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Limitations on ACI Code Minimum Thickness Requirements for Flat Slab

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Abstract

Reinforced concrete two-way flat slabs are considered one of the most used systems in the construction of commercial buildings due to the ease of construction and suitability for electrical and mechanical paths. Long-term deflection is an essential parameter in controlling the behavior of this slab system, especially with long spans. Therefore, this study is devoted to investigating the validation of the ACI 318-19 Code long-term deflection limitations of a wide range of span lengths of two-way flat slabs with and without drop panels. The first part of the study includes nonlinear finite element analysis of 63 flat slabs without drops and 63 flat slabs with drops using the SAFE commercial software. The investigated parameters consist of the span length (4, 5, 6, 7, 8, 9, and 10m), compressive strength of concrete (21, 35, and 49 MPa), the magnitude of live load (1.5, 3, and 4.5 kN/m^2), and the drop thickness ($0.25t_{slab}$, $0.5t_{slab}$, and $0.75t_{slab}$). In addition, the maximum crack width at the top and bottom are determined and compared with the limitations of the ACI 224R-08. The second part of this research proposes modifications to the minimum slab thickness that satisfy the permissible deflection. It was found, for flat slabs without drops, the increase in concrete compressive strength from 21MPa to 49MPa decreases the average long-term deflection by (56, 53, 50, 44, 39, 33 and 31%) for spans (4, 5, 6, 7, 8, 9, and 10 m) respectively. In flat slab with drop panel, it was found that varying drop panel thickness t_2 from $0.25t_{slab}$ to $0.75t_{slab}$ decreases the average long-term deflection by (45, 41, 39, 35, 31, 28 and 25%) for span lengths (4, 5, 6, 7, 8, 9 and 10 m) respectively. Limitations of the minimum thickness of flat slab were proposed to vary from Ln/30 to Ln/19.9 for a flat slab without a drop panel and from Ln/33 to Ln/21.2 for a flat slab with drop panel. These limitations demonstrated high consistency with the results of Scanlon and Lee's unified equation for determining the minimum thickness of slab with and without drop panels.

Keywords: Long-term Deflection; Allowable Deflection; Flat Slab; Drop Panel Thickness; Concrete Compressive Strength; Crack width; Span Length.

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1. Introduction

A flat plate slab (or known also as a flat slab without a drop panel) is a two-way reinforced concrete slab that transfers loads directly to the supporting columns without the aid of beams or drop panels or capitals. In case of the presence of column capitals, drop panels, or both the slab is called a flat slab. The flat plate, that is common in

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residential building, has several advantages such as cost savings due to low story height and simple/quick construction and formwork, and flat ceiling that has high fire resistance (few sharps corners for concrete spalling) and less obstruction to light diffusion. The flat slab is satisfactory for long spans and heavy loads, in particular, the flat slab is economical for parking, warehouses, and industrial buildings [1-3].

The deflection is a crucial issue in the design of flat slabs with or without drop panels. Most Standards like ACI 318-19 [4], CSA A23.3-04 [5], AS 3600 [6] and Euro code 2 [7] propose two alternative ways for the control of deflection. The first approach is to calculate the deflection and to compare the calculated deflection with the allowable limits. The second approach controls indirectly the deflection by limiting minimum slab thickness or maximum span/depth ratio.

The flexural stiffness EI (E: the concrete modulus of elasticity and I: the moment of inertia) of a flexural member is an essential variable in the calculation of deflection. For the reinforced concrete members, the amount of section cracking affects significantly the moment of inertia and consequently, this effect must be considered in the analysis of deflection [8]. Generally, there are two different methods for considering the cracking effect: the effective moment of inertia method [9] and the mean curvature method [10]. Furthermore, creep and shrinkage have important effects on the long-term deflection, and therefore literature provides several ways for considering this effect, the most famous one is the ACI 318 method. The analysis for deflection can be done by using a range of refined methods [11], like a non-linear analysis or finite element analysis [12]. Recent work has used the Artificial Neural Network approach [13] for the prediction of deflection. However, the approaches for calculating the deflection in flat slabs are complicated and involving several approximations due to complex behavior at the service load stage (cracking, time-dependent effect, tension stiffening). Therefore, the direct calculation of deflection for the typical situations is impractical and engineers prefer to control the deflection using the minimum slab thickness or maximum span/depth ratio approach.

The minimum slab thickness or maximum span/depth ratio approach is the focus of many researches for decades. Several studies [14-18] have proposed different expressions for the maximum allowable span/depth ratio for slabs (including flat plate and flat slabs) considering the effects of different factors such as sustained load, aspect ratio, reinforcement ratio, support condition, concrete modulus of elasticity, target maximum permissible incremental deflection and long-term deflection effects.

Vollum and Hossain [19] have studied the span/depth rules given in Euro code 2 and they have found that the deflections calculated in flat slabs dimensioned with span/depth rules of Euro code 2 can be excessive in external and corner panels since the rules fail to allow for the effect of cracking during construction. Lee and Scanlon [20] have compared the minimum slab (one-way and two-way) provisions of various Standards (ACI 318-08, Euro code 2, BS 8110-1:1997, and AS 3600-2001 and the unified equation proposed by Scanlon and Lee [15]) by performing a parametric study to evaluate the effects of several relevant design parameters. The results show that ACI 318 conditions need a revision to cover the range of the affected design parameters. Furthermore, applicability limitations require to be added to ACI provisions, especially for flat slab provisions which seem to be sufficient for the limit of L/240 (for typical loading and spans) but insufficient in many cases for the limit of L/480. Bertero [21] has investigated the effectiveness of ACI 318 provisions for minimum thickness of two-way slabs for controlling the deflection to be within the allowable limits. This study evaluates (from a statistical viewpoint) the calculated deflections for two-way slabs having minimum thickness specified according to the ACI 318-14 requirements and as a result, it provides recommendations for upcoming ACI code revision. Hasan and Taha [22] have investigated the effects of several parameters (aspect ratio, live load, concrete strength) on the long-term deflection of flat plate slabs without edge beams (corner panels). They have highlighted the effect of not account for the aspect ratio in five Standards (ACI 318-14, CSA A23.3-14, AS 3600, BS8110, Euro code 2) provisions for the minimum slab thickness. Moreover, the applicability of the ACI 318-14 requirements for the thickness of flat plat slab without edge beam appeared to be sufficient to satisfy the permissible deflection limits L/360 and L/240 for typical spans and concrete strength while they were insufficient in many cases for the limit of L/480. Sanabra-Loewe et al. [23] have assessed the ACI 318 code and Eurocode 2 methods for the minimum slenderness ratio of R.C. slabs. The evaluated factors were: load, span, and permissible deflection. The results highlight the shortcoming of the Eurocode 2 and ACI 318 code provisions. Al-Nu'man & Abdullah [24] have developed a simulation model that considering the materials and loads uncertainties and along with the sensitivity analysis of results. The results indicate that the ACI 318-14 minimum thickness requirements are adequate for 4m and 6m span or less for flat plate and flat slab respectively. Depending on the characteristic strength of concrete, the redistribution factor, and the total steel ratio, Santos and Henriques [25] have proposed new span/depth limits satisfying both deflection and ductility requirements. However, these limits are restricted to the cases of beams and one-way slabs.

From the above review of literature, it is clear that there is a common consensus that the minimum thickness provisions required by ACI 318 code for flat slabs cannot ensure the deflection to comply with the maximum permissible limits for all flat slabs. Therefore, the objective of the present paper is to study the domain of applicability of ACI minimum thickness provisions for flat slab for controlling the long-term deflection and to provide the community of engineers the limitations for these provisions. The present paper addresses this issue by selecting the slab thickness according to the ACI 318-19 provisions, then, calculating the deflections using the Nonlinear Finite element Analysis for 126 case studies of flat slabs (with and without drop panels) for a range of span lengths and practical selected values of several influencing parameters (live loads, materials strengths, and drop panel thickness) and comparing the computed deflections with the ACI 318-19 permissible values (L/240, L/480).

2. Nonlinear Finite Element Analysis

The methodology of the present study is devoted to calculate the long-term deflection of flat slabs with thicknesses that determined according to ACI 318-19 Code minimum thickness requirements and to compare the calculated deflections with ACI 318-19 Code permissible limits. To achieve this goal, a nonlinear Finite Element Analysis was performed to investigate the long-term deflection in flat slabs. The SAFE software was considered here for this purpose. The long-term deflection was calculated according to the procedure illustrated in [26]. This procedure includes the calculation of deflection for three cases:

- Case 1: the immediate deflection due to short-term loads: DL + SDL + LL,
- Case 2: the immediate deflection due to sustained loads: DL + SDL + Ψ_L LL,
- Case 3: the long-term deflection due to sustained loads: DL + SDL + Ψ_L LL.

Where DL, SDL and LL represent the slab self-weight, superimposed dead load and live load applied on the slab respectively. Ψ_L is the percentage of live load considered to be sustained.

Using SAFE software analysis options, the nonlinear (cracked) analysis was performed for cases 1 and 2, instead, for case 3 the nonlinear (long-term cracked i.e. with creep and shrinkage effects) analysis was carried out.

The value of long-term deflection was determined as a linear combination of case 3 + case 1 - case 2, where the difference between case 1 and case 2 represents the incremental deflection (without creep and shrinkage) due to non-sustained loading on a cracked structure.

Two layouts of the flat slabs were considered for analysis in the present study. both cases consist of three equal spans in each direction without edge beams, however, the first one is without drop panels (i.e. flat plate), see Figure 1, and the second layout with drop panels as shown in Figure 2. The drop panel dimensions were selected to comply with ACI 318-19 requirements for the drop panel as detailed in Figure 3.

The ACI code provisions for the minimum thickness of flat slab take into account only two effects: span length and yield strength of steel f_y. However, this paper considers the effects of several factors on the long-term deflection and as a result on the minimum thickness requirements, these are: span length L, concrete compressive strength f_c', service live load, and drop panel thickness t_2. The range of values for each one of these factors was selected to be consistent with that used in the real practice and with available ACI 318-19 provisions. The selected values were: span length L (4, 5, 6, 7, 8, 9, 10) m, concrete compressive strength f_c' (21, 35, 49) MPa, service live load (1.5, 3, 4.5) kN/m^2, and drop panel thickness t_2 ($0.25\mathrm{t_{slab}}$, $0.5\mathrm{t_{slab}}$, $0.75\mathrm{t_{slab}}$). On the contrary, the other parameters were considered fixed through the analysis and their specified values were:

- Steel reinforcement properties: yield strength f_y = 420 MPa (Grade 60), Modulus of elasticity Es = 200 GPa,
- Modulus of elasticity of concrete Ec = $4700\sqrt{f_c'}$.
- Superimposed dead load = 2 kN/m^2,
- Dimension of squared columns supporting flat slabs with span length 4, 5, 6, 7, 8, 9 and 10 m are 300, 300, 350, 400, 450, 500 and 550 mm respectively,
- The percentage of live load that considered to be sustained Ψ_L = 25%.
- The time-dependent factor or creep coefficient = 2, i.e. for sustained load duration five years or more as specified in ACI 318-19.

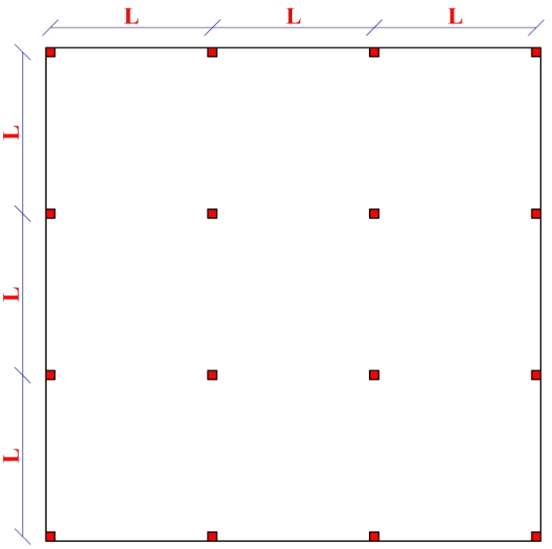

Figure 1. Two-way flat slab without drop panel

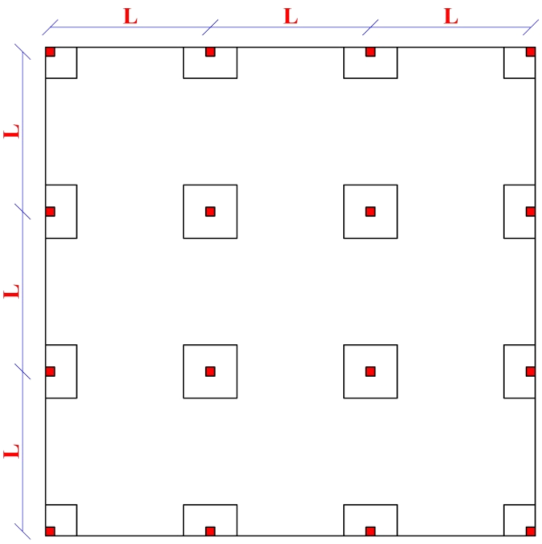

Figure 2. Two-way flat slab with drop panel

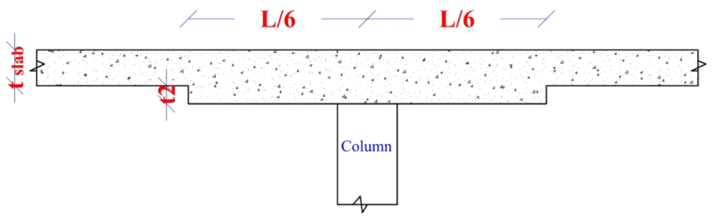

Figure 3. Drop panel detail

Consequently, in total 126 case studies of flat slabs were analyzed to study the effects of factors considered in this paper. These case studies were divided equally into two main groups. The first one includes 63 case studies of the flat slab without drop panels and the second one comprises 63 case studies of flat slabs with drop panels. The two groups were similar in the range of values for span length and live load (values stated above), however, the concrete compressive strength was varied in the first one and had a fixed value f_c'=21 MPa in second group. Furthermore, the range of values for drop panel thickness (given above) was considered in the second group only.

3. Results and Discussion

Using the nonlinear Finite Element Analysis, the long-term deflection was investigated at different points of 126 case studies of flat slabs. Figures 4 and 5 show the resulting long-term deflection for two extreme case studies of the flat slab without drop panel having the same concrete strength (f_c'=21MPa) and live load (LL=4.5 kN/m^2) but with different values for span length (L=4m for Figure 4 and L=10m for Figure 5). Figures 6 and 7 illustrate the long-term deflection for another two case studies similar to that shown in Figures 4 and 5 respectively but for the flat slab with a drop (t_2=0.25t_{slab}). From these four figures, it is clear that the maximum long-term deflection occurs at corner panels and nearly at the midpoint of the diagonal line between the corner and interior columns. The same finding was drawn from all other cases and therefore the long-term deflection given in the next sections will be at the midpoint of the diagonal line between the corner and interior columns for the corner panels.

Due to the large campaign of case studies considered in the present paper, it is convenient to discuss the results into two subsections, firstly for the cases of flat slabs without drop panel and secondly for the cases of flat slabs with drop panel.

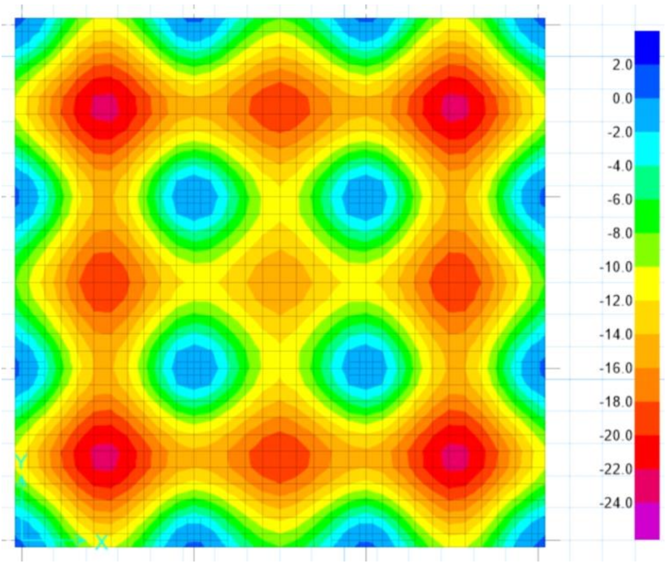

Figure 4. Long-term deflection for flat slab without drop (L=4m, LL=4.5 kN/m^2, t=315 mm and $f'_c = 21$MPa)

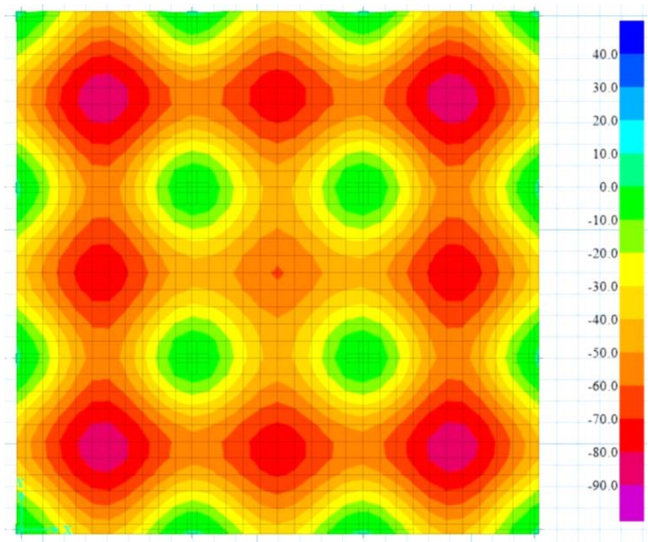

Figure 5. Long-term deflection for flat slab without drop (L=10m, LL=4.5 kN/m^2, t=315 mm and $f'_c = 21$MPa)

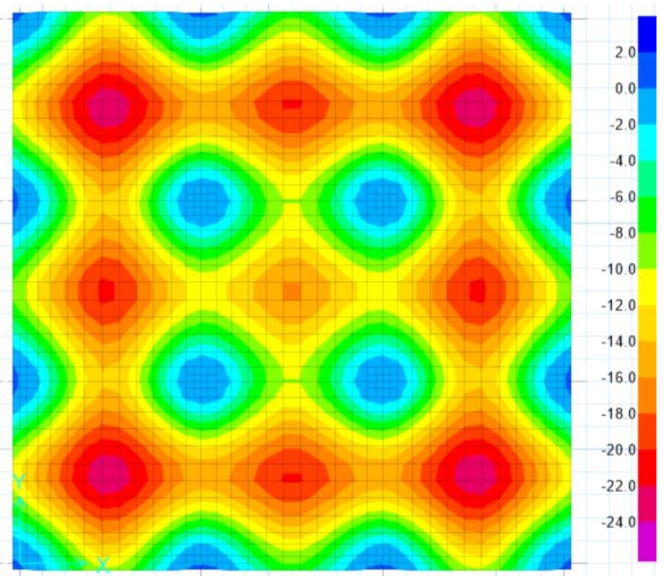

Figure 6. Long-term deflection for flat slab with drop (L=4m, LL=4.5 kN/m^2, $f'_c = 21$MPa, t=290 mm and t_2=0.25t_{slab})

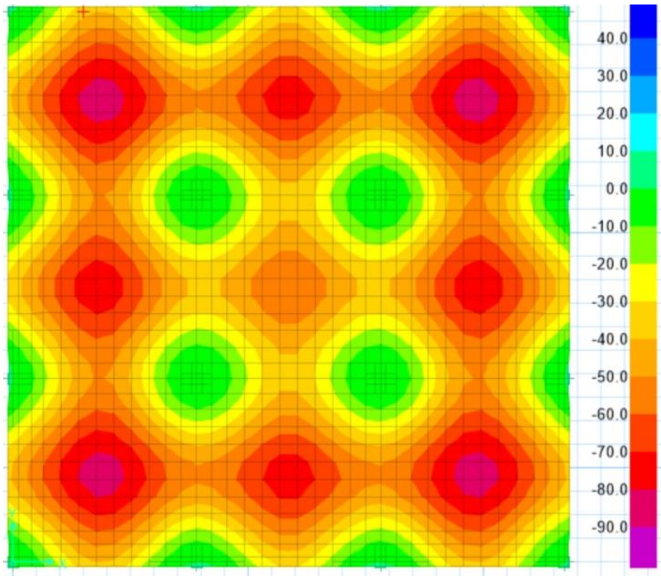

Figure 7. Long-term deflection for flat slab with drop (L=10m, LL=4.5 kN/m^2, $f'_c = 21$MPa, t=290 mm and t_2=0.25t_{slab})

3.1. Two-way Flat Slab without Drop Panels

Analysis results of maximum long-term deflection for the 63 case studies of the flat slab without drop panel are given in Table 1 and shown graphically in Figures 8, 9 and 10. As shown, the results were obtained from analyzing flat slabs having span lengths varied from 4 to 10 m, and for three values of concrete compressive strengths (21, 35, 49) MPa and three values of live loads (1.5, 3, 4.5) kN/m^2. The resulting maximum long-term deflections were compared with the ACI 318-19 allowable deflection limits: L/480 (roof or floor construction supporting or attached to non-structural elements likely to be damaged by large deflections) and L/240 (roof or floor construction supporting or attached to non-structural elements not likely to be damaged by large deflections). Although the slab thickness was dimensioned according to ACI 318-19 minimum thickness requirements (Ln/30) for all cases, the calculated maximum long-term deflection exceeds one or both allowable limits in many cases. As an example, for the cases with LL=1.5 kN/m^2, the calculated deflections exceed the limit of L/240 when the span length is larger than 4, 6, 8 m for f'_c values of 21, 35, 49 MPa respectively. Furthermore, Figures 8, 9 and 10 show a nearly linear increase in maximum long-term deflection as the span length changes from 4 to 10 m, but with a slope that becomes steeper for weak concrete strength. In other words, improving the concrete compressive strength from 21 to 49 MPa reduces the maximum long-term deflection by an average of (56, 53, 50, 44, 39, 33 and 31%) for spans (4, 5, 6, 7, 8, 9 and 10 m) respectively. These percentages indicate that the efficiency of using stronger concrete (f'_c=49 MPa) is the highest when the slab span length is 4 m. Regarding the effect of live loads, as expected, changing the live load from 1.5 to 4.5

kN/m^2 leads to more deflection, however, this effect is more pronounced for a small span length of 4 m and is diminished gradually for a larger span length. This behavior can be explained by referring to any short-term deflection elastic equation (for example wL^4/384EI) where the span length L has power 4 while the loads w has power 1 and consequently the effect of the increase in span length is dominated.

Table 1 also compares the maximum cracks width at the top and bottom faces of the slab with the ACI 224R-08 [27] allowable limit of 0.3 mm that corresponds to the exposure condition: humidity, moist air and soil. From these analysis results, there is a clear trend of increasing the crack width with the increase in span length and as a result exceeding the allowable limits 0.3 mm for span length more than 7 m.

Table 1. Analysis results for flat slab without drop panel with different values of spans length, concrete compressive strength and live loads

Two-way flat slab without drop panels, $f_y = 420$ MPa

LL=1.5 kN/m^2

Span (L), m	t_{slab} $\frac{L_n}{30}$ mm	$f'_c = 21$MPa long term def mm	$f'_c = 21$MPa maximum crack width mm top face	$f'_c = 21$MPa maximum crack width mm bott face	$f'_c = 35$MPa long term def mm	$f'_c = 35$MPa maximum crack width mm top face	$f'_c = 35$MPa maximum crack width mm bott face	$f'_c = 49$MPa long term def mm	$f'_c = 49$MPa maximum crack width mm top face	$f'_c = 49$MPa maximum crack width mm bott face	allowable deflections (mm) $\frac{L}{480}$	allowable deflections (mm) $\frac{L}{240}$	Allowable crack width mm
4	125	12.6	0.12	0.15	8.1	0.17	0.12	6.1	0.16	0.12	8.3	**16.6**	0.30
5	160	**22.9**	0.18	0.17	12.7	0.19	0.17	10.5	0.20	0.17	10.4	**20.8**	0.30
6	190	**34.8**	0.22	0.21	19.5	0.23	0.21	16.3	0.24	0.22	12.5	**25.0**	0.30
7	220	**47.2**	0.25	0.25	**30.7**	0.26	0.26	22.2	0.26	0.26	14.5	**29.1**	0.30
8	255	**55.7**	0.29	0.32	**44.8**	0.30	0.32	30.1	0.31	0.33	16.6	**33.3**	0.30
9	285	**66.6**	0.32	0.38	**53.2**	0.32	0.38	**41.2**	0.31	0.37	18.7	**37.5**	0.30
10	315	**79.1**	0.31	0.38	**67.0**	0.32	0.38	**53.0**	0.31	0.37	20.8	**41.6**	0.30

LL= 3 kN/m^2

Span (L), m	t_{slab} $\frac{L_n}{30}$ mm	$f'_c = 21$MPa long term def mm	$f'_c = 21$MPa maximum crack width mm top face	$f'_c = 21$MPa maximum crack width mm bott face	$f'_c = 35$MPa long term def mm	$f'_c = 35$MPa maximum crack width mm top face	$f'_c = 35$MPa maximum crack width mm bott face	$f'_c = 49$MPa long term def mm	$f'_c = 49$MPa maximum crack width mm top face	$f'_c = 49$MPa maximum crack width mm bott face	allowable deflections (mm) $\frac{L}{480}$	allowable deflections (mm) $\frac{L}{240}$	Allowable crack width mm
4	125	**18.8**	0.15	0.14	10.8	0.15	0.13	7.7	0.15	0.13	8.3	**16.6**	0.30
5	160	**31.6**	0.18	0.19	19.7	0.18	0.18	12.4	0.19	0.18	10.4	**20.8**	0.30
6	190	**40.4**	0.21	0.23	**28.3**	0.22	0.22	17.7	0.22	0.22	12.5	**25.0**	0.30
7	220	**52.1**	0.24	0.27	**40.0**	0.23	0.26	29.0	0.24	0.26	14.5	**29.1**	0.30
8	255	**60.0**	0.30	0.33	**45.9**	0.29	0.32	**37.4**	0.29	0.33	16.6	**33.3**	0.30
9	285	**70.2**	0.30	0.35	**57.8**	0.30	0.35	**48.3**	0.30	0.34	18.7	**37.5**	0.30
10	315	**82.2**	0.32	0.39	**70.7**	0.31	0.39	**55.4**	0.31	0.39	20.8	**41.6**	0.30

LL=4.5 kN/m^2

Span (L), m	t_{slab} $\frac{L_n}{30}$ mm	$f'_c = 21$MPa long term def mm	$f'_c = 21$MPa maximum crack width mm top face	$f'_c = 21$MPa maximum crack width mm bott face	$f'_c = 35$MPa long term def mm	$f'_c = 35$MPa maximum crack width mm top face	$f'_c = 35$MPa maximum crack width mm bott face	$f'_c = 49$MPa long term def mm	$f'_c = 49$MPa maximum crack width mm top face	$f'_c = 49$MPa maximum crack width mm bott face	allowable deflections (mm) $\frac{L}{480}$	allowable deflections (mm) $\frac{L}{240}$	Allowable crack width mm
4	125	**22.5**	0.14	0.14	15.0	0.16	0.14	9.5	0.15	0.14	8.3	**16.6**	0.30
5	160	**33.9**	0.17	0.18	**23.8**	0.18	0.18	18.1	0.18	0.18	10.4	**20.8**	0.30
6	190	**44.9**	0.21	0.22	**33.1**	0.21	0.22	**26.4**	0.21	0.22	12.5	**25.0**	0.30
7	220	**54.3**	0.24	0.26	**43.1**	0.24	0.26	**35.5**	0.24	0.26	14.5	**29.1**	0.30
8	255	**62.1**	0.29	0.31	**51.6**	0.26	0.32	**41.2**	0.29	0.32	16.6	**33.3**	0.30
9	285	**73.3**	0.31	0.34	**63.7**	0.30	0.34	**50.3**	0.30	0.35	18.7	**37.5**	0.30
10	315	**85.2**	0.35	0.35	**74.3**	0.35	0.35	**60.7**	0.35	0.36	20.8	**41.6**	0.30

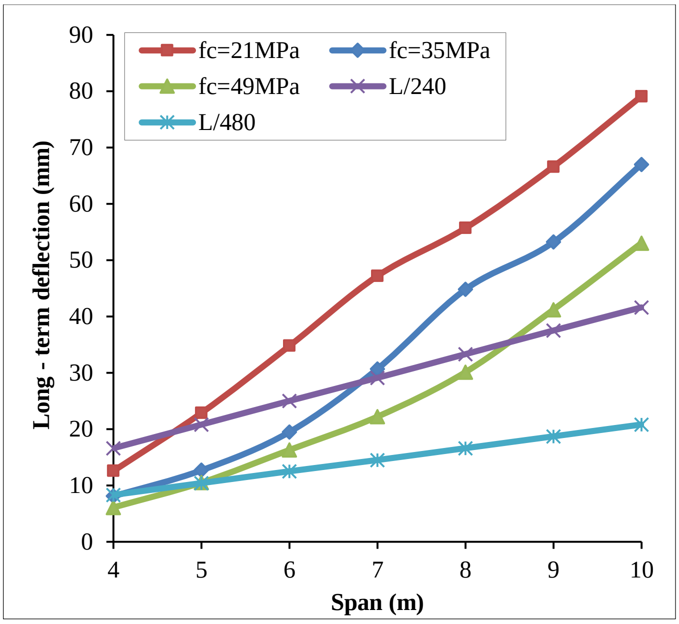

Figure 8. Long-term deflection versus span length at different concrete compressive strength for flat slab without drop (LL=1.5 kN/m^2)

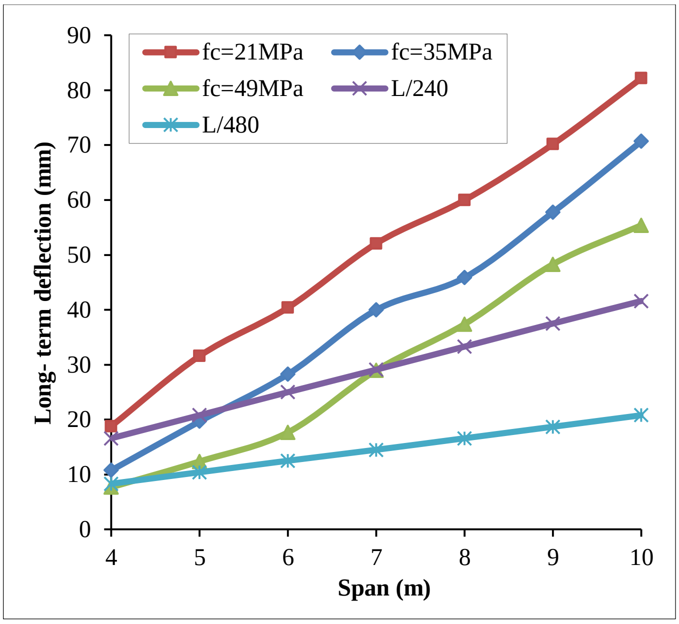

Figure 9. Long-term deflection versus span length at different concrete compressive strength for flat slab without drop (LL=3 kN/m^2)

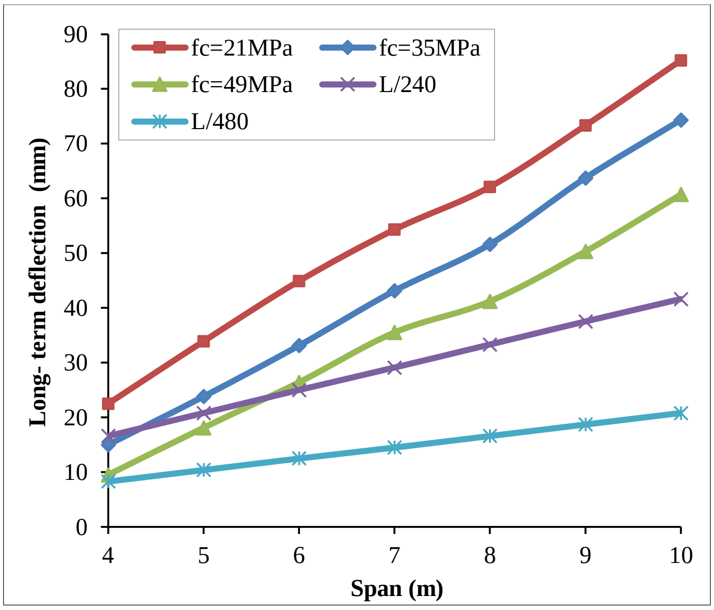

Figure 10. Long-term deflection versus span length at different concrete compressive strength for flat slab without drop (LL=4.5 kN/m^2)

3.2. Two-way Flat Slab with Drop Panels

From the analysis of 63 case studies of the flat slab with drop panel, Table 2 provides the resulting maximum long-term deflections, also, Figures 11, 12, and 13 show these results graphically. The variables in this analysis were the span lengths (varied from 4 to 10 m), live loads (1.5, 3, 4.5) kN/m^2 and drop panel thickness t_2 (0.25t_{slab}, 0.5t_{slab}, 0.75t_{slab}). Since the effect of concrete compressive strength became clear from the above analysis of the flat slabs without drop panel, a fixed value of f'_c=21MPa was considered here for the analysis of flat slabs with drop panel. The resulting maximum long-term deflections were compared with the ACI 318-19 allowable deflection limits L/480 and L/240. In spite of the slab thickness was selected to comply with ACI 318-19 minimum thickness requirements (Ln/33) for all cases, the computed maximum long-term deflection exceeds one or both allowable limits in many cases. As an example, for the cases with LL=1.5 kN/m^2, the calculated deflections exceed the limit of L/240 when the span length is larger than 4, 5, 7 m for drop panel thickness t_2 of 0.25t_{slab}, 0.5t_{slab}, 0.75t_{slab} respectively. Moreover, Figures 11, 12 and 13 show a nearly linear relation between the resulting maximum long-term deflection and the span length. However, the slopes of these relations reduce as the drop panel becomes thicker. In other words, varying drop panel thickness t_2 from 0.25t_{slab} to 0.75t_{slab} decreases the average long-term deflection by (45, 41, 39, 35, 31, 28 and

25%) for span lengths (4, 5, 6, 7, 8, 9 and 10 m) respectively. These percentages show that the positive effect of drop panel thickness is important for small spans and it becomes less significant for larger spans. Concerning the live load effect, a similar finding to that drawn above for flat slab without drop was found here i.e. increasing the live load leads to larger long-term deflection but this effect becomes less important with the increase in span lengths.

In addition to the maximum long-term deflection, Table 2 shows the resulting maximum cracks width at the top and bottom faces of slab. These results exhibit a logical increase in the width of the cracks as the span length varies from 4 to 10 m. The comparison of the resulting maximum cracks width with the ACI 224R-08 [27] allowable limit of 0.3 mm (that corresponds to the exposure condition: humidity, moist air and soil) indicates that the crack width fails to comply with the allowable limit (0.3 mm) when the span length is more than 7 m.

Table 2. Analysis results for flat slab with drop panel with different values of spans length, drop panel thickness and live loads

Two-way flat slab with drop panels, $f_y = 420$ MPa, $f'_c = 21$MPa																
LL=1.5 kN/m²																
Span (L) m	**t_{slab} $\frac{L_n}{33}$ mm**	**t_2=0.25t_{slab}**				**t_2=0.5t_{slab}**				**t_2=0.75t_{slab}**				**Allowable deflections (mm)**		**Allowable crack width mm**
		t_2 mm	**long term def mm**	**Maximum crack width mm**		**t_2 mm**	**long term def mm**	**Maximum crack width mm**		**t_2 mm**	**long term def mm**	**Maximum crack width mm**				
				top face	**bott face**			**top face**	**bott face**			**top face**	**bott face**	**$\frac{L}{480}$**	**$\frac{L}{240}$**	
4	115	29	12.8	0.18	0.11	58	9.1	0.21	0.10	87	7.2	0.24	0.10	8.3	**16.6**	0.30
5	145	37	**24.9**	0.21	0.16	73	18.8	0.23	0.15	109	13.1	0.28	0.15	10.4	**20.8**	0.30
6	175	44	**34.8**	0.24	0.20	88	**25.1**	0.28	0.19	132	20.5	0.31	0.19	12.5	**25.0**	0.30
7	200	50	**46.1**	0.26	0.23	100	**37.1**	0.29	0.22	150	26.7	0.31	0.22	14.5	**29.1**	0.30
8	230	58	**55.4**	0.29	0.27	115	**43.9**	0.31	0.27	173	**35.3**	0.32	0.26	16.6	**33.3**	0.30
9	260	65	**65.7**	0.31	0.33	130	**53.7**	0.31	0.33	195	**45.7**	0.32	0.29	18.7	**37.5**	0.30
10	290	73	**78.2**	0.32	0.36	145	**63.8**	0.34	0.38	218	**55.9**	0.34	0.37	20.8	**41.6**	0.30
LL=3 kN/m²																
Span (L) m	**t_{slab} $\frac{L_n}{33}$ mm**	**t_2=0.25t_{slab}**				**t_2=0.5t_{slab}**				**t_2=0.75t_{slab}**				**Allowable deflections (mm)**		**Allowable crack width mm**
		t_2 mm	**long term def mm**	**Maximum crack width mm**		**t_2 mm**	**long term def mm**	**Maximum crack width mm**		**t_2 mm**	**long term def mm**	**Maximum crack width mm**				
				top face	**bott face**			**top face**	**bott face**			**top face**	**bott face**	**$\frac{L}{480}$**	**$\frac{L}{240}$**	
4	115	29	**18.5**	0.15	0.12	58	13.5	0.18	0.12	87	9.8	0.21	0.11	8.3	**16.6**	0.30
5	145	37	**29.7**	0.19	0.16	73	22.2	0.23	0.16	109	18.3	0.24	0.16	10.4	**20.8**	0.30
6	175	44	**40.1**	0.23	0.20	88	**29.1**	0.27	0.20	132	23.5	0.28	0.20	12.5	**25.0**	0.30
7	200	50	**50.7**	0.26	0.23	100	**42.3**	0.27	0.23	150	**32.6**	0.30	0.23	14.5	**29.1**	0.30
8	230	58	**60.1**	0.26	0.27	115	**50.4**	0.28	0.27	173	**42.1**	0.31	0.27	16.6	**33.3**	0.30
9	260	65	**70.2**	0.32	0.30	130	**58.5**	0.30	0.32	195	**50.6**	0.31	0.32	18.7	**37.5**	0.30
10	290	73	**80.7**	0.32	0.36	145	**69.1**	0.33	0.35	218	**60.9**	0.34	0.34	20.8	**41.6**	0.30
LL=4.5 kN/m²																
Span (L) m	**t_{slab} $\frac{L_n}{33}$ mm**	**t_2=0.25t_{slab}**				**t_2=0.5t_{slab}**				**t_2=0.75t_{slab}**				**Allowable deflections (mm)**		**Allowable crack width mm**
		t_2 mm	**long term def mm**	**Maximum crack width mm**		**t_2 mm**	**long term def mm**	**Maximum crack width mm**		**t_2 mm**	**long term def mm**	**Maximum crack width mm**				
				top face	**Bott. face**			**top face**	**bott face**			**top face**	**bott face**	**$\frac{L}{480}$**	**$\frac{L}{240}$**	
4	115	29	**23.1**	0.15	0.13	58	**17.2**	0.18	0.12	87	12.8	0.21	0.12	8.3	**16.6**	0.30
5	145	37	**35.7**	0.19	0.17	73	**26.2**	0.22	0.16	109	**22.4**	0.23	0.16	10.4	**20.8**	0.30
6	175	44	**43.2**	0.23	0.20	88	**35.1**	0.26	0.20	132	**27.6**	0.25	0.20	12.5	**25.0**	0.30
7	200	50	**54.3**	0.23	0.23	100	**46.2**	0.25	0.23	150	**39.3**	0.27	0.23	14.5	**29.1**	0.30
8	230	58	**64.1**	0.25	0.27	115	**54.5**	0.26	0.27	173	**47.6**	0.35	0.27	16.6	**33.3**	0.30
9	260	65	**73.5**	0.27	0.31	130	**62.8**	0.29	0.31	195	**55.2**	0.36	0.31	18.7	**37.5**	0.30
10	290	73	**84.5**	0.30	0.35	145	**75.1**	0.32	0.33	218	**65.3**	0.36	0.31	20.8	**41.6**	0.30

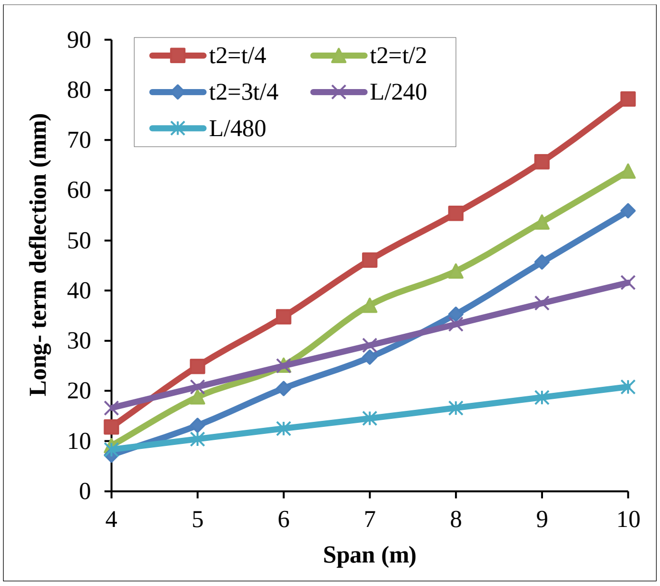

Figure 11. Long-term deflection versus span length for different thickness of drop panels (LL=1.5 kN/m^2)

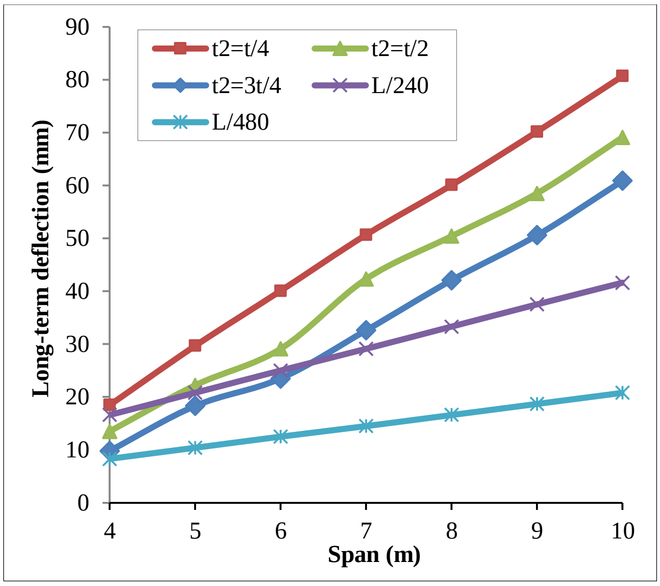

Figure 12. Long-term deflection versus span length for different thickness of drop panels (LL=3 kN/m^2)

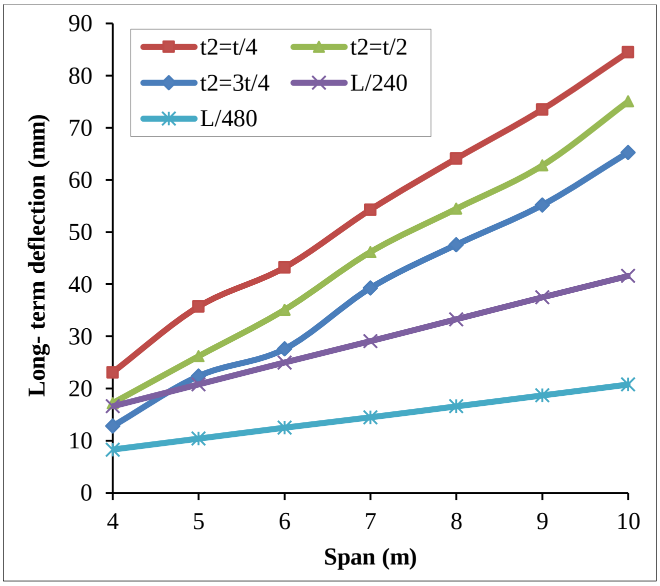

Figure 13. Long-term deflection versus span length for different thickness of drop panels (LL=3 kN/m^2)

4. Proposed Minimum Thickness of Flat Slab

4.1. Modifications of the ACI-318 Code Limitations

Based on the above discussion of the results obtained in the present study, it is clear that for the control of deflection the use of a single formula for the minimum thickness for all flat slabs without a drop (Ln/30) or with drop (Ln/33) as specified by ACI code (for f_y = 420 MPa, exterior panel without edge beam) is a serious issue. The main shortcoming of the ACI formulas is its restriction to a single variable (span length) and the ignoring of other influencing factors like concrete compressive strength, applied live loads, and drop panel thickness.

Consequently, the 126 case studies considered here were re-analyzed using the nonlinear finite element analysis in order to specify, for each case, the appropriate minimum thickness that can ensure the complying of long-term deflection with the allowable limit of L/240. For this purpose, the re-analysis was performed with a gradual increase in the slab thickness (increments of 5 mm) for each case and then the maximum long-term deflection was investigated and compared the limit L/240. According to ACI 318-19 code, in any case, the flat slab thickness should be at least 125 mm for slab without a drop and 100 mm for slab with a drop, therefore these values were considered as the starting values for the slab thickness in the analysis.

Table 3 gives the analysis results for the 63 cases of the flat slab without a drop. It shows, for each case study, the resulting appropriate minimum slab thickness and the corresponding maximum calculated long-term deflection. Based on these results, a new proposed formula for minimum slab thickness that corresponds to each case study was proposed and provided in Table 3. As shown, these formulas vary from Ln/30 to Ln/19.9 which is a wide range as compared with the single formula provided by ACI code (Ln/30).

Regarding the re-analysis of the 63 cases of the flat slab with a drop, the analysis results were given in Table 4. These results include, for each case study, the investigated appropriate minimum slab thickness, the maximum computed long-term deflection and as a result the proposed new formula for the minimum slab thickness. As shown, the proposed formulas for the cases of slab with drop panel have a range from Ln/33 to Ln/21.2 which provides evidence that the single ACI code formula (Ln/33) cannot be satisfactory for all cases.

Table 3. Proposed minimum thickness of flat slab without drop panels that satisfies the ACI limit L/240

Two-way flat slab without drop panels, $f_y = 420$ MPa										
L.L=1.5 kN/m²										
Span (L) m	**$f'_c = 21$MPa**			**$f'_c = 35$MPa**			**$f'_c = 49$MPa**			**Allowable deflections mm**
	long term def $\leq \frac{L}{240}$			**long term def $\leq \frac{L}{240}$**			**long term def $\leq \frac{L}{240}$**			
	$\frac{L_n}{A}$	**t_{slab} mm**	**long term def (mm)**	$\frac{L_n}{A}$	**t_{slab} mm**	**long term def (mm)**	$\frac{L_n}{A}$	**t_{slab} mm**	**long term def (mm)**	$\frac{L}{240}$
4	$\frac{L_n}{30.0}$	125	12.6	$\frac{L_n}{30.0}$	125	8.1	$\frac{L_n}{30.0}$	125	6.1	**16.6**
5	$\frac{L_n}{27.6}$	170	16.7	$\frac{L_n}{30.0}$	160	12.7	$\frac{L_n}{30.0}$	160	10.5	**20.8**
6	$\frac{L_n}{26.2}$	215	23.8	$\frac{L_n}{30.0}$	190	19.5	$\frac{L_n}{30.0}$	190	16.3	**25.0**
7	$\frac{L_n}{24.9}$	265	29.1	$\frac{L_n}{29.3}$	225	26.1	$\frac{L_n}{30.0}$	220	22.2	**29.1**
8	$\frac{L_n}{23.2}$	325	33.2	$\frac{L_n}{27.4}$	275	29.7	$\frac{L_n}{30.0}$	260	30.1	**33.3**
9	$\frac{L_n}{22.6}$	375	37.5	$\frac{L_n}{26.1}$	325	35.4	$\frac{L_n}{29.3}$	290	35.1	**37.5**
10	$\frac{L_n}{21.2}$	445	41.4	$\frac{L_n}{24.5}$	385	39.0	$\frac{L_n}{27.0}$	350	37.1	**41.6**
L.L=3 kN/m²										
Span (L) m	**$f'_c = 21$MPa**			**$f'_c = 35$MPa**			**$f'_c = 49$MPa**			**Allowable deflections mm**
	long term def $\leq \frac{L}{240}$			**long term def $\leq \frac{L}{240}$**			**long term def $\leq \frac{L}{240}$**			
	$\frac{L_n}{A}$	**t_{slab} mm**	**long term def (mm)**	$\frac{L_n}{A}$	**t_{slab} mm**	**long term def (mm)**	$\frac{L_n}{A}$	**t_{slab} mm**	**long term def (mm)**	$\frac{L}{240}$
4	$\frac{L_n}{28.4}$	130	15.1	$\frac{L_n}{30.0}$	125	10.8	$\frac{L_n}{30.0}$	125	7.7	**16.6**
5	$\frac{L_n}{26.1}$	180	20.2	$\frac{L_n}{30.0}$	160	19.7	$\frac{L_n}{30.0}$	160	12.4	**20.8**
6	$\frac{L_n}{25.6}$	220	25.0	$\frac{L_n}{28.2}$	200	24.2	$\frac{L_n}{30.0}$	190	17.7	**25.0**
7	$\frac{L_n}{23.5}$	280	27.5	$\frac{L_n}{26.9}$	240	29.1	$\frac{L_n}{30}$	220	29.0	**29.1**
8	$\frac{L_n}{22.3}$	340	32.0	$\frac{L_n}{26.4}$	285	33.3	$\frac{L_n}{28.4}$	265	33.3	**33.3**
9	$\frac{L_n}{21.7}$	390	37.5	$\frac{L_n}{25.0}$	340	36.2	$\frac{L_n}{27.4}$	310	36.0	**37.5**
10	$\frac{L_n}{20.5}$	460	41.5	$\frac{L_n}{23.6}$	400	40.0	$\frac{L_n}{26.6}$	355	41.6	**41.6**
L.L=4.5 kN/m²										
Span (L) m	**$f'_c = 21$MPa**			**$f'_c = 35$MPa**			**$f'_c = 49$MPa**			**Allowable deflections mm**
	long term def $\leq \frac{L}{240}$			**long term def $\leq \frac{L}{240}$**			**long term def $\leq \frac{L}{240}$**			
	$\frac{L_n}{A}$	**t_{slab} mm**	**long term def (mm)**	$\frac{L_n}{A}$	**t_{slab} mm**	**long term def (mm)**	$\frac{L_n}{A}$	**t_{slab} mm**	**long term def (mm)**	$\frac{L}{240}$
4	$\frac{L_n}{26.4}$	140	15.0	$\frac{L_n}{30.0}$	125	15.0	$\frac{L_n}{30.0}$	125	9.5	**16.6**
5	$\frac{L_n}{24.7}$	190	20.4	$\frac{L_n}{27.6}$	170	18.7	$\frac{L_n}{30.0}$	160	18.1	**20.8**
6	$\frac{L_n}{24.0}$	235	25.0	$\frac{L_n}{26.9}$	210	24.6	$\frac{L_n}{28.9}$	195	24.6	**25.0**
7	$\frac{L_n}{22.7}$	290	28.8	$\frac{L_n}{25.8}$	255	29.1	$\frac{L_n}{27.5}$	240	28.0	**29.1**
8	$\frac{L_n}{21.5}$	350	33.3	$\frac{L_n}{24.7}$	305	32.1	$\frac{L_n}{27.4}$	275	33.3	**33.3**
9	$\frac{L_n}{20.9}$	405	36.7	$\frac{L_n}{23.9}$	355	36.7	$\frac{L_n}{26.1}$	325	37.1	**37.5**
10	$\frac{L_n}{19.9}$	475	41.6	$\frac{L_n}{23.0}$	410	40.2	$\frac{L_n}{25.5}$	370	40.7	**41.6**

Table 4. Proposed minimum thickness of flat slab with drop panels that satisfies the ACI limit L/240

Two-way flat slab with drop panels, $f_y = 420$ MPa, $f'_c = 21$MPa													
L.L=1.5 kN/m²													
Span (L) m	**t_2=0.25t_{slab}**				**t_2=0.5t_{slab}**				**t_2=0.75t_{slab}**				**allowable deflections mm**
	long term def $\leq \frac{L}{240}$				**long term def $\leq \frac{L}{240}$**				**long term def $\leq \frac{L}{240}$**				
	$\frac{L_n}{A}$	**t_{slab} mm**	**t_2**	**long term def (mm)**	**$\frac{L_n}{A}$**	**t_{slab} mm**	**t_2**	**long term def (mm)**	**$\frac{L_n}{A}$**	**t_{slab} mm**	**t_2**	**long term def (mm)**	**$\frac{L}{240}$**
4	$\frac{L_n}{33.0}$	115	29	12.8	$\frac{L_n}{33.0}$	115	58	9.1	$\frac{L_n}{33.0}$	115	87	7.2	**16.6**
5	$\frac{L_n}{31.3}$	150	38	21.7	$\frac{L_n}{33.0}$	145	73	18.8	$\frac{L_n}{33.0}$	145	109	13.1	**20.8**
6	$\frac{L_n}{28.2}$	200	50	25.0	$\frac{L_n}{30.5}$	185	93	24.6	$\frac{L_n}{33.0}$	175	132	20.5	**25.0**
7	$\frac{L_n}{28.0}$	235	59	29.0	$\frac{L_n}{30.0}$	220	110	29.1	$\frac{L_n}{33.0}$	200	150	26.7	**29.1**
8	$\frac{L_n}{26.0}$	290	73	33.3	$\frac{L_n}{29.0}$	260	135	31.5	$\frac{L_n}{31.4}$	240	180	32.0	**33.3**
9	$\frac{L_n}{25.0}$	340	85	37.5	$\frac{L_n}{27.8}$	305	153	37.5	$\frac{L_n}{30.3}$	280	210	36.5	**37.5**
10	$\frac{L_n}{23.3}$	405	102	41.1	$\frac{L_n}{25.5}$	370	185	41.0	$\frac{L_n}{27.7}$	340	255	40.0	**41.6**
L.L= 3 kN/m²													
Span (L) m	**t_2=0.25t_{slab}**				**t_2=0.5t_{slab}**				**t_2=0.75t_{slab}**				**allowable deflections mm**
	long term def $\leq \frac{L}{240}$				**long term def $\leq \frac{L}{240}$**				**long term def $\leq \frac{L}{240}$**				
	$\frac{L_n}{A}$	**t_{slab} mm**	**t_2**	**long term def (mm)**	**$\frac{L_n}{A}$**	**t_{slab} mm**	**t_2**	**long term def (mm)**	**$\frac{L_n}{A}$**	**t_{slab} mm**	**t_2**	**long term def (mm)**	**$\frac{L}{240}$**
4	$\frac{L_n}{30.8}$	120	30	16.4	$\frac{L_n}{33.0}$	115	58	13.5	$\frac{L_n}{33.0}$	115	87	9.8	**16.6**
5	$\frac{L_n}{28.4}$	165	42	20.8	$\frac{L_n}{33.0}$	145	73	22.2	$\frac{L_n}{33.0}$	145	109	18.3	**20.8**
6	$\frac{L_n}{27.5}$	205	52	24.1	$\frac{L_n}{30.5}$	185	93	24.5	$\frac{L_n}{33.0}$	175	132	23.5	**25.0**
7	$\frac{L_n}{26.9}$	245	62	29.1	$\frac{L_n}{29.3}$	225	113	28.7	$\frac{L_n}{31.4}$	210	158	28.7	**29.1**
8	$\frac{L_n}{24.7}$	305	77	31.0	$\frac{L_n}{27.9}$	270	135	33.2	$\frac{L_n}{30.2}$	250	188	32.3	**33.3**
9	$\frac{L_n}{23.6}$	360	90	37.2	$\frac{L_n}{26.1}$	325	163	35.5	$\frac{L_n}{28.8}$	295	222	36.3	**37.5**
10	$\frac{L_n}{22.2}$	425	103	41.6	$\frac{L_n}{24.8}$	380	190	41.6	$\frac{L_n}{27.2}$	350	263	41.4	**41.6**
L.L=4.5 kN/m²													
Span (L) m	**t_2=0.25t_{slab}**				**t_2=0.5t_{slab}**				**t_2=0.75t_{slab}**				**allowable deflections mm**
	long term def $\leq \frac{L}{240}$				**long term def $\leq \frac{L}{240}$**				**long term def $\leq \frac{L}{240}$**				
	$\frac{L_n}{A}$	**t_{slab} mm**	**t_2**	**long term def (mm)**	**$\frac{L_n}{A}$**	**t_{slab} mm**	**t_2**	**long term def (mm)**	**$\frac{L_n}{A}$**	**t_{slab} mm**	**t_2**	**long term def (mm)**	**$\frac{L}{240}$**
4	$\frac{L_n}{28.4}$	130	35	15.4	$\frac{L_n}{30.8}$	120	60	15.4	$\frac{L_n}{33.0}$	115	87	12.8	**16.6**
5	$\frac{L_n}{26.8}$	175	44	20.8	$\frac{L_n}{28.4}$	165	83	19.8	$\frac{L_n}{33.0}$	145	109	20.7	**20.8**
6	$\frac{L_n}{26.2}$	215	54	24.7	$\frac{L_n}{28.2}$	200	100	24.0	$\frac{L_n}{31.3}$	180	135	25.0	**25.0**
7	$\frac{L_n}{25.3}$	260	65	29.1	$\frac{L_n}{27.5}$	240	120	28.4	$\frac{L_n}{30.0}$	220	165	29.1	**29.1**
8	$\frac{L_n}{23.9}$	315	79	32.2	$\frac{L_n}{26.4}$	285	143	33.2	$\frac{L_n}{28.4}$	265	199	33.1	**33.3**
9	$\frac{L_n}{22.6}$	375	94	36.5	$\frac{L_n}{25.0}$	340	170	36.0	$\frac{L_n}{27.8}$	305	229	37.5	**37.5**
10	$\frac{L_n}{21.2}$	445	112	41.3	$\frac{L_n}{23.0}$	410	205	41.0	$\frac{L_n}{25.5}$	370	278	41.4	**41.6**

4.2. Scanlon & Lee Unified Slab Thickness Equation

In 2006, Scanlon & Lee [15] presented a unified equation to estimate the minimum thickness for non-prestressed one-way and two-way slabs and beams. The proposed equation takes into account many parameters relating to the geometrical and material characteristics of the flat slab, such as the support conditions, the existence of drop panel, aspect ratio for edge supported slab, and the modulus of elasticity of concrete. The general form of the proposed equation is as follows:

$$\frac{l_n}{h} = \beta\left[\left(\frac{\Delta_{inc}}{l}\right)_{allow}\frac{0.0167 \times K_{DP} \times E_C \times b}{K \times K_{SS} \times K_{AR} \times (\lambda W_S + W_{L\,(add)})}\right]^{1/3} \quad (1)$$

where: l_n: is the clear span in mm; h: is the minimum thickness in mm; β: edge support coefficient (for slab without edge support equals to 1.0 and for edge supported equals to long span / short span); $(\Delta_{inc}/l)_{allow}$: is the targeted incremental deflection which equals to 1/480 for flat slab; K_{DP}: drop panel coefficient which equals to 1.0 for slabs without drop and 1.35 for slabs with drop panels; E_C: is the modulus of elasticity of concrete; b: is the strip width which equals to 1000mm; K: is the coefficient of end support condition which equals to 1.4 for both ends continuous, 2.0 for one end continuous and 5.0 for both ends continuous; K_{SS}: is the coefficient column supported condition of two way slabs which equal to 1.35 for column supported and 1.0 for other cases; K_{AR}: is the edge supported condition which equals to 0.2 + 0.4 β for edge supported slabs and 1.0 for other cases; λ: is the time-dependent factor of sustained loads according to ACI 318-14 Code. W_S: is the sustained load in kN/m^2 which equals to the self-weight plus superimposed dead load plus 0.25 of the live load; and $W_{L\,(add)}$: is the additional live load in kN/m^2 which equals to 0.75 of the live load.

For comparison reasons, Equation 1 is implemented on the investigated cases of slabs with and without drop panels. The results were listed in Tables 5 and 6. In general, high consistence was found between the results of the Scanlon and Lee equation and the proposed limitation especially for slabs without drop panels. Higher thickness was recorded by using the equations of Scanlon and Lee than the proposed limitations and the ACI-318 Code limitations. All the output of the equation and the proposed limitations were satisfied the required allowable deflection that indicated by the ACI-318 Code. That demonstrated the efficiency of the proposed limitations by means of agree with the results of the equation and at the same time satisfying the allowable deflection requirements. Moreover, the proposed limitations considered effect of thickness of the drop panels which is neglected in the Scanlon and Lee equation.

Table 5. Minimum thickness of flat slab without drop panels based on the proposed limitations, ACI-318 Code limitations and Scanlon and Lee equation

Two-way flat slab without drop panels, $f_y = 420$ MPa									
L.L=1.5 kN/m^2									
Span (L) m	$f'_c = 21$MPa			$f'_c = 35$MPa			$f'_c = 49$MPa		
	Proposed t mm	ACI-318 t mm	Scanlon and Lee eq. t mm	Proposed t mm	ACI-318 t mm	Scanlon and Lee eq. t mm	Proposed t mm	ACI-318 t mm	Scanlon and Lee eq. t mm
4	**125**	125	130.0	**125**	125	118	**125**	125	110
5	**160**	160	174.0	**160**	160	157	**160**	160	147
6	**220**	190	222.0	**190**	190	200	**190**	190	187
7	**260**	220	271.0	**225**	220	245	**220**	220	228
8	**310**	255	325.0	**275**	255	292	**260**	255	273
9	**360**	285	381.0	**330**	285	342	**300**	285	319
10	**425**	315	440.0	**385**	315	394	**355**	315	368
L.L=3 kN/m^2									
Span (L) m	$f'_c = 21$MPa			$f'_c = 35$MPa			$f'_c = 49$MPa		
	Proposed t mm	ACI-318 t mm	Scanlon and Lee eq. t mm	Proposed t mm	ACI-318 t mm	Scanlon and Lee eq. t mm	Proposed t mm	ACI-318 t mm	Scanlon and Lee eq. t mm
4	**125**	125	138.0	**125**	125	125	**125**	125	117
5	**175**	160	183.0	**160**	160	165	**160**	160	155
6	**220**	190	231.0	**200**	190	209	**190**	190	195
7	**280**	220	282.0	**245**	220	255	**230**	220	238
8	**330**	255	336.0	**290**	255	303	**270**	255	283
9	**380**	285	393.0	**340**	285	354	**320**	285	331
10	**445**	315	452.0	**400**	315	407	**370**	315	380
L.L=4.5 kN/m^2									
Span (L) m	$f'_c = 21$MPa			$f'_c = 35$MPa			$f'_c = 49$MPa		
	Proposed t mm	ACI-318 t mm	Scanlon and Lee eq. t mm	Proposed t mm	ACI-318 t mm	Scanlon and Lee eq. t mm	Proposed t mm	ACI-318 t mm	Scanlon and Lee eq. t mm
4	**135**	125	144.0	**125**	125	131	**125**	125	123
5	**185**	160	191.0	**170**	160	173	**160**	160	162
6	**235**	190	240.0	**210**	190	217	**200**	190	204
7	**290**	220	292.0	**260**	220	264	**245**	220	247
8	**340**	255	347.0	**305**	255	314	**290**	255	293
9	**400**	285	405.0	**355**	285	365	**335**	285	341
10	**460**	315	465.0	**410**	315	419	**390**	315	391

Table 6. Minimum thickness of flat slab without drop panels based on the proposed limitations, ACI-318 Code limitations and Scanlon and Lee equation

Two-way flat slab with drop panels, $f_y = 420$ MPa, $f'_c = 21$MPa									
L.L=1.5 kN/m²									
Span (L) m	**t_2=0.25t_{slab}**			**t_2=0.5t_{slab}**			**t_2=0.75t_{slab}**		
	Proposed t mm	**ACI-318 t mm**	**Scanlon and Lee eq. t mm**	**Proposed t mm**	**ACI-318 t mm**	**Scanlon and Lee eq. t mm**	**Proposed t mm**	**ACI-318 t mm**	**Scanlon and Lee eq. t mm**
4	115	115	116.0	115	115	116.0	115	115	116.0
5	150	145	154.0	145	145	154.0	145	145	154.0
6	200	175	196.0	185	175	196.0	175	175	196.0
7	235	200	240.0	220	200	240.0	200	200	240.0
8	290	230	287.0	260	230	287.0	240	230	287.0
9	340	260	366.0	305	260	366.0	280	260	366.0
10	405	290	387.0	370	290	387.0	340	290	387.0
L.L= 3 kN/m²									
Span (L) m	**t_2=0.25t_{slab}**			**t_2=0.5t_{slab}**			**t_2=0.75t_{slab}**		
	Proposed t mm	**ACI-318 t mm**	**Scanlon and Lee eq. t mm**	**Proposed t mm**	**ACI-318 t mm**	**Scanlon and Lee eq. t mm**	**Proposed t mm**	**ACI-318 t mm**	**Scanlon and Lee eq. t mm**
4	120	115	123.0	115	115	123.0	115	115	123.0
5	165	145	163.0	145	145	163.0	145	145	163.0
6	205	175	205.0	185	175	205.0	175	175	205.0
7	245	200	250.0	225	200	250.0	210	200	250.0
8	305	230	298.0	270	230	298.0	250	230	298.0
9	360	260	348.0	325	260	348.0	295	260	348.0
10	425	290	400.0	380	290	400.0	350	290	400.0
L.L=4.5 kN/m²									
Span (L) m	**t_2=0.25t_{slab}**			**t_2=0.5t_{slab}**			**t_2=0.75t_{slab}**		
	Proposed t mm	**ACI-318 t mm**	**Scanlon and Lee eq. t mm**	**Proposed t mm**	**ACI-318 t mm**	**Scanlon and Lee eq. t mm**	**Proposed t mm**	**ACI-318 t mm**	**Scanlon and Lee eq. t mm**
4	130	115	129.0	120	115	129.0	115	115	129.0
5	175	145	170.0	165	145	170.0	145	145	170.0
6	215	175	214.0	200	175	214.0	180	175	214.0
7	260	200	260.0	240	200	260.0	220	200	260.0
8	315	230	308.0	285	230	308.0	265	230	308.0
9	375	260	359.0	340	260	359.0	305	260	359.0
10	445	290	411.0	410	290	411.0	370	290	411.0

5. Conclusions

The nonlinear Finite Element Analysis was used in order to study the effectiveness of using ACI minimum thickness provisions for flat slab for the controlling of long-term deflection. The analysis involved 126 case studies that considered the effects of several influencing parameters: slab span length, concrete compressive strength, the applied live load, and the thickness of the drop panel. From the analysis results, the main findings can be summarized as follow:

- ACI 318-19 minimum thickness provisions required for the control of deflection in flat slab (with or without drop) cannot be satisfactory (i.e. to comply with the ACI allowable limits L/480 and L240) for all cases because they consider the effects of only the span length and yield strength of steel and ignoring the effects of the other influencing factors like the concrete compressive strength, live load, and the drop panel thickness. Therefore, these ACI code provisions have a serious problem and need a real revision;
- The effect of using high concrete compressive strength on reducing the long-term deflection was found to be significant especially for small spans. It was observed that the increase in concrete compressive strength from 21MPa to 49MPa decreases the average long-term deflection by (56%, 53%, 50%, 44%, 39%, 33% and 31%) for spans (4, 5, 6, 7, 8, 9 and 10 m) respectively;

- In flat slab with drop panel, the use of thicker drop panel has an important positive effect on the reduction of long-term deflection especially for small spans. It was found that varying drop panel thickness t_2 from $0.25t_{slab}$ to $0.75t_{slab}$ decreases the average long-term deflection by (45, 41, 39, 35, 31, 28 and 25%) for span lengths (4, 5, 6, 7, 8, 9 and 10 m) respectively;
- Concerning the live load effect, it was observed that increasing the live load leads to larger long-term deflection but this effect becomes less important with the increase in span lengths;
- Formulas for calculating the minimum thickness of flat slab were proposed to vary from Ln/30 to Ln/19.9 for flat slab without drop panel and from Ln/33 to Ln/21.2 for flat slab with drop panel;
- High constancy was observed between the results of Scanlon and Lee equation and the proposed limitations of the minimum thickness of slabs with and without drop panels.

6. Declarations

6.1. Author Contributions

Conceptualization, B.I.A., M.A., A.B. and A.A.S.; methodology, B.I.A., M.A., A.B. and A.A.S.; software, B.I.A.; validation, M.A., A.B. and A.A.S.; formal analysis, B.I.A.; investigation, B.I.A., M.A., A.B. and A.A.S.; data curation, A.B. and A.A.S; writing—original draft preparation, B.I.A. and M.A; writing—review and editing, A.B. and A.A.S.; visualization, B.I.A., M.A., A.B. and A.A.S.; supervision, B.I.A., M.A., A.B. and A.A.S.; project administration, B.I.A., M.A., A.B. and A.A.S. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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