Optimum Design & Efficiency of One-Way Slab According to ACI

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Abstract - *The paper presents a comparison review of one-way solid slab design, considering span to depth limitations given in different international building codes. Span to depth ratio limitations are mainly provided for deflection control. In ACI Code, the span to depth ratio has small values compared with the Egyptian Code ECP. Using the ACI span to depth ratio limitations in one-way slab design always give overdesign slab thickness and steel reinforcement less than the minimum values.*

The parametric study was carried to apply the span to depth ration limitations in both ACI and ECP to a one-way solid slab. Based on this study, recommendations are given to modify the span to depth limitations provided in ACI to design one-way solid slabs to optimize the design of such slabs. Also, the paper determines the effect of optimum design on the overall costs of one-way slabs considering two main variables thicknesses and deferent compressive strength of the concrete.

Key Words: one-way slabs, deflection, span-to-depth ratio, cost optimization, details of reinforcement

1. INTRODUCTION

One-way solid slabs are widely used in buildings of all types of use. Codes give provisions to preliminary determine the thickness of this kind of slabs like all other concrete elements. These provisions aim to get the thickness that will lead to safe values of deflection. The span to depth ratios for the one-way slab design recommended in the ACI Code [1] is smaller than the ECP-203 Code values [2]. In other words, the provisions of the ACI Code give a larger thickness of one-way slabs than the ECP Code. Design of one-way slabs using ACI Code span to depth ratio, in most cases, leads to the use of minimum steel ratio, i.e., the value of thickness is overestimated.

In this paper, a review of span to depth provisions in both the ACI Code and ECP-203 Code is given. According to the ACI Code procedure, a trial to design one-way slabs using ECP-203 span to depth ratio is carried out. The differences in steel ratio and the concrete amount obtained using ACI and ECP-203 Codes have been studied in detail. An alternative detailing of steel reinforcement for a one-way slab is proposed. The comparison of the concrete and steel quantities shows the effectiveness of alternative detailing of one-way slabs on the overall cost.

2. DESIGN PROVISIONS

Slabs are usually slender members (have a relatively small thickness compared to their spans). To avoid damage to the architectural finishes in contact with slab due to excessive deflection, Codes set limits on the span to depth ratio. These limits define the minimum slab thickness as a function of the span. This relation in different Codes will be reviewed in the following section:

2.1 ACI Code

ACI Code states that the minimum slab overall thickness (h) for solid non prestressed slabs shall not be less than the limits given in Table 7.3.1.1 unless the calculated deflection limits are satisfied. Accordingly, the span to depth ratio for the simply-supported one-way slab, not more than 20. This provision is used for the initial estimation of slab thickness in the design. The exact requirements are provided in SBC 304 [3].

2.2 Eurocode EC-2 [4]

According to EC-2 clause 7.4.2 [4], the primary span to depth ratio has the form:

$$\frac{L}{d} = k\left[11 + 1.5\sqrt{f_{ck}}\frac{\rho_0}{\rho} + 3.2\sqrt{f_{ck}}\left(\frac{\rho_0}{\rho} - 1\right)^{3/2}\right] \quad if\ \rho \leq \rho_0$$

$$\frac{L}{d} = k\left[11 + 1.5\sqrt{f_{ck}}\frac{\rho_0}{\rho - \rho'} + \frac{1}{12}\sqrt{f_{ck}}\sqrt{\frac{\rho'}{\rho_0}}\right] \quad if\ \rho > \rho_0$$

$k -$ *factor taking account of the different structural systems*

$\rho_0 -$ *reference reinforcement ratio* $= \sqrt{f_{ck}} \times 10^{-3}$

$\rho -$ *is the required tension reinforcement ratio at mid − span*

$\rho' -$ *is the required compression reinforcement ratio at mid − span*

The primary span to depth ratio for simply-supported slabs ranges from 14 to 20, depending on the steel ratio.

The span to depth ratio in EC 2 is used to check for deflection and not determine the slab thickness.

According to EC 2, the initial determination of the slab thickness, the span to depth ratio can be assumed 20 (as in ACI Code), but the relationship is between span and effective depth.

2.3 Egyptian Code (ECP-203)

According to ECP-203, it is not essential to check for deflection in one-way simply-supported solid slabs if the span to depth ratio is not exceeding 25. This case is valid for the possibility of slabs under uniform loads and a live load of less than 5 KN/m2 (Clause 4.3.1.3.1 and Table 4.10). This condition is always used to determine the preliminary value of the overall slab thickness.

3. PARAMETRIC STUDY

For comparison between span to depth ration limits in ACI Code and Egyptian Code, one-way solid slabs of span 2.0, 3.0, 4.0, and 5.0 m were considered. The span to depth ratio for all slabs was taken 20 as per ACI Code and 25 as per ECP203 Code. The reinforcement ratio was assumed to be minimum as per ACI Code. Concrete strength was made 28 MPa, and steel yield strength was 420MPa. For all slab models, the load-carrying capacity and deflection were determined according to the ACI Code procedure. Chart 1 shows the relationship between the imposed load capacity (live load) and the slab span for both cases of span to depth ratio.

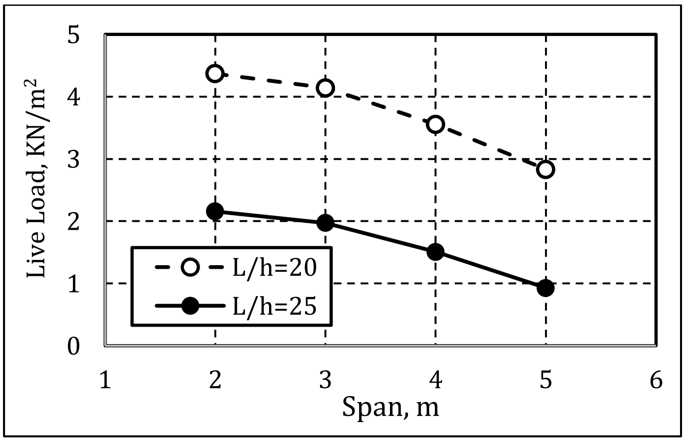

Chart -1: Live Load-carrying capacity-span relationship, case of minimum steel ratio

For the case of span to depth ratio 20, the slabs with minimum steel ratio can sustain, in addition to dead loads, live load equals or greater than 3 KN/m². This value of live load covers most practical cases. So, steel reinforcement in one-way slabs designed considering minimum slab thickness recommended by ACI Code will be minimum.

The same models were analyzed for the case of the maximum steel percentage according to ACI Code. The imposed load capacity (live load) has been determined for both cases of span to depth ratio. Chart 2 shows the relation between slab span and live load capacity.

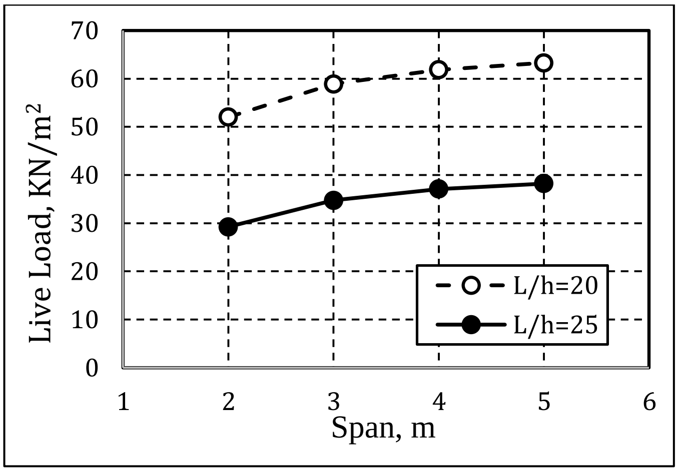

Chart -2: Live Load-carrying capacity-span relationship-case of maximum steel ratio

In ASCE [6], the superimposed live load on buildings varies between 2.0 and 7.5 KN/m². In common practice [7], one-way slabs on beams are most suitable for spans of 2.0 to 5.0 m and a live load of 2.5 to 5.0 KN/m2. From Chart 2, for the case of maximum steel percentage, the slabs can sustain live loads of tremendous values. For the case of span to depth ratio 20, the live load ranges from 54 to 66 KN/m², and for ratio 25, it ranges from 29 to 38 KN/m². One-way slab with maximum steel ratio can sustain live load more than seven times the maximum practical value of the live load on buildings as per ASCE [6], in case of span to depth ratio 20, and about four times in case of depth-ratio 25. The steel percentage in the one-way slab under maximum live load in Code (7.5 KN/m²) approximately will be ranged from 0.2 to 0.14 maximum steel percentage depending on concrete compressive strength. For the case of concrete strength 28 MPa, the steel percentage under maximum live load equals 0.18 of the maximum steel ratio.

The relation between the predicted deflection and the span is presented in Chart 3 for instantaneous deflection under live load capacity of slabs with minimum and maximum steel ratio.

For all cases, predicted deflections are under the ACI Code limit, except for the case of span 2.0 m with maximum steel percentage for both span-to-depth ratios (20 and 25). This result was expected because the live load capacity of the slab in these two cases was found to be 54.6 KN/m² and 29.2 KN/m², respectively. The live load carrying capacity is 6 to 4 times the maximum practical value [7].

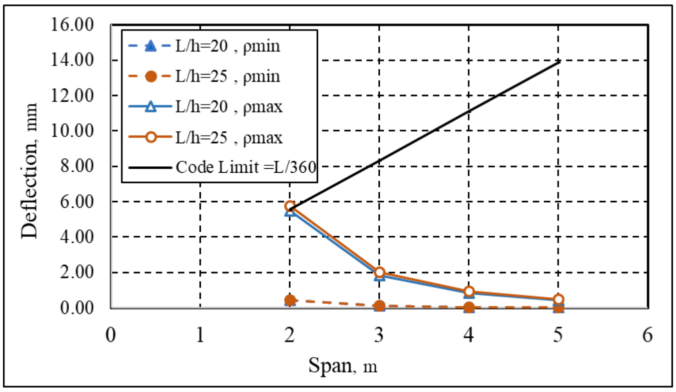

Chart -3: Instantaneous deflection due to Live Load

Chart 4 shows the predicted values of long-term deflection for the models used in the parametric study. All predicted values of long-term deflection are less than the ACI Code limit. From both Charts 3 and 4, the calculated deflection for slabs with span to depth ratio 20 and 25 is approximately the same.

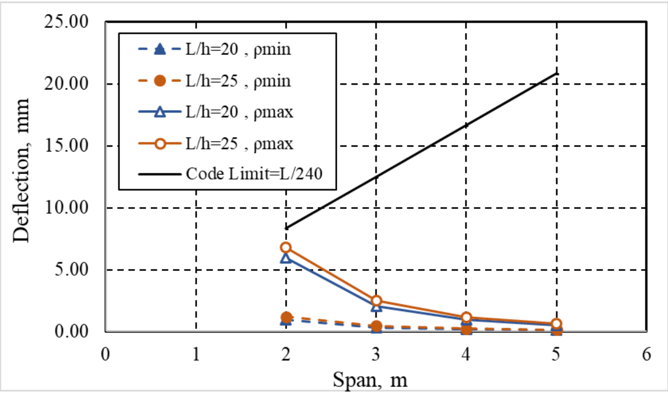

Chart -4: Long-Term deflection and slab span relationship

Simply-supported one-way slab models of span 2.0, 3.0, 4.0, and 5.0 m under live load 2.0, 4.0, 6.0, and 8.0 KN/m² have been designed according to ACI design procedure, but with a span to depth ratio of 25. The predicted deflection, instantaneous, and long-term are shown in Charts 5 and 6, respectively. All deflections are within the Code limit.

Despite using a span to depth ratio larger than the ACI Code recommended value, the instantaneous deflection due to live loads within the practical range is minimal compared with the Code limit. The ratio of the predicted values of deflection to the Code limit is 0.071; 0.141; 0.212 and 0.283 for the cases of live load equals 2.0; 4.0; 6.0 and 8.0 KN/m², respectively. Based on these results, it can be concluded that the use of span to depth ratio of 25 in the design of one-way slab will give very safe values of the instantaneous deflection due to live load

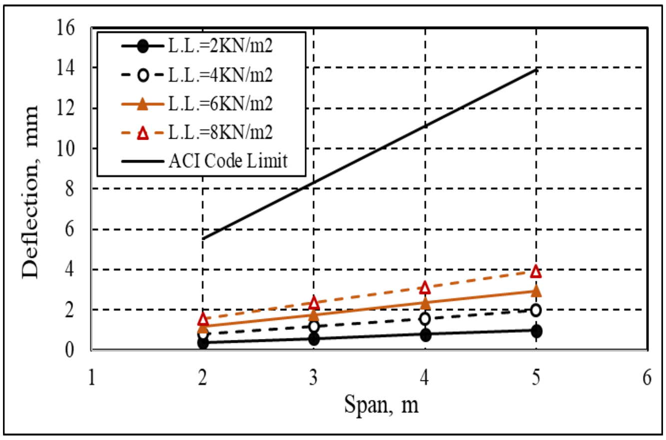

Chart -5: Deflection due to Live load for L/h=25

For the case of long-term deflection, the ratio of the predicted values of deflection to the Code limit is 0.212; 0.26; 0.306, and 0.353 for the cases of live load equals 2.0; 4.0; 6.0 and 8.0 KN/m², respectively. The shown ratios enable us to make the same conclusion for the case of long-term deflection. The predicted long-term deflection of the one-way slab using a span to depth ratio of 25 under live load in the practical range is very safe.

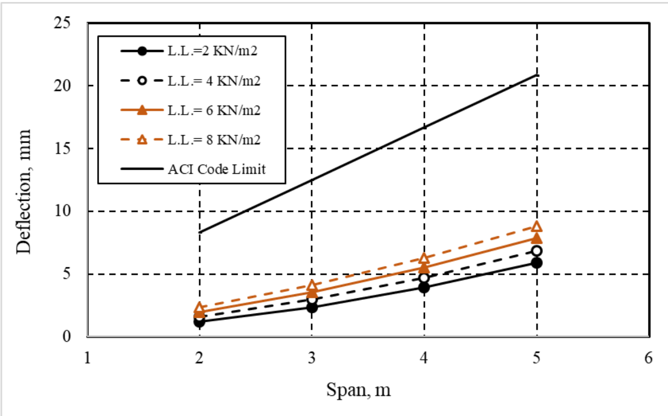

Chart -6: Long Term Deflection for L/h=25

The use of a span to depth ratio of 25 instead of 20 in the design of a one-way slab will result in a 20% reduction in the slab thickness and slab own weight. The decrease in the slab weight will result in a reduction in the loads transmitted from the slabs to the beams and consequently to a decrease in the loads on both the columns and the foundations. Practically in conventional concrete framing systems, the self-weight of slabs may represent 50% of the total self-weight of the overall skeleton (not including foundations). This means that the use of a span to depth ratio of 25 will result in a reduction of the total skeleton weight and total concrete volume, not less than 10%, with very safe values of expecting deflections.

4. RECOMMENDED ECONOMICAL DESIGN

Some selected models of one-way slabs have been analyzed using SAP2000 software [8] and manually. The chosen models have a short span of 2.0 and 3.0 meters and are subject to imposed dead load (flooring) of 2.0 KN/m^2 and Live Load of 3.0 KN/m^2 (as average practical values). Table 1 shows the properties and the design results of the chosen one-way slab models. The first three models have a span of 2.0 m, span to depth ratio of 20, and the long span was determined 4.0, 6.0, and 8.0 m (degree of rectangularity of the slab is 2.0; 3.0 and 4.0, respectively). The second three models are the same as the first three but with a span to depth ratio of 25. Models 7, 8, and 9 have a span of 3.0 m with a span to depth ratio of 20 and with a degree of rectangularity 2.0, 3.0, and 4.0. The last three models have a span to depth ratio of 25 and the same parameters as models 7, 8, and 9. The details of the selected models are shown in Table -1.

Table -1: Slabs Models for Design Analysis

Slab Model	Slab width, m	Slab length, m	Span to depth ratio	Slab Thickness, mm
1	2	4	20	100
2	2	6	20	100
3	2	8	20	100
4	2	4	25	80
5	2	6	25	80
6	2	8	25	80
7	3	6	20	150
8	3	9	20	120
9	3	12	20	150
10	3	6	25	120
11	3	9	25	120
12	3	12	25	120

For all models, the maximum bending moment at the center and the moment in the slab strip at the quarter of the longitudinal direction have been determined and shown in Table -2.

The conventional detailing of reinforcement is presented in Chart 7. The main steel reinforcement is calculated for the maximum bending moment at the center of the slab. The main steel (A_{s1}) extended over the short span and arranged along the longitudinal direction. Away from the center of the slab, the moment has values less than the maximum at the center. Consequently, the used reinforcing steel will be more than the required steel to resist the actual moment. The negative steel (A_{s2}) is determined according to the ACI Code provision to resist the negative moment of wl^2/24. The secondary steel (A_{s3}) is used as the minimum steel required for shrinkage and temperature. The calculated values of the required steel for all models are shown in Table -2. The values highlighted are the minimum required steel area. For all cases of span to depth ratio 20, all steel used is minimum. It can be concluded that the span to depth ratio of 20 gives an overestimation of slab thickness and always will result in values of the designed steel area less than the minimum.

Table -2: Moments in The Models

Model of Slab	SAP2000 Results		Manual Results	
	Mu@L/2 (KN.m)	Mu@L/4 (KN.m)	Mu@L/2 (KN.m)	Mu@L/4 (KN.m)
1	3.79	2.87	4.8	2.88
2	4.482	3.37	4.8	2.88
3	4.668	3.5	4.8	2.88
4	3.54	2.68	4.5	2.7
5	4.21	3.165	4.5	2.7
6	4.399	3.3	4.5	2.7
7	9.63	5.46	12. 5	7.5
8	11.244	6.27	12. 5	7.5
9	11.628	6.466	12. 5	7.5
10	8.99	5.1	11. 5	6.9
11	10.57	5.89	11. 5	6.9
12	10.97	6.13	11. 5	6.9

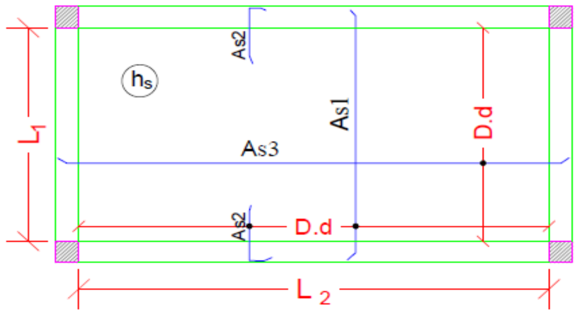

Chart -7: Conventional Details of Reinforcement of One-Way Solid Slab

An alternative reinforcing detailing is proposed to save the amount of the required steel. In the proposed detailing (Chart 8), the steel at the middle of the slab is calculated to resist the maximum moment at the center, while at the first and fourth quarter of the longitudinal side, the steel reinforcement has been obtained considering the actual moments at these locations. The moments at the quarters, in most cases, approximately equal to 0.6 of the maximum moment at the center (Table -2). In the recommended arrangement, the main steel (in a short direction) has two values, one under the maximum moment at the middle strip of width 0.5 long spans (A_{s1}). The second value (A_{s2}) will be placed at the first and fourth quarter of the slab and is determined considering the value of the design moment 0.6 of the maximum moment. As shown in Table -2, only the main steel (A_{s1}) differs from the minimum values, while the others are minimum. The total reinforcing steel area is presented in Table -3 for all models according to conventional and recommended detailing. The reinforcing steel area has been determined for the moments obtained from SAP2000 results and manual calculations.

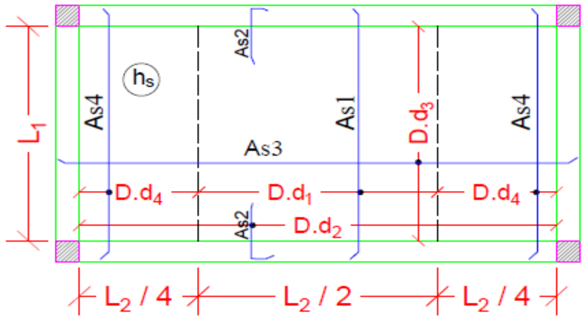

Chart -8: Recommended Details of Reinforcement of One-Way Solid Slab

Table-3: Design values of Steel reinforcement

Slab Model	Slab width, m	As1, mm^2/m.	As2, mm^2/m.	As3, mm^2/m.	As4, mm^2/m.
1	2	180	180	180	180
2	2	180	180	180	180
3	2	180	180	180	180
4	2	176	144	144	144
5	2	210	144	144	144
6	2	220	144	144	144
7	3	270	270	270	270
8	3	270	270	270	270
9	3	270	270	270	270
10	3	270	216	216	216
11	3	303	216	216	216
12	3	315	216	216	216

Table-3: Total Values of Steel reinforcement and saving percentage in steel and concrete

Slab number	Total Steel Area		Reduction in steel %	Reduction in Concrete Volume %
	Conventional	Recommended		
1	3456	3456	0.0	0
2	5184	5184	0.0	0
3	6912	6912	0.0	0
4	3020.8	2892.8	4.2	20
5	4939.2	4543.2	8.0	20
6	6745.6	6137.6	9.0	20
7	11664	11664	0.0	0
8	17496	17496	0.0	0
9	23328	23328	0.0	0
10	10303.2	9817.2	4.7	20
11	16345.8	15171.3	7.2	20
12	22226.4	20444.4	8.0	20

The recommended detailing of slab reinforcement causes a decrease of the required steel of 7% on average. For the case of manual design, this reduction will be 10%.

5. CONCLUSIONS

The span to depth ratio limit of ACI Code gives large values of slab thickness and, consequently, steel reinforcements values less than the minimum, in most practical cases of one-way slabs.

Using span to depth 25, as recommended by the Egyptian Code, for the design of one-way solid slabs by ACI Code provisions, leads to safe deflection values, and at the same time, reduction in the slab weight and concrete volume of 20%.

Considering that the slab weight represents 50% of the weight of the structure, the use of a span to depth ratio of 25 will also result in an approximately 10% total reduction of the overall weight of the skeleton.

The use of the recommended detailing of steel reinforcement allows getting a reduction in the used steel by 10%.

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