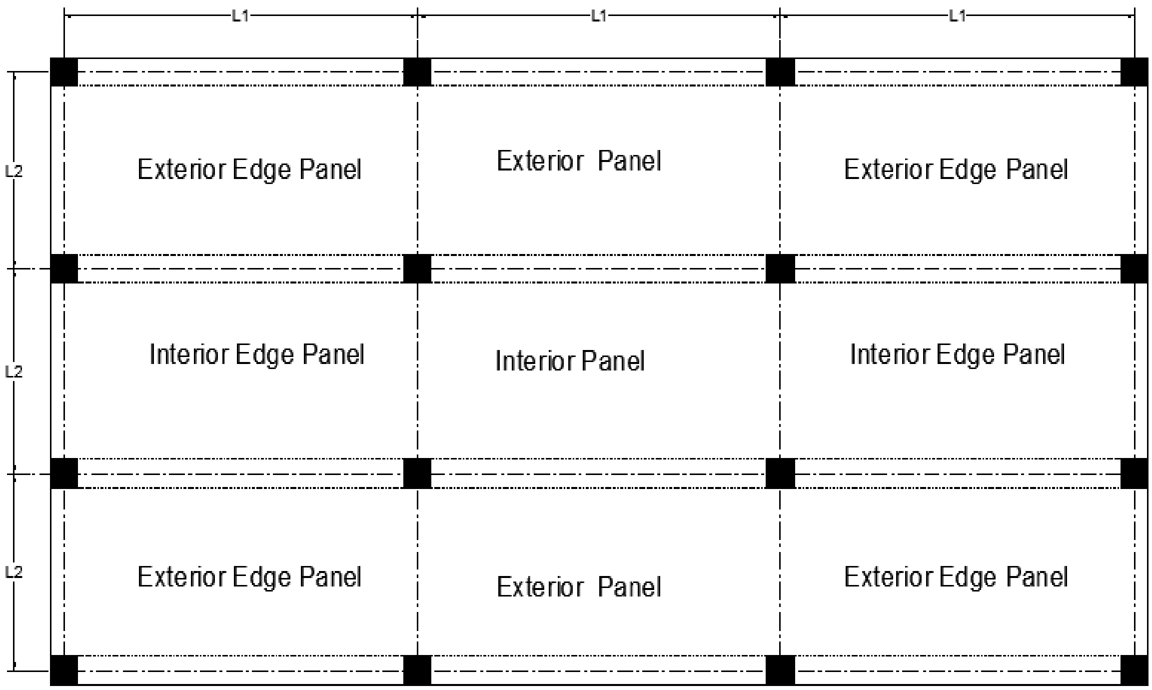


Figure 3.2: One-way slab panel labelling according to the location

### 3.6.2 Parametric study for the minimum thickness for case of low relative beam-slab stiffness

This section aims to propose minimum slab thickness for one-way supported on beams with low relative beam slab thickness. The study includes all the panel locations shown in Figure 3.2 and for three spans configuration of 10x4.9m, 7.5x3.6m and 6.1x3m as illustrated in Table 3.6 and Table 3.7, where for each relative beam-slab stiffness, a slab thickness has been found (by trial and error) that would ensure that the LTD under the supporting beams are lower the ACI 318-19 permissible deflection of ℓ/240 and ℓ/480.

The final reported cases are 160, which have been obtained through many trailed models which reached 756 SAFE models.

Table 3.6:Parametric study details of one-way slabs with low relative beam-slab stiffness (ℓ/240 deflection limit)

| Panel location | Interior | | | Interior edge | | | Exterior | | | Exterior edge | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slab type | Beam depth, mm | Slab thickness, mm | Relative stiffness | Beam depth, mm | Slab type | Beam depth, mm | Slab thickness, mm | Relative stiffness | Beam depth, mm | Slab type | Beam depth, mm | Slab thickness, mm |
| 10 x 4.9 m | 405 | 225 | 0.64 | 430 | 10 | 405 | 225 | 0.64 | 430 | 10 | 405 | 225 |
| | 428 | 218 | 0.98 | 480 | 260 | 428 | 218 | 0.98 | 480 | 0.94 | 428 | 218 |
| | 445 | 192 | 1.46 | 505 | 224 | 445 | 192 | 1.46 | 505 | 1.8 | 445 | 192 |
| | 460 | 175 | 2.2 | 535 | 200 | 460 | 175 | 2.2 | 535 | 3.11 | 460 | 175 |
| | 470 | 161 | 3 | 537 | 164 | 470 | 161 | 3 | 537 | 4 | 470 | 161 |
| | | | | 545 | 161 | | | | 545 | | | |
| | | | | | | | | | | | | |
| 7.5 x 3.6 m | 270 | 161 | 0.64 | 265 | 7.5 | 270 | 161 | 0.64 | 265 | 7.5 | 270 | 161 |
| | 302 | 136 | 1.6 | 285 | 165 | 302 | 136 | 1.6 | 285 | 0.94 | 302 | 136 |
| | 310 | 125 | 2.29 | 311 | 155 | 310 | 125 | 2.29 | 311 | 1.49 | 310 | 125 |
| | 318 | 119 | 3.06 | 321 | 140 | 318 | 119 | 3.06 | 321 | 2.34 | 318 | 119 |
| | 338 | 114 | 4 | 328 | 118 | 338 | 114 | 4 | 328 | 3 | 338 | 114 |
| | | | | 338 | 114 | | | | 338 | | | |
| | | | | | | | | | | | | |
| 6.1 x 3 m | 222 | 146 | 0.55 | 200 | 6.1 | 222 | 146 | 0.55 | 200 | 6.1 | 222 | 146 |
| | 230 | 110 | 1.52 | 227 | 118 | 230 | 110 | 1.52 | 227 | 1.52 | 230 | 110 |
| | 250 | 102 | 2.54 | 237 | 111 | 250 | 102 | 2.54 | 237 | 2.12 | 250 | 102 |
| | 257 | 93 | 3.73 | 256 | 96 | 257 | 93 | 3.73 | 256 | 2.5 | 257 | 93 |
| | | | | 222 | 93 | | | | 222 | | | |

Table 3.7: Parametric study details of one-way slabs with low relative beam-slab stiffness (ℓ/480 deflection limit)

| Panel location | Interior | | | Interior edge | | | Exterior | | | Exterior edge | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slab type | Slab thickness, mm | Beam depth, mm | Relative stiffness | Slab thickness, mm | Beam depth, mm | Relative stiffness | Slab thickness, mm | Beam depth, mm | Relative stiffness | Slab thickness, mm | Beam depth, mm | Relative stiffness |
| 10 x 4.9 m | 277 | 470 | 0.55 | 337 | 640 | 0.84 | 255 | 525 | 1.36 | 337 | 640 | 1.1 |
| | 245 | 545 | 1.35 | 320 | 700 | 1.36 | 235 | 560 | 2.18 | 320 | 700 | 1.75 |
| | 225 | 590 | 2.31 | 280 | 785 | 3.06 | 220 | 600 | 3.4 | 280 | 785 | 3.93 |
| | 212 | 605 | 3.03 | 266 | 797 | 3.78 | 205 | 605 | 4.46 | 266 | 797 | 4.13 |
| | 180 | 640 | 6.1 | 230 | 806 | 6.17 | 195 | 630 | 5.8 | 261 | 806 | 5.38 |
| | 175 | 650 | 7 | 210 | 812 | 8.37 | 188 | 645 | 7 | 258 | 812 | 5.67 |
| | 165 | 660 | 8.79 | 202 | 818 | 10.26 | | | | 245 | 817 | 6.8 |
| | 161 | 670 | 10 | 184 | 820 | 12.91 | | | | 240 | 820 | 7.33 |
| | | | | 177 | 823 | 14.68 | | | | 235 | 825 | 7.98 |
| | | | | 172 | 825 | 16.13 | | | | 218 | 828 | 10.16 |
| | | | | 170 | 826 | 16.77 | | | | 198 | 830 | 13.7 |
| | | | | 167 | 827 | 17.75 | | | | 192 | 832 | 15.15 |
| | | | | 164 | 828 | 18.75 | | | | 188 | 844 | 17 |
| | | | | 161 | 832 | 20 | | | | | | |
| | | | | | | | | | | | | |
| 7.5 x 3.6 m | 187 | 350 | 0.96 | 215 | 355 | 0.64 | 190 | 340 | 0.82 | 215 | 355 | 0.84 |
| | 166 | 374 | 1.75 | 205 | 375 | 0.9 | 181 | 354 | 1.44 | 205 | 375 | 1.17 |
| | 155 | 405 | 3.16 | 185 | 410 | 1.7 | 167 | 372 | 2.19 | 185 | 410 | 2.35 |
| | 142 | 425 | 4.4 | 170 | 440 | 2.82 | 148 | 394 | 3.86 | 170 | 440 | 3.61 |
| | 125 | 438 | 7.21 | 160 | 455 | 3.81 | 142 | 425 | 4.4 | 160 | 455 | 4.88 |
| | 121 | 440 | 8 | 146 | 470 | 5.65 | 138 | 430 | 6.15 | 146 | 470 | 7.2 |
| | 114 | 445 | 10 | 142 | 480 | 6.6 | 134 | 446 | 8 | 142 | 480 | 8.4 |

| Panel location | Interior | | | Interior edge | | | Exterior | | | Exterior edge | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slab type | Slab thickness, mm | Beam depth, mm | Relative stiffness | Slab thickness, mm | Beam depth, mm | Relative stiffness | Slab thickness, mm | Beam depth, mm | Relative stiffness | Slab thickness, mm | Beam depth, mm | Relative stiffness |
| | | | | 138 | 485 | 7.46 | | | | 138 | 485 | 9.48 |
| | | | | 124 | 489 | 10.62 | | | | 134 | 492 | 11 |
| | | | | 118 | 492 | 12.58 | | | | | | |
| | | | | 114 | 494 | 14 | | | | | | |
| | | | | | | | | | | | | |
| 6.1 x 3 m | 150 | 231 | 0.57 | 160 | 245 | 0.57 | 152 | 232 | 0.74 | 160 | 245 | 0.75 |
| | 137 | 270 | 1.29 | 150 | 280 | 1.1 | 144 | 260 | 1.27 | 150 | 280 | 1.42 |
| | 125 | 395 | 2.32 | 140 | 300 | 1.72 | 130 | 280 | 2.23 | 140 | 300 | 2.47 |
| | 110 | 300 | 3.67 | 130 | 310 | 2.42 | 120 | 290 | 3.21 | 130 | 310 | 3.11 |
| | 95 | 308 | 6.29 | 117 | 318 | 3.67 | 114 | 295 | 3.98 | 117 | 318 | 4.7 |
| | 93 | 312 | 7 | 111 | 329 | 4.84 | 109 | 302 | 5 | 111 | 329 | 6.17 |
| | | | | 103 | 333 | 6.35 | | | | 109 | 335 | 7 |
| | | | | 101 | 335 | 6.87 | | | | | | |
| | | | | 93 | 337 | 9 | | | | | | |

# CHAPTER FOUR

## Results and discussion

The results of the parametric studies detailed in chapter 3 are presented and discussed in this chapter. The presented results in section 4.1 are the short term elastic uncracked deflection using three approaches (ACI crossing beam method, SAFE and ANSYS) while the deflection presented in the other sections are the long term deflection (LTD).

### 4.1 Comparison of SAFE with ACI crossing beam approach and ANSYS

In this section, the short-term uncracked elastic deflection obtained using the ACI crossing beam method is compared with those obtained using SAFE and ANSYS software. This deflection has been used for the evaluation of the ACI crossing beam method principals isolating the effect of the approximate method in determining the cracked moment of inertia required in the long-term deflection calculation procedure.

For the mid panel deflection, as per Figure 4.1 to 4.3, it is clear that the ANSYS and SAFE results are close to each other, while the ACI crossing beam approach is producing close results (with respect to ANSYS and SAFE) at aspect ratio 2, though it produces a higher deflection in interior panels of large span with aspect ratio 1.

For the long span deflections as per Figure 4.4 to 4.6, it is illustrated that the deflections obtained using SAFE and ANSYS are close to each other; however, the ACI crossing beam approach is producing close result (with respect to SAFE and ANSYS) at aspect ratio 1, even though it produces a significant difference in results at aspect ratio of 2.

The above observations show that:

1. SAFE model using shell slab element are adequate to be used in the deflection calculation as alternative for the ANSYS model using tetrahedra elements.
2. ACI crossing beam approach as an approximate method is giving non-conservative results at certain aspect ratios of certain panel location.

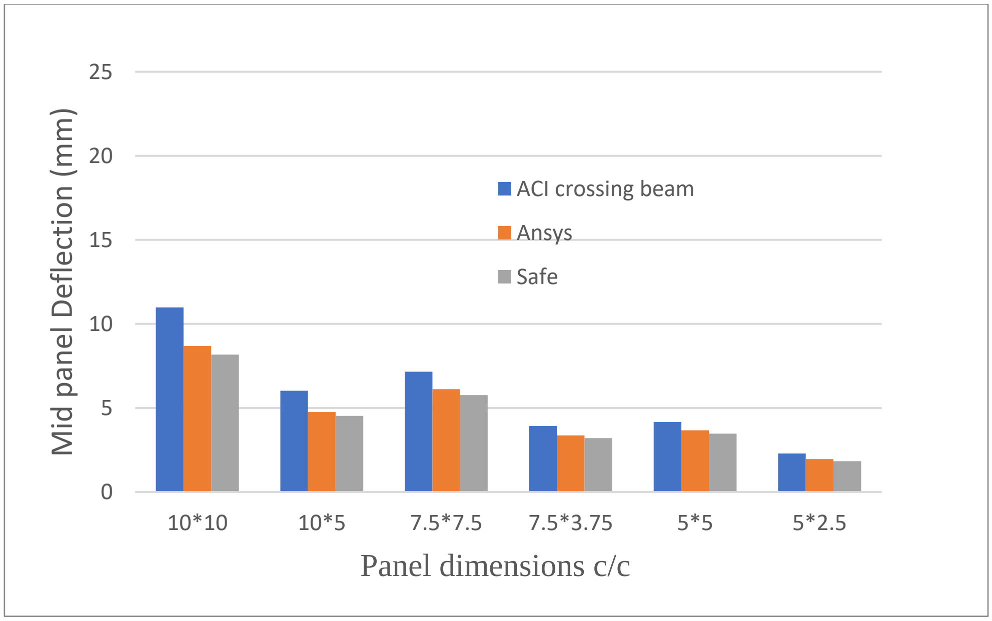


Figure 4.1: Mid panel deflection for interior panel flat plate slabs, refer to Table B.1

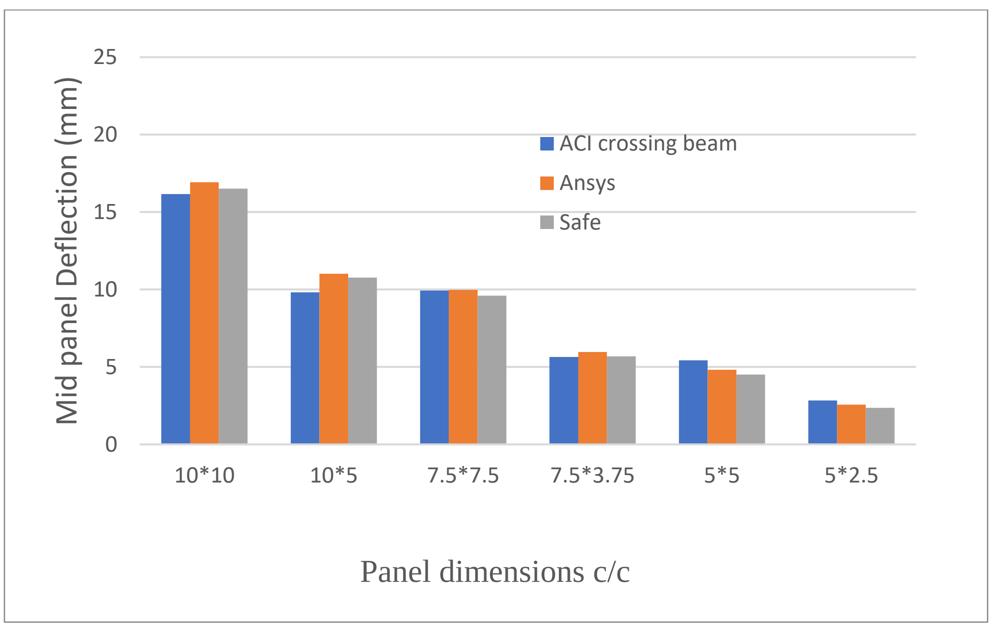


Figure 4.2: Mid panel deflection for edge panel flat plate slabs, refer to Table B.2

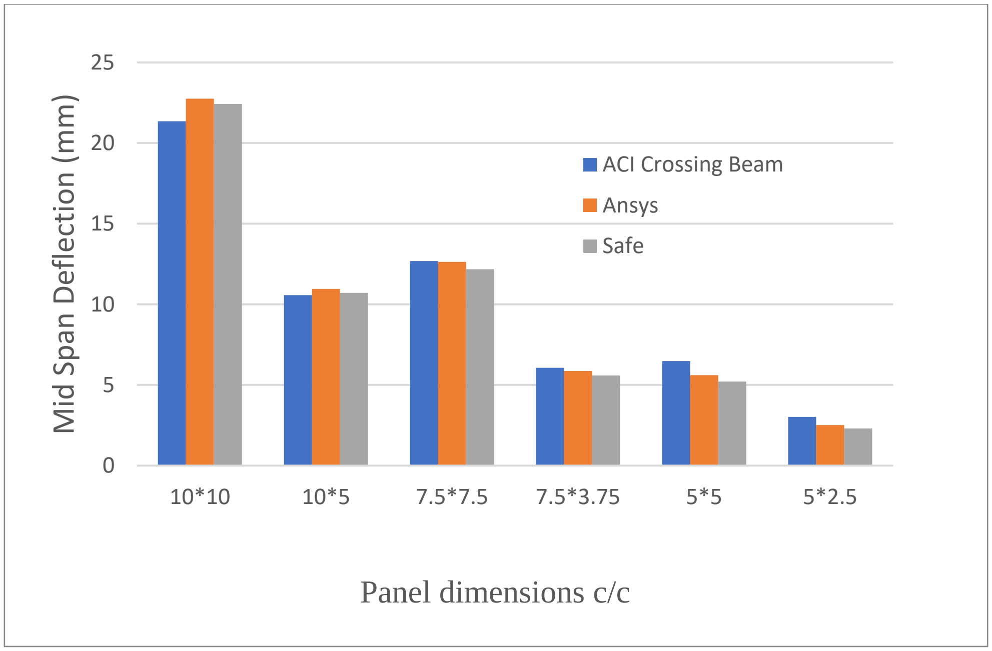


Figure 4.3: Mid panel deflection for corner panel flat plate slabs, refer to Table B.3

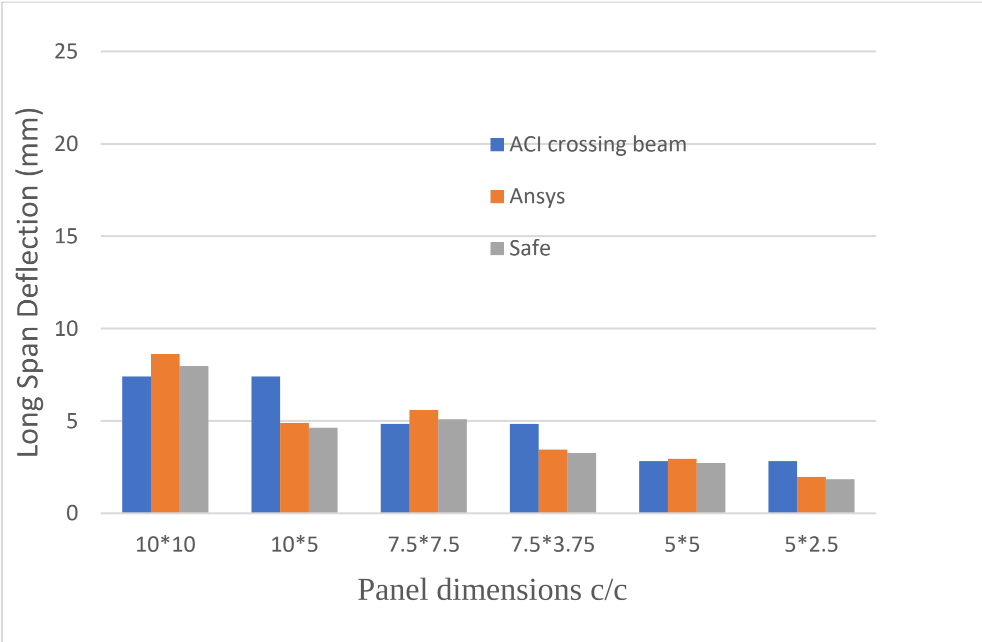


Figure 4.4: Long span deflection for interior panel flat plate slabs, refer to Table B.1

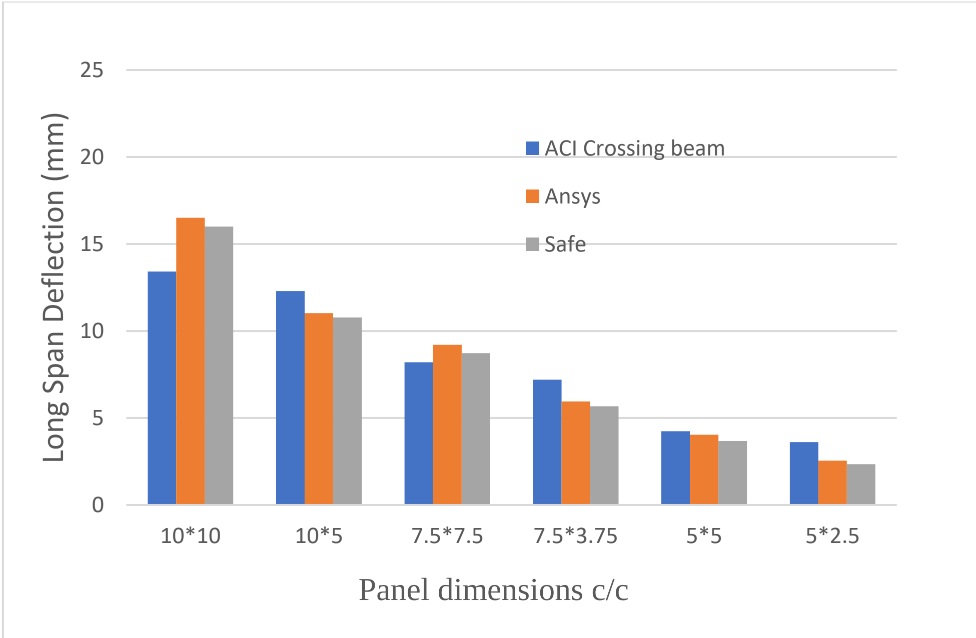


Figure 4.5: Long span deflection for edge panel flat plate slabs, refer to Table B.2

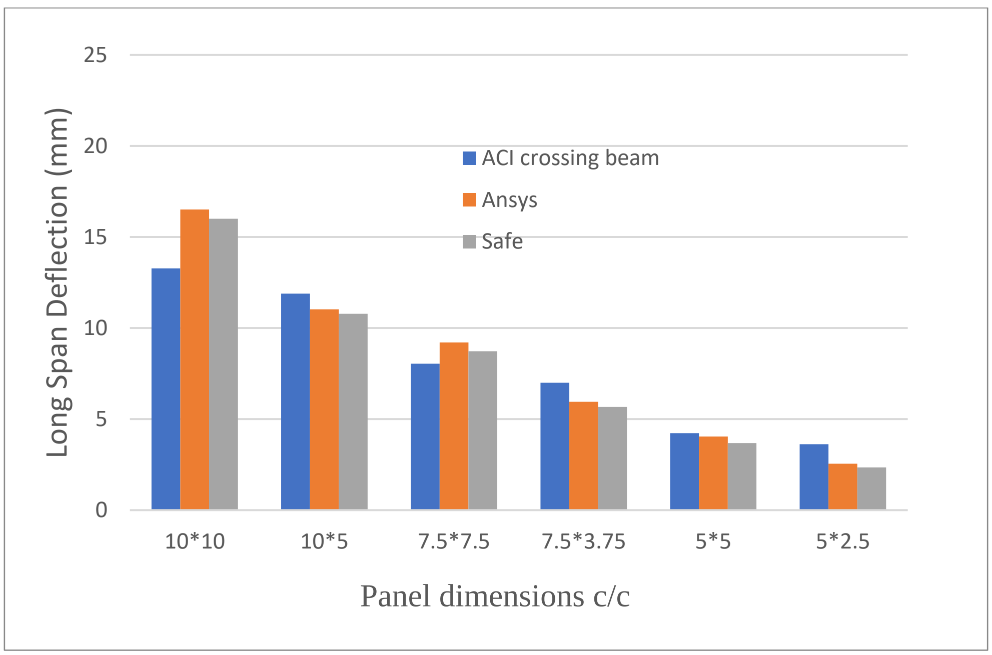


Figure 4.6: Long span deflection for corner panel flat plate slabs, refer to Table B.3

## 4.2 Flat plate slabs with aspect ratio 1 to 3

The aspect ratio of the flat plate slab has not considered a parameter in the ACI 318-19 provisions for the determination of the slab thickness. In the current study, the effect of the aspect ratio (ranging from 1 to 3) on the long-term deflection is studied to indicate the cases that satisfy the ACI maximum allowable deflection limit provisions, and proposing a minimum thickness for the cases of not satisfying the allowable permissible deflection.

### 4.2.1 Evaluation of ACI 318-19 provisions for flat plate thickness

This section presents the results of the LTD of three panel location interior edge and corner panel of flat plates with aspect ratio ranging from 1 to 3

#### 4.2.1.1 Flat plate slab panels with aspect ratio range between 1 and 2

This section presents the LTD (both mid-panel and long span) of the flat plate cases of the range of aspect ratio 1 to 2. As could be seen in Table 4.1 and Figure 4.7 to 4.9, for the ℓ/240 deflection limit, apart from the case of large slab panels (aspect ratio of 1 and 1.5 with large span of 10 m), all the cases satisfy this limit. On the other hand, for the ℓ/480 deflection limit, apart from the case of small slab panels (aspect ratio of 2 at the large span of 5 m), all the cases did not satisfy this limit. These results are in agreement with the results obtained by (Hasan S. and Taha B, 2020).

In both observations, it could be noted that as the aspect ratio is getting smaller (square slab), the deflection is getting larger, indicating a noticeable effect of aspect ratio on the flat plate LTD

#### 4.2.1.2 Flat plate slab panels with aspect ratio of 2 to 3

This section presents the LTD of the flat plate cases with the range of aspect ratio 2 to 3. For the cases of aspect ratio larger than 2, the used thickness was as same that used for two-way flat plate slabs. Figure 4.7, to 4.9 show that the use of ACI 318-19 thickness satisfies the normal ℓ /240 deflection for all the three slab panel locations (interior, edge and corner panel). For the other deflection limit of ℓ/480, apart from the case of large slab panel (long span of 10 m), all the other cases satisfy this limit. Based on that, as the Table 8.3.1.1 of ACI318-19 is providing the minimum thickness for flat plates to satisfy ordinary deflection limit of ℓ /240, the current study considers that this table could be recommended to apply to all flat plate slabs regardless of the aspect ratios; therefore, the current study suggest to revise the restriction put by ACI318-19 on the aspect ratio for flat plate thickness provisions.

Table 4.1: Results of the Parametric Study for flat plate slabs.

| Long span | Short span | Aspect ratio | Case Number* | Slab thickness (ℓn /33) (mm) | Interior Panel | | Case Number* | Slab thickness (ℓn /30) (mm) | Edge panel | | Corner Panel | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Mid# Panel LTD (mm) | Long Span LTD (mm) | | | Mid# Panel LTD (mm | Long Span LTD (mm) | Mid# Panel LTD (mm) | Long Span LTD (mm) |
| 10 | 10 | 1 | 1 | 291 | 35.07 | 31.34 | 2 | 320 | 56.04 | 53.33 | 81.3 | 53.33 |
| 10 | 6.66 | 1.5 | 3 | 291 | 26.88 | 27.18 | 4 | 320 | 42.04 | 41.62 | 42.14 | 41.62 |
| 10 | 5 | 2 | 5 | 291 | 26.23 | 26.51 | 6 | 320 | 35.67 | 35.43 | 34.92 | 35.43 |
| 10 | 4 | 2.5 | 7 | 291 | 26.25 | 26.36 | 8 | 320 | 30.29 | 30.29 | 30.24 | 30.29 |
| 10 | 3.33 | 3 | 6 | 291 | 26.82 | 26.67 | 10 | 320 | 27.51 | 27.49 | 27.68 | 27.49 |
| 7.5 | 7.5 | 1 | 11 | 215 | 27.7 | 22.35 | 12 | 237 | 30.4 | 27.13 | 38.83 | 27.13 |
| 7.5 | 5 | 1.5 | 13 | 215 | 17.17 | 16.84 | 14 | 237 | 18.73 | 18.43 | 18.8 | 18.43 |
| 7.5 | 3.75 | 2 | 15 | 215 | 15.61 | 15.57 | 16 | 237 | 16.15 | 16 | 16.01 | 16 |
| 7.5 | 3 | 2.5 | 17 | 215 | 14.54 | 14.65 | 18 | 237 | 14.23 | 14.24 | 14.29 | 14.24 |
| 7.5 | 2.5 | 3 | 19 | 215 | 14.2 | 14.22 | 20 | 237 | 13.14 | 13.12 | 13.11 | 13.12 |
| 5 | 5 | 1 | 21 | 140 | 16.28 | 12.55 | 22 | 154 | 14.08 | 11.21 | 15.8 | 11.21 |
| 5 | 3.33 | 1.5 | 23 | 140 | 8.77 | 8.5 | 24 | 154 | 8.13 | 7.87 | 8.09 | 7.87 |
| 5 | 2.5 | 2 | 25 | 140 | 7.55 | 7.6 | 26 | 154 | 6.52 | 6.46 | 6.42 | 6.46 |
| 5 | 2 | 2.5 | 27 | 140 | 6.89 | 6.89 | 28 | 154 | 5.89 | 5.87 | 5.82 | 5.87 |
| 5 | 1.66 | 3 | 29 | 140 | 6.53 | 6.55 | 30 | 154 | 5.62 | 5.61 | 5.6 | 5.61 |

*: Each case represents a 3x3 panels slab using the slab thickness given for the case used for all the 9 slab panels.
#: The deflections are used in section 4.3.3.

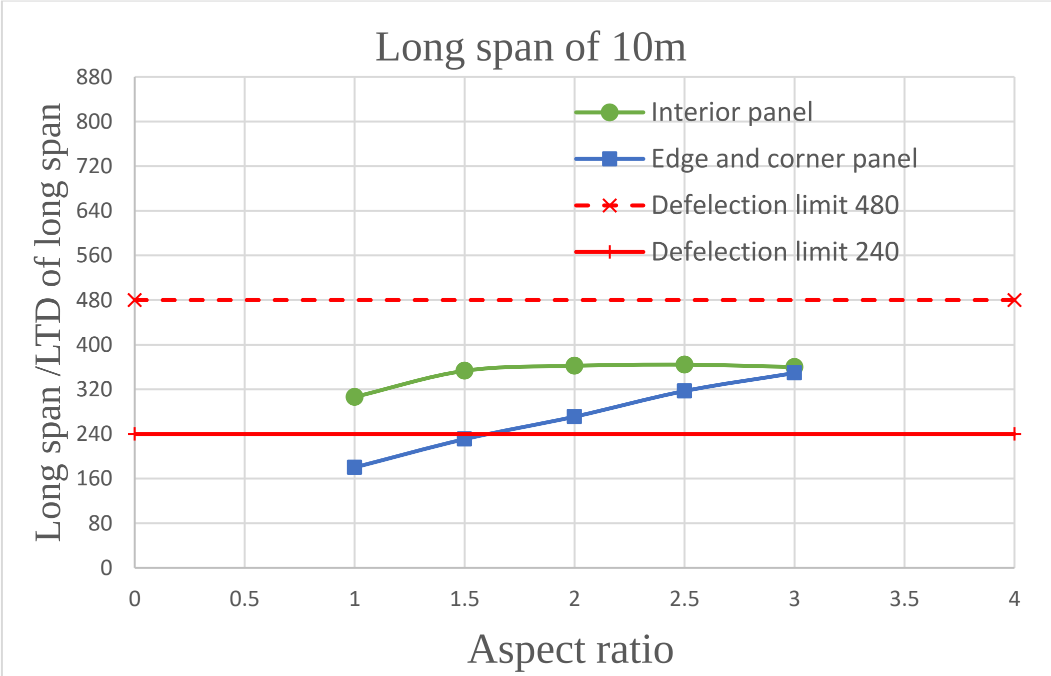


Figure 4.7: Flat plate slab floor panel aspect ratio versus long span /LTD for long span of 10 m

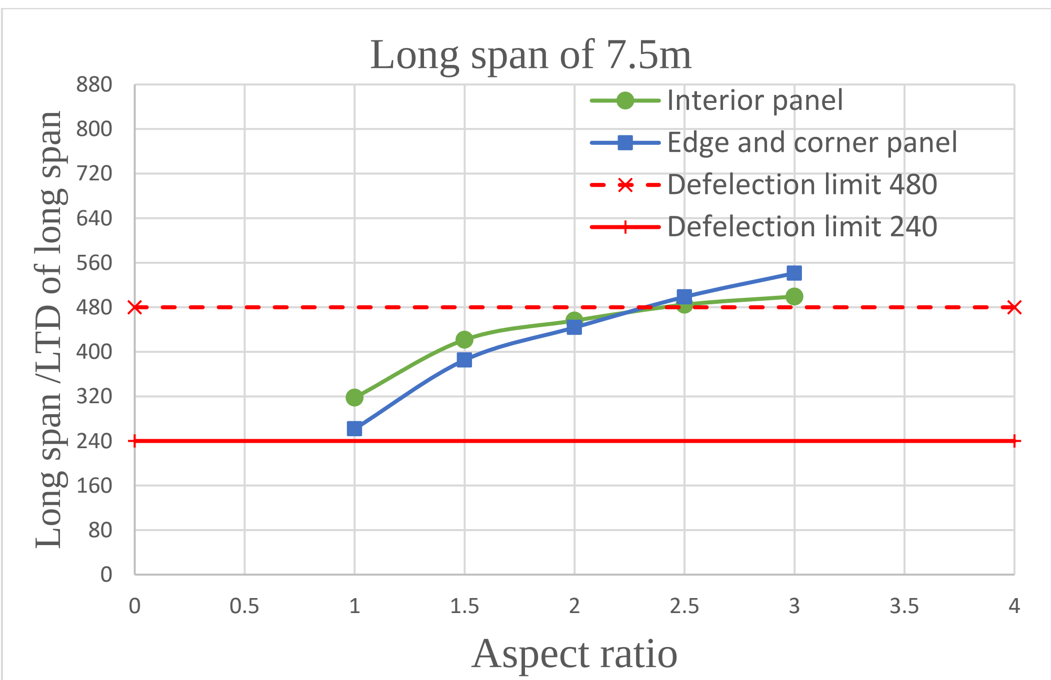


Figure 4.8 Flat plate slab floor panel aspect ratio versus long span /LTD for long span of 7.5 m

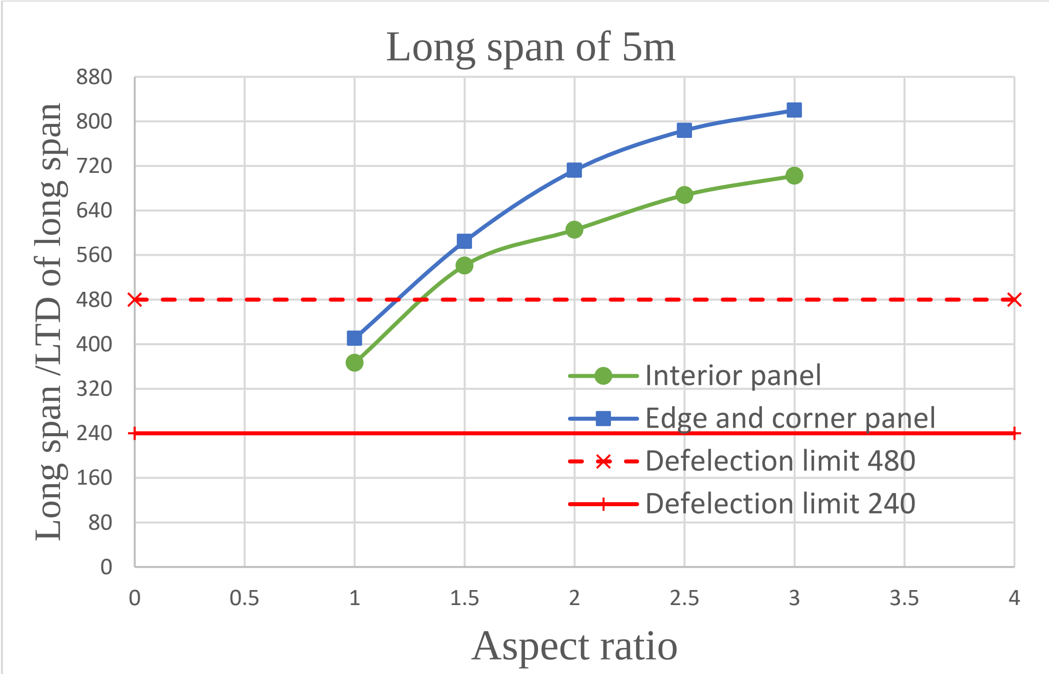


Figure 4.9: Flat plate slab floor panel aspect ratio versus long span /LTD for long span of 5 m

### 4.2.2 Proposed minimum thickness for flat plates

Based on the results and discussion of the pervious section, it can be observed that for the control of deflection of flat plate slabs, ACI 318-19 uses a formula for thickness of (ℓn /30) for the exterior panel and (ℓn /33) for the interior panels, but with ignoring the effect of aspect ratio on the deflection calculation.

Reanalyzing those cases that were not satisfying the permissible deflection of ℓ/240 and ℓ/480, the SAFE Finite Element analyses were used in order to ensure that the LTD of the long span is within the allowable deflection of ℓ /240 and ℓ/480 as illustrated in Table 4.2 to 4.4. The re-analysis was carried out many times with a gradual increase in the thickness of the slab of until the LTD were less than the permissible deflection of ℓ/240 and ℓ/480.

The value of thickness (ℓn /30) for exterior panels, and (ℓn /33) for interior panel was considered as the first values at the beginning the analysis for the determination of the flat plate slab thickness. Table 4.2 ,Table 4.3, Figure 4.10 and Figure 4.11 present the proposed slab thickness $\frac{\ell n}{A}$ and the correction factor with new proposed equation for each panel location for the failed cases to satisfy the ℓ/480, as could be seen, the largest change required is for the large span of 10m with aspect ratio of 1, corner and edge panel where ℓn /19.09 is required instead of the recommended ℓn /30 by ACI 318-19.

On the other hand, the ACI 318-19 are adequate for the case of

- Large span of 5m with aspect ratio equal or greater than 1.5
- Large span of 7.5m with aspect ratio equal or greater than 2.5

For the (ℓ/240) deflection limit, a change in minimum thickness of the flat plate slabs is only required in the case of large span 10m with aspect ratio 1 and 1.5 in the exterior panel to satisfy the allowable permissible deflection, as illustrated in Table 4.4.

Table 4.2: Proposed thickness for interior panel flat plate slabs for satisfying ℓ/480 limit by using SAFE software.

| L1 | L2 | Aspect ratio | proposed $\frac{\ell n}{A}$ | Proposed thickness of flat plate slab | Revised long span LTD, mm | $\frac{\ell}{480}$ limit, mm | Correction factor |
|---|---|---|---|---|---|---|---|
| 10 | 10 | 1 | $\frac{\ell n}{27.27}$ | 352 | 19.94 | 20 | 1.21 |
| 10 | 6.66 | 1.5 | $\frac{\ell n}{30.28}$ | 317 | 19.5 | 20 | 1.09 |
| 10 | 5 | 2 | $\frac{\ell n}{30.67}$ | 313 | 19.5 | 20 | 1.08 |
| 10 | 4 | 2.5 | $\frac{\ell n}{30.87}$ | 311 | 19.85 | 20 | 1.07 |
| 10 | 3.33 | 3 | $\frac{\ell n}{30.97}$ | 310 | 19.87 | 20 | 1.07 |
| 7.5 | 7.5 | 1 | $\frac{\ell n}{27.63}$ | 257 | 14.6 | 14.79 | 1.19 |
| 7.5 | 5 | 1.5 | $\frac{\ell n}{31.56}$ | 225 | 14.6 | 14.79 | 1.05 |
| 7.5 | 3.75 | 2 | $\frac{\ell n}{32.42}$ | 219 | 14.55 | 14.79 | 1.02 |
| 7.5 | 3 | 2.5 | $\frac{\ell n}{33}$ | 215 | 14.65 | 14.79 | 1 |
| 7.5 | 2.5 | 3 | $\frac{\ell n}{33}$ | 215 | 12.55 | 14.79 | 1 |
| 5 | 5 | 1 | $\frac{\ell n}{30.07}$ | 153 | 9.49 | 9.58 | 1.1 |
| 5 | 3.33 | 1.5 | $\frac{\ell n}{33}$ | 140 | 8.5 | 9.58 | 1 |
| 5 | 2.5 | 2 | $\frac{\ell n}{33}$ | 140 | 7.6 | 9.58 | 1 |
| 5 | 2 | 2.5 | $\frac{\ell n}{33}$ | 140 | 6.89 | 9.58 | 1 |
| 5 | 1.66 | 3 | $\frac{\ell n}{33}$ | 140 | 6.55 | 9.58 | 1 |

Table 4.3: Proposed thickness for edge and corner flat plate slabs satisfying ℓ/480 limit by using SAFE.

| L1 | L2 | Aspect ratio | proposed $\frac{\ell n}{A}$ | Proposed thickness of flat plate slab | Revised long span LTD, mm | $\frac{\ell}{480}$ limit, mm | Correction factor |
|---|---|---|---|---|---|---|---|
| 10 | 10 | 1 | $\frac{\ell n}{19.09}$ | 503 | 19.99 | 20 | 1.57 |
| 10 | 6.66 | 1.5 | $\frac{\ell n}{22.43}$ | 428 | 19.84 | 20 | 1.34 |
| 10 | 5 | 2 | $\frac{\ell n}{24.24}$ | 396 | 19.75 | 20 | 1.24 |
| 10 | 4 | 2.5 | $\frac{\ell n}{25.33}$ | 379 | 19.51 | 20 | 1.18 |
| 10 | 3.33 | 3 | $\frac{\ell n}{26.09}$ | 368 | 19.86 | 20 | 1.15 |
| 7.5 | 7.5 | 1 | $\frac{\ell n}{22.9}$ | 310 | 14.49 | 14.79 | 1.31 |
| 7.5 | 5 | 1.5 | $\frac{\ell n}{26.69}$ | 266 | 14.73 | 14.79 | 1.12 |
| 7.5 | 3.75 | 2 | $\frac{\ell n}{28.98}$ | 245 | 14.72 | 14.79 | 1.04 |
| 7.5 | 3 | 2.5 | $\frac{\ell n}{30}$ | 237 | 14.24 | 14.79 | 1 |
| 7.5 | 2.5 | 3 | $\frac{\ell n}{30}$ | 237 | 13.12 | 14.79 | 1 |
| 5 | 5 | 1 | $\frac{\ell n}{28.22}$ | 163 | 9.51 | 9.58 | 1.06 |
| 5 | 3.33 | 1.5 | $\frac{\ell n}{30}$ | 154 | 7.87 | 9.58 | 1 |
| 5 | 2.5 | 2 | $\frac{\ell n}{30}$ | 154 | 6.46 | 9.58 | 1 |
| 5 | 2 | 2.5 | $\frac{\ell n}{30}$ | 154 | 5.87 | 9.58 | 1 |
| 5 | 1.66 | 3 | $\frac{\ell n}{30}$ | 154 | 5.6 | 9.58 | 1 |

Table 4.4: Proposed thickness for edge and corner panel flat plate slabs satisfying ℓ/240 by using SAFE.

| L1 | L2 | Aspect ratio | proposed $\frac{\ell n}{A}$ | Proposed thickness of flat plate slab | Revised long span LTD, mm | $\frac{\ell}{240}$ limit, mm | Correction factor |
|---|---|---|---|---|---|---|---|
| 10 | 10 | 1 | $\frac{\ell n}{26.09}$ | 368 | 39.96 | 40 | 1.15 |
| 10 | 6.66 | 1.5 | $\frac{\ell n}{29.18}$ | 329 | 39.14 | 40 | 1.02 |
| 10 | 5 | 2 | $\frac{\ell n}{30}$ | 320 | 35.43 | 40 | 1 |
| 10 | 4 | 2.5 | $\frac{\ell n}{30}$ | 320 | 30.29 | 40 | 1 |
| 10 | 3.33 | 3 | $\frac{\ell n}{30}$ | 320 | 27.49 | 40 | 1 |
| 7.5 | 7.5 | 1 | $\frac{\ell n}{30}$ | 237 | 27.13 | 29.58 | 1 |
| 7.5 | 5 | 1.5 | $\frac{\ell n}{30}$ | 237 | 18.43 | 29.58 | 1 |
| 7.5 | 3.75 | 2 | $\frac{\ell n}{30}$ | 237 | 16 | 29.58 | 1 |
| 7.5 | 3 | 2.5 | $\frac{\ell n}{30}$ | 237 | 14.24 | 29.58 | 1 |
| 7.5 | 2.5 | 3 | $\frac{\ell n}{30}$ | 237 | 13.12 | 29.58 | 1 |
| 5 | 5 | 1 | $\frac{\ell n}{30}$ | 154 | 11.21 | 19.17 | 1 |
| 5 | 3.33 | 1.5 | $\frac{\ell n}{30}$ | 154 | 7.87 | 19.17 | 1 |
| 5 | 2.5 | 2 | $\frac{\ell n}{30}$ | 154 | 6.46 | 19.17 | 1 |
| 5 | 2 | 2.5 | $\frac{\ell n}{30}$ | 154 | 5.87 | 19.17 | 1 |
| 5 | 1.66 | 3 | $\frac{\ell n}{30}$ | 154 | 5.61 | 19.17 | 1 |

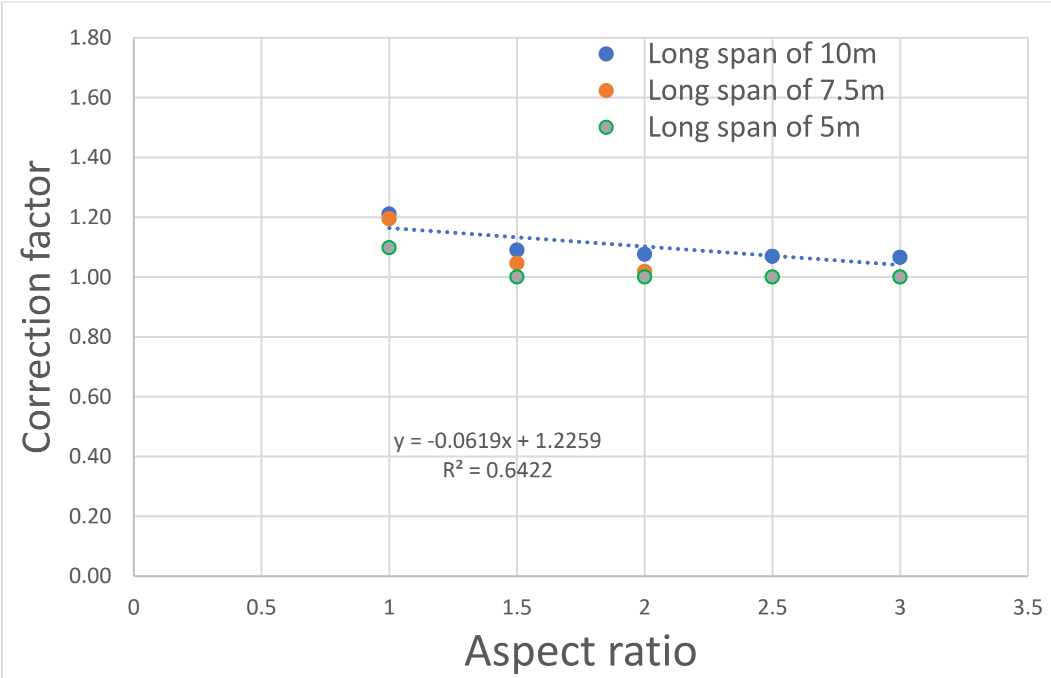


Figure 4.10: Proposed equation for different aspect ratio of interior panel for one-way slabs that satisfy the ℓ/480.

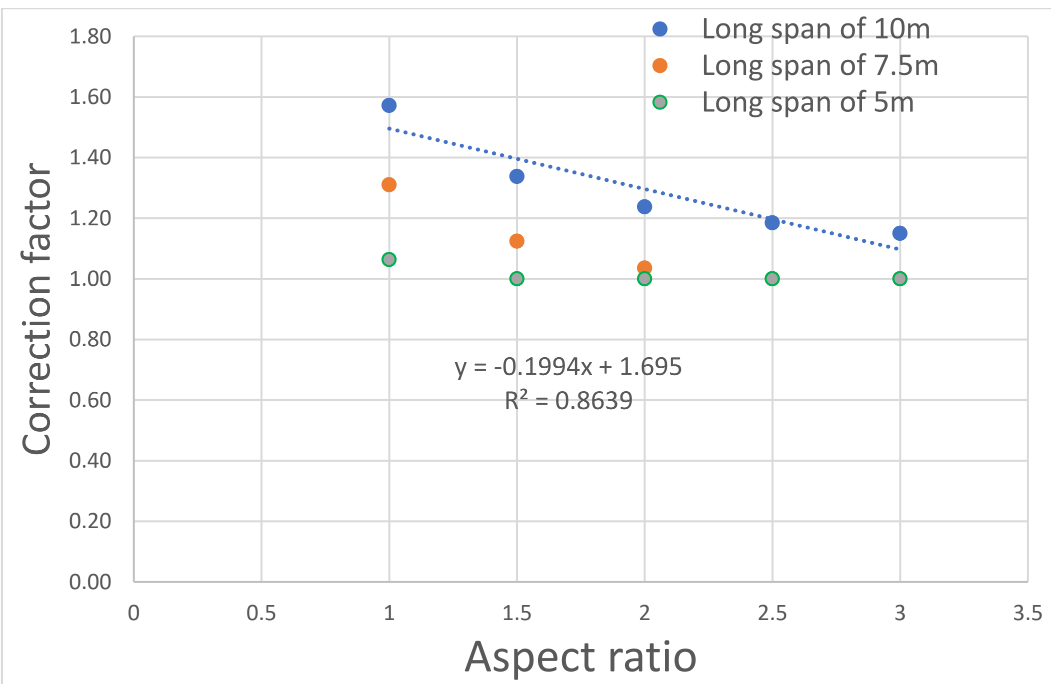


Figure 4.11: Proposed equation for different aspect ratio of edge and corner panel for one-way slabs that satisfy the ℓ/480.

## 4.3 Two-way slabs with different relative beam-slab stiffness

This section displays the long-term deflection of interior, edge and corner panel flat plates and beam-slabs of six groups as detailed in Table 3.3; it studies the effects of the aspect ratio and the beam-slab relative stiffness on the LTD.

### 4.3.1 Interior panels long span deflection

The LDT of interior flat plates and beam-slabs (using ACI318-19 provisions) for different aspect ratio and relative beam-slab stiffnesses are presented in Figure 4.12 and 4.13, the LTDs are shown as a ratio of the long spans, and the ℓ /240 and ℓ /480 deflection limits are also shown. As could be seen, considering the deflection limit of ℓ /240, ACI318-19 provisions give realistic minimum thickness value of both flat plate slabs and beam-slabs.

For the ℓ/480 deflection limit, it is clear that ACI318-19 recommended thicknesses are only working in the following cases:

- Case 1.1: for flat plate slab with long span of 5m and aspect ratio 2
- Case 1.2: for beam-slab with relative beam-slab stiffness of 0.2 in all spans with aspect ratio 2, in 5 m long span of aspect ratio 1. The same slab thickness is used in case 1.1 and case 1.2 even there are beams in case 1.2. This is reason for having different results in these two cases.
- Case 1.3: for beam-slab with relative stiffness of 2: in all spans with aspect ratio 1, at 5 m span of aspect ratio 2

It appears that the $\ell n/33$, does not provide the adequate thickness for interior flat plate slab panel at;

- Slab panel with aspect ratio 1
- Slab panels with large span equal and greater than 7.5m

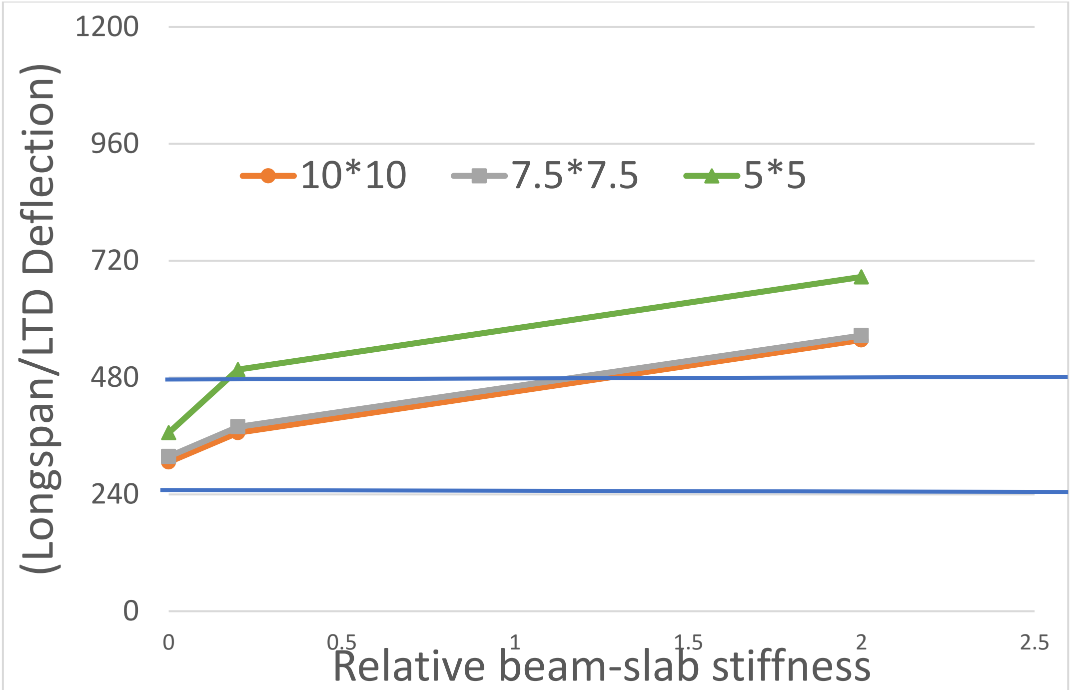


Figure 4.12: Long span deflection of interior panel of aspect ratio 1 refer to the Table B.4, Table B.7 and Table 4.1

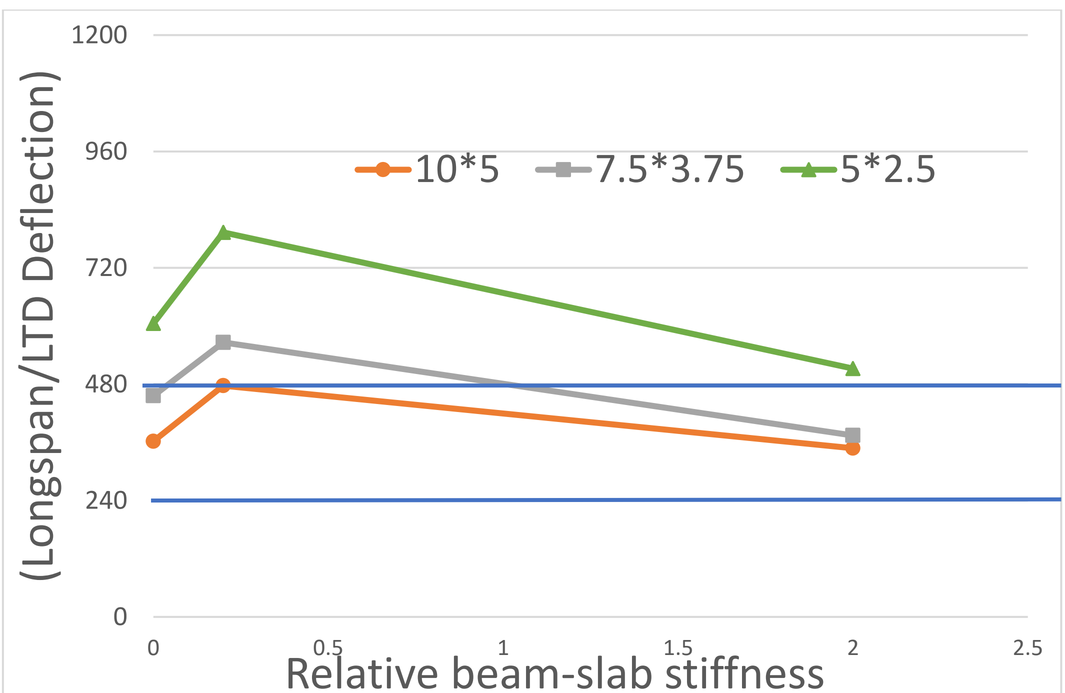


Figure 4.13: Long span deflection of interior panel of aspect ratio 2 refer to the Table B.4, Table B.7 and the Table 4.1.

### 4.3.2 Edge and corner panels long span deflection

The LDT of edge and corner flat plates and beam-slabs using ACI318-19 provisions for different aspect ratio and the relative beam-slab stiffness. This analysis is performed similar to the one presented in the previous section but the location of the panels are edge and corner panel instead of interior panels. In Figure 4.14 to 4.17, the LTDs are shown as a ratio of the long spans, and the $\ell$ /240 and $\ell$ /480 deflection limits are also shown.

For the deflection limit of $\ell$ /240, at aspect ratio 2, it can be observed that, ACI318-19 provisions provide adequate minimum slab thickness values for all spans of both flat plates and beam-slabs. At aspect ratio 1, it can be seen that, the ACI318-19 provisions are not satisfactory in flat plate with large span of 10 m and beam-slabs with relative beam-slab stiffness of 0.2.

For the $\ell$/480 deflection limit, it is obvious that ACI318-19 minimum thicknesses are only working with the following cases:

- Case 2.1: In Flat plates: at aspect ratio 2 with long spans of 5m and 7.5m, at aspect ratio 1 with long spans of 5m
- Case 2.2: In Beam-Slab with relative beam-slab stiffness of 0.2: at 5 m and 7.5m long spans with aspect ratio 2, at 5 m span of aspect ratio 1. The same thickness is used in case 2.1 and case 2.2 even there are beams in case 2.2, and the reason for having different results in these two cases is using the same thickness in both cases, while there are beams in case 2.2.
- Case 2.3: In Beam-Slab with relative stiffness of 2: only at long span of 5m with aspect ratio 1. At aspect ratio 2, ACI318-19 reduces the thickness of beam-slabs system due to the increase in the aspect ratio resulting in an increase in the deflection at aspect ratio 2 and having cases not satisfying the $\ell$/480 deflection limit.

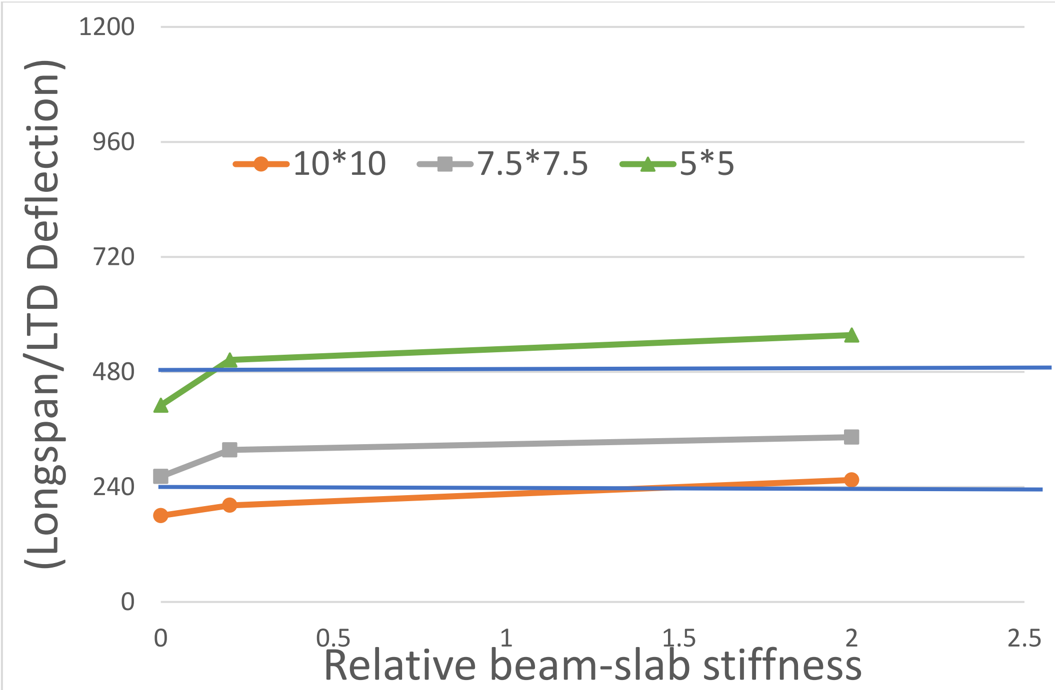


Figure 4.14: Long span deflection of edge panel of aspect ratio 1, refer to Table B.5, Table B.8 and Table 4.1.

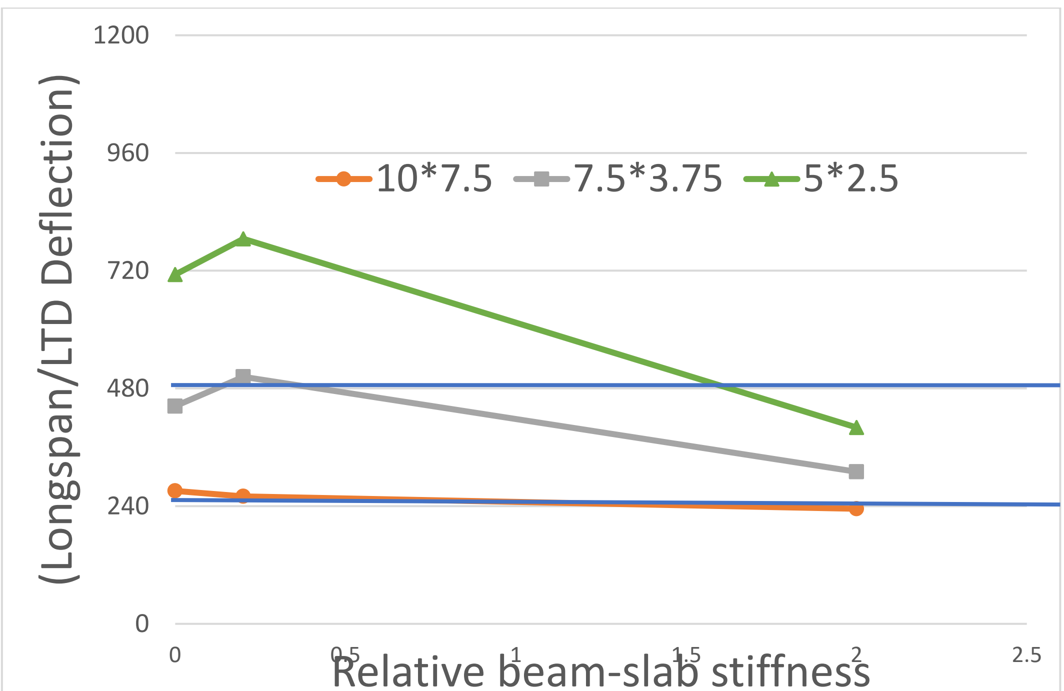


Figure 4.15: Long span deflection of edge panel of aspect ratio 2, refer to Table B.5, Table B.8 and Table 4.1.

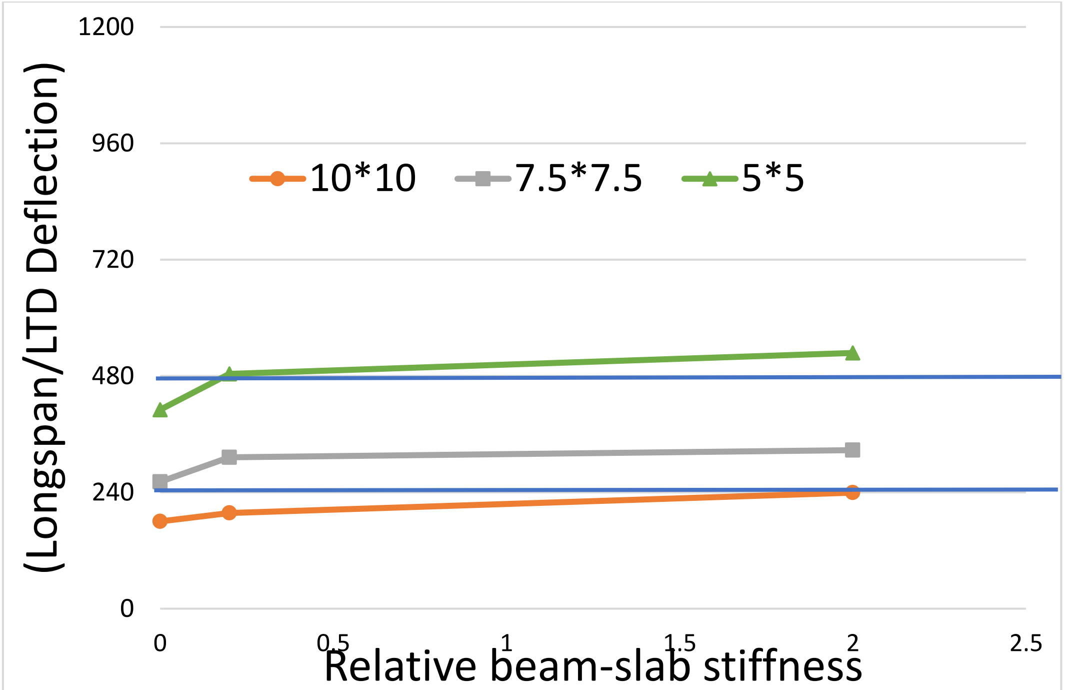


Figure 4.16: Long span deflection of corner panel of aspect ratio 1, refers to Table B.6, Table B.9 and Table 4.1.

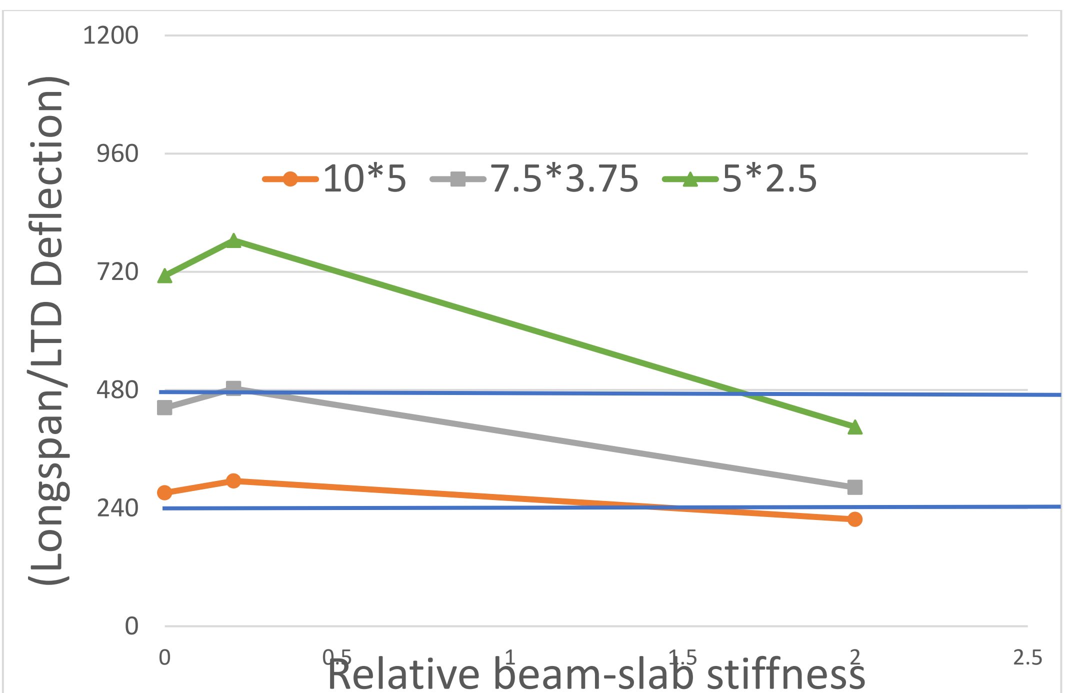


Figure 4.17: Long span deflection of corner panel of aspect ratio 2, refers to Table B.6, Table B.9 and Table 4.1.

### 4.3.3 Interior panel/mid panel deflection

This section presents the mid panel deflection of interior beam-slabs and flat plates (using ACI318-19 provisions) for different aspect ratio and relative beam-slab stiffnesses are presented in Figure 4.18 and Figure 4.19. The LTDs are shown as a ratio of the diagonal span, and the $\ell$ /240 and $\ell$ /480 deflection limits are also shown. As could be seen, considering the deflection limit of $\ell$ /240, ACI318-19 provisions provide suitable minimum thickness value of both flat plate slabs and beam-slabs similar to the long span deflection cases.

For the $\ell$/480 deflection limit, it is obvious that ACI318-19 thicknesses are only working in the following cases:

- Case 3.1: For flat plate slabs with long span of 5m and aspect ratio of 2
- Case 3.2: In Beam-Slab with relative stiffness of 0.2: In all spans with aspect ratio 2, in 5 m long span of aspect ratio 1. The same thickness is used in case 3.1 and case 3.2 even there are beams in case 3.2. This the reason for having different results in these two cases.
- Case 3.3: For Beam-Slab with relative beam-slab stiffness of 2: Only at 5 m long span of aspect ratio 1

It seems that $\ell n$/33, does not provide the adequate slab thickness for interior slab panel in;

- Slab panels with aspect ratio of 1
- Slab panels with long span equal and greater than 5m

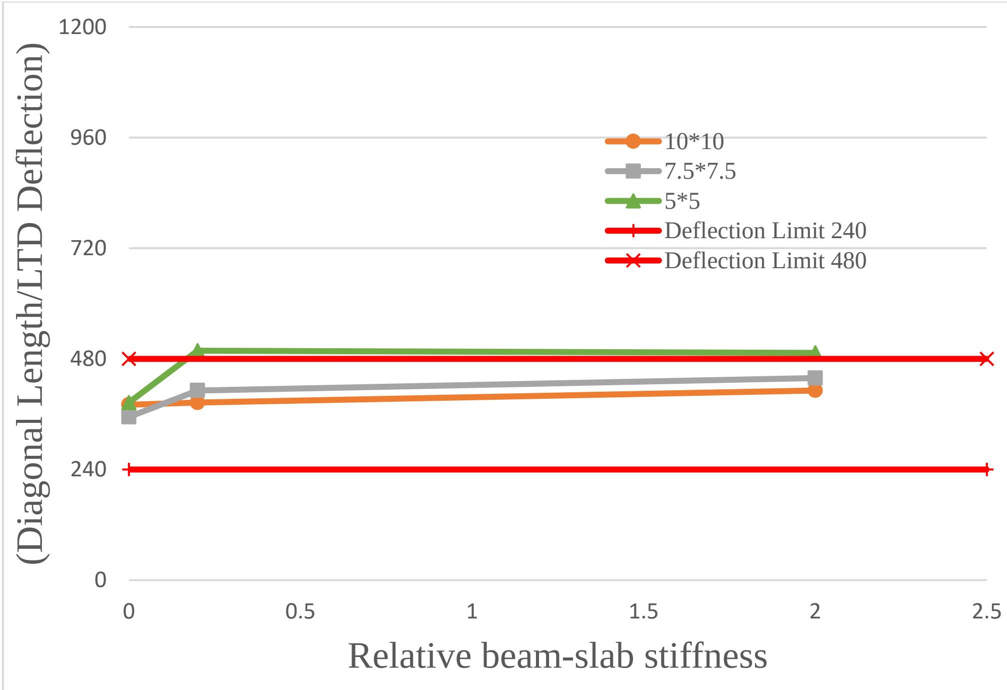


Figure 4.18: Mid panel deflection of interior panel of aspect ratio 1, refers to Table B.4, Table B.7 and Table 4.1.

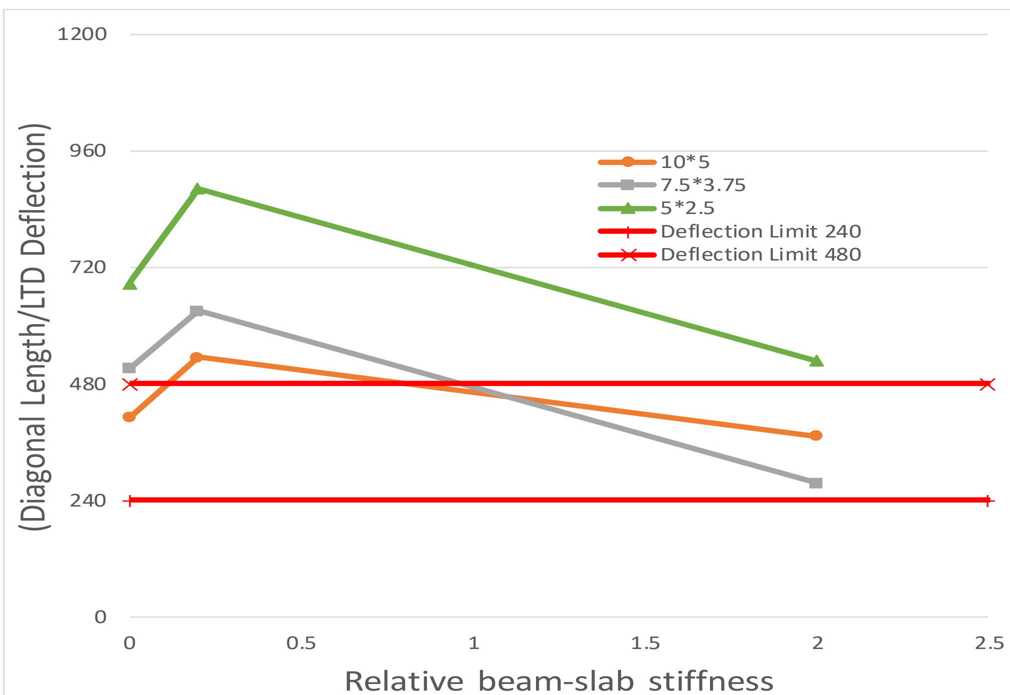


Figure 4.19: Mid panel deflection of interior panel of aspect ratio 2, refers to Table B.4, Table B.7 and Table 4.1.

### 4.3.4 Edge and corner panel mid panel deflection

The mid panel LDT for corner and edge flat plates and beam-slabs (using ACI318-19 provisions) for different aspect ratio and the relative beam-slab stiffness are presented in In Figure 4.20 to 4.23. The LTDs are shown as a ratio of the diagonal length, and the ℓ /240 and ℓ /480 deflection limits are shown as well.

For deflection limit of ℓ /240, at aspect ratio 2, it can be observed that, ACI318-19 provisions give sufficient minimum slab thickness value at all spans of both flat plates and beam-slabs. At aspect ratio 1, it can be observed that, ACI318-19 provisions are not satisfying the deflection limit of ℓn /240 only at corner panel with the long span of 10 m of flat plates and beam-slabs.

For the ℓ/480 deflection limit, it is shown that the ACI318-19 minimum thicknesses are only working in the following cases:

- Case 4.1: For flat plate slabs with long span of 5m and 7.5m long span with aspect ratio of 2.
- Case 4.2: For Beam-Slab with relative beam-slab stiffness of 0.2: At 5 m and 7.5m long spans with aspect ratio 2, at 5 m long span only at the corner panel of aspect ratio 1. The same slB thickness is used in case 4.1 and case 4.2 even there are beams in case 4.2, and the reason for having different results in these two cases is using same thickness in both cases, while there are beams in case 4.2.
- Case 4.3: For Beam-Slab with relative stiffness of 2: All the cases are not satisfying the deflection limit of ℓ/480.

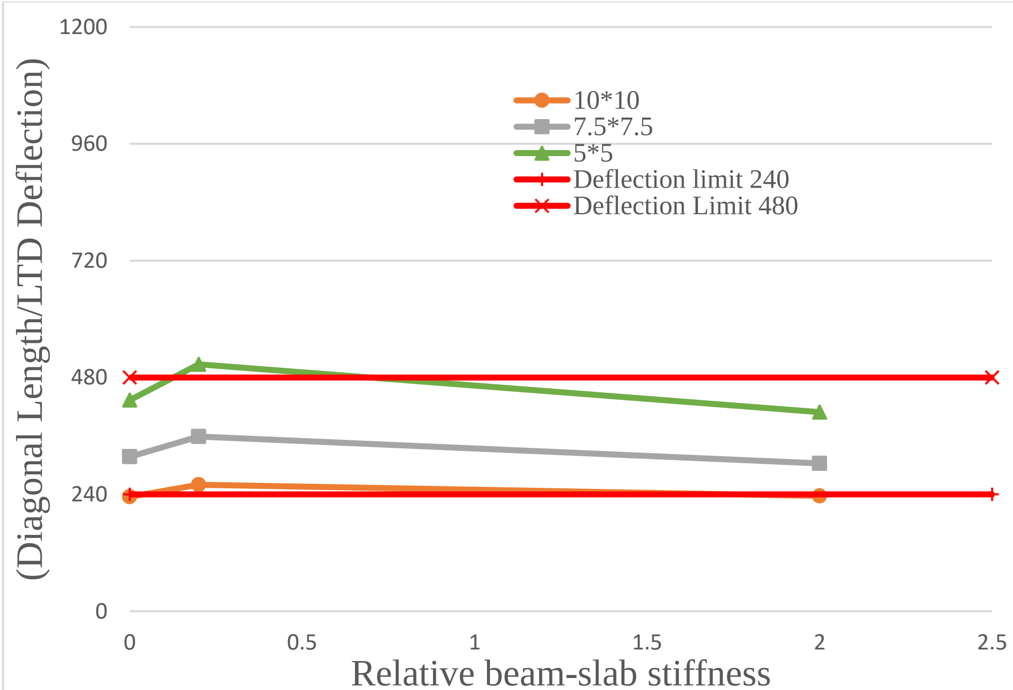


Figure 4.20: Mid panel deflection of edge panel of aspect ratio 1, refers to Table B.5, Table B.8 and Table 4.1.

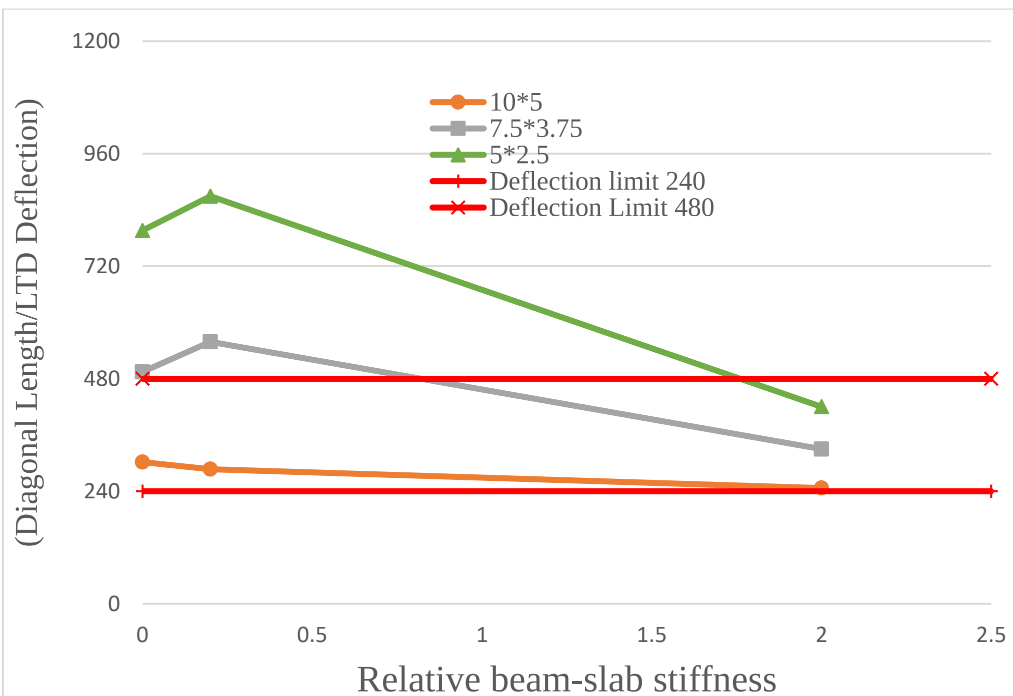


Figure 4.21: Mid panel deflection of edge panel of aspect ratio 2, refers to Table B.5, Table B.8 and Table 4.1.

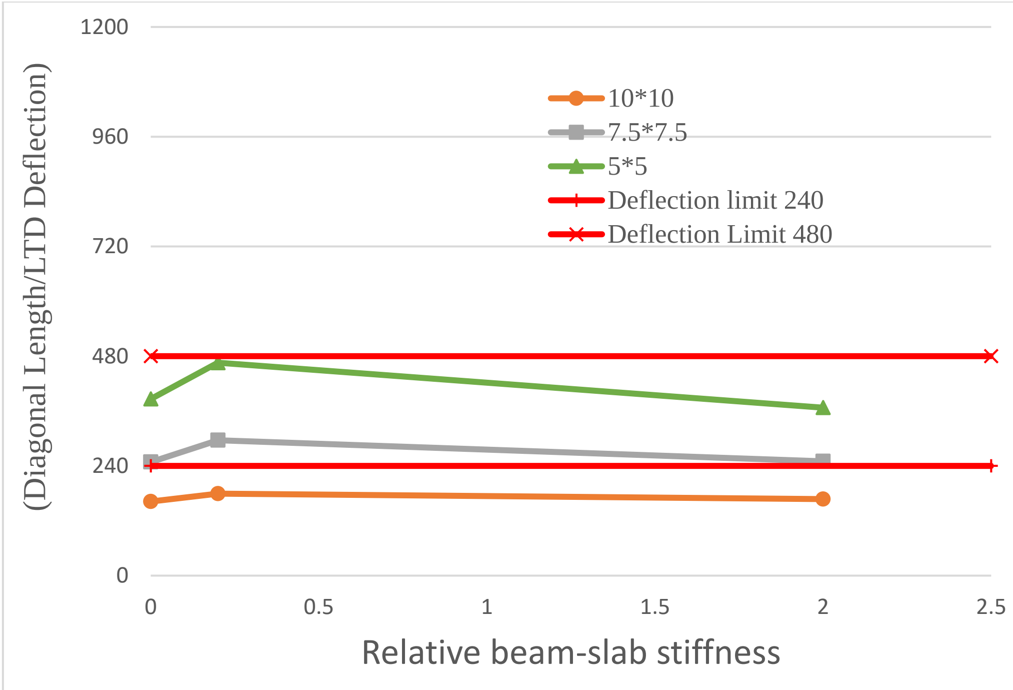


Figure 4.22: Mid panel deflection of corner panel of aspect ratio 1, refers to Table B.6, Table B.9 and Table 4.1.

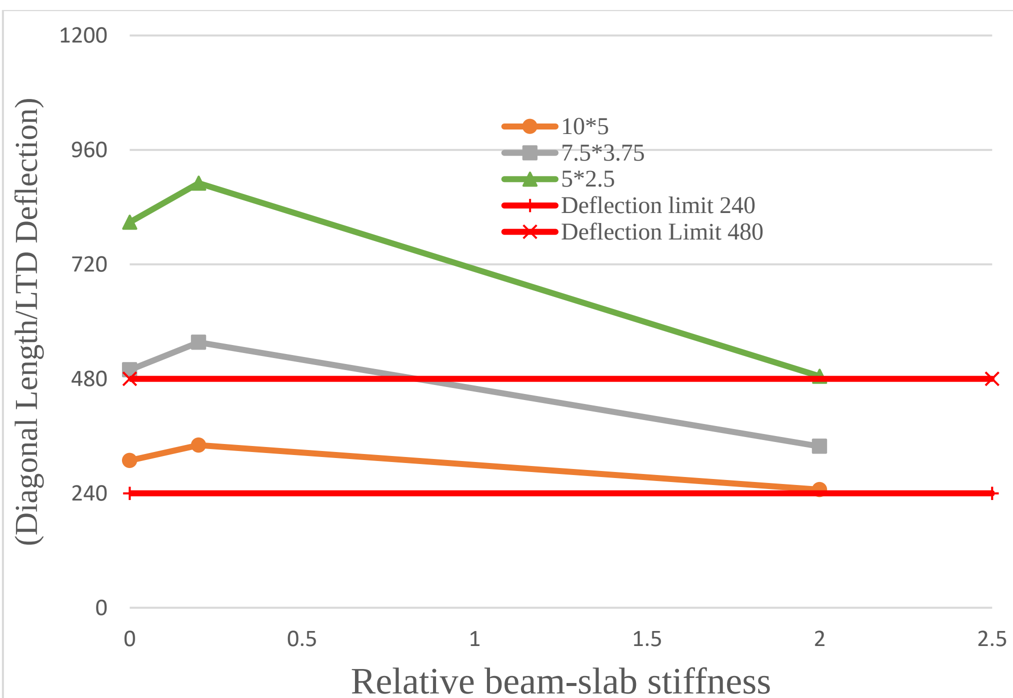


Figure 4.23: Mid panel deflection of corner panel of aspect ratio 2, refers to Table B.6, Table B.9 and Table 4.1.

## 4.4 Evaluation of Bondy's approach for flat plate thickness

As an alternative for using the long span in the determination of the flat plate slabs thickness, (Bondy, K. B, 2005) suggested the use of the diagonal span as the base in determining the flat plate thickness. In the current study this approach has been evaluated considering the long-term deflection of the interior, edge and corner panel flat plates for different aspect ratios for the cases shown in the Table 3.4.

The reported LTD is for the long span (LSDs) and the mid panel. In Figure 4.24, to 4.26, the mid panel deflections are shown as a ratio of the diagonal span, LSDs are shown as a ratio of the long span; in addition, the $\ell$ /240 and $\ell$ /480 deflection limits are also shown.

For the deflection limit of $\ell$ /240, it could be observed that Bondy's approach is adequate for all the studied cases. Further, this approach might not be economical for small spans, as the resulted deflections would be very small.

For the deflection limit of $\ell$ /480, it is clear that the use of Bondy's approach produce satisfactory results (deflections) only at the interior panels. For the edge and corner panels, the thickness is not adequate especially in the case of long span of 10m.

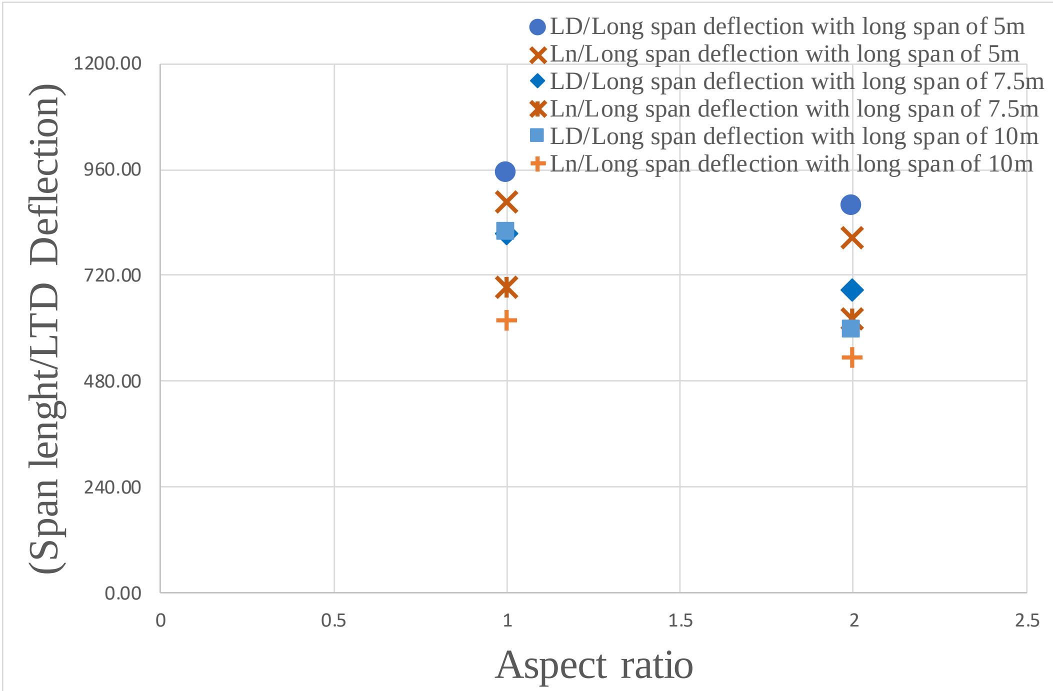


Figure 4.24: LTDs of mid panel and long span of interior flat plate slabs with aspect ratio 1 and 2, refer to Table B.10.

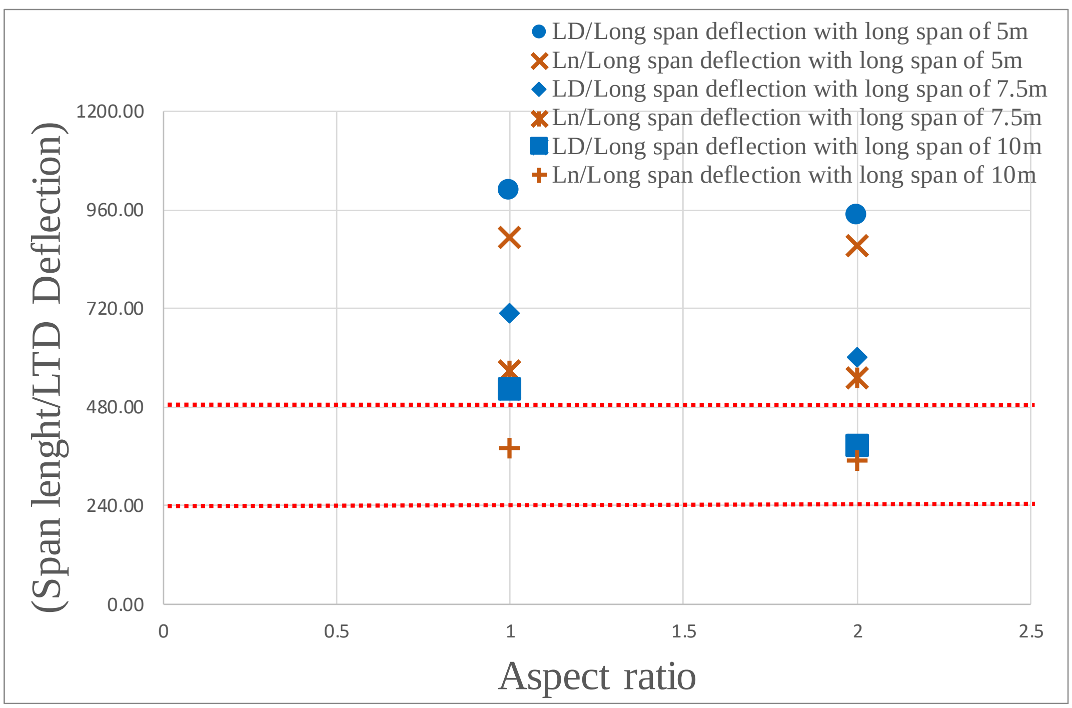


Figure 4.25: LTDs of mid panel and long span of edge flat plate slabs with aspect ratio 1 and 2, refer to Table B.11.

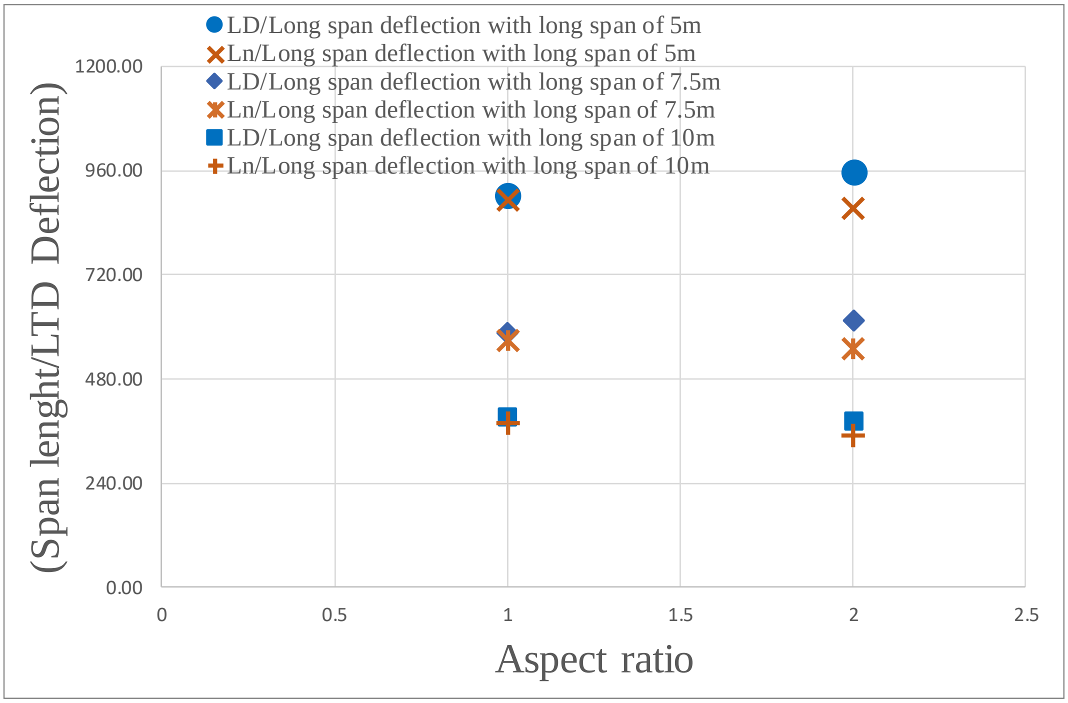


Figure 4.26: LTDs of mid panel and long span of corner flat plate slabs with aspect ratio 1 and 2, refer to Table B.12.

## 4.5 One-way slabs

The ACI 318-19 provision for the one-way slab thickness (see Table 2.1) do not include any restriction on the required minimum relative beam-slab stiffness for the supporting beams. Not having such restrictions might lead to having a large LTD under the supporting beam.

### 4.5.1 Minimum relative beam-slab stiffness of the Supporting beam

This section demonstrates the LTD of the parametric study detailed in Table 3.5. The resulted LTDs along the long span (the location of the supporting beams) are listed in Table 4.5 to Table 4.8 and shown in Figure 4.27 to Figure 4.2929. In these presentations of results, the ℓ/240 and ℓ/480 deflection limits are displayed for comparison. The relative beam-slab stuffiness has been increased through multiple studied cases until the LDT reached the deflection limits.

As could be seen, for interior, interior edge, exterior and exterior edge slab panels, the required relative beam-slab stiffness (to ensure that the long beam LTD is within the allowable deflection of ℓ /240 (Case A) and ℓ /480 (Case B)) increases with the increase of the supporting long side length. In all cases, there is a sharp decrease in the required relative stiffness at the range of low values of the relative beam-slab stiffness until the stiffness of 3 to 5, beyond that, the effects of the relative stiffness became less effective.

Table 4.9 summarize all the minimum relative beam-slab stiffnesses required to satisfy the deflection limits of ℓ/240 and ℓ/480 along the supporting beams. As listed, as a safe side recommendation, and before going with the ACI318-19 provisions for the one-way slab thickness, a minimum relative beam-slab stiffness for the supporting beam of 5 and 20 is required to be provided to satisfy the deflection limit of ℓ/240 and ℓ/480, respectively.

Table 4.5: LTD results of parametric study (Interior edge panel)

| Panel dimension (m) | Flat plate slab thickness (ℓn/33) (mm) | LTD of Flat plate slab (mm) | Beam-slab thickness (ℓ/28) (mm) | LTD (mm) | | | | | | | | | | | | | | Deflection limit(mm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Relative beam-slab stiffness | | | | | | | | | | | | | | | |
| | | | | 1 | 2 | 3 | 4 | 5 | 7 | 9 | 10 | 11 | 13 | 15 | 17 | 19 | 20 | ℓ/240) | ℓ/480) |
| 10x4.9 | 291 | 26.6 | 161 | 83.3 | 61.6 | 51.1 | 38.2 | 44.8 | 39.4 | 33.3 | 30.6 | 27.4 | 25.1 | 23.0 | 21.5 | 20.3 | 19.6 | 40 | 20 |
| 7.5x3.6 | 215 | 15.5 | 114 | 98.5 | 61.3 | 35.6 | 29.9 | 27.1 | 22.8 | 19.5 | 17.1 | 15.1 | 14.6 | | | | | 29.5 | 14.7 |
| 6.1x3 | 173 | 10.3 | 93 | 82.3 | 46.9 | 31.2 | 22.2 | 19.1 | 15.0 | 11.3 | | | | | | | | 23.7 | 11.8 |
| Yellow color: denoted to the first long term deflection that is satisfy the deflection limit of (ℓ/240) | | | | | | | | | | | | | | | | | | | |
| Blue color: denoted to the first long term deflection that is satisfy the deflection limit of (ℓ/480) | | | | | | | | | | | | | | | | | | | |

Table 4.6: LTD results of parametric study (Exterior edge panel)

| Panel dimension(m) | Flat plate slab thickness (ℓn/30) (mm) | LTD of Flat plate slab (mm) | Beam-slab thickness (ℓ/24) (mm) | LTD (mm) Relative beam-slab stiffness | | | | | | | | | | | | Deflection limit (mm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | 4 | 5 | 7 | 9 | 10 | 11 | 13 | 15 | 17 | (ℓ/240) | (ℓ/480) |
| 10x4.9 | 320 | 35.1 | 188 | 70.9 | 52.8 | 44.7 | 38.2 | 34.5 | 29.4 | 26.9 | 24.5 | 22.1 | 20.7 | 20.1 | 19.4 | 40 | 20 |
| 7.5x3.6 | 237 | 16.1 | 134 | 62.1 | 35.1 | 28.1 | | 22.1 | 18.9 | 15.6 | 14.3 | 14.7 | | | | 29.58 | 14.79 |
| 6.1x3 | 190 | 9.7 | 109 | 50.2 | 29.6 | 21.2 | | 14.5 | 10.6 | | | | | | | 23.75 | 11.88 |

Yellow color: denoted to the first long term deflection that is satisfy the deflection limit of (ℓ/240)

Blue color: denoted to the first long term deflection that is satisfy the deflection limit of (ℓ/480)

Table 4.7: LTD results of parametric study (Interior panel)

| Panel dimension(m) | Flat plate slab thickness (ℓn/33) (mm) | LTD of Flat plate slab (mm) | Beam-slab thickness (ℓ/28) (mm) | LTD (mm) Relative beam-slab stiffness | | | | | | | | Deflection limit(mm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1.00 | 2.00 | 3.00 | 4.00 | 5.00 | 7.00 | 9.00 | 10.00 | ℓ/240) | ℓ/480) |
| 10x4.9 | 290.9 | 26.58 | 161 | 72.3 | 51.11 | 38.24 | | 30.20 | 23.4 | 20.3 | 18.7 | 40 | 20 |
| 7.5x3.6 | 215 | 15.52 | 114 | 88.8 | 56.7 | 31.8 | 26.4 | 23.9 | 19.0 | 16.3 | 14.9 | 29.58 | 14.79 |
| 6.1x3 | 173 | 10.32 | 93 | 82.3 | 46.9 | 31.1 | 22.2 | 19.1 | 15.0 | 11.3 | | 23.75 | 11.88 |

Yellow color: denoted to the first long term deflection that is satisfy the deflection limit of (ℓ/240)

Blue color: denoted to the first long term deflection that is satisfy the deflection limit of (ℓ/480)

Table 4.8: LTD results of parametric study (Exterior panel)

| Panel dimension (m) | Flat plate slab thickness (ℓn/30) (mm) | LTD of Flat plate slab (mm) | Beam-slab thickness (ℓ/24) (mm) | LTD (mm) Relative beam-slab stiffness | | | | | | | Deflection limit(mm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | 4 | 5 | 7 | 8 | ℓ/240) | ℓ/480) |
| 10x4.9 | 320 | 35.1 | 188 | 58.8 | 41.9 | 31.5 | | 23.4 | 19.2 | 20.3 | 40.00 | 20 |
| 7.5x3.6 | 237 | 16.1 | 134 | 60.4 | 30.9 | 24.6 | | 18.5 | 15.1 | 13.6 | 29.58 | 14.79 |
| 6.1x3 | 190 | 9.7 | 109 | 46.5 | 24.5 | 19.7 | 11.7 | | | | 23.75 | 11.88 |
| Yellow color: denoted to the first long term deflection that is satisfy the deflection limit of (ℓ/240) | | | | | | | | | | | | |
| Blue color: denoted to the first long term deflection is satisfy the deflection limit of (ℓ/480) | | | | | | | | | | | | |

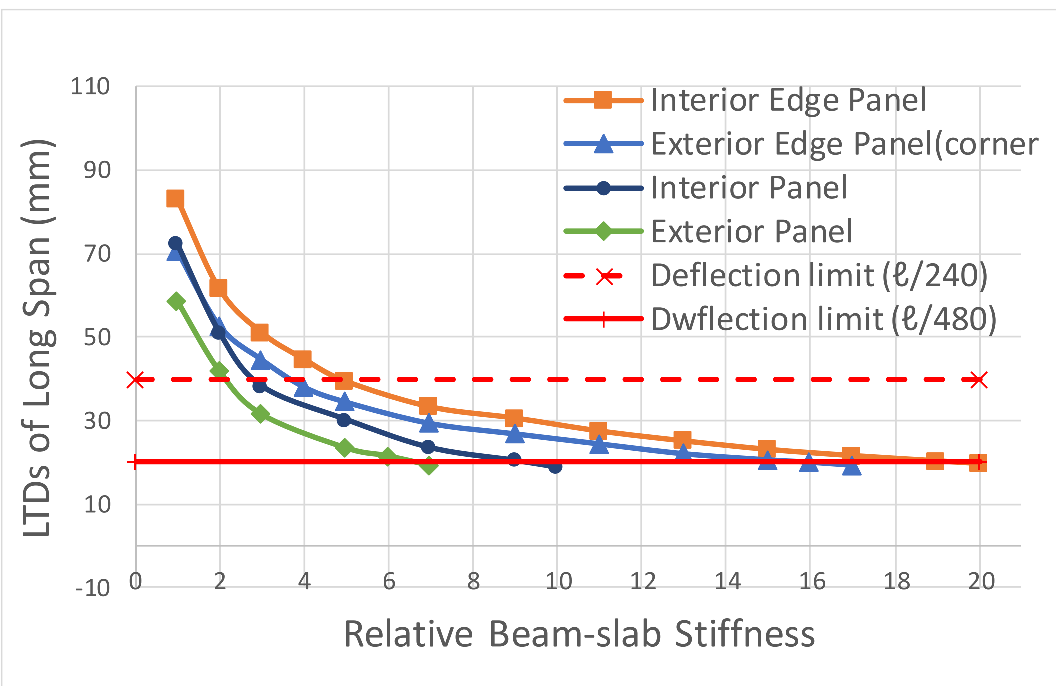


Figure 4.27: LTDs of the supporting beam versus the relative beam-slab stiffness of 10x4.9 m slab panel

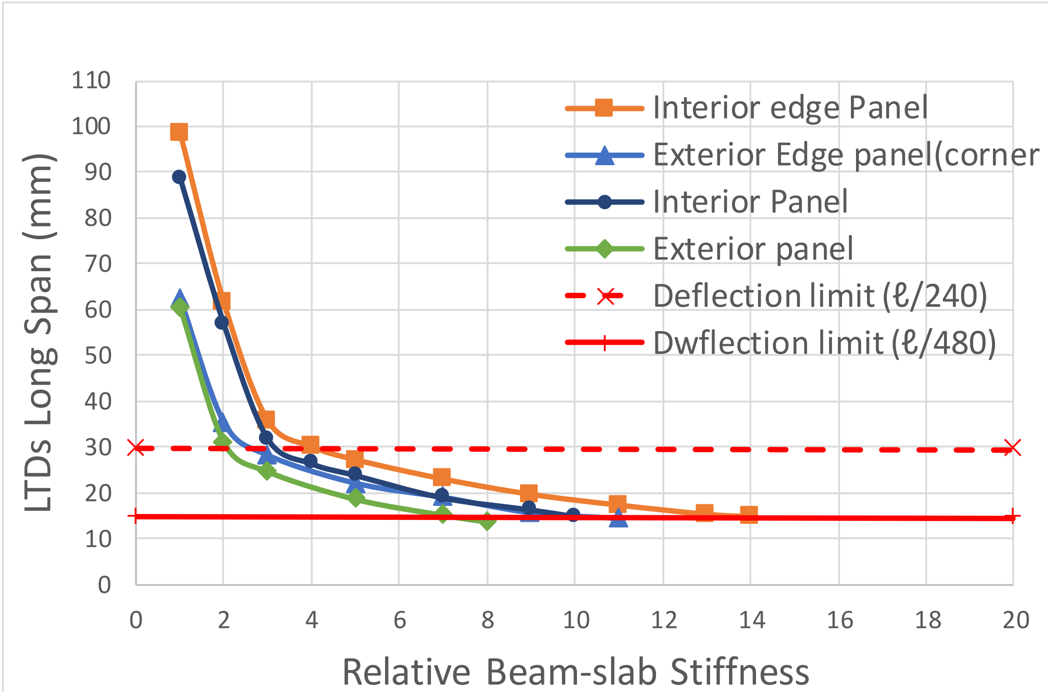


Figure 4.28: LTDs of the supporting beam versus the relative beam-slab stiffness of 7.5x3.6m slab panel

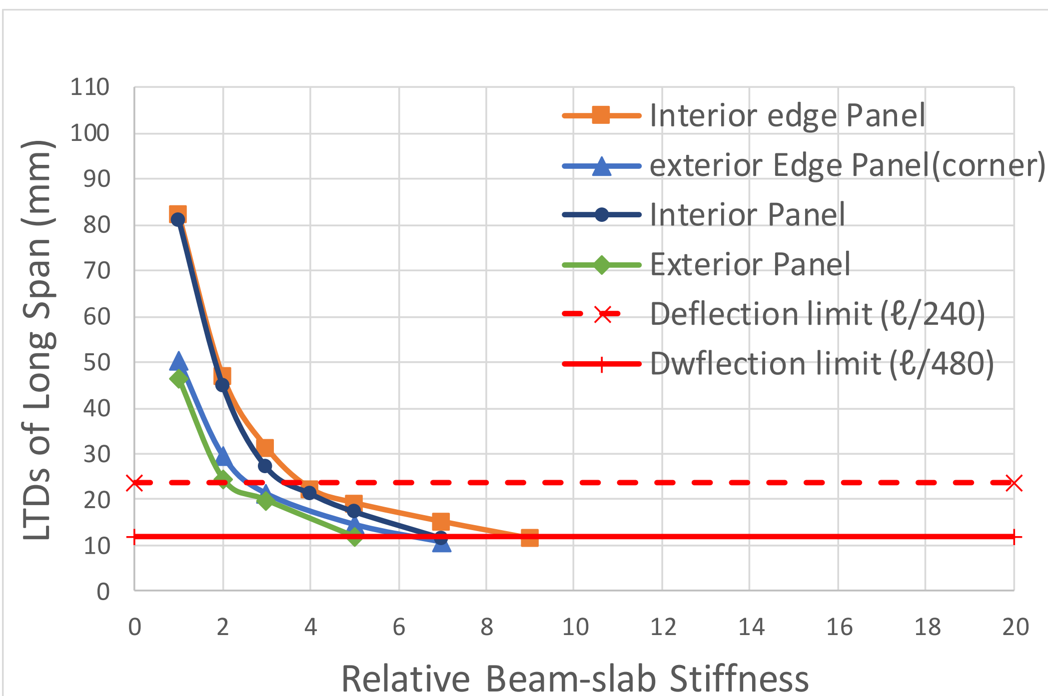


Figure 4.29: LTDs of the supporting beam versus the relative beam-slab stiffness of 6.1x3m slab panel

Table 4.9: Minimum proposed relative beam-slab stiffness.

| Slab Panel | Minimum Relative Beam-Slab Stiffness | | | | | |
|---|---|---|---|---|---|---|
| | Case A (ℓ/240) | | | Case B (ℓ/480) | | |
| | 6.1 x 3.0 m | 7.5 x 3.6m | 10 x 4.9m | 6.1 x 3.0m | 7.5 x 3.6m | 10 x 4.9m |
| Interior edge | 4 | 5 | 7 | 9 | 13 | 20 |
| Exterior edge | 3 | 3 | 4 | 7 | 11 | 17 |
| Interior | 4 | 4 | 3 | 9 | 10 | 10 |
| Exterior | 3 | 3 | 3 | 4 | 8 | 7 |

### 4.5.2 Proposing minimum thicknesses for one-way slab cases of low relative beam-slab stiffness

The result of the parametric study detailed in Table 3.7 are presented in this section. The determined minimum thicknesses and LTDs are listed in Table 4.10 to Table 4.15 and shown in the Figure 4.30 to 4.37. The calculated deflection has been found by increasing the slab thickness with decreasing the beam height (having low relative beam-slab stiffness) through many iterations until the LDT reached the deflection limits of ℓ/240 and ℓ/480. The aims of this approach were to find sufficient one-way slab thickness in case of having a restriction on the beam height (low relative beam stiffness). In this presentation of results, ℓ/240 and ℓ/480 deflection limits are indicated for the comparison.

For the studied interior, interior edge, exterior and exterior edge one-way slab panels of spans 10x4.9m, 7.5x3.6m and 6.1x 3m, Table 4.10 to Table 4.15 and the Figure 4.30 to 4.37 to present the proposed minimum thickness and the correction factor with new proposed equation for each panel location needs to be used with the ACI 318-19 equation in case of having low relative beam-slab stiffness. The increase in the factor value indicate the need for large thickness compared to those recommended by the ACI 318-19 provisions for one-way slabs (ℓ/28 for internal panel and ℓ/24 for exterior panel). The results show a significant effect of the relative beam-slab stiffness on the required slab thickness.

Table 4.10: Proposed minimum thickness of one-way slabs (10 x 4.9m) that satisfying ℓ/240.

| Panel location | Relative beam-slab stiffness | Slab thickness, mm | Beam depth, mm | LTD deflection of long span (supported beam) | ℓ/240 deflection limit | Ratio (A) (ℓ/thickness) | Proposed thickness (ℓ/ratio(A)) | correction factor (28/ ratio and |
|---|---|---|---|---|---|---|---|---|
| Interior | 0.64 | 225 | 405 | 39.8 | 40 | 20 | ℓ/20 | 1.40 |
| | 0.98 | 218 | 428 | 39.02 | 40 | 20.64 | ℓ/20.64 | 1.36 |
| | 1.46 | 192 | 445 | 39.49 | 40 | 23.44 | ℓ/23.44 | 1.19 |
| | 2.2 | 175 | 460 | 38.88 | 40 | 25.71 | ℓ/25.71 | 1.09 |
| | 3 | 161 | 470 | 38.24 | 40 | 28 | ℓ/28 | 1 |
| Interior edge | 0.42 | 274 | 430 | 39.1 | 40 | 16.42 | ℓ/16.42 | 1.70 |
| | 0.72 | 260 | 480 | 39.19 | 40 | 17.31 | ℓ/17.31 | 1.62 |
| | 1.38 | 224 | 505 | 40.32 | 40 | 20.09 | ℓ/20.09 | 1.39 |
| | 2.4 | 200 | 535 | 39.07 | 40 | 22.5 | ℓ/22.50 | 1.24 |
| | 4.52 | 164 | 537 | 39.58 | 40 | 27.44 | ℓ/27.44 | 1.02 |
| | 5 | 161 | 545 | 39.42 | 40 | 28 | ℓ/28 | 1 |
| Exterior | 0.47 | 226 | 400 | 39.63 | 40 | 19.91 | ℓ/19.91 | 1.21 |
| | 1.06 | 220 | 425 | 39 | 40 | 20.45 | ℓ/20.45 | 1.17 |
| | 1.2 | 215 | 430 | 39.32 | 40 | 20.93 | ℓ/20.93 | 1.15 |
| | 2.5 | 188 | 450 | 39.42 | 40 | 24 | ℓ/24 | 1 |
| Exterior edge | 0.55 | 274 | 430 | 39.1 | 40 | 16.42 | ℓ/16.42 | 1.46 |
| | 0.94 | 260 | 480 | 39.19 | 40 | 17.31 | ℓ/17.31 | 1.39 |
| | 1.8 | 224 | 505 | 40.32 | 40 | 20.09 | ℓ/20.09 | 1.19 |
| | 3.11 | 200 | 535 | 39.07 | 40 | 22.50 | ℓ/22.50 | 1.07 |
| | 4 | 188 | 545 | 38.2 | 40 | 24 | ℓ/24 | 1 |

Table 4.11: Proposed minimum thickness of one-way slabs (7.5 x 3.6m) that satisfying ℓ/240.

| Panel location | Relative beam-slab stiffness | Slab thickness, mm | Beam depth, mm | LTD deflection of long span (supported beam) | ℓ/240 deflection limit | Ratio (A)(ℓ/thickness) | Proposed thickness ((ℓ/ratio(A)) | correction factor (28/ ratio and 24/ratio) |
|---|---|---|---|---|---|---|---|---|
| Interior | 0.64 | 161 | 270 | 28.98 | 29.58 | 19.88 | ℓ/19.88 | 1.41 |
| | 1.6 | 136 | 302 | 29.16 | 29.58 | 23.53 | ℓ/23.53 | 1.19 |
| | 2.29 | 125 | 310 | 29.55 | 29.58 | 25.6 | ℓ/25.60 | 1.09 |
| | 3.06 | 119 | 318 | 29.19 | 29.58 | 26.89 | ℓ/26.89 | 1.04 |
| | 4 | 114 | 338 | 26.47 | 29.58 | 28 | ℓ/28 | 1 |
| Interior edge | 0.46 | 175 | 265 | 29.57 | 29.58 | 18.29 | ℓ/18.29 | 1.53 |
| | 0.71 | 165 | 285 | 29.54 | 29.58 | 19.39 | ℓ/19.39 | 1.44 |
| | 1.17 | 155 | 311 | 29.53 | 29.58 | 20.65 | ℓ/20.65 | 1.36 |
| | 1.8 | 140 | 321 | 29.39 | 29.58 | 22.86 | ℓ/22.86 | 1.23 |
| | 3.26 | 118 | 328 | 28.58 | 29.58 | 27.12 | ℓ/27.12 | 1.03 |
| | 4 | 114 | 338 | 29.98 | 29.58 | 28 | ℓ/28 | 1 |
| Exterior | 0.64 | 161 | 270 | 28.98 | 29.58 | 19.88 | ℓ/19.88 | 1.21 |
| | 1.6 | 140 | 295 | 29.16 | 29.58 | 22.86 | ℓ/22.86 | 1.05 |
| | 2.32 | 134 | 302 | 29.27 | 29.58 | 24 | ℓ/24 | 1 |
| Exterior edge | 0.61 | 175 | 265 | 29.57 | 29.58 | 18.29 | ℓ/18.29 | 1.31 |
| | 0.94 | 165 | 285 | 29.54 | 29.58 | 19.39 | ℓ/19.39 | 1.24 |
| | 1.49 | 155 | 311 | 29.53 | 29.58 | 20.65 | ℓ/20.65 | 1.16 |
| | 2.34 | 140 | 321 | 29.39 | 29.58 | 22.86 | ℓ/22.86 | 1.05 |
| | 3 | 134 | 331 | 28.11 | 29.58 | 24 | ℓ/24 | 1 |

Table 4.12: Proposed minimum thickness of one-way slabs (6.1 x 3m) that satisfying ℓ/240.

| Panel location | Relative beam-slab stiffness | Slab thickness, mm | Beam depth, mm | LTD deflection of long span (supported beam) | ℓ/240 deflection limit | Ratio (A)(ℓ/thickness) | Proposed thickness (ℓ/ratio(A)) | correction factor (28/ ratio and 24/ratio) |
|---|---|---|---|---|---|---|---|---|
| Interior | 0.55 | 146 | 222 | 23.37 | 23.75 | 17.81 | ℓ/17.81 | 1.57 |
| | 1.52 | 110 | 230 | 23.2 | 23.75 | 23.64 | ℓ/23.64 | 1.18 |
| | 2.54 | 102 | 250 | 23.34 | 23.75 | 25.49 | ℓ/25.49 | 1.10 |
| | 3.73 | 93 | 257 | 23.6 | 23.75 | 28 | ℓ/28 | 1 |
| Interior edge | 0.59 | 128 | 200 | 23.22 | 23.75 | 20.31 | ℓ/20.31 | 1.38 |
| | 1.16 | 118 | 227 | 23.4 | 23.75 | 22.03 | ℓ/22.03 | 1.27 |
| | 1.63 | 111 | 237 | 23.46 | 23.75 | 23.42 | ℓ/23.42 | 1.20 |
| | 3.21 | 96 | 256 | 23.52 | 23.75 | 27.08 | 27.08 | 1.03 |
| | 4 | 93 | 222 | 263 | 23.75 | 28 | ℓ/28 | 1 |
| Exterior | 0.72 | 146 | 222 | 23.37 | 23.75 | 17.81 | ℓ/17.81 | 1.35 |
| | 0.97 | 135 | 225 | 23.32 | 23.75 | 19.26 | ℓ/19.26 | 1.25 |
| | 1.98 | 110 | 230 | 23.2 | 23.75 | 23.64 | ℓ/23.64 | 1.02 |
| | 2.29 | 109 | 237 | 23.59 | 23.75 | 24 | ℓ/24 | 1 |
| Exterior edge | 0.78 | 128 | 200 | 23.22 | 23.75 | 20.31 | ℓ/20.31 | 1.18 |
| | 1.52 | 118 | 227 | 23.4 | 23.75 | 22.03 | ℓ/22.03 | 1.09 |
| | 2.12 | 111 | 237 | 23.46 | 23.75 | 23.42 | ℓ/23.42 | 1.02 |
| | 2.5 | 109 | 248 | 23.49 | 23.75 | 24 | ℓ/24 | 1 |

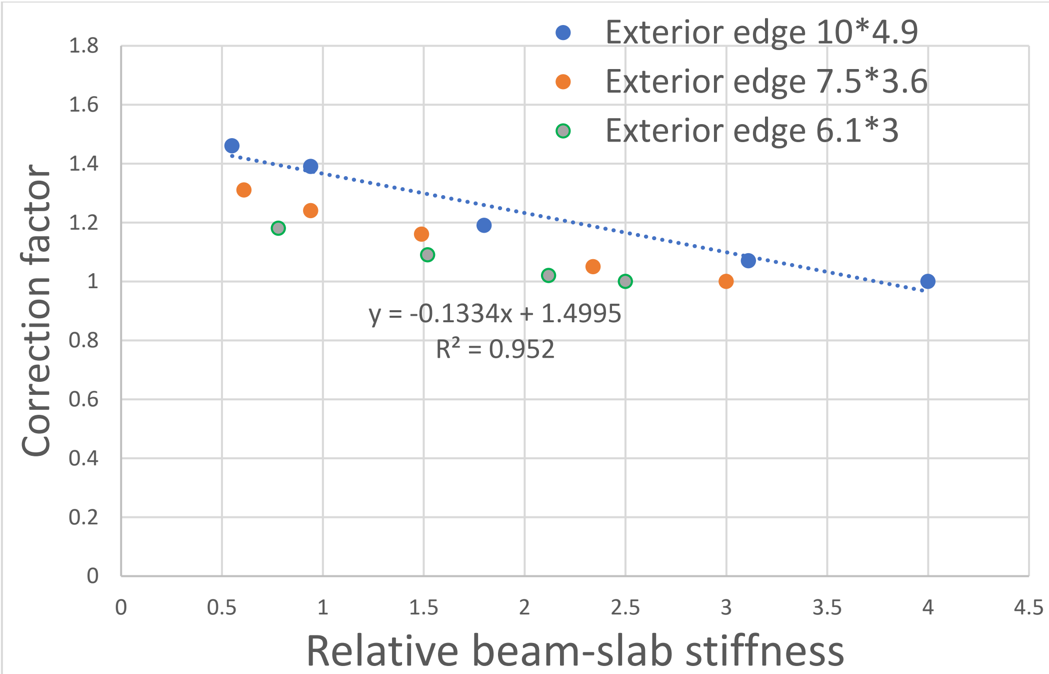


Figure 4.30: Proposed equation for different relative beam-slab of exterior edge panel for one-way slabs that satisfy the ℓ/240.

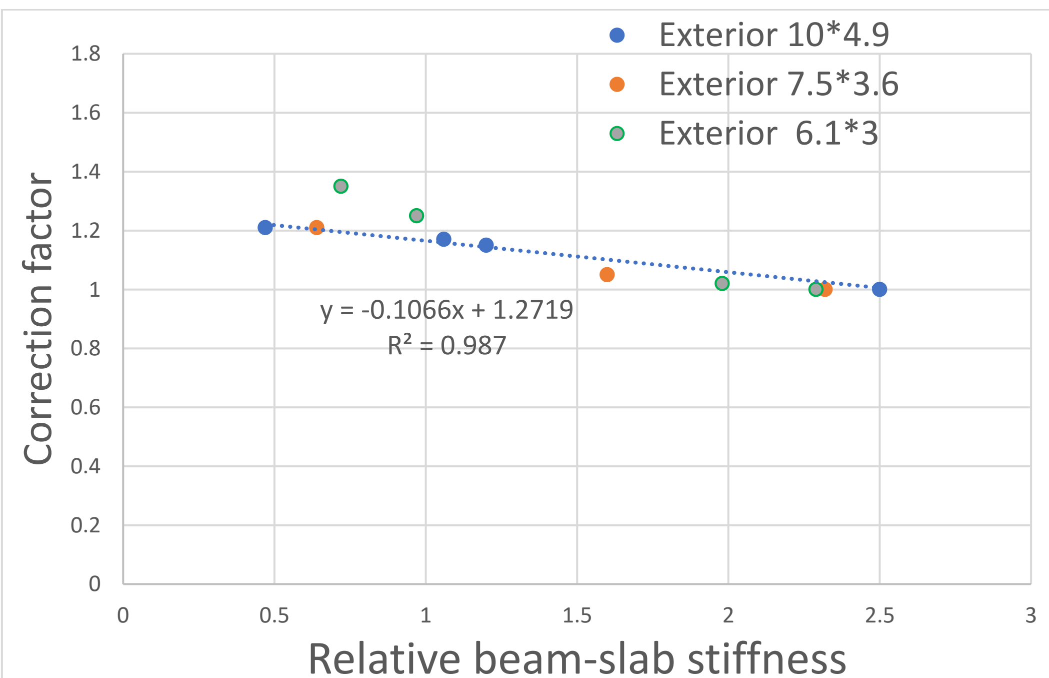


Figure 4.31: Proposed equation for different relative beam-slab of exterior panel for one-way slabs that satisfy the ℓ/240.

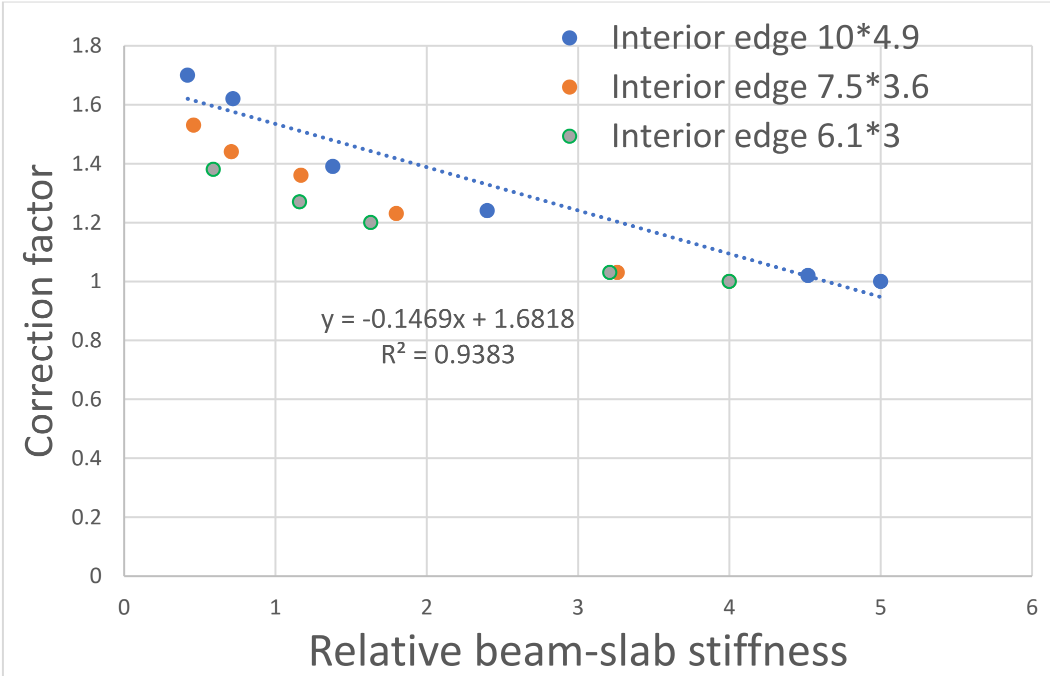


Figure 4.32: Proposed equation for different relative beam-slab stiffness of interior edge panel for one-way slabs that satisfy the ℓ/240.

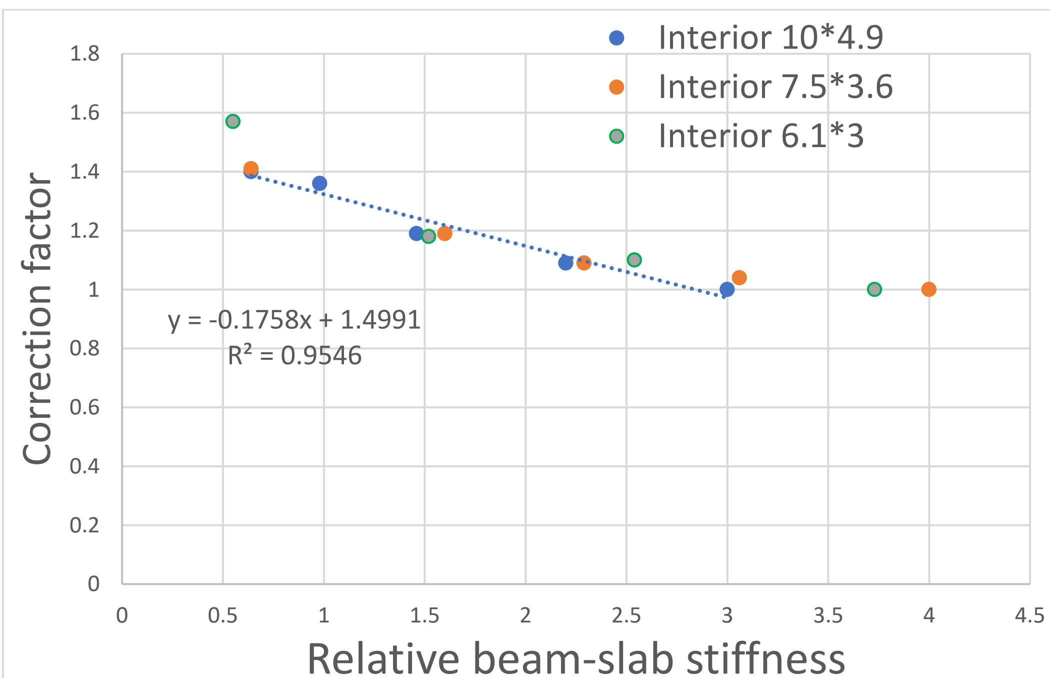


Figure 4.33: Proposed equation for different relative beam-slab stiffness of interior panel for one-way slabs that satisfy the ℓ/240.

Table 4.13: Proposed minimum thickness of one-way slabs (10 x 4.9m) that satisfying ℓ/480.

| Panel location | Relative beam-slab stiffness | Slab thickness, mm | Beam depth, mm | LTD deflection of long span (supported beam) | ℓ/480 deflection limit | Ratio (ℓ/thickness) | Proposed thickness (ℓ/ratio) | correction factor (28/ ratio and 24/ratio) |
|---|---|---|---|---|---|---|---|---|
| Interior | 0.55 | 277 | 470 | 19.97 | 20 | 16.2 | ℓ/16.2 | 1.72 |
| | 1.35 | 245 | 545 | 19.86 | 20 | 18.4 | ℓ/18.4 | 1.52 |
| | 2.31 | 225 | 590 | 19.89 | 20 | 20.0 | ℓ/20.0 | 1.40 |
| | 3.03 | 212 | 605 | 19.69 | 20 | 21.2 | ℓ/21.2 | 1.32 |
| | 6.1 | 180 | 640 | 19.91 | 20 | 25.0 | ℓ/25.0 | 1.12 |
| | 7 | 175 | 650 | 19.57 | 20 | 25.7 | ℓ/25.7 | 1.09 |
| | 8.79 | 165 | 660 | 19.63 | 20 | 27.3 | ℓ/27.3 | 1.03 |
| | 10 | 161 | 670 | 18.77 | 20 | 28 | ℓ/28 | 1 |
| Interior edge | 0.84 | 337 | 640 | 19.91 | 20 | 13.4 | ℓ/13.4 | 2.10 |
| | 1.36 | 320 | 700 | 19.67 | 20 | 14.1 | ℓ/14.1 | 1.99 |
| | 3.06 | 280 | 785 | 19.73 | 20 | 16.1 | ℓ/16.1 | 1.74 |
| | 3.78 | 266 | 797 | 19.91 | 20 | 16.9 | ℓ/16.9 | 1.66 |
| | 6.17 | 230 | 806 | 20.38 | 20 | 19.6 | ℓ/19.6 | 1.43 |
| | 8.37 | 210 | 812 | 20.6 | 20 | 21.4 | ℓ/21.4 | 1.31 |
| | 10.26 | 202 | 818 | 20.44 | 20 | 22.3 | ℓ/22.3 | 1.26 |
| | 12.91 | 184 | 820 | 20.41 | 20 | 24.5 | ℓ/24.5 | 1.14 |
| | 14.68 | 177 | 823 | 20.06 | 20 | 25.4 | ℓ/25.4 | 1.10 |
| | 16.13 | 172 | 825 | 20 | 20 | 26.2 | ℓ/26.2 | 1.07 |
| | 16.77 | 170 | 640 | 19.97 | 20 | 26.5 | ℓ/26.5 | 1.06 |
| | 17.75 | 167 | 700 | 19.93 | 20 | 26.9 | ℓ/26.9 | 1.04 |
| | 18.75 | 164 | 828 | 19.9 | 20 | 27.4 | ℓ/27.4 | 1.02 |
| | 20 | 161 | 832 | 19.67 | 20 | 28 | ℓ/28 | 1 |

| Panel location | Relative beam-slab stiffness | Slab thickness, mm | Beam depth, mm | LTD deflection of long span (supported beam) | ℓ/480 deflection limit | Ratio (ℓ/thickness) | Proposed thickness (ℓ/ratio) | correction factor (28/ ratio and 24/ratio) |
|---|---|---|---|---|---|---|---|---|
| Exterior | 1.36 | 255 | 525 | 19.83 | 20 | 17.6 | ℓ/17.6 | 1.36 |
| | 2.18 | 235 | 560 | 20 | 20 | 19.1 | ℓ/19.1 | 1.25 |
| | 3.4 | 220 | 600 | 19.66 | 20 | 20.5 | ℓ/20.5 | 1.17 |
| | 4.46 | 205 | 605 | 19.98 | 20 | 22.0 | ℓ/22.0 | 1.09 |
| | 5.8 | 195 | 630 | 19.65 | 20 | 23.1 | ℓ/23.1 | 1.04 |
| | 7 | 188 | 645 | 19.2 | 20 | 24 | ℓ/24 | 1 |
| Exterior edge | 1.1 | 337 | 640 | 19.91 | 20 | 13.4 | ℓ/13.4 | 1.80 |
| | 1.75 | 320 | 700 | 19.67 | 20 | 14.1 | ℓ/14.1 | 1.71 |
| | 3.93 | 280 | 785 | 19.73 | 20 | 16.1 | ℓ/16.1 | 1.49 |
| | 4.13 | 266 | 797 | 19.91 | 20 | 16.9 | ℓ/16.9 | 1.42 |
| | 5.38 | 261 | 806 | 19.92 | 20 | 17.2 | ℓ/17.2 | 1.39 |
| | 5.67 | 258 | 812 | 19.83 | 20 | 17.4 | ℓ/17.4 | 1.38 |
| | 6.8 | 245 | 817 | 20 | 20 | 18.4 | ℓ/18.4 | 1.31 |
| | 7.33 | 240 | 820 | 19.78 | 20 | 18.8 | ℓ/18.8 | 1.28 |
| | 7.98 | 235 | 825 | 20 | 20 | 19.1 | ℓ/19.1 | 1.25 |
| | 10.16 | 218 | 828 | 20 | 20 | 20.6 | ℓ/20.6 | 1.16 |
| | 13.7 | 198 | 830 | 19.93 | 20 | 22.7 | ℓ/22.7 | 1.06 |
| | 15.15 | 192 | 832 | 19.86 | 20 | 23.4 | ℓ/23.4 | 1.02 |
| | 17 | 188 | 844 | 19.41 | 20 | 24 | ℓ/24 | 1 |

Table 4.14: Proposed minimum thickness of one-way slabs (7.5 x 3.6m) that satisfying ℓ/480.

| Panel location | Relative beam-slab stiffness | Slab thickness, mm | Beam depth, mm | LTD deflection of long span (supported beam) | ℓ/480 deflection limit | Ratio (ℓ/thickness) | Proposed thickness (ℓ/ratio) | correction factor (28/ ratio and 24/ratio) |
|---|---|---|---|---|---|---|---|---|
| Interior | 0.96 | 187 | 350 | 14.66 | 14.79 | 17.1 | ℓ/17.1 | 1.64 |
| | 1.75 | 166 | 374 | 14.74 | 14.79 | 19.3 | ℓ/19.3 | 1.45 |
| | 3.16 | 155 | 405 | 14.77 | 14.79 | 20.6 | ℓ/20.6 | 1.36 |
| | 4.4 | 142 | 425 | 14.66 | 14.79 | 22.5 | ℓ/22.5 | 1.24 |
| | 7.21 | 125 | 438 | 14.59 | 14.79 | 25.6 | ℓ/25.6 | 1.09 |
| | 8 | 121 | 440 | 14.78 | 14.79 | 26.4 | ℓ/26.4 | 1.06 |
| | 10 | 114 | 445 | 14.95 | 14.79 | 28 | ℓ/28 | 1 |
| Interior edge | 0.64 | 215 | 355 | 14.77 | 14.79 | 14.9 | ℓ/14.9 | 1.88 |
| | 0.9 | 205 | 375 | 14.51 | 14.79 | 15.6 | ℓ/15.6 | 1.80 |
| | 1.7 | 185 | 410 | 14.71 | 14.79 | 17.3 | ℓ/17.3 | 1.62 |
| | 2.82 | 170 | 440 | 14.59 | 14.79 | 18.8 | ℓ/18.8 | 1.49 |
| | 3.81 | 160 | 455 | 14.75 | 14.79 | 20.0 | ℓ/20.0 | 1.40 |
| | 5.65 | 146 | 470 | 14.67 | 14.79 | 21.9 | ℓ/21.9 | 1.28 |
| | 6.6 | 142 | 480 | 14.74 | 14.79 | 22.5 | ℓ/22.5 | 1.24 |
| | 7.46 | 138 | 485 | 14.53 | 14.79 | 23.2 | ℓ/23.2 | 1.21 |
| | 10.62 | 124 | 489 | 14.66 | 14.79 | 25.8 | ℓ/25.8 | 1.09 |
| | 12.58 | 118 | 492 | 14.7 | 14.79 | 27.1 | ℓ/27.1 | 1.03 |
| | 14 | 114 | 494 | 14.62 | 14.79 | 28 | ℓ/28 | 1 |
| Exterior | 0.82 | 190 | 340 | 14.71 | 14.79 | 16.8 | ℓ/16.8 | 1.43 |
| | 1.44 | 181 | 354 | 14.54 | 14.79 | 17.7 | ℓ/17.7 | 1.36 |
| | 2.19 | 167 | 372 | 14.79 | 14.79 | 19.2 | ℓ/19.2 | 1.25 |

| Panel location | Relative beam-slab stiffness | Slab thickness, mm | Beam depth, mm | LTD deflection of long span (supported beam) | ℓ/480 deflection limit | Ratio (ℓ/thickness) | Proposed thickness (ℓ/ratio) | correction factor (28/ ratio and 24/ratio) |
|---|---|---|---|---|---|---|---|---|
| | 3.86 | 148 | 394 | 14.47 | 14.79 | 21.6 | ℓ/21.6 | 1.11 |
| | 4.4 | 142 | 425 | 14.66 | 14.79 | 22.5 | ℓ/22.5 | 1.07 |
| | 6.15 | 138 | 430 | 14.64 | 14.79 | 23.2 | ℓ/23.2 | 1.04 |
| | 8 | 134 | 446 | 13.63 | 14.79 | 24 | ℓ/24 | 1 |
| Exterior edge | 0.84 | 215 | 355 | 14.77 | 14.79 | 14.9 | ℓ/14.9 | 1.61 |
| | 1.17 | 205 | 375 | 14.51 | 14.79 | 15.6 | ℓ/15.6 | 1.54 |
| | 2.35 | 185 | 410 | 14.71 | 14.79 | 17.3 | ℓ/17.3 | 1.39 |
| | 3.61 | 170 | 440 | 14.59 | 14.79 | 18.8 | ℓ/18.8 | 1.28 |
| | 4.88 | 160 | 455 | 14.75 | 14.79 | 20 | ℓ/20 | 1.2 |
| | 7.2 | 146 | 470 | 14.67 | 14.79 | 21.9 | ℓ/21.9 | 1.10 |
| | 8.4 | 142 | 480 | 14.74 | 14.79 | 22.5 | ℓ/22.5 | 1.07 |
| | 9.48 | 138 | 485 | 14.53 | 14.79 | 23.2 | ℓ/23.2 | 1.04 |
| | 11 | 134 | 492 | 14.37 | 14.79 | 24 | ℓ/24 | 1 |

Table 4.15: Proposed minimum thickness of one-way slabs (6.1x 3m) that satisfying ℓ/480.

| Panel location | Relative beam-slab stiffness | Slab thickness, mm | Beam depth, mm | LTD deflection of long span (supported beam) | ℓ/480 deflection limit | Ratio (ℓ/thickness) | Proposed thickness (ℓ/ratio) | correction factor (28/ ratio and 24/ratio) |
|---|---|---|---|---|---|---|---|---|
| Interior | 0.57 | 150 | 231 | 11.88 | 11.88 | 17.3 | ℓ/17.3 | 1.62 |
| | 1.29 | 137 | 270 | 11.88 | 11.88 | 19.0 | ℓ/19.0 | 1.48 |
| | 2.32 | 125 | 395 | 11.8 | 11.88 | 20.8 | ℓ/20.8 | 1.35 |
| | 3.67 | 110 | 300 | 11.76 | 11.88 | 23.6 | ℓ/23.6 | 1.18 |
| | 6.29 | 95 | 308 | 11.66 | 11.88 | 27.4 | ℓ/27.4 | 1.02 |
| | 7 | 93 | 312 | 11.63 | 11.88 | 28 | ℓ/28 | 1 |
| Interior edge | 0.57 | 160 | 245 | 11.46 | 11.88 | 16.3 | ℓ/16.3 | 1.72 |
| | 1.1 | 150 | 280 | 11.6 | 11.88 | 17.3 | ℓ/17.3 | 1.62 |
| | 1.72 | 140 | 300 | 11.46 | 11.88 | 18.6 | ℓ/18.6 | 1.51 |
| | 2.42 | 130 | 310 | 11.8 | 11.88 | 20 | ℓ/20 | 1.4 |
| | 3.67 | 117 | 318 | 11.4 | 11.88 | 22.2 | ℓ/22.2 | 1.26 |
| | 4.84 | 111 | 329 | 11.1 | 11.88 | 23.4 | ℓ/23.4 | 1.20 |
| | 6.35 | 103 | 333 | 11.53 | 11.88 | 25.2 | ℓ/25.2 | 1.11 |
| | 6.87 | 101 | 335 | 11.41 | 11.88 | 25.7 | ℓ/25.7 | 1.09 |
| | 9 | 93 | 337 | 11.36 | 11.88 | 28 | ℓ/28 | 1 |
| Exterior | 0.74 | 152 | 232 | 11.63 | 11.88 | 17.1 | ℓ/17.1 | 1.4 |
| | 1.27 | 144 | 260 | 11.53 | 11.88 | 18.1 | ℓ/18.1 | 1.33 |
| | 2.23 | 130 | 280 | 11.87 | 11.88 | 20 | ℓ/20 | 1.2 |
| | 3.21 | 120 | 290 | 11.63 | 11.88 | 21.7 | ℓ/21.7 | 1.11 |
| | 3.98 | 114 | 295 | 11.63 | 11.88 | 22.8 | ℓ/22.8 | 1.05 |
| | 5 | 109 | 302 | 11.73 | 11.88 | 24 | ℓ/24 | 1 |

| Panel location | Relative beam-slab stiffness | Slab thickness, mm | Beam depth, mm | LTD deflection of long span (supported beam) | ℓ/480 deflection limit | Ratio (ℓ/thickness) | Proposed thickness (ℓ/ratio) | correction factor (28/ ratio and 24/ratio) |
|---|---|---|---|---|---|---|---|---|
| Exterior edge | 0.75 | 160 | 245 | 11.46 | 11.88 | 16.3 | ℓ/16.3 | 1.48 |
| | 1.42 | 150 | 280 | 11.6 | 11.88 | 17.3 | ℓ/17.3 | 1.38 |
| | 2.47 | 140 | 300 | 11.46 | 11.88 | 18.6 | ℓ/18.6 | 1.29 |
| | 3.11 | 130 | 310 | 11.8 | 11.88 | 20.0 | ℓ/20 | 1.20 |
| | 4.7 | 117 | 318 | 11.4 | 11.88 | 22.2 | ℓ/22.2 | 1.08 |
| | 6.17 | 111 | 329 | 11.1 | 11.88 | 23.4 | ℓ/23.4 | 1.02 |
| | 7 | 109 | 335 | 10.68 | 11.88 | 24 | ℓ/24 | 1 |

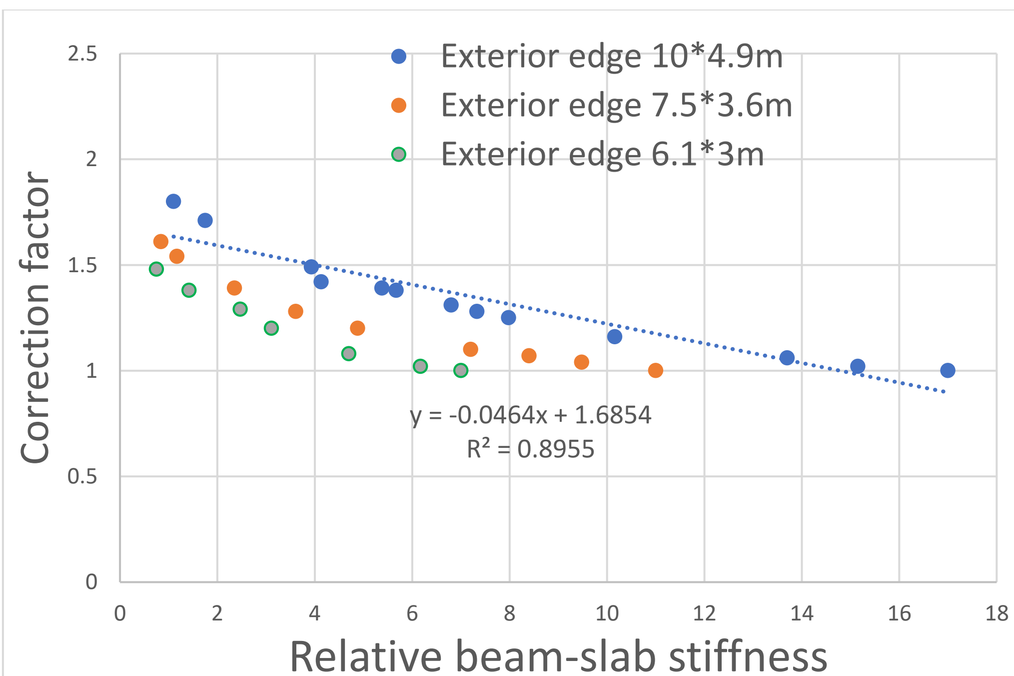


Figure 4.34: Proposed equation for different relative beam-slab stiffness of exterior edge panel for one-way slabs that satisfy the ℓ/480.

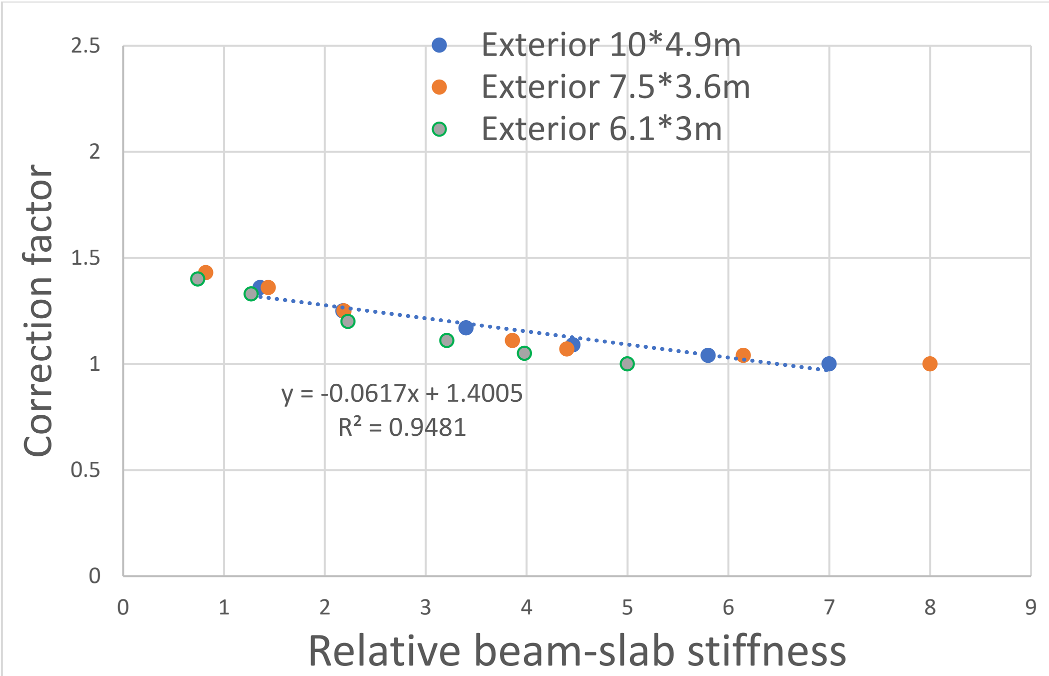


Figure 4.35: Proposed equation for different relative beam-slab stiffness of exterior panel for one-way slabs that satisfy the ℓ/480.

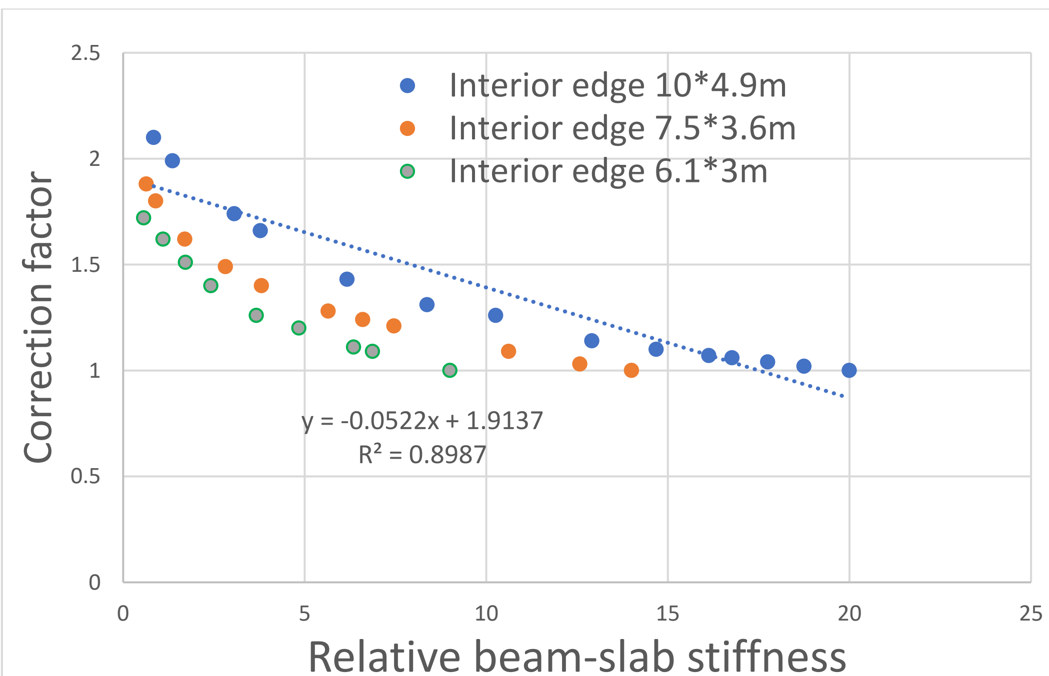


Figure 4.36: Proposed equation for different relative beam-slab stiffness of interior edge panel for one-way slabs that satisfy the ℓ/480.

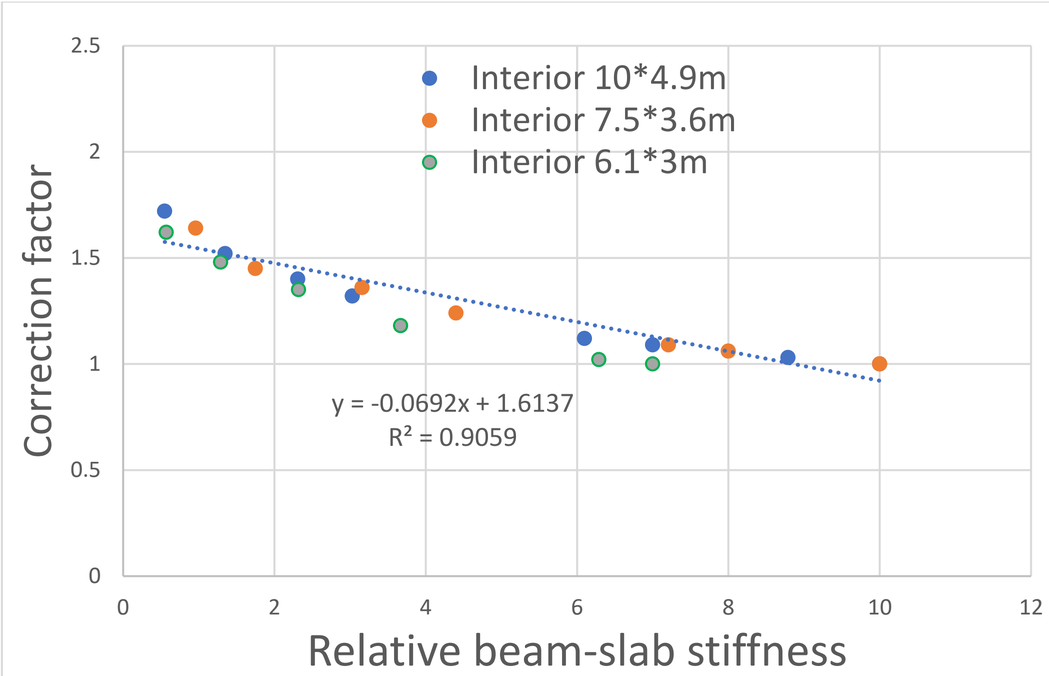


Figure 4.37: Proposed equation for different relative beam-slab stiffness of interior panel for one-way slabs that satisfy the ℓ/480.

# CHAPTER FIVE

## 5.1 Conclusion

Through a parametric study for the deflection analysis using the Finite Element SAFE software, Finite Element ANSYS software and the ACI Crossing Beam approach, the following conclusions are could be drawn:

### 5.1.1 Flat Plate Aspect Ratio

- The aspect ratio of flat plate slabs had a noticeable effect on the LTD, where for slab panels of the same long span length and different aspect ratio, as the aspect ratio is getting smaller (square slab) the LTD increases, the behavior which are overlooked by ACI318-19 two-way slab deflection control provisions

- ACI318-19 deflection provisions for flat plates provided adequate results for the ℓ /240 LTD limit in slabs long span up to 7.5 m and rectangular panels of long span of 10.0 m, but these provisions were inadequate in most of the cases (except rectangular panels of long span of 5 m) to satisfy the ℓ /480 limit.

- In the current study, minimum slab thicknesses have been proposed for the cases of flat plate slabs not satisfying the ℓ /240 and ℓ /480 deflection limits.

- The current study proposes using the slab thickness proposed for two-way flat plate slabs (Table 8.3.1.1 of ACI318-19) to all flat plate slabs regardless of the aspect ratio taking the long span as the active span.

### 5.1.2 Two-way Beam-Slab System

- Evaluating the ℓ/240 deflection limit for both mid panel and long span deflection, the ACI318-19 provisions for beam-slab systems showed to be satisfactory in all cases of interior panels. For edge and corner panels, the provisions were not satisfactory in case of relative beam-slab stiffness of 0.2 and aspect ratio of 1.

### 5.1.3 One-way Beam-Slab System

- The relative beam-slab stiffness of the beams supporting the one-way slabs has an effect on the LTD deflection of the supporting beams; the current study suggests specifying a minimum relative beam-slab stiffness for the supporting beams of 5 to satisfy the LTD limit of ℓ /240, and 20 to satisfy the LTD limit of ℓ /480 along the supporting beams.

- For low relative beam-slab stiffness in one-way slab cases, the current study proposes revised minimum slab thickness

### 5.1.4 Bondy's approach for Flat plate Thickness

- The Bondy's approach for the determination of the flat plat thickness based on the diagonal span has been showed to be adequate for L/240 deflection limit, but with uneconomical solution for short spans. For the ℓ/480 deflection limit, the approach achieves satisfactory results (deflections) only at interior panels.

### 5.1.5 Slab Deflection analysis methods

- Considering linear elastic uncracked deflection, the results of ANSYS and SAFE method were close to each other, while the ACI crossing beam method produced results close to the SAFE and ANSYS results at aspect ratio 1, while it showed a significant difference at aspect ratio 2.

## 5.2 Proposed future studies

The current performed the deflection analysis for slabs keeping some of the variables constant. In the direction, the following future studies are recommended to be done in order to have a full understanding for the parameters not studied in the current study. These studies include conducting the long-term deflection calculation for the following cases:

- Flat plate slabs as a second comparison approach among the ACI crossing beam, SAFE and ANSYS approaches
- One-way slabs having supporting beams in both the short and long directions.
- One-way slabs with aspect ratio greater than 2.1 for the evaluation of the ACI 318-19 deflection provisions.
- Flat plate slabs and one-way slabs in the buildings with more than one floors.
- Varied concrete compressive strength for the evaluation of the ACI 318-19 deflection provisions.
- Using the slab reinforcement amount obtained from the design.

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# APPENDIX A

In this appendix, the way of analyzing short term deflection of flat plate slabs in three different panels (interior, edge and exterior) are presented full using the method of ACI crossing beam. In addition, the way of the calculation of the relative beam-slab stiffness is also explained for all three panels.

## A.1 Theoretical calculation by ACI crossing beam approach

The calculating the short-term deflection by the ACI Crossing Beam of the Flat plate slab with 10 x 10 m span length as illustrated in the Figure A.1, Super imposed dead load=2.5 kN/m$^2$, Live load=1.92 kN/m$^2$, column width of 0.4m, column length of 0.4m, column height of 3m, $f_y = 420$ Mpa, fc=20 Mpa.

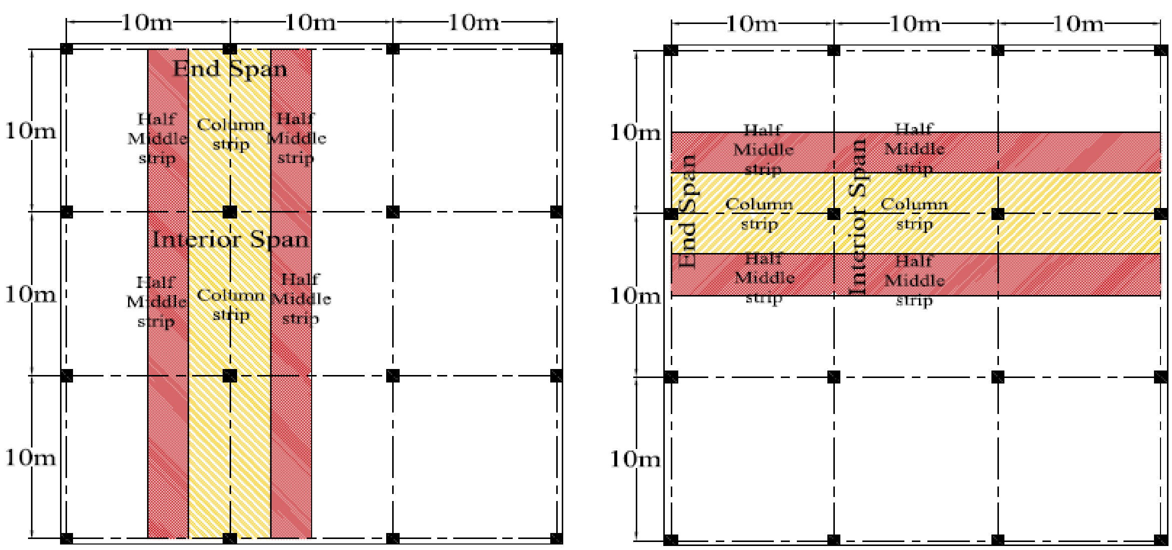


Figure A.1: Flat plate slab example with 10 x 10m

Super imposed dead load=2.5 kN/m$^2$
Live load=1.92 kN/m$^2$
L1=10 m
L2=10 M
fć=20 MP

C1=0.4 m column width

C2=0.4 m column length

Hc=3 m   clear Height of colum

Concrete density = 24 kN/m$^2$

**Long direction**

Ln=L1-c1/2-C2/2=10-0.4/2-0.4/2= 9.6 m    clear long span

h=$\ell n$/30=9.6/30=0.32 m thickness of flat plate

H=Hc+h/2=3+0.32/2=3.16 m

Is= L2 x h$^3$ /12=10 x 0.32$^3$/12=0.0273 m^4 moment of inertia of the slab

Slab self-weight = h×24=7.68 kN/m$^2$

W=h x 24+DL+LL=0.32 x 24+2.5+1.92=12.1 kN/m$^2$

The modulus of elasticity of concrete = 4700 √ fc'=21019038 kN/m$^2$

width of column strip ($b_c$) = 0.5 x L2 = 0.5×10 = 5 m

Width of middle strip($b_m$)= 0.5 x L2 = 0.5×10 = 5 m

$I_c = \frac{b_c \times h^3}{12}$ = 0.01365 m$^4$ moment of inertia of the column strip

$I_m = \frac{b_m \times h^3}{12}$ = 0.01365 m$^4$ moment of inertia of the middle strip

Delta Frame Fixed

$$\Delta_{f,ref} = \frac{wL^4}{384 E_C I_s}$$

$E_C = 4700 \times \sqrt{f\acute{c}} = 4700 \times \sqrt{20} = 21019038$ kN/m

$DL = 0.32 * 24 = 7.68$ kN/m^2

$w = (7.68 + 2.5 + 1.92) * 10 = 121$ kN/m

$\Delta_{f,ref} = \frac{121 * 10^4 * 1000}{384 * 21019038 * 0.0273} = 5.49$ mm

**A.1.1 Flexural stiffness of slab-beams at both ends**

$\frac{C1}{L1} = \frac{0.4}{10} = 0.04,\ \frac{C2}{L2} = \frac{0.4}{10} = 0.04$

$C1$ and $C2$ are the width of the column measured parallel to L1 and L2.

$K_{AB} = 4.03$ flexural stiffness of beam, from (Table A14) in (MacGregor, J G. and Wight, J K., 2012).

$COF_{AB} = 0.5019$ carry over factor

$M_{AB} = 0.08364$ fixed end moment coefficient.

$q_u = q_{DL} + q_{LL} = 1 * (7.68 + 2.5) + 1 * (1.92) = 12.1$ kN/m$^2$

**Fixed end moment, $FEM$**

$FEM = M_{AB} * q_u * L2 * L1^2 = 0.08364 * 12.1 * 10 * 10^2 = 1012.044\ kN.m$

$$K_{sb} = K_{AB}\frac{E_{cs}I_s}{L1}$$

$$K_{sb} = 4.03 * \frac{21019038 * 0.0273}{10} = 231310.42$$

**A.1.2 Flexural stiffness of column members at both ends**

H = 3.16 m = 3000 mm. Hc = 3 m=3000 mm as shown in the Figure A.2

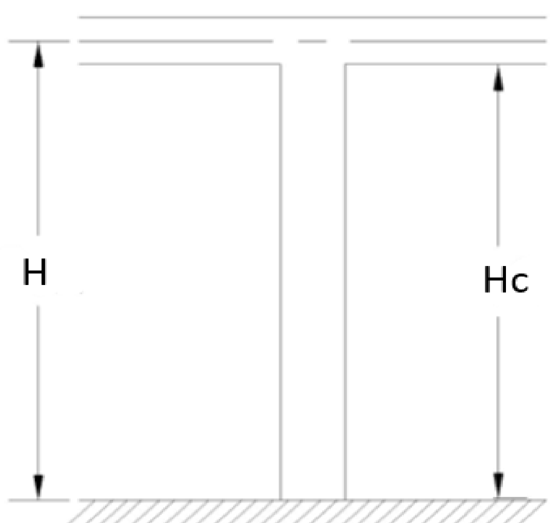


Figure A.2: Column height from ground to floor ta/tb = 0, H/Hc = 1.0533

K=4.212 column stiffness, from (PCA Notes on ACI 318-11, 2013) (Table A7)

$$I_c = \frac{(C1)^4}{12} = \frac{0.4^4}{12} 0.00213$$

$$Kc = \frac{k * E_{CS} * I_C}{H} = \frac{4.212 * 21019038 * 0.0213}{3} = 62956.22$$

$$\mathrm{C} = \left(1 - 0.63 * \frac{x}{y}\right) * \frac{\mathrm{x}^3 * \mathrm{y}}{3}$$

x=0.32m, y=0.4m as shown in the Figure A.3.

$\mathrm{C} = \left(1 - 0.63 * \frac{0.32}{0.4}\right) * \frac{0.32^3 * 0.4}{3} = 0.00216$ m^4 moment of inertia of the column

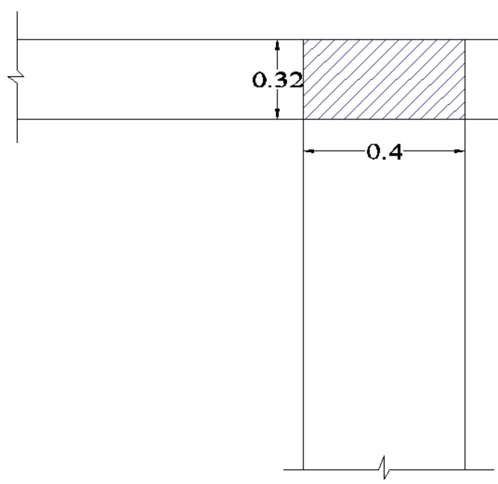


Figure A.3: Column stiffness taking from the thickness of the slab and width of the column

### A.1.3 Effect of column torsion

$C_2 = 0.4\, m, \;\; L2 = 10\, m$

$$Kt = \frac{9 E_{cs} C}{\left[L_2 \left(1 - \frac{C_2}{L_2}\right)\right]}$$

$$Kt = \frac{9 * 21019038 * 0.00216}{\left[10 * \left(1 - \frac{0.4}{10}\right)^3\right]} = 46335.3$$

From Figure A.4:

$$K_{ec} = \frac{\sum K_c \times \sum K_t}{\sum K_c \times \sum K_t}$$

Equivalent column stiffness

$$K_{ec} = \frac{K_c*(K_t*2)}{K_c+(K_t*2)} = \frac{62956.22*(46335.3*2)}{62956.22+(46335.3*2)} = 37488.34$$

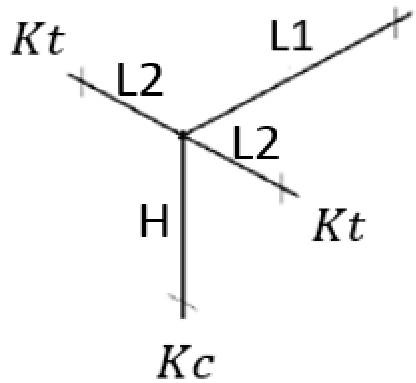


Figure A.4: Flexural stiffnesses of column member

### A.1.4 Slab-beam joint distribution factors, *DF*

$K_{sb}$ and $K_{ec}$ are shown in the Figure A.5.

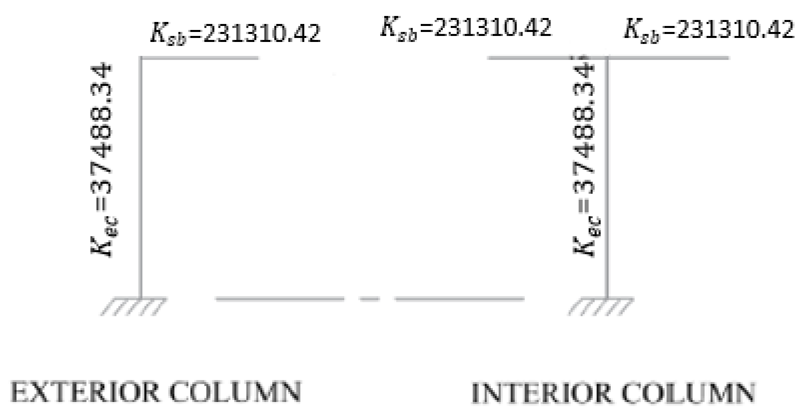


Figure A.5: Equivalent column stiffness and slab stiffnesses

At exterior joint

$$DF = \frac{K_{sb}}{K_{sb} + K_{ec}} = \frac{231310.42}{231310.42 + 37488.34} = 0.8605$$

At interior joint joint

$$DF = \frac{K_{sb}}{K_{sb} + K_{sb} + K_{ec}} = \frac{231310.42}{231310.42 + 231310.42 + 37488.34} = 0.4625$$

M net =159.81 kN.m  Exterior negative moment at the end span as illustrated in Table A.1.

Table A.1: Moment distribution method


| joint | 1.0000 | 2.0000 | | 3.0000 | | 4.0000 |
|---|---|---|---|---|---|---|
| Member | 1--2 | 2--1 | 2--3 | 3--2 | 3--4 | 4--3 |
| DF | 0.8605 | 0.4625 | 0.4625 | 0.4625 | 0.4625 | 0.8605 |
| COF | 0.5019 | 0.5019 | 0.5019 | 0.5019 | 0.5019 | 0.5019 |
| FEM | 1012.0440 | -1012.0440 | 1012.0440 | -1012.0440 | 1012.0440 | -1012.0440 |
| Dist | -870.8981 | 0 | 0 | 0 | 0 | 870.8981 |
| Co | 0 | -437.1212 | 0 | 0 | 437.1212 | 0 |
| Dist | 0 | 202.1772 | 202.1772 | -202.1772 | -202.1772 | 0 |
| Co | 101.4768 | 0 | -101.4768 | 101.4768 | 0 | -101.4768 |
| Dist | -87.3242 | 46.9350 | 46.9350 | -46.9350 | -46.9350 | 87.3242 |
| Co | 23.5576 | -43.8298 | -23.5576 | 23.5576 | 43.8298 | -23.5576 |
| Dist | -20.2721 | 10.8959 | 10.8959 | -10.8959 | -10.8959 | 20.2721 |
| Co | 5.4689 | -10.1750 | -5.4689 | 5.4689 | 10.1750 | -5.4689 |
| Dist | -4.7061 | 2.5295 | 2.5295 | -2.5295 | -2.5295 | 4.7061 |
| Co | 1.2696 | -2.3621 | -1.2696 | 1.2696 | 2.3621 | -1.2696 |
| Dist | -1.0925 | 0.5872 | 0.5872 | -0.5872 | -0.5872 | 1.0925 |
| Co | 0.2947 | -0.5484 | -0.2947 | 0.2947 | 0.5484 | -0.2947 |
| Neg.M | 159.8185 | -1242.9556 | 1143.1012 | -1143.1012 | 1242.9556 | -159.8185 |

$$\theta = \frac{M_{net}}{K_{ec}}$$

$$\theta = \frac{159.8185}{42560.91} = 0.004263$$

$$\Delta\theta = \theta \times \left(\frac{L}{8}\right)\left(\frac{I_s}{I_e}\right)$$

$\Delta\theta = 0.004263 * \frac{10}{8} * (1) = 5.3289$ mm due to rotating

Load factor of column strip for end span

LF $= \frac{0.60+\frac{1+0.75}{2}}{2} = 0.7375$ as shown in Table 2.5 and Table 2.6, from (ACI 318-14, 2014) section 8-10.

Load factor of column strip for interior span

LF $= \frac{0.75+0.6}{2} = 0.675$ as shown in Table 2.5 and Table 2.6, from (ACI 318-14, 2014) section 8-10.

### A.1.5 Deflection calculation

Deflection of the column strip and middle strip for End span in long direction

$$\Delta c = LF \times \Delta_{f,ref} \times \frac{I_s}{I_c} + \Delta\theta$$

$\Delta c = 0.7375 \times 5.49 * \frac{0.0273}{0.01365} + 5.3289 = 13.42\ mm$ column strip deflection

$$\Delta m = LF \times \Delta_{f,ref} \times \frac{I_s}{I_m} + \Delta\theta$$

$\Delta m = 0.2625 \times 5.49 \times \frac{0.0273}{0.01365} + 5.3289 = 8.21\ mm$ middle strip deflection

Deflection of the column strip and middle strip for interior span in long direction

$\Delta c = 0.675 \times 5.49 \times \frac{0.0273}{0.01365} = 7.41\ mm$ column strip deflection

$\Delta m = 0.325 \times 5.49 \times \frac{0.0273}{0.01365} = 3.56\ mm$ middle strip deflection

Because of the similarity, the deflection calculation of long direction equal to the deflection calculation of short direction as shown in the Figure A.6.

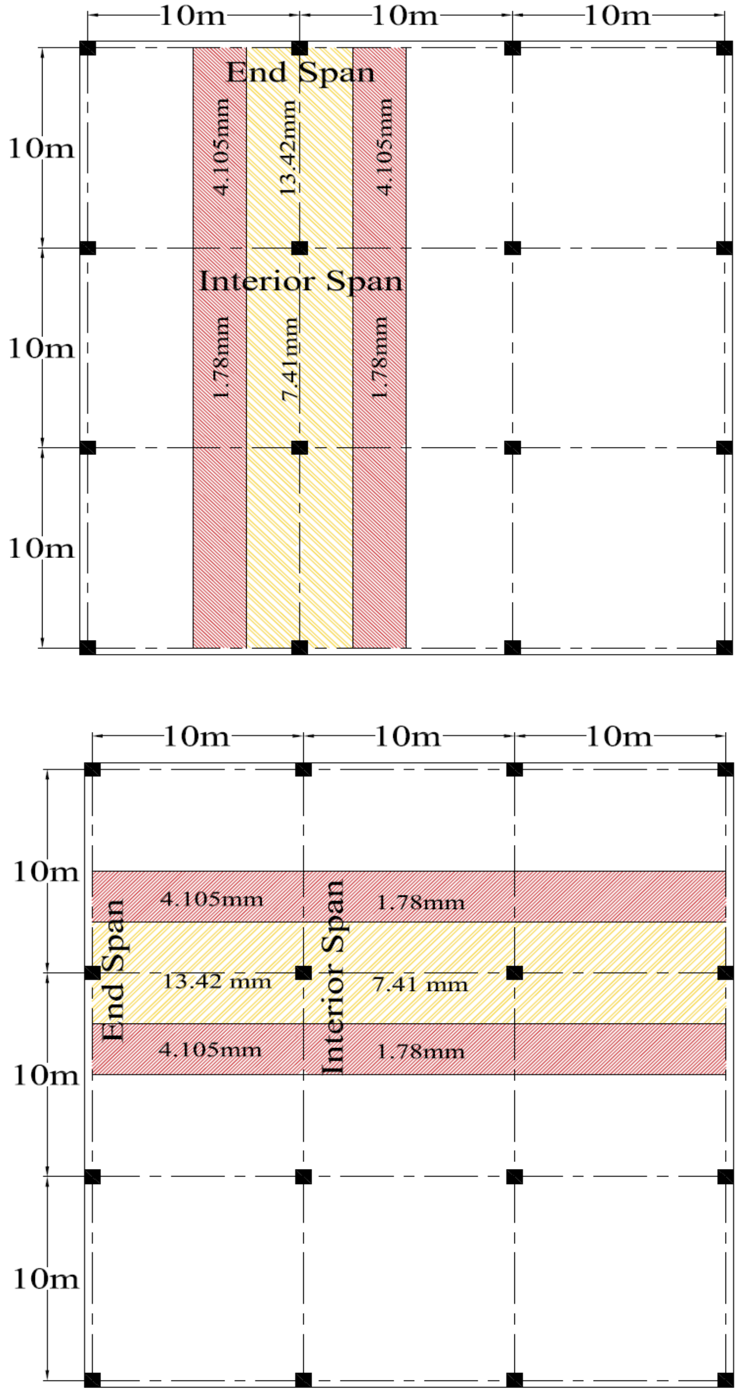


Figure A.6: Column strip and half of middle strip deflection of end span and interior span for the flat plate slabs

Corner panel

$$\Delta = \frac{(\Delta c\ long\ direction + \Delta m\ Shortdirection) + (\Delta c\ short\ direction + \Delta m\ longdirection)}{2}$$

$$= \frac{(13.42+8.21)+((13.42+8.21))}{2} = 21.63mm$$

Edge panel

$$\Delta = \frac{(\Delta c\ long\ direction + \Delta m\ Shortdirection) + (\Delta c\ short\ direction + \Delta m\ longdirection)}{2}$$

$$= \frac{(13.42 + 3.56) + (7.41 + 8.21)}{2} = 16.3\ mm$$

Interior panel

$$\Delta = \frac{(\Delta c\ long\ direction + \Delta m\ Shortdirection) + (\Delta c\ short\ direction + \Delta m\ longdirection)}{2}$$

$$= \frac{(7.41 + 3.56) + (7.41 + 3.56)}{2} = 10.98\ mm$$

## A.2 Relative stiffness

Relative stiffens of Two-way beam-slabs can be calculated as a ratio of the moment of inertia of beam to the moment of inertia of slab.

Calculating the relative stiffness of two-way beam-slabs for interior, edge and corner panel as shown in the Figure A.7 with;

L1=1000 mm

L2=1000 mm

Beam width ($b_w$)= 400 mm

Beam height (H)= 730 mm

Thickness of the slab ($h$) = 235 mm

$f_y = 420$ MPa

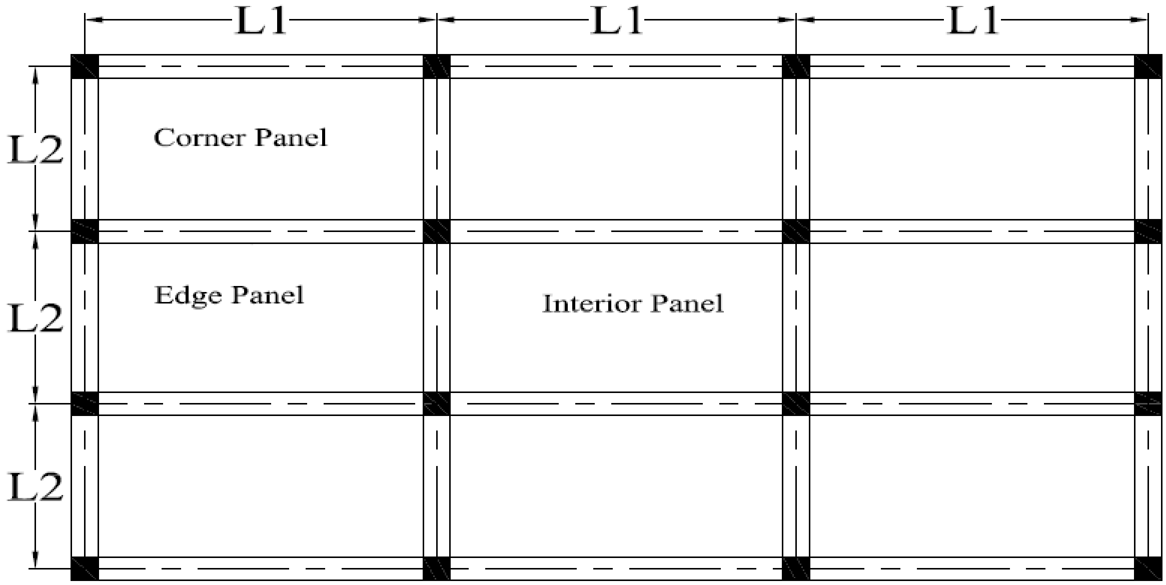


Figure A.7: Two-way beam slabs

### A.2.1 Relative stiffness for interior panel

$$\alpha = \frac{EI_b}{EI_s}$$

$$I_b = Ct\frac{b_w(H_b)^3}{12}$$

Moment of inertia for interior beam

$$Ct = 1 + (A-1)B^3 + \frac{3(1-B)^2(A-1)}{1+B(A-1)}$$

$$B = \frac{h_f}{H_b} = \frac{235}{730} = 0.3219$$

$$A = \frac{b}{b_w}$$

$b = (b_w + 2h_w \leq b_w + 8h_f)$ as shown in the Figure A.8.

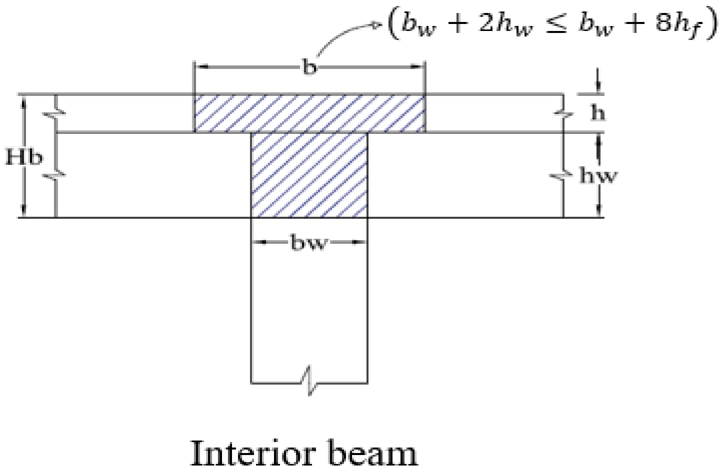


Figure A.8: Interior beam of two-way beam-slab

$b_w + 2h_f = 400 + 2 * (730 - 235) = 1390$

$b_w + 8h_f = 400 + 8 * 235 = 2280$

$b = 1390\ mm \le 2280$ mm

$$A = \frac{b}{b_w} = \frac{1390}{400} = 3.475$$

$$Ct = 1 + (3.475 - 1) \times 0.3219^3 + \frac{3(1 - 0.3219)^2(3.475 - 1)}{1 + 0.3219 \times (3.475 - 1)} = 1.6942$$

$$I_b = Ct\frac{b_w {H_b}^3}{12} = 1.6942 \times \frac{0.4 \times 0.73^3}{12} = 0.02197\ m^4$$

Moment of inertia for interior span

$L_2 = 10$ for interior span as shown in Figure A.9.

$$I_s = \frac{L_2 h^3}{12} = \frac{5 \times 0.235^3}{12} = 0.01081$$

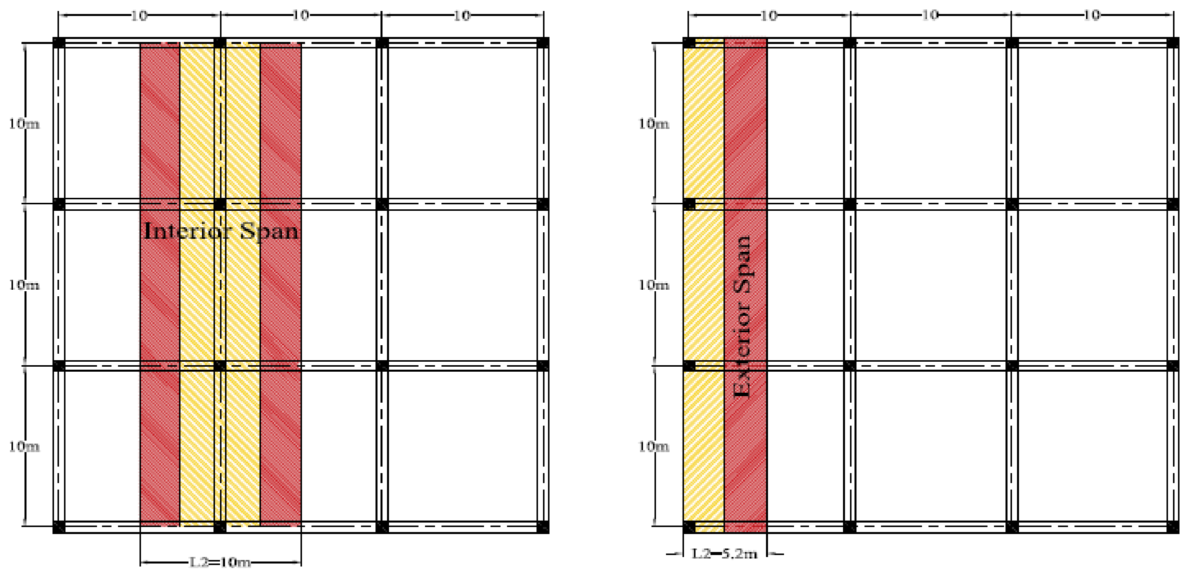


Figure A.9: Exterior and interior span of two-way beam-slabs by method of ACI crossing beam approach

$$\alpha = \frac{EI_b}{EI_s} = \frac{0.02197}{0.01081} = 2.03$$

$$\alpha_{fm} = \frac{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4}{4} = \frac{2.03 + 2.03 + 2.03 + 2.03}{4} = 2.03$$

$$h = \frac{\ell_n \left(0.8 + \frac{f_y}{1400}\right)}{36 + 9\beta} = \frac{9600 \left(0.8 + \frac{420}{1400}\right)}{36 + 9 \times 1} = 234.67mm$$

Using the thickness of 235 mm for interior panel is satisfied

### A.2.2 Relative stiffness for edge panel

Moment inertia for edge beam

$$I_b = Ct \frac{b_w {H_b}^3}{12}$$

$$Ct = 1 + (A - 1)B^3 + \frac{3(1-B)^2(A-1)}{1+B(A-1)}$$

$$B = \frac{h_f}{H_b} = \frac{235}{730} = 0.3219$$

$$A = \frac{b}{b_w}$$

$b = (h_w \leq 4h_f)$ as shown in the Figure A.10.

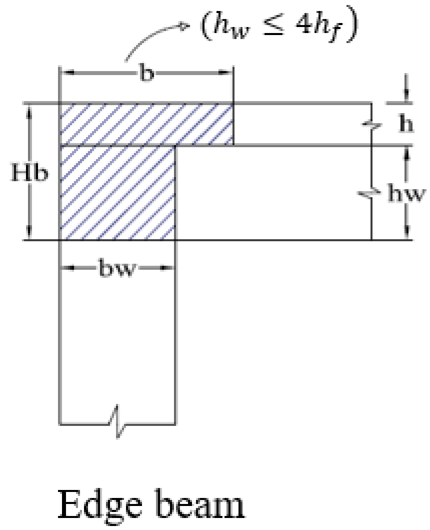


Figure A.10: Edge beam of two-way beam-slab.

$$h_w = 7300 - 235 = 495\,mm$$

$$4h_f = 4 * 235 = 940\,mm$$

$$b = 495 + b_w = 495 + 400 = 895mm$$

$$A = \frac{b}{b_w} = \frac{895}{400} = 2.2375$$

$$Ct = 1 + (2.2375 - 1) \times 0.3219^3 + \frac{3(1 - 0.3219)^2(2.2375 - 1)}{1 + 0.3219 \times (2.2375 - 1)} = 1.4342$$

$$I_b = Ct\frac{b_w(H_b)^3}{12} = 1.4342 \times \frac{0.4 \times 0.73^3}{12} = 0.0186\,m^4$$

Moment of inertia for exterior span

$L_2 = \frac{10}{2} + \frac{0.4}{2} = 5.2\,m$ for exterior span

$$I_s = \frac{L_2 h^3}{12} = \frac{5.2 \times 0.235^3}{12} = 0.005623$$

$$\alpha = \frac{EI_b}{EI_s} = \frac{0.0186}{0.005623} = 3.31$$

$$\alpha_{\text{fm}} = \frac{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4}{4} = \frac{2.03 + 2.03 + 3.31 + 2.03}{4} = 2.35$$

$$\beta = \frac{9600}{9600}$$

$$h = \frac{\ell_{\text{n}}\left(0.8 + \frac{\text{f}_{\text{y}}}{1400}\right)}{36 + 9\beta} = \frac{9600\left(0.8 + \frac{420}{1400}\right)}{36 + 9 \times 1} = 234.67$$

Using the thickness of 235 mm for edge panel is satisfied

### A.2.3 Relative stiffness for corner panel

$$\alpha_{\text{fm}} = \frac{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4}{4} = \frac{2.03 + 3.31 + 2.03 + 3.31}{4} = 2.67$$

$$h = \frac{\ell_{\text{n}}\left(0.8 + \frac{\text{f}_{\text{y}}}{1400}\right)}{36 + 9\beta} = \frac{9600\left(0.8 + \frac{420}{1400}\right)}{36 + 9 \times 1} = 234.67$$

Using the thickness of 235 mm for corner panel is satisfied

# APPENDIX B

## Table of results

This Appendix lists the table of the results of the parametric studies presented and discussed in chapter 4.

Table B.1: Short term deflection results of interior panel flat plate slab, calculated by SAFE, ANSYS and ACI crossing approach ( data of Figure 4.1 and 4.4).

| L1 | L2 | Aspect ratio | h(mm) | Mid panel deflection (mm) | | | Long span deflection (mm) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | ACI crossing beam | ANSYS | SAFE | ACI crossing beam | Ansys | Safe |
| 10 | 10 | 1 | 320 | 10.98 | 8.69 | 8.18 | 7.41 | 8.62 | 7.96 |
| 10 | 5 | 2 | 320 | 6.02 | 4.76 | 4.53 | 7.41 | 4.89 | 4.64 |
| 7.5 | 7.5 | 1 | 237 | 7.16 | 6.12 | 5.77 | 4.83 | 5.59 | 5.09 |
| 7.5 | 3.75 | 2 | 237 | 3.93 | 3.37 | `3.21 | 4.83 | 3.45 | 3.26 |
| 5 | 5 | 1 | 154 | 4.17 | 3.67 | 3.47 | 2.81 | 2.95 | 2.72 |
| 5 | 2.5 | 2 | 154 | 2.29 | 1.96 | 1.84 | 2.81 | 1.96 | 1.84 |

Table B.2: Short term deflection results of edge panel flat plate slab, calculated by SAFE, ANSYS and ACI crossing approach ( data of Figure 4.2 and 4.5).

| L1 | L2 | Aspect ratio | h (m) | Mid panel deflection (mm) | | | Long span deflection (mm) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | ACI crossing beam | ANSYS | SAFE | ACI crossing beam | Ansys | Safe |
| 10 | 10 | 1 | 320 | 16.3 | 16.93 | 16.51 | 13.42 | 16.51 | 16 |
| 10 | 5 | 2 | 320 | 10.23 | 11.02 | 10.77 | 12.3 | 11.03 | 10.78 |
| 7.5 | 7.5 | 1 | 237 | 10.08 | 9.97 | 9.6 | 8.2 | 9.21 | 8.73 |
| 7.5 | 3.75 | 2 | 237 | 5.85 | 5.97 | 5.69 | 7.2 | 5.95 | 5.67 |
| 5 | 5 | 1 | 154 | 5.33 | 4.82 | 4.51 | 4.24 | 4.04 | 3.68 |
| 5 | 2.5 | 2 | 154 | 2.83 | 2.57 | 2.36 | 3.61 | 2.55 | 2.35 |

Table B.3: Short term deflection results of corner panel flat plate slab, calculated by SAFE, ANSYS and ACI crossing approach ( data of Figure 4.3 and 4.6).

| L1 | L2 | Aspect ratio | h(mm) | Mid panel deflection (mm) | | | Long span deflection (mm) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | ACI crossing beam | ANSYS | SAFE | ACI crossing beam | Ansys | Safe |
| 10 | 10 | 1 | 320 | 21.63 | 22.75 | 22.43 | 13.42 | 16.51 | 16 |
| 10 | 5 | 2 | 320 | 10.98 | 10.96 | 10.71 | 12.3 | 11.03 | 10.78 |
| 7.5 | 7.5 | 1 | 237 | 12.68 | 12.63 | 12.18 | 8.04 | 9.21 | 8.73 |
| 7.5 | 3.75 | 2 | 237 | 13.01 | 12.63 | 12.18 | 8.2 | 9.21 | 8.73 |
| 5 | 5 | 1 | 154 | 6.29 | 5.87 | 5.59 | 7.2 | 5.95 | 5.67 |
| 5 | 2.5 | 2 | 154 | 3 | 2.51 | 2.31 | 3.61 | 2.55 | 2.35 |

Table B.4: LTD results of interior panel beam-slab with relative beam-slab stiffness of 0.2, calculated by SAFE.

| L1 | L2 | Aspect ratio | h(mm) | Beam height (mm) | Relative beam-slab stiffness | Mid panel deflection (mm) | Long span deflection (mm) |
|---|---|---|---|---|---|---|---|
| 10 | 10 | 1 | 293 | 452 | 0.197 | 29.81 | 26.18 |
| 10 | 5 | 2 | 293 | 405 | 0.202 | 20.14 | 20.13 |
| 7.5 | 7.5 | 1 | 217 | 313 | 0.196 | 23.84 | 18.75 |
| 7.5 | 3.75 | 2 | 217 | 278 | 0.197 | 12.68 | 12.54 |
| 5 | 5 | 1 | 141 | 183 | 0.195 | 12.6 | 9.27 |
| 5 | 2.5 | 2 | 141 | 162 | 0.195 | 5.88 | 5.8 |

Table B.5: LTD results of edge panel from beam-slab with relative beam-slab stiffness of 0.2, calculated by SAFE.

| L1 | L2 | Aspect ratio | h(mm) | Beam height (mm) | Relative beam-slab stiffness | $h + 0.10h$ | Mid panel deflection (mm) | Long Span deflection (mm) |
|---|---|---|---|---|---|---|---|---|
| 10 | 10 | 1 | 290 | 290 | 0.275 | 319 | 50.73 | 47.63 |
| 10 | 5 | 2 | 286 | 286 | 0.289 | 314.6 | 37.56 | 36.93 |
| 7.5 | 7.5 | 1 | 215 | 215 | 0.271 | 236.5 | 26.87 | 22.39 |
| 7.5 | 3.75 | 2 | 212 | 212 | 0.286 | 233.2 | 14.29 | 14.1 |
| 5 | 5 | 1 | 139 | 139 | 0.274 | 152.9 | 12.04 | 9.11 |
| 5 | 2.5 | 2 | 135 | 135 | 0.2899 | 148.5 | 5.97 | 5.86 |

Table B.6: LTD results of corner panel beam-slab with relative beam-slab stiffness of 0.2, calculated by SAFE.

| L1 | L2 | Aspect ratio | h(mm) | Beam height (mm) | Relative beam-slab stiffness | $h + 0.10h$ | Mid panel deflection (mm) | Long span deflection (mm) |
|---|---|---|---|---|---|---|---|---|
| 10 | 10 | 1 | 290 | 453 | 0.276 | 319 | 73.5 | 48.63 |
| 10 | 5 | 2 | 286 | 404 | 0.29 | 314.6 | 31.62 | 32.54 |
| 7.5 | 7.5 | 1 | 215 | 312 | 0.273 | 236.5 | 32.56 | 22.74 |
| 7.5 | 3.75 | 2 | 211 | 278 | 0.291 | 232.1 | 14.35 | 14.71 |
| 5 | 5 | 1 | 139 | 182 | 0.276 | 152.9 | 1311 | 9.5 |
| 5 | 2.5 | 2 | 137 | 162 | 0.2899 | 150.7 | 5.83 | 5.87 |

Table B.7: LTD results of interior panel beam-slab with relative beam-slab stiffness of 2, calculated by SAFE.

| L1 | L2 | Aspect ratio | h(mm) | Beam height (mm) | Relative beam-slab stiffness | Mid panel deflection (mm) | Long span deflection (mm) |
|---|---|---|---|---|---|---|---|
| 10 | 10 | 1 | 235 | 730 | 2 | 32.23 | 17.23 |
| 10 | 5 | 2 | 193 | 538 | 2 | 28.97 | 27.59 |
| 7.5 | 7.5 | 1 | 174 | 505 | 2 | 22.37 | 12.54 |
| 7.5 | 3.75 | 2 | 142 | 371 | 2 | 28.97 | 18.97 |
| 5 | 5 | 1 | 112 | 297 | 2 | 12.72 | 6.7 |
| 5 | 2.5 | 2 | 91 | 216 | 2 | 9.82 | 8.98 |

Table B.8: LTD results of edge panel beam-slab with relative beam-slab stiffness of 2, calculated by SAFE.

| L1 | L2 | Aspect ratio | h(mm) | Beam height (mm) | Relative beam-slab stiffness | Mid panel deflection (mm) | Long span deflection (mm) |
|---|---|---|---|---|---|---|---|
| 10 | 10 | 1 | 235 | 700 | 2 | 55.63 | 37.72 |
| 10 | 5 | 2 | 193 | 524 | 2 | 43.68 | 40.92 |
| 7.5 | 7.5 | 1 | 174 | 485 | 2 | 31.75 | 20.65 |
| 7.5 | 3.75 | 2 | 142 | 360 | 2 | 24.2 | 22.9 |
| 5 | 5 | 1 | 112 | 284 | 2 | 14.93 | 8.26 |
| 5 | 2.5 | 2 | 91 | 210 | 2 | 12.35 | 11.49 |

Table B.9: LTD results of corner panel beam-slab with beam-slab relative stiffness of 2, calculated by SAFE.

| L1 | L2 | Aspect ratio | h(mm) | Beam height (mm) | Relative beam-slab stiffness | Mid panel deflection (mm) | Long span deflection (mm) |
|---|---|---|---|---|---|---|---|
| 10 | 10 | 1 | 235 | 674 | 2 | 78.73 | 40.11 |
| 10 | 5 | 2 | 193 | 500 | 2 | 43.53 | 44.23 |
| 7.5 | 7.5 | 1 | 174 | 468 | 2 | 38.58 | 21.71 |
| 7.5 | 3.75 | 2 | 142 | 343 | 2 | 23.6 | 25.19 |
| 5 | 5 | 1 | 112 | 274 | 2 | 16.62 | 8.72 |
| 5 | 2.5 | 2 | 91 | 200 | 2 | 10.69 | 11.36 |

Table B.10: LTD results of interior panel flat plate slabs with using Bondy's approach

| L1 | L2 | Ld | Ld clear, (Ldc) | Aspect ratio | h(mm), Ldc/33 | Mid panel Deflection (mm) | Long Span Deflection (mm) |
|---|---|---|---|---|---|---|---|
| 10 | 10 | 14.14 | 13.6 | 1 | 412 | 16.59 | 15.52 |
| 10 | 5 | 11.18 | 10.6 | 2 | 322 | 17.84 | 18.01 |
| 7.5 | 7.5 | 10.61 | 10.0 | 1 | 305 | 12.32 | 10.24 |
| 7.5 | 3.75 | 8.39 | 7.8 | 2 | 237 | 11.38 | 11.43 |
| 5 | 5 | 7.07 | 6.5 | 1 | 197 | 6.82 | 5.19 |
| 5 | 2.5 | 5.59 | 5.0 | 2 | 153 | 5.73 | 5.7 |

Table B.11: LTD results of edge panel flat plate slabs with using Bondy's approach.

| L1 | L2 | Ld | Ld clear, (Ldc) | Aspect ratio | h(mm), Ldc/30 | Mid panel Deflection (mm) | Long Span Deflection (mm) |
|---|---|---|---|---|---|---|---|
| 10 | 10 | 14.14 | 13.6 | 1 | 453 | 26.03 | 25.34 |
| 10 | 5 | 11.18 | 10.6 | 2 | 354 | 27.55 | 27.44 |
| 7.5 | 7.5 | 10.61 | 10.0 | 1 | 335 | 14.21 | 12.5 |
| 7.5 | 3.75 | 8.39 | 7.8 | 2 | 261 | 13.01 | 12.9 |
| 5 | 5 | 7.07 | 6.5 | 1 | 217 | 6.47 | 5.15 |
| 5 | 2.5 | 5.59 | 5.0 | 2 | 168 | 5.32 | 5.27 |

Table B.12: LTD results of corner panel flat plate slabs with using Bondy's approach.

| L1 | L2 | Ld | Ld clear, (Ldc) | Aspect ratio | h(mm), Ldc/30 | Mid panel Deflection (mm) | Long Span Deflection (mm) |
|---|---|---|---|---|---|---|---|
| 10 | 10 | 14.14 | 13.6 | 1 | 453 | 34.47 | 25.34 |
| 10 | 5 | 11.18 | 10.6 | 2 | 354 | 27.68 | 27.44 |
| 7.5 | 7.5 | 10.61 | 10.0 | 1 | 335 | 17.09 | 12.5 |
| 7.5 | 3.75 | 8.39 | 7.8 | 2 | 261 | 12.73 | 12.9 |
| 5 | 5 | 7.07 | 6.5 | 1 | 217 | 7.21 | 5.15 |
| 5 | 2.5 | 5.59 | 5.0 | 2 | 168 | 5.25 | 5.27 |

## پوختە

ئەم توێژینەوە لێکۆڵینەوە دەکات لە بری هاتنە خوارەوەی بنمیچی کۆنکریتی شیشدار بە ئامانجی تێگەیشتنێکی باشترلە پارامیتەرەکانی ڕێژەی ڕووبەر (لای درێژ/لای کورت) (aspect ratio) و رەقبونی ڕێژەیی رایەڵ بۆ بنمیچ (relative beam-slab stiffness) و هەڵسەنگاندنی بڕگەکانی ACI318-19 بۆ کۆنترۆڵکردنی بری هاتنە خوارەوەی بنمیچ. ئەم توێژینەوە هەردوو شێوازەکانی حیساب کردنی هاتنە خوارەوەی بنمیچی لە خۆوە گرتووە (هاتنە خوارەوەی درێژخایەنی بنمیچ long term deflection) LTD) و هاتنە خوارەوەی کورتخایەنی بنمیچ short term deflection) بۆ هەڵسەنگاندنی پارامێتەرەکانی ئاماژەپێکراو وەهەروەها هاتنە خوارەوەی کورتخایەنی بنمیچ بە کار هاتووە بۆ بەراورد کردنی شێوازەکانی حیساب کردنی هاتنە خوارەوەی بنمیچ ,Finite Element SAFE software) ANSYS software and the ACI crossing beam approach).

وەک چۆن ڕێژەی ڕووبەرلە ACI318-19 نیە کە کاریگەرییان هەیە لەسەر دۆزینەوەی ئەستووری بنمیچی پلێتی تەخت (flat plate slab). شیکارکردنی هاتنە خوارەوەی درێژخایەنی پارامێتری بنمیچ (LTD) ئەنجام دراوە بە بەکارهێنانی بەرنامەی SAFE بۆ لای درێژی جیاواز (5م، 7.5م، 10م) و ڕێژەی ڕووبەری جیاواز لە پانێلە جیاوازەکانی (ناوەوە و لێوار و گۆشە). ئەنجامەکان دەریانخست کە ڕێژەی ڕووبەر کاریگەرییەکی بەرچاوی هەیە لەسەر LTD لای درێژ (long span) و کە ئەستوورییە پێشنیار کراوەکانی ACI318-19 بەشێکی سنووری ڕێگە پێدراوی هاتنەخوارەوەی بنمیچ deflection) ℓ/240 limit) بە دیهێناوە لە پانێڵەکانی لای درێژ تاوەکو 7.5 م بە مەودای ڕێژەی ڕووبەری 1 بۆ 2 هەروها لە پانێڵەکانی لای درێژی بەرز 10 م بە ڕێژەی ڕووبەری 1. بۆ سنووری ڕێگە پێدراوی هاتنەخوارەوەی بنمیچ ℓ/480، جگە لە پانێڵی چوارگۆشەی لای درێژی 5 م، لە هەموو حاڵەتەکانی تردا بڕگەکان بەس نەبوون بۆ جێبەجێکردنی سنووری ڕێگە پێدراوی هاتنەخوارەوەی بنمیچ ℓ/480. بۆ ڕێژەی ڕووبەری گەورەتر لە 3، لەم توێژینەوەیەدا پێشنیاری بەکارهێنانی هەمان ACI318-19 دەکات بۆ ئەستووری بنمیچی تەختی پلێت بە وەرگرتنی درێژای درێژ(long span) وەک (span)ی چالاک، بۆ حاڵەتە لادراوەکانی سنووری ڕێگەپێدراوی بنمییچ ، توێژینەوەکە کەمترین ئەستووری پێشنیار کردووە بۆ بنمیچی تەختی پلێتی (گۆشە و لێوار و ناوەوە) بۆ جێبەجێکردنی هەردوو سنووری ڕێگەپێدراوی ℓ/240 و ℓ/480.

بۆ کاریگەری ڕەقبوونی ڕێژەیی بنمیچ بە رایەل (relative beam-slab stiffness) بۆ بنمیچ بە رایەلی دوو لایەنە (two-way beam-slab) لەسەر LTD ی سیستەمی پانێلی (ناوەوە و لێوار و گۆشە) ،بە بەکارهێنانئ LTD ی هەردووهاتنەخوارەوەی بنمیچی لای درێژ (long span deflection) و پانێلی ناوەڕاست (mid panel deflection)، پارامێتری توێژینەوەکە دەریخست کە بڕگەکانی ACI318-19 گونجاون بۆ پانێلی بنمیچی تەختی ناوەوە؛ بەڵام، بڕگەکان گونجاو نین بۆ پانێڵەکانی لێوار و گۆشە لە کاتێکدا کە ڕەقبوونی ڕێژەیی بنمیچ بە رایەل یەکسان بێت بە 0.2.

بۆ کاریگەری ڕەقبوونی ڕێژەیی بنمیچ بە رایەل بۆ بنمیچی یەک لایەنە (one-way slab) (10x4.9 م،7.5 x3.6 م و 6.1x3 م پانێلی تەختە) بە ڕێژەی ڕووبەری زیاتر لە 2، توێژینەوەکە دەریخست کە لەگەڵ بەکارهێنانی ئەستووری بنمحچی پێشنیارکراوی ACI318-19 پێویستە کەمترین ڕەقبوونی ڕێژەیی بنمیچ بە رایەل 5 هەبێت بۆ جێبەجێکردنی سنووری هاتنە خوارەوەی بنمیچ ℓ/240 و 20 هەبێت بۆ جێبەجێکردنی سنووری هاتنە خوارەوەی بنمیچ ℓ/480 بە درێژایی رایەلی هەڵگری بنمیچ . بۆ ڕەقبوونی ڕێژەیی بنمیچ بە رایەلی کەم، توێژینەوەکە پێشنیاری پێداچوونەوە دەکات بۆ کەمترین ئەستووری بنمیچ بۆ دڵنیابوون لەوەی کە LTD لە ژێر رایەلی لای درێژدا لە چوارچێوەی ڕێگەپێدراوی سنووری هاتنە خوارەوەی بنمیچ ℓ/480 و ℓ/240 بێت.

جگە لەوەش، رێگای Bondy بە لەبەرچاوگرتنی LTD ی بنمیچی پلێتی تەختی ( پانێلی ناوەوە و لێوار و گۆشە) بۆ ڕێژەی ڕووبەری جیاواز هەڵسەنگێنراوە. لە هەموو ئەو حاڵەتانەی کە لێکۆڵینەوەیان لەسەر کراوە، دەرکەوتووە کە رێگای Bondy گونجاوە بۆ سنووری رێگەپێدراوی هاتنە خورەوەی بنمیچ ℓ/240. سەبارەت بە سنووری رێگەپێدراوی هاتنەخوارەوەی بنمیچ لە ℓ/480، رێگای بۆندی ئەنجامێکی بەرهەمهێنا کە جێگەی رەزامەندیە تەنها لە پانێڵەکانی ناوەوە.

هەروەها توێژینەوەکە دەریخست کە ACI crossing beam approach ورد نییە بۆ حیسابکردنی بری هاتنە خوارەوەی بنمیچی کورتخایەنی لاستیک لە لای درێژ لە بنمیچی پلێتی تەخت لە شوێنە جیاوازەکانی پانێلی (ناوەوە، لێوار، و گۆشە) تەنانەت لە پانێڵەکانی بنمیچی تەختی لاکێشە (ڕێژەی ڕووبەری 2) کاتێک بەراورد دەکرێت لەگەڵ ئەنجامەکانی هاتنەخوارەوەی بنمیچ بە SAFE و ANSYS، کە چی ئەنجامەکانی SAFE و ANSYS نزیکترن لە نێوان خۆیاندا.

زانكۆی پۆلیتەكنیكی هەولێر

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