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RESEARCH PAPER

Aspect Ratio Consideration in Flat Plate Concrete Slab Deflection

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A B S T R A C T:

This paper addresses the effect of the aspect ratio (long span/short span), concrete strength grade and live load on the long-term deflection of uniformly loaded corner flat plate floor panels without edge beams. It outlines in particular the effects of not considering the aspect ratio parameter in five national codes of practice provisions for the minimum slab thickness and tries to search for the “slab reference span” along which the calculated actual relative deflection and the maximum permissible deflection are determined. The calculations of deflections have been done by the finite element SAFE software through a parametric study with variable long span length, aspect ratio, thickness as recommended by ACI 318-14, concrete grade and live load.

The results showed that, for the range of concrete grade and live load studied, the slab panel aspect ratio parameter has the largest effect on the long-term deflection; the parameter which is overlooked by all the five codes of practice. In spite of this effect, the applicability of the ACI 318-14 provisions for thickness of flat plat floors without beams seemed to be adequate for the L/360 limit, L/240 limit for typical spans and concrete strength grade but showed to be inadequate in many cases to satisfy the L/480 limit. Further, the results showed that the relative deflection along the long span could be recommended for deflection control in flat plate floors without edge beams.

KEY WORDS: Flat Plate, Aspect Ratio, Long Term Deflection, Permissible Deflection.
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1. INTRODUCTION

In flat plate/slab floors, the main challenge in the structural design is the deflection control. Excessive deflections of a flat plate floor/roof may render a structure unusable considering both an esthetical and a functional point of view; noticeable deflections may create an impression of faulty construction work or may give a sense of instability. Nevertheless, the major effect of large deflections is usually to cause damage to construction carried by the floor not to the floor itself. Such damage could be seen though cracking of brittle partitions, jamming and miss-alignment of doors.

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The current paper claims that ACI 318-14 code (2014) deflection provisions for flat plate floor panels without edge beams might lack: i) the inclusion of the aspect ratio; ii) assigning explicitly the L/480 long-term deflection (*LTD*) limit to floors supporting masonry partitions; and iii) specifying clearly the span direction (short, long or diagonal) that is required to be used in calculating/checking the permissible maximum deflection.

The current research conducted a nonlinear cracked analysis to obtain the *LTD* for 600 flat plate corner panel cases using finite element SAFE software, for the range of concrete strength (20-40 MPa) and live load (2.4-5 kN/m^2) used in practice and for aspect ratios ranging from 1 to 2. For each panel, three LTD deflections have been recorded at the middle of each of the short, long and diagonal spans resulting in having a record of 1800 deflection values to evaluate. To this limit, the scope of the current study is to:

- Evaluate the ACI 318-14 code provisions for deflection considering varied aspect ratio, concrete strength grade, live load;
- Determine the "*Slab Reference Span*" for deflection control; for this purpose, the current paper evaluates the relative deflection along all three slab panel directions (short, long and diagonal).
- Recommend a proper LTD limit for floors supporting masonry walls;

1.1 ACI Provisions for Flat Plate Panel Deflection Control.

For slab panels (including flat plate panels), ACI 318 (2014) recommends two alternative procedures for control of deflection. Deflection is controlled by specifying minimum thickness as a ratio of the long span of the slab (maximum span-to-depth ratio). This provision is attractive as a mean of deflection control due to its simplicity; however, it has been criticized by many researchers (Scanlon and Lee (2010), Bondy (2005), Hwang and Chang (1996), Hilbert (1985)) for not providing an allowance for the actual load level, concrete strength, steel quantities, and the desired deflection limit.
Furthermore, there is another dispute in the slab's recommended minimum thickness, which is not having any inclusion for the slab panel aspect ratio. For example, for slab panels between 4x8 m to 8x8 m (keeping the long span constant), ACI 318-14 recommends the same *l/d*, as only the long span (*l*) is included in the code provisions. The current paper tries to investigate the impact of the slab aspect ratio on the calculated *LTD* in flat plate slabs.
Thompson and Scanlon (1988) conducting Finite Analysis of 300 slabs considering many variables including the slab aspect ratio; Scanlon concluded that for square slab panels, the ACI minimum thickness should be increased by 10 %. In Further, as an inclusion for the flat slab aspect ratio in the recommended minimum thickness, Bondy (2005) suggested basing the limiting span for deflection on the panel diagonal dimension. This is because of the fact that the maximum deflection of the center of the slab panel is an additive function of the spans of both orthogonal directions (Bondy, 2005).
In the 2nd procedure for determination of flat plate panel thickness (which is applicable to all two-way slab types), the theoretical calculated deflection along a "slab reference span" needs to be compared with a maximum calculated permissible deflection. ACI 318 (2014) is silent about the slab reference span direction (short span, long or diagonal span) that is required to be used. Bondy (2005) suggested the use of the diagonal span for this purpose and advised adding a statement in the ACI 318 about this span direction.
The authors made a survey for the "*slab reference span*" direction used for checking of deflection, see **Table 1**. As seen, in spite of having an agreement about the span direction "***Lc***" that the theoretical deflection is calculated along it, there is an extensive disagreement about the span direction "***Lr***" that the maximum calculated permissible deflection is calculated along it. As a matter of functionality to prevent damage to partitions, the purpose of the deflection control is to minimize its variation along a line; therefore, it is an inaccurate to compare deflections calculated along the diagonal span with the maximum permissible deflection calculated along another span {long span [as it is the case in ACI 435 (2003) MacGregor and Wight (2012), ACI SP17 (2015)] or the short span [as it is the case in Nilson et al (2016)]}.
The authors believe that Regan (1981)'s approach is the realistic one considering the slab function in limiting cracks in partitions, as it considers the relative deflection along any line, while in the other approaches, the relative deflection along the long and short spans are neglected, and in some approaches, the mid-panel (diagonal) deflection is compared with a permissible deflection based on other spans (long or short). In the current paper, Regan's approach is selected to be used, where the relative deflection calculated along any span (short, long or diagonal) needs to be compared with the maximum permissible deflection based on the same span aiming to determine the span direction "slab reference span" along which the critical relative deflection occurs.

Table 1: Two-way slab span directions "Slab Reference Span" used for deflection checking against ACI 318 code provisions.

Slab Type	Author	Span "Lc" used for calculating the deflection	Span "Lr" used for determining the maximum permissible deflection
Flat Plate	(ACI 435R-95, 2003, pp. ,66)	*Mid-panel*	***Diagonal span***
	(ACI SP-17(14): Volume 2, 2015, pp. ,139)	*Mid-panel*	***Diagonal span*** *(based on ref* (ACI 435R-95, 2003) *)*
		Mid-panel	***Long span*** *(as another possibility)*
	(MacGregor, J G. and Wight, J K., 2012, pp. ,762)	*Mid-panel*	***Long span***
	(Regan, 1981, pp. ,45)		***Diagonal span*** (for the absolute maximum deflection at the mid-panel); ***Long/short span*** (when the deflection check is made for the sake of the partitions). In this case, the relative deflection in the partition span (mostly Long or Short span) under consideration is calculated.
Slabs with supporting beams	(ACI 435R-95, 2003, pp. ,65), (Nawy, 2009, pp. ,532)	*Mid-panel*	***Long span***
	(Nilson, A., Darwin, D., Dolan, C., 2016, pp. ,444)	*Mid-panel*	***Short span***

1.2 Slab Aspect Ratio in International Codes

ACI 318-14 and CSA A23.3-14 codes considers the aspect ratio in determining the minimum slab thickness only in the case of edge-supported slabs with beams having beam /slab relative stiffness not less than 0.2, while in flat plates/flat slabs floors, no consideration is taken for the aspect ratio. On the other hand, AS 3600 (2018), BS 8110 (1997) and EN 1992 (2004) codes do not include the aspect ratio in determining the slab thickness in all slab types (with/without edge supports).

1.3 Deflection Limitation Affecting Masonry Partitions in International Codes

As a measure to avoid large deflections in slabs and consequently preventing noticeable cracks and functional and esthetic problems in non-structural elements including masonry partitions, the codes of practice have set limits (see **Table 2**) on that part of the total deflection occurring after the installation of the non-structural elements; this deflection part (LTD) is the sum of the *long-term effect* of the sustained loads and the immediate deflection due to any additional live load. This limit is $L/500$ (L:Span) in BS8110-97 and EN 1992-04, $L/500$ *(floors supporting masonry partitions where provision is made to minimize the effect of movement) or L/1000 (other cases) in* AS 3600, while in ACI 318-14 and CSA A23.3-14, it could be either $L/240$ or $L/480$ as the term "*not likely (or likely) to be damaged*" stated in the code to specify the use of any of them is ambiguous with respect to floor slabs supporting masonry partitions. Thus, in order to match other codes of practice, the current paper urges to add a definite inclusion of such floors in ACI 318 and CSA A23.3.14, and to consider them as non-structural elements likely to be damaged with excessive deflection.

Considering the "Slab Reference Span" for *LTD* control, among all the five codes of practice, only CSA A23.3-14 and AS3600-18 have a definition for it. As this definition is not stated in ACI 318-14, the current paper search for such a definition for the "Slab Reference Span" in flat plates. AS3600-18 presents a sophisticated approach for the spans that the deflection is checked along it, where it states:

"In general, deflection limits should be applied to all spanning directions. This includes, but is not limited to, each individual member and the diagonal spans across each design panel. For flat slabs with uniform loadings, only the column strip deflections in each direction need be checked."

Table 2: Long term deflection limits and Slab Reference Span in different codes (applicable also to floors supporting partitions)

Code	Long term deflection limit		Slab Reference Span for check
(ACI 318 , 2014)	L/240 floor slabs supporting non-structural elements not likely to be damaged with excessive deflection	L/480 otherwise	**Not specified**
(CSA A23.3-14, 2014)	L/240 floor slabs supporting non-structural elements not likely to be damaged with excessive deflection	L/480 otherwise	Long clear span
(AS 3600-18, 2018)	L/500 floors supporting **masonry partitions** where provision is made to minimize the effect of movement	L/1000 otherwise	-All spans (short, long and Diagonal) for slabs with beams, -Long/Short clear span in flat slab case.
(BS EN 8110-1-97, 1997)	L/500 ≤ 20 mm		**Not specified**
(EN 1992-1-1-04, 2004)	L/500		**Not specified**

1.4 Deflection Calculations

In the current paper, the deflection of a uniformly loaded flat plate corner panel has been determined by two methods: i) SAFE software, with finite element slab mesh of 0.5 m; ii) Theoretical calculation based on the equivalent frame approach.

SAFE is a software produced by CSI (Computers & Structures, Inc.) (2016); it is a special purpose analysis, design, and detailing software for concrete slab systems. For the current slab deflection analysis, the slabs have been modelled using 4-nodded thin shell bending elements with six degree of freedoms per node (three rotation and three displacements); The shell elements capture out-of-plane bending and shear behavior, as well as in-plane deformations with no inclusion of transverse shear deformation. The *LDT* is calculated as (using nonlinear cracked analysis type in SAFE):

$LDT = L_1 + S_1 - S_2$, Where,

L_1: Long-term deflection of 25% live load and 100% self-weight, super imposed deal

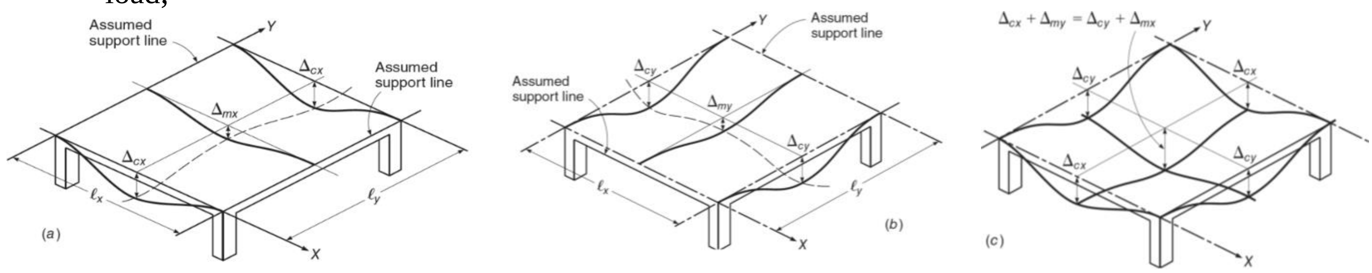
S_1: Immediate deflection of 100% live load and 100% self-weight, super imposed deal

S_2: Immediate deflection of 100% live load and 25% self-weight, super imposed deal

In the theoretical calculation, the deflection is calculated using the equivalent frame method for the first interior design frames, with dividing the slab panel into column and middle strips in each direction (ACI 435R-95 (2003), Nilson et al (2016)). **Figure 1** shows actual deformed shape of a slab panel; In this approach, the equivalent frame method is used to analyze the slab in two directions, then to take the average deflection of two parallel column strips and to add the deflection of the middle strip spanning orthogonally to obtain an approximation for the maximum deflection at the center of the slab panel (Crossing-Beam Approach) using Branson effective moment of inertia approach (ACI 318 , 2014) for cracked concrete. The calculated LTD included:

- Deflection affecting construction/equipment installed on the slab, which is equal to the long term nonlinear cracked deflection under full self-weight, superimposed dead and 25 % live load plus the short term nonlinear cracked deflection for 75% of the live load.

- Nonlinear Cracked deflection under full live load;



(A) X- DIRECTION BENDING; (B) Y- DIRECTION BENDING (C) COMBINED BENDING

Figure (1) Basic of equivalent frame method deflection analysis (from Nilson et al (Nilson, A., Darwin, D., Dolan, C., 2016))

2. PARAMETRIC STUDY

A parametric study has been performed for the slab deflection evaluation, taking one-story prototype structure consisting of 3 x 3 reinforced concrete flat plate panels without edge beams, having same span length in each direction, designed according to ACI 318-14, taking the ***corner*** panels as the studied panel, as they experience the largest deflection in the studied model. The study program is divided into six main groups as detailed in **Table 3**, and taking the below as constant, in both the SAFE analysis and the theoretical calculation:

- Modulus of rupture is based on ACI-specified value of 0.62 √ f_c’ (ACI 318-14, section 19.2.3.1)
- Slab tension reinforcement ratio for cracking analysis= 0.0018,
- Slab compression reinforcement ratio for cracking analysis= 0.0,
- The modulus of elasticity of concrete= 4700 √ f_c’ (ACI 318-14, section 19.2.2.1);
- Combined creep and shrinkage time dependent factor = 2 (ACI 318-14, section 24.2.4.1.3);
- Yield strength of reinforcement: 420 MPa;
- Superimposed dead load (SDL) = 2.4 kN/m^2 (including an allowance for partitions)
- Columns: 0.4 x 0.4 m, 3.5 m height, fixed at bottom.

In summary, each group consisted of 100 cases with different slab aspect ratio, live loads and concrete strength grades. The selected range of long spans (5 to 10 m) and concrete strength grades (20 – 40 MPa) are those typically encountered in practice; the lowest live load value taken (2.4 kN/m^2) as this given by ASCE/SEI 7 (2010) provisions for offices.

Table 3: Parametric Study Variables Summary

Group	Slab thick, mm	Span			Concrete compressive strength, MPa	Slab live loads, kN/m^2
		Long span (*L1*), m	Short span (*L2*) cases, m	Aspect ratio range cases		
C05	153.3	5	2.5,3.0,3.5,4.0,5.0	2 to 1	20, 25, 30, 35, 40	2.4, 3.0, 4.0, 5.0
C06	186.7	6	3.0,3.5,4.5,5.5,6.0	2 to 1	20, 25, 30, 35, 40	2.4, 3.0, 4.0, 5.0
C07	220.0	7	3.5,4.0,5.0.6.0.7.0	2 to 1	20, 25, 30, 35, 40	2.4, 3.0, 4.0, 5.0
C08	253.3	8	4.0,5.0,6.0,7.0,8.0	2 to 1	20, 25, 30, 35, 40	2.4, 3.0, 4.0, 5.0
C09	286.7	9	4.5,6.0,7.0,8.0,9.0	2 to 1	20, 25, 30, 35, 40	2.4, 3.0, 4.0, 5.0
C10	320.0	10	5.0,6.0,7.0,9.0,10.0	2 to 1	20, 25, 30, 35, 40	2.4, 3.0, 4.0, 5.0

3. RESULTS AND DISCUSSION

3.1 Long Term Deflection Along all Span Directions (Short, Long, Diagonal)

Figure 2 presents the results of the parametric study including the *absolute LTD* (measured in mm) along three directions (Diagonal span, Interior column strip along each of the short and long span) of the flat plate corner panels. In total, there are 1800 deflection values divided into six long span groups; each group has 300 deflection values (100 deflection values at each direction).

As could be seen in **Figure 2**, in spite of the fact that ACI 318-14 provisions make no difference between all the flat slab cases of the same long span (each group in the current paper), it is clear that there is a noticeable variation in the *LTD* in all directions (short, long and diagonal); this variation increases with the increase of the long span length. This variation is ignored by ACI 318-14 provisions, due to not having any allowance for concrete grade, aspect ratio or live loading in flat plate floors.

As an overview of the rate of variation in the *LTD* within each group, **Table 4** lists the minimum and maximum *LTD* along the long span (*L1*) within the groups. As could be seen, within each group, the lowest LTD value occurred at the case of rectangular panels (aspect ratio of 2), lowest live load (2.4 kN/m^2) and largest concrete grade (40 MPa), while the highest LTD value occurred at the case of square panels (aspect ratio of 1), highest live load (5.0 kN/m^2) and lowest concrete grade (20 MPa). This variation in the *LTD* values within each group along the long span ranged from the largest in group C10 (35.4 mm equal to *L1*/282.5) to the smallest in group C05 (11.3 mm equal to *L1*/442.5).

Table 4: Long-term deflection variation along the long span within each group

Group	Long span (*L1*), mm	Group	Deflection within group, mm		Variation, mm	L1 / variation ratio
			Minimum	Maximum		
C05	5000	C05	3.8	15.1	11.3	442.5
C06	6000	C06	5.5	19.6	14.1	425.5
C07	7000	C07	7.7	27.0	19.3	362.7
C08	8000	C08	10.2	35.6	25.4	315.0
C09	9000	C09	14.0	44.7	30.7	293.2
C10	10000	C10	18.3	53.7	35.4	282.5

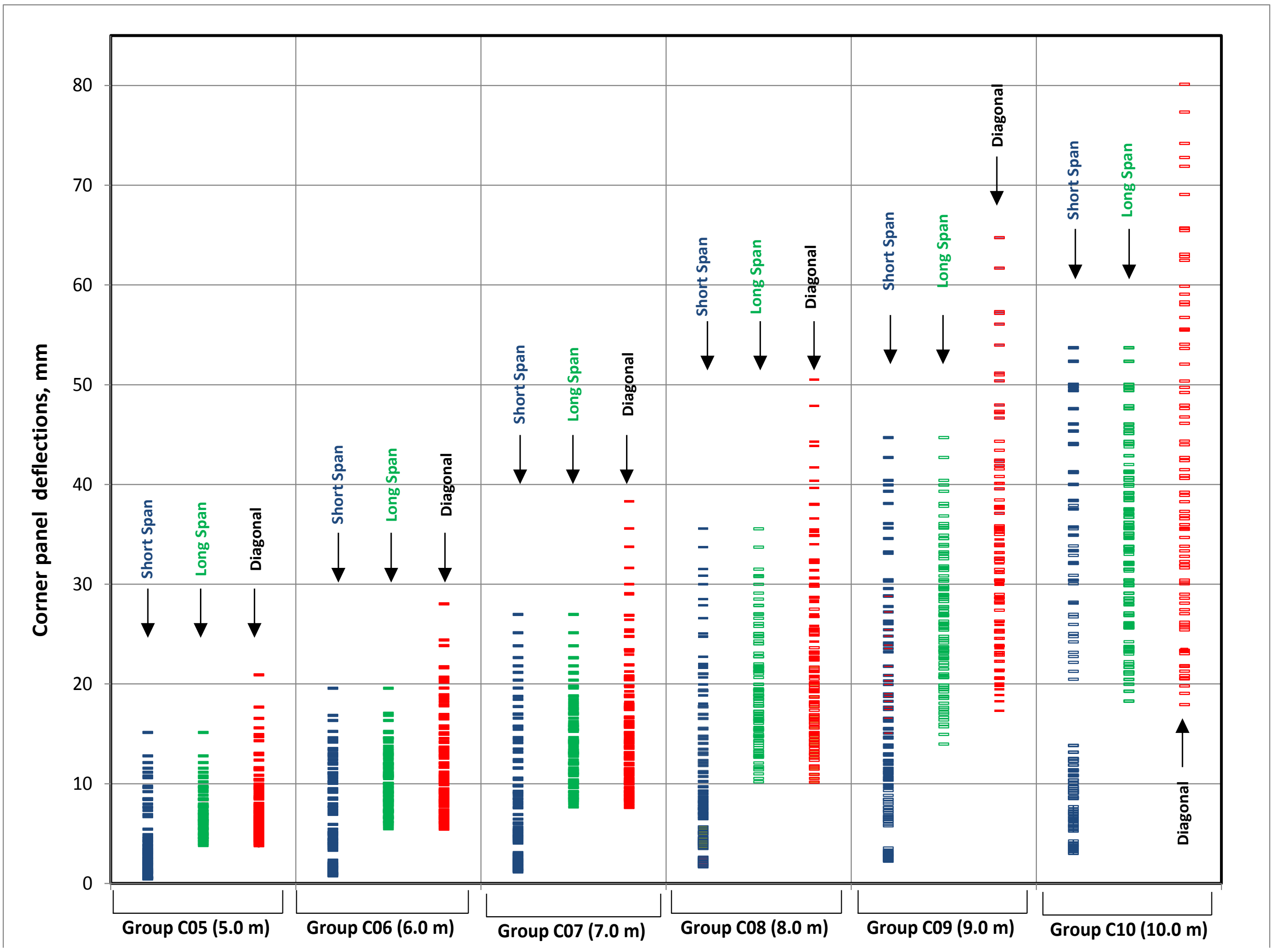


Figure (2) Variation of the corner flat slab panel absolute LTD within the tested groups

3.2 Slab Panel Maximum Relative Deflection

The absolute *LTD* along panel spans (short, long and diagonal) of **Figure 2** are re-presented in **Figure 3** as a ratio of *LTD* to the span that the deflection is measured along it. As could be seen, as the long span is getting larger, the number of cases exceeding the *L*/240 and *L*/480 limits is increasing, as detailed in **Table 5**. As seen, up to 7 m long span, ACI 318 (2014) provisions for the minimum slab thickness are sufficient to assure that the long-term deflections are not exceeding the *L*/240 limit; however, these provisions resulted in long term deflections exceeding the *L*/480 limit in all the long span values.

The relative *LTD* deflection occurred along the long direction in almost all the cases (592 cases out of 600 cases (or 98.7%)), except at 10 x 10 m square panels with low concrete grade (*fc'* = 20, 25 MPa), where the maximum relative deflection occurred at the diagonal direction; even in these cases, the difference did not exceed L/20. Based on that, and consistent with CSA A23.3-14 code (2014), this observation suggests adopting the long span direction in the calculation and evaluation of the *LTD*.

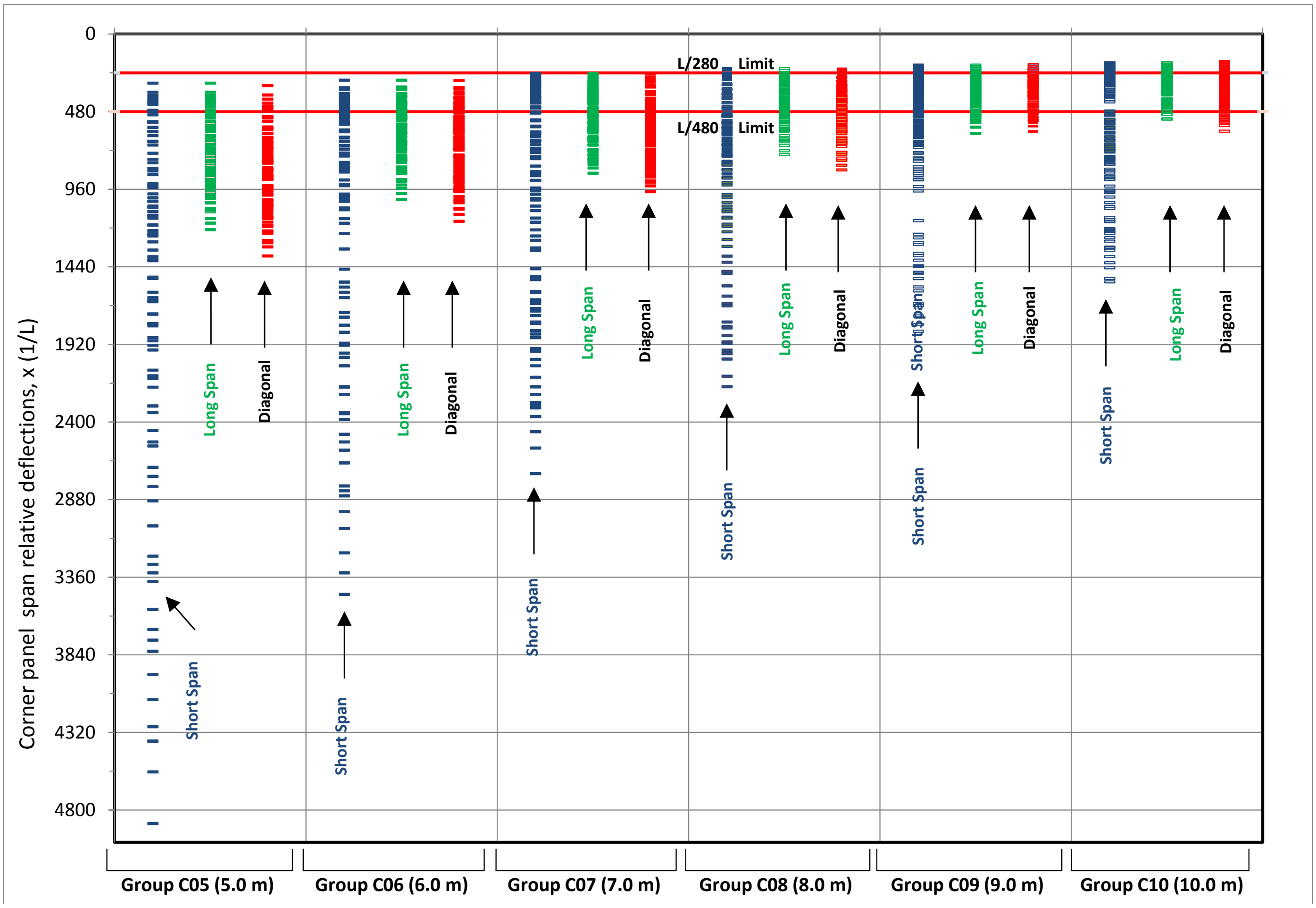


Figure (3) Variation of the corner flat slab panel relative LTD within the tested groups

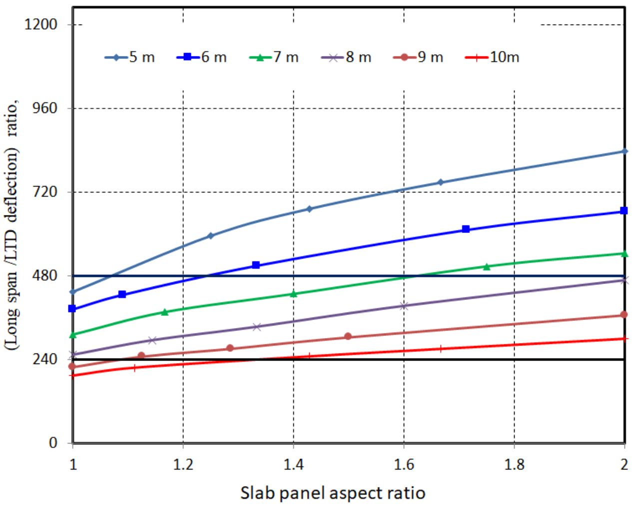
Table 5: Cases of relative LTD along long span exceeding ACI 318 (2014) limits

Group (each group consists of 100 cases)	Number of cases with relative LTD exceeding L/240			Number of cases with relative LTD exceeding L/480		
	Short Span	Long Span	Diagonal Span	Short Span	Long Span	Diagonal Span
C05	0	0	0	10	11	07
C06	0	0	0	18	27	20
C07	0	0	0	23	46	30
C08	2	2	2	31	71	53
C09	7	11	7	43	90	75
C10	14	24	17	41	97	87

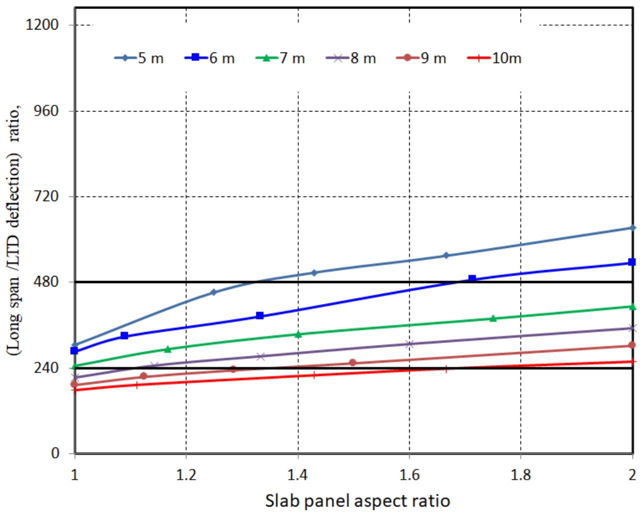
3.3 Slab Panel Relative Deflection Along the Long Span

As the relative *LTD* along the long span appeared to the critical in 98.7 % of the cases, as detailed in the previous section, the deflection results along this span is presented in full in **Table 6.** Hence, the increase in the slab deflection is a combined effect to the three tested variables; the individual effects for each variable are listed in **Table 7**, where the range of the individual effect for each variable (live load, concrete strength, aspect ratio) are reported within each group. As seen, the aspect ratio and the concrete had the largest effect on the *LTD* deflection followed by the live load with the effects being more pronounced at larger spans. The live load had a lesser effect on the LTD deflections compared to the concrete strength due to the status of the applying the live loads, where only 25% of the live load is considered to have long term effect while the other 75% of the live load is considered to have only the short-term effect (immediate deflection). Further, the effect of the concrete strength on the deflection is pronounced through the modulus of elasticity of concrete which is proportional to the square root of compressive strength.

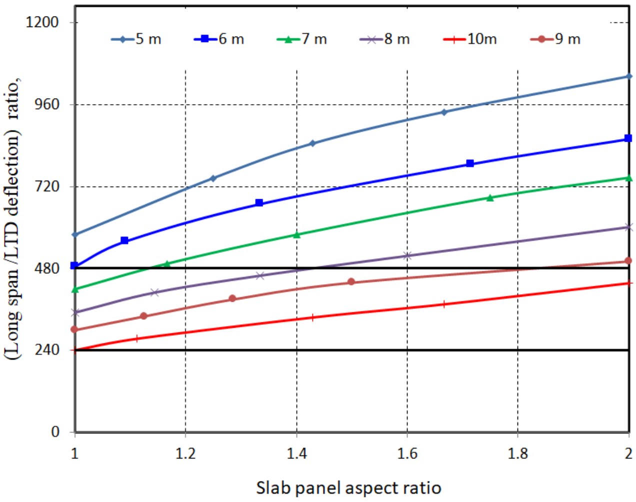
Figure 4 shows the trend of the change in maximum *LTD* along the long span as a function of the panel aspect ratio, where the length "*L*" is taken as the clear long span length. This trend is compared with ACI 318-14 provisions for *LTD* part for panels not attached to normal non-structural elements (*L*/240) and for panels attached to non-structural elements likely to be damaged by large deflection (*L*/480). As could be seen, for the *L*/240 limit, the slabs of long span up to 7.0 m conformed to ACI 318-14 maximum permissible deflection provisions. For higher long span lengths, the non-conformity appeared at cases of low concrete grade and high live load. On the other side, for the *L*/480 limit, the slabs did not perform well in most of the cases. This observation (for slabs with minimum reinforcement ratio) conforms Scanlon and Lee (2010) finding that "*the ACI values (deflection provisions) for flat plates (and flat slabs) seem to be adequate for the L/240 limit for typical spans and loading but may be inadequate in many cases to satisfy the L/480 limit*".



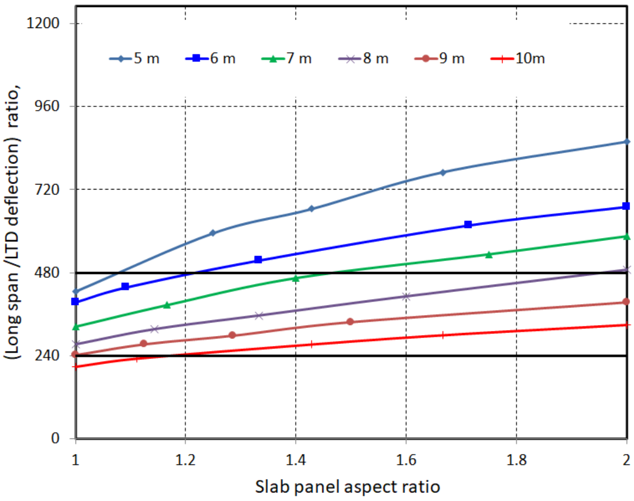
a) Concrete grade of 20 MPa, live load of 2.4 kN/m²



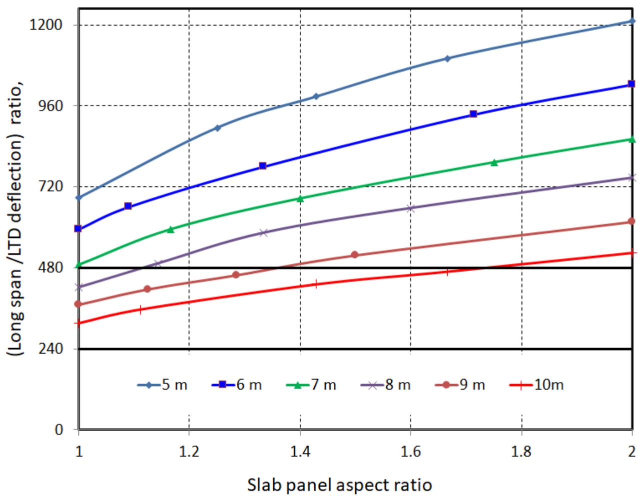
b) Concrete grade of 20 MPa, live load of 5.0 kN/m²



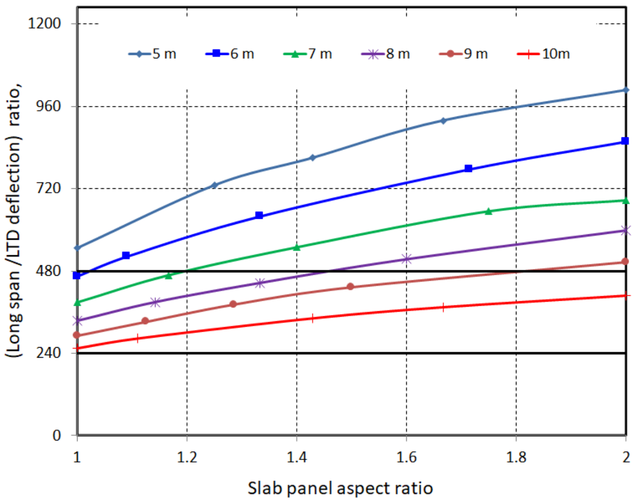
c) Concrete grade of 20 MPa, live load of 2.4 kN/m²



d) Concrete grade of 30 MPa, live load of 5.0 kN/m²



a) Concrete grade of 40 MPa, live load of 2.4 kN/m²



f) Concrete grade of 40 MPa, live load of 5.0 kN/m²

Figure (4) Flat slab floor panel aspect ratio versus (long span/LDT deflection) Ratio

Table 6: Long-Term Deflection along the long span

Group	Long Span, m	Short Span, m	Aspect ratio	Slab thick, mm	Long Term Deflection part, mm																			
					f_c'=20 MPa				f_c'=25 MPa				f_c'=30 MPa				f_c'=35 MPa				f_c'=40 MPa			
					Live load, kN/m^2				Live load, kN/m^2				Live load, kN/m^2				Live load, kN/m^2				Live load, kN/m^2			
					2.4	3	4	5	2.4	3	4	5	2.4	3	4	5	2.4	3	4	5	2.4	3	4	5
C05	5	2.5	2	153.3	5.5	5.9	6.5	7.3	4.8	5.1	5.6	6.2	4.4	4.6	4.9	5.4	4.0	4.2	4.6	4.9	3.8	3.9	4.3	4.6
		3.0	1.67	153.3	6.2	6.5	7.3	8.3	5.4	5.7	6.1	6.9	4.9	5.2	5.7	6.0	4.5	4.7	5.1	5.5	4.2	4.4	4.7	5.0
		3.5	1.43	153.3	6.8	7.3	8.2	9.0	6.1	6.4	7.0	7.6	5.4	5.8	6.2	6.9	5.0	5.3	5.8	6.2	4.7	4.9	5.3	5.7
		4.0	1.25	153.3	7.7	8.4	9.4	10.2	6.7	7.0	7.9	8.8	6.2	6.4	7.0	7.7	5.7	6.0	6.4	7.0	5.1	5.4	6.0	6.3
		5.0	1	153.3	10.6	11.6	12.8	15.1	9.2	9.8	11.1	12.1	8.0	8.5	9.6	10.8	7.3	7.6	8.5	9.6	6.7	6.9	7.6	8.4
C06	6	3.0	2	186.7	8.4	9.0	9.9	10.5	7.1	7.4	8.2	9.3	6.5	6.8	7.3	8.3	5.9	6.2	6.6	7.2	5.5	5.7	6.1	6.5
		3.5	1.71	186.7	9.2	10.0	10.8	11.5	7.7	8.1	9.1	10.0	7.1	7.4	8.2	9.1	6.5	6.8	7.3	7.9	6.0	6.2	6.7	7.2
		4.5	1.33	186.7	11.0	11.9	12.6	14.6	9.4	1.1	11.2	11.8	8.4	8.8	9.9	10.8	7.8	8.1	8.7	9.7	7.2	7.5	7.9	8.8
		5.5	1.09	186.7	13.2	13.8	15.1	17.0	11.3	12.0	12.9	14.6	10.0	10.8	12.0	12.8	9.2	9.6	10.6	11.6	8.5	8.9	9.6	10.7
		6.0	1	186.7	14.6	15.2	16.9	19.6	12.9	13.5	14.4	16.3	11.5	12.4	13.4	14.2	10.8	11.0	12.1	13.1	9.4	10.0	11.1	12.0
C07	7	3.5	2	220.0	12.1	12.7	14.4	16.0	10.2	10.9	12.0	13.1	8.9	9.2	10.4	11.3	8.2	8.5	9.1	10.1	7.7	8.0	8.5	9.6
		4.0	1.75	220.0	13.0	13.7	15.8	17.4	11.0	12.1	13.0	14.3	9.6	10.2	11.4	12.4	8.8	9.2	9.9	11.1	8.3	8.6	9.2	10.1
		5.0	1.40	220.0	15.4	16.0	18.2	19.8	13.1	14.0	15.4	17.1	11.4	12.1	13.3	14.2	10.4	10.8	12.0	13.1	9.6	9.9	10.9	12.0
		6.0	1.17	220.0	17.5	18.8	21.1	22.6	15.4	16.2	18.0	19.8	13.4	14.2	15.2	17.1	12.0	12.8	14.1	15.5	11.1	11.6	13.0	14.1
		7.0	1	220.0	21.2	22.6	25.1	27.0	18.5	19.6	21.8	23.8	15.8	16.6	17.7	20.4	14.6	15.5	17.0	18.8	13.5	14.4	15.7	17.0
C08	8	4.0	2	253.3	16.2	17.8	20.0	21.7	14.3	14.8	16.7	18.9	12.6	13.2	14.3	15.5	11.0	11.7	12.9	13.8	10.2	10.5	11.4	12.7
		5.0	1.6	253.3	19.3	21.3	23.1	24.8	16.4	17.2	19.4	21.3	14.7	15.3	16.4	18.5	12.8	13.6	14.8	16.1	11.6	12.1	13.3	14.8
		6.0	1.33	253.3	22.8	24.3	26.1	27.9	18.3	19.4	21.7	24.0	16.6	17.3	18.5	21.3	15.0	15.6	16.8	18.9	13.0	14.1	15.4	17.1
		7.0	1.14	253.3	25.8	27.0	29.1	30.8	21.2	22.7	25.0	27.0	18.5	19.1	21.0	24.0	17.0	17.8	18.8	21.5	15.4	16.3	17.8	19.5
		8.0	1	253.3	30.0	31.5	33.7	35.5	25.1	26.6	28.5	30.9	21.6	22.0	24.7	27.9	19.4	19.9	21.8	24.8	18.0	18.9	20.6	22.7
C09	9	4.5	2.00	286.7	23.4	24.8	26.9	28.5	19.2	20.6	22.6	24.5	17.2	18.1	19.9	21.9	15.7	16.4	17.7	19.7	14.0	14.9	16.0	17.0
		6	1.50	286.7	28.3	29.6	31.8	34.0	23.7	25.7	27.6	29.7	19.6	20.9	23.4	25.6	18.5	19.4	21.0	23.3	16.7	17.5	18.7	19.9
		7	1.29	286.7	31.7	32.8	34.9	36.8	26.9	28.6	30.8	32.6	22.1	23.7	26.9	28.9	20.7	21.5	23.6	26.1	18.8	19.5	20.7	22.5
		8	1.13	286.7	34.6	35.9	37.8	40.0	29.8	31.4	33.8	35.7	25.4	27.3	29.4	31.6	23.1	24.4	27.0	29.0	20.7	21.5	22.8	26.0
		9	1.00	286.7	39.3	40.4	42.7	44.7	34.6	36.1	38.1	40.0	28.8	30.4	33.1	35.6	26.3	27.8	30.3	33.2	23.2	24.1	26.0	29.6
C10	10	5	2.00	320.0	32.1	33.5	35.6	37.4	26.9	27.9	30.4	32.2	22	23.8	26.1	29.1	20	21.2	23.7	25.8	18.3	19.3	21	23.5
		6	1.67	320.0	35.6	36.7	38.7	40.4	29.9	31.5	33.8	35.9	25.6	27.1	29.9	32	21.7	23.3	26	28.3	20.4	21.2	23.2	25.6
		7	1.43	320.0	38.6	39.8	42	43.8	33.2	34.7	37	38.9	28.6	30	33	35.1	24.2	26.1	29.1	31.3	22.2	23	25.7	28
		9	1.11	320.0	44.3	45.7	47.9	49.7	39.1	40.7	42.9	45.1	35.1	36.2	39.2	41.3	30	32	34.6	37.1	26.9	28.6	31.5	33.8
		10	1.00	320.0	49.4	49.8	52.3	53.7	44	45.4	47.6	50	40	41.3	44.1	46.1	33.4	35.7	38.4	41.2	30.4	32.1	34.9	37.6

Table 7: Maximum Live load, concrete grade, aspect ratio individual contribution to the *LDT* variation along long span within each group (while keeping the other two variables constant)

Group	*L1*, m	combined LDT variation, mm	*L1* / LDT variation ratio	*LDT* variation due to live load		*LDT* variation due to concrete grade		*LDT* variation due to aspect ratio	
				mm	*L1*/variation	mm	*L1*/variation	mm	*L1*/variation
C05	5	11.3	442.5	4.6	1087.0	6.7	746.3	7.9	632.9
C06	6	14.1	425.5	5.0	1000.0	7.5	666.7	9.1	549.5
C07	7	19.3	362.7	5.8	862.1	10.0	500.0	11.0	454.5
C08	8	25.4	315.0	6.3	793.7	13.1	381.7	13.9	359.7
C09	9	30.7	293.2	7.0	714.3	16.7	299.4	16.2	308.6
C10	10	35.4	282.5	7.0	714.3	19.0	263.2	18.0	277.8

3.4 Live Load Deflection

The instant deflection under the live load is required by the ACI 318-14 code to be less than the maximum permissible deflection of L/360 (for floors supporting non-structural elements likely to be damaged by large deflection, the critical case). For Group C10, and taking the long span direction as the "reference span", this limit would be 27.78 mm. **Table 8** presents the short term cracked deflections under live load for Group C10; the reported are less than the limits, conforming to ACI 318-14 requirements. The results of the other groups (C05 to C09) showed the same trend of results.

Table 8: Short term cracked concrete deflection under live load for group C10 (long span = 10 m, slab thickness = 320 mm)

Short Span, m	Aspect ratio	Short term deflection, mm																			
		f_c'=20 MPa				f_c'=25 MPa				f_c'=30 MPa				f_c'=35 MPa				f_c'=40 MPa			
		LL, kN/m²				*LL, kN/m²*				*LL, kN/m²*				*LL, kN/m²*				*LL, kN/m²*			
		2.4	3	4	5	2.4	3	4	5	2.4	3	4	5	2.4	3	4	5	2.4	3	4	5
5	2.00	11.3	12.6	14.6	16.4	8.7	10.2	12.3	14.1	6.2	7.9	10.2	12.3	4.4	5.6	8.2	10.4	3.7	4.6	6.2	8.7
6	1.67	12.4	13.8	16.0	18.0	9.8	11.3	13.5	15.6	7.3	9.0	11.4	13.5	5.1	6.7	9.3	11.6	4.4	5.2	7.4	9.8
7	1.43	13.6	15.0	17.4	19.4	10.9	12.4	14.7	16.9	8.4	10.0	12.5	14.7	5.9	7.7	10.4	12.8	5.0	5.9	8.5	11.0
9	1.11	15.7	17.5	19.9	22.0	13.1	14.8	17.2	19.6	10.9	12.4	15.0	17.4	8.3	10.3	12.9	15.3	6.8	8.2	11.1	13.5
10	1.00	18.3	20.1	22.4	23.9	15.4	17.1	19.8	22.2	12.7	14.6	17.3	19.8	10.1	11.9	15.1	17.7	8.3	10.0	13.0	15.8

3.5 Theoretical Calculation for Deflection

As a check for the *LTD* calculated by SAFE, five flat plate floor cases from group C8 have been re-analyzed theoretically using equivalent frame method for the deflection calculation (ACI 318 , 2014); these deflections are compared with the corresponding *LTD* obtained from the SAFE analysis in **Table 9**. The SAFE models produced larger deflection in square panels; as the aspect ratio decreases (smaller panels), the theoretical approach produced larger deflection. This is attributed mainly to the fact that SAFE model is capable of modelling the degradation in the slab moment of inertia due cracking for every 0.5 x 0.5 m slab elements, this is in contrast to the theoretical approach in calculating the moment of inertia of a concrete member based on the weighted-average properties for the sections at the maximum positive and negative average moments. As could be seen in **Table 9**, in the ACI-318 (2014) approach, the aspect ratio has a limited effect on the deflection of the long direction column strip (from 24.5 mm to 22.7 mm for aspect ratio of 1 to 2), while the aspect ratio affects the deflection of the middle strip deflection (perpendicular to the long direction), and consequently affecting the diagonal deflection, which is the sum of the long span column strip deflection plus the short span middle strip deflection (refer to Figure 1.C). This might be the reason for not considering the aspect ratio in the ACI 318 provisions for deflection control as it might have been believed that only the deflection along long direction are required to be checked and it is not affected by the aspect ratio. In contrast, SAFE results (**Table 9)** showed that there around 77% increase in the long span column strip in panels of square panels compared with panels of aspect ratio of 2. This observation indicates that the ACI 318 approach in dealing with aspect ratio might be not quite accurate, urging the need for an inclusion of the aspect ratio in the code of practice deflection provisions.

Table 9: Comparison between SAFE and theoretical long-term deflection (C8 group, live load= 3 kN/m^2, SDL = 2.4 kN/m^2, slab thickness = 253.3 kN/m^2, f_c' = 20 MPa)

aspect ratio	SAFE deflection, mm		Theoretical calculated deflection, mm			Ratio (SAFE /hand calculation)	
	long span col. strip	Diagonal	long span col. strip	Middle strip	Summation (diagonal)	long span col. strip	diagonal
2.00	17.82	17.71	22.66	0.90	23.6	0.786	0.754
1.60	21.26	21.24	24.52	2.19	26.7	0.867	0.794
1.33	24.29	25.46	25.63	4.40	30.0	0.948	0.847
1.14	26.96	32.18	25.93	7.49	33.4	1.040	0.964
1.00	31.51	44.31	24.51	14.42	38.9	1.286	1.139

3.6 Scanlon and Lee Unified Slab Thickness Equation

Scanlon and Lee (2006) proposed a unified span-to-depth ratio minimum thickness equation for one-way, two-way non-prestressed slab floors and beams, considering the amount of the applied load (dead & live load), aspect ratio (but for edge-supported slabs only), concrete strength grade (through the modulus of elasticity) using effective moment of inertia, I_e, equal to 0.52 I_g (gross moment of inertia). In addition, this equation accounts for the long-time deflection multiplier, the moment continuity at the panel edges, drop panels, beams and LDT limits. Scanlon and Lee (2006) reported that the use of this unified equation for flat slabs results in slab thickness in large spans compared to what ACI 318-05 values.

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

W_S: sustained load (kN/m^2), equal to the self-weight, superimposed dead load plus 25% of the live load. As self weight depends on the slab thickness, there is a need for an estimated slab thickness. In the current paper calculation, this estimated thickness is based on ACI 318 provisions.

$W_{L(add)}$: additional live load (kN/m^2); 75% of the live load

β: for slab without edge supports = 1, for edge-supported slabs β= long span / short span;

κ: end-support condition coefficient

(both ends continuous=1.4, one end continuous = 2, both ends discontinuous = 5.0)

$\left(\frac{\Delta_{inc}}{l}\right)_{allow}$: required/targeted incremental deflection limit (LDT)

k_{DP}= 1, except k_{DP}= 1.35 for slab with drop panels;

k_{SS}= 1, except k_{SS}= 1.35 for column-supported two-way slabs;

k_{AR}= 1, except k_{AR}= 0.2 + 0.4 ß for edge-supported slabs;

Ec: Modulus of elasticity of concrete, $4700\sqrt{fc'}$ (ACI 318-14, section 19.2.2.1);

b = 1000 mm; λ : time-dependent factor for sustained loads (ACI 318-14, Section 24.2.4.1.3)

Scanlon and Lee (2006)'s equation has been used in the current study to estimate the slab thickness and compare it with the ACI 318-14 provisions (for the cases of *fc'* of 20, 30 and 40 MPa) for a targeted LDT of L/480, as detailed in **Table 10**. The calculations have been made in 2 iterations; in the 1st one, the slab thickness was estimated using ACI- provisions (l/30); in the 2nd one, the slab thickness of the 1st iteration has been used. As could be seen, Scanlon and Lee's equation proposes larger slab thickness compared with the ACI 318-14 provisions; the difference increases as the *fc'* getting smaller, live load getting larger and the long spans getting larger. This trend of requiring larger slab thickness is corresponding to the results of the current paper, the need to increase slab thickness as the concrete grade getting smaller, and the live load getting larger. However, this equation, does not account for aspect ratio because the equation account for it in edge-supported slabs only. This means that even this equation produces same slab thickness for panels of 8 x 8 m and 8 x 4 m, the concern that the current paper aim to raise. It could be expected that the use of Scanlon and Lee (2006)'s equation will limit the deflection in flat plate slabs within the L/480, but not accounting for the aspect ratio might produce non-economical thickness at rectangular panels. This matter could be evaluated more in further studies evaluating the equations for the cases studied in the current paper

Table 10: Slab thickness as per Scanlon and Lee (2006)'s unified equation

A) 1st iteration, using ACI 318 proposed slab thickness

Group	Long span, m	Aspect ratio	Slab thick as per ACI, mm	Scanlon and Lee 2006 slab thickness, mm											
				f_c'=20 MPa				f_c'=30 MPa				f_c'=40 MPa			
				Live load, kN/m²				*Live load, kN/m²*				*Live load, kN/m²*			
				2.4	**3**	**4**	**5**	**2.4**	**3**	**4**	**5**	**2.4**	**3**	**4**	**5**
C05	**5**	**1-2**	**153.3**	176.0	178.8	183.4	187.7	164.5	167.1	171.4	175.5	156.8	159.3	163.4	167.2
C06	**6**	**1-2**	**186.7**	221.5	224.8	230.0	235.0	207.0	210.1	215.0	219.6	197.3	200.2	204.9	209.4
C07	**7**	**1-2**	**220**	269.1	272.7	278.6	284.1	251.5	254.9	260.4	265.6	239.8	243.0	248.2	253.1
C08	**8**	**1-2**	**253.3**	318.6	322.6	328.9	335.1	297.8	301.5	307.4	313.2	283.9	287.4	293.1	298.5
C09	**9**	**1-2**	**286.7**	370.0	374.2	381.1	387.7	345.8	349.8	356.2	362.4	329.6	333.4	339.5	345.4
C10	**10**	**1-2**	**320**	423.0	427.5	434.8	441.9	395.3	399.5	406.4	413.0	376.8	380.8	387.4	**393.7**

B) 2nd iteration, using slab thickness of 1st iteration

Group	Long Span, m	Aspect ratio		Scanlon and Lee 2006 slab thickness, mm											
				f_c'=20 MPa				f_c'=30 MPa				f_c'=40 MPa			
				Live load, kN/m²				*Live load, kN/m²*				*Live load, kN/m²*			
				2.4	**3**	**4**	**5**	**2.4**	**3**	**4**	**5**	**2.4**	**3**	**4**	**5**
C05	**5**	**1-2**		180.1	183.3	188.4	193.2	166.4	169.4	174.2	178.8	157.3	160.3	164.9	169.3

C06	**6**	**1-2**		228.6	232.3	238.2	243.7	211.0	214.5	220.0	225.3	199.3	202.7	208.0	213.1
C07	**7**	**1-2**		280.2	284.3	290.8	297.0	258.3	262.2	268.4	274.2	243.8	247.6	253.5	259.2
C08	**8**	**1-2**		334.5	339.0	346.2	353.0	308.1	312.3	319.1	325.6	290.7	294.8	301.3	307.5
C09	**9**	**1-2**		391.5	396.4	404.1	411.5	360.3	364.9	372.2	379.2	339.8	344.2	351.3	358.0
C10	**10**	**1-2**		451.1	456.2	464.5	472.4	414.9	419.8	427.6	435.1	391.0	395.7	403.3	**410.5**

Sample calculation for the case of 10 x10 m slab, *fc'*=40 MPa, live load = 5 kN/m^2

- *SDL* = 2400 N/m^2
- Live Load = 5000 N/m^2
- Clear span, long, l_n = 10 – 0.4 = 9.6 m
- Width, b = 1000 mm
- Estimate slab thickness:
  $h = l/30 = (10-0.4)/30 = 0.32$ m
- Slab self-weight =
  (0.32 m) × 24000 N/m3= 7680 N/m^2
- Sustained load
  W_s = 7680+2400 + 0.25 x 5000 = 11330 N/m^2
- Additional live load,
  $WL_{(add)}$ = 0.75 x 5000 N/m^2 = 3750 N/m^2

- E= 4700 √ *40 x 1000000* = 29.73 E9 N/m^2
- $\beta = 1.0$, $k_{DP} = 1.0$, $\kappa = 2.0$, $k_{AR} = 1.0$, $k_{SS} = 1.35$,
- Deflection limit = 1/480

$$\frac{l_n}{h} = \beta \left[\left(\frac{\Delta_{inc}}{l}\right)_{allow} \frac{0.0167\ k_{DP}\ E_c\ b}{\kappa\ k_{AR}\ k_{SS}\ (\lambda\ W_S + W_{L\ (add)})} \right]^{1/3}$$

$$h = \frac{9.6}{1\left[\left(\frac{1}{480}\right)_{allow} \frac{0.0167\ x\ 1\ x\ 29.73\ \mathrm{E9}\ x\ 1000}{2\ x\ 1\ x\ 1.35\ (2\ (11330) + 3750)} \right]^{1/3}} = 0.393$$

in the 2nd iteration, using this thickness (0.393 m) for estimating the self-weight, the thickness would be 0.410 m.

4.CONCLUSIONS:

The conclusions drawn from the current study could be summarized as below:

1- ACI 318-14 and CSA A23.3-14 deflection provisions do not specify explicitly L/240 or L/480 as the long term deflection limit for floors supporting masonry walls; therefore, based on the other three codes of practice (AS 3600 (2018), BS 8110 (1997) and EN 1992 (2004)), the current research believes that the L/480 limit needs to be considered.

2- Within each group (constant long span), the slab panel aspect ratio and concrete strength had the largest effect on the slab *LTD* followed by the live load with the effects being more pronounced at larger spans

2- ACI 318-14 provisions for flat plates seem to be adequate for the *L*/240 limit for slab floor panels up to long span of 7.0 m, but they are inadequate in most of the cases to satisfy the *L*/480 limit

3- There is a need for the code of practice provisions for flat plat panel thickness to include the panel aspect ratio effect; the effect which is even not accounted for in Scanlon and Lee (2006)'s unified equation.

4- As an accurate practice, the actual relative deflection calculated along a span should be compared with the corresponding maximum permissible deflection calculated along the same span direction

5- The long span is suggested to be taken as the "***slab reference span***" for flat plate slabs, along which the calculated actual relative deflection and the maximum permissible deflection are determined.

REFERENCES

ACI 318 . (2014). *Building Code Requirments for Reinforced Concrete (ACI 318-14) and Comentray.* Detroit: American Concrete Institute, Farmington Hills.

ACI 435R-95. (2003). *Control of Deflection in Concrete Structures (ACI435R-95).* Detroit: American Concrete Institute.

ACI SP-17(14): Volume 2. (2015). *"The Reinforced Concrete Design Handbook" An ACI Handbook; A Companion to ACI 318-14.* Detroit: American Concrete Institute, Farmington Hills.

AS 3600-18. (2018). *Australian Standard for Concrete Structures.* Sydney: Standards Australia.

ASCE/SEI 7-10. (2010). *Minimum Design Loads for Buildings and Other Structures.* Virginia: American Society of Civil Engineers.

Bondy, K. B. (2005). ACI Code Deflection Requirements - Time for a Change ? Serviceability of Concrete: A Symposium Honoring Dr. Edward G. Nawy,. *ACI Special Publications. SP-225-06*, 133-145 pp.

BS EN 8110-1-97. (1997). *British Standard Code: Design of Concrete Structures.* London,: British Standards Institution.

CSA A23.3-14. (2014). *Design of Concrete Structures.* Ontario, Canada: Canadian Standards Association.

CSI. (2016). *SAFE 2016, Key Features and Termnology.* USA: Computers & Structures, Inc.

EN 1992-1-1-04. (2004). *Eurocode 2: Design of Concrete Structures. General Rules and Rules for Buildings - Part 1-1 : General rules and rules for buildings.* London: British Standards Institution.

Gilbert, R. I. (1985). "Deflection Control of Slabs using Allowable Span to Depth Ratios". *ACI Journal, 82*(01), 67-72 pp.

Hwang, Sh. J. and Chang, K. Y. (1996). Deflection Control of Two-way Reinforced Concrete Slab. *ASCE, Journal of Structural Engineering*, pp 160-169.

MacGregor, J G. and Wight, J K. (2012). *Reinforced Concrete: Mechanics & Design* (6th ed.). New Jersey, USA: Pearson Education, Inc.

Nawy, E. G. (2009). *Reinforced Concrete: A Fundemental Approach* (6th Edition. ed.). New Jersey: Pearson International Edition.

Nilson, A., Darwin, D., Dolan, C. (2016). *Design of Concrete Structures* (15th Edition ed.). New York: McGraw-Hill Company.

Regan, P. I. (1981). *"Behaviour of Reinforced Concrete Flat Slabs".* The Construction Industry Research and Information Association (CIRIA). London: CIRIA Report 89.

Scanlon, A. and Lee, Y. H. (2010). Comparison of One- and Two-Way Slab Minimum Thickness Provisions in Building Codes and Standards. *ACI Structural Journal*, *107*(2), pp 157-163.

Scanlon, A., and Lee, Y. H. (2006). Unified Span-to-Depth Ratio Equation for Nonprestressed Concrete Beams and Slabs. *ACI Structural Journal, V. 103*(No. 1, Jan.-Feb), pp. 142-148.

Thompson, D.P., and Scanlon, A. (1988). Minimum Thickness Requirements for Control of Two-Way Slab Deflections. *ACI Structural Journal, V. 85*(No. 1, Jan.-Feb), pp 12-22.