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Simulations of short- and long-term deflections of flat plates considering effects of construction sequences

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Abstract. The structural designs of RC flat plates that have no flexural stiffness by boundary beams may be governed not by strength conditions but by serviceabilities. Specially, since over-loading and tensile cracking in early-aged slabs significantly increase the short- and long-term deflections of a flat plate system, a construction sequence and its impact on the slab deflections may be decisive factors in designs of flat plate systems. In this study, the procedure of simulating slab deflections with considering construction sequences, concrete cracking, and long-term effects is proposed. The proposed method is practically useful, as it can predict well the slab deflections at construction and service stages only with a few input data. The proposed method is verified by comparisons with measured results in a real-scale test.

Keywords: flat plate; deflection; construction load; reinforced concrete; deflection simulation

1. Introduction

A flat plate system has many advantages such as a reduction of floor height, an increase of constructability, and an increase of space utilization. Recently, various studies on the safety of the flat plate system were performed (Tian *et al*. 2012, Chung *et al*. 2013, Mirzaei and Sasani 2013, Choi *et al*. 2014, Kim *et al*. 2014). However, due to its low flexural stiffness, its structural design may be governed not by strength conditions but by serviceability. In particular, the flat plate system will be influenced by construction loads: the self-weight and construction load transferred through shores can damage immediate and long-term performances when the early age slab is overloaded (Gardner *et al*. 1987, Hossain and Vollum 2002, Lee *et al*. 2007, Vollum and Afshar 2009, Park *et al*. 2011, 2012). The initial damage that occurs in unhardened concrete remains even after the concrete has hardened. The initial cracks which are caused by the self-weight and construction load at early stage cannot be recovered if there is no special consideration. These cracks reduce the moment of inertia of the flat plate and intensify its short- and long-term deflections.

The present structural design code (ACI Committee 318 2011) provides guidelines for slab thickness in flat plate systems. These guidelines are based on experiences related to slab construction sequence and its impact on the immediate and long term deflections of flat plate systems. These guidelines are provided to help engineers select the minimum slab thickness without going through the extensive calculations that these systems may require (Lee and Scanlon 2010, Lee *et al*. 2013). The code also allows the engineer to reduce these thicknesses as long as the engineer performs structural calculation to verify the serviceability requirements. By recent changes of design or construction conditions including the longer span, the shorter construction cycle, and the higher concrete strength, the current regulations for minimum slab thickness may be inappropriate for a safe design. It may be more reasonable guidelines that the design code presents only a serviceability condition and let the engineers check it by slab deflection simulations.

To analyze the damage and deflections of flat plates under construction, the procedure of slab deflection calculation while considering the construction steps should be used. Generally, placed slab concrete cannot be supported by itself for very long and should be transferred either entirely or partially to lower floors connected by shores, because unhardened slab concrete cannot sufficiently develop its strength and stiffness until it is hardened completely. During construction, slabs that have been placed at various times constitute a system, where adjacent slabs are connected by shores. In floor system connected by shores, the more construction load is applying to the lower floor, and maximum construction load is more than double the self-weight of one floor slab (Stivaros and Halvorsen 1990, Puente *et al*. 2007). However, during construction, since the slab concrete hardens and the strength and stiffness of concrete changes, slab deflection and damage cannot be judged only from the amount of construction load. Slab deflection should be calculated

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considering strength and stiffness changes of slab concrete according to the point of time of construction load as well as the change of construction load according to construction step. For this, the procedure of calculation of construction load in each construction step while considering construction load, development of strength and stiffness, and effective section stiffness degradation according to crack should be proposed. Several studies (Rangan 1976, Gardner *et al*. 1987, Chang and Hwang 1996, Hossain and Vollum 2002, Kang *et al*. 2013, Hwang *et al*. 2016) were performed to analyze the structural behaviors of flat plate under construction and propose the reasonable prediction method.

Rangan (1976) took into account the early cracking caused by heavy construction loads, shrinkage deformations, etc for calculation of deflection of flat plate and compared with the experimental data. Gardner and Fu (1987) described an experimental investigation into the effect of early age construction loads on the long-term deflection of reinforced concrete flat slabs. It was presented that for long-term deflection problem the most important parameters are elastic deflection due to sustained loads, creep deflection due to construction and sustained load, and shrinkage deflection. Chang and Hwang (1996) proposed deflection calculation of flat plate subjected to gravity loads. The proposed method was further directed toward the general problem concerning progressive cracking of concrete, varied boundary condition due to discontinuity of flat plate, and long-term effects. Hossain and Vollum (2002) proposed an improved method for taking account of the effect of striking, peak construction loads or service load on long-term deflections of one-way slab. The proposed method (Hossain and Vollum 2002) was based on nonlinear finite element analysis using the MC90 moment-curvature relationship (CEB-FIP 1993).

The studies focused on the cracking and long-term deflection effect of concrete on deflection calculation, and moment redistribution by the reduced stiffness. Even though Hossain and Vollum (2002) considered a construction load including striking or service load, the characteristics of real construction load, which increases stepwise according to construction activities, were not included.

This study presents a calculation method of change of flat-plate deflection under and after construction by considering a change of construction load and material properties according to construction steps. For this, the construction steps according to the change of construction load are defined, and the procedure of construction sequential deflection analysis is proposed. The proposed method includes the effect of changes of construction load, slab concrete's cracking, and long-term deflections. Especially, stiffness degradation of the flat-plate by the cracks, which cannot be recovered by itself, is considered in the proposed method. Finally, by applying the magnification factors to the elastic analysis results and consisting with structural design codes and guidelines, the practically useful computer-aided method is developed.

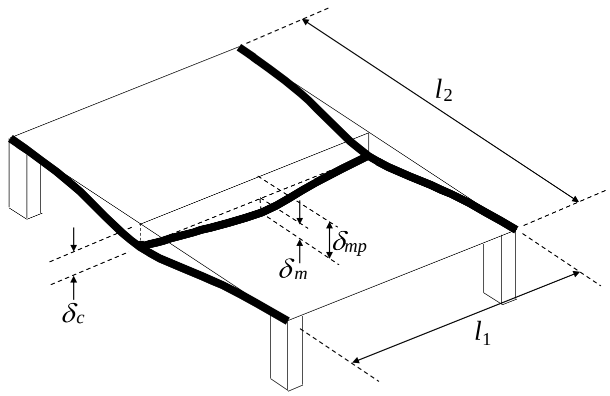


Fig. 1 Crossing beam method

2. Design parameters affecting deflection of flat plate

Generally, the most influential factors on slab deflection are 1) an amount of construction load, 2) a modulus of elasticity of slab, and 3) slab cracks and effective section stiffness. The amount of construction load and modulus of elasticity of the slab are the given values as the input variable in each construction step. Slab cracks and effective section stiffness are determined by acting moments depending on applied load, concrete strength by slab age, slab thickness, reinforcement ratio etc., in each construction step. The deflection analysis method proposed in this study presents a direct procedure of slab deflection calculation by applying the magnification factor by the effective moment of inertia to the elastic deflection calculated with modulus of elasticity and the factor depending on the ratio of construction load in each construction step.

The deflection at midspan of the flat-plate can be calculated by the crossing beam method (Scanlon and Murray 1982, Stivaros and Halvorsen 1990, ACI Committee 435 2003, Kang *et al*. 2013). In the crossing beam method, by regarding column strip and middle strip of each direction as continuous beam and overlapping each calculated deflection, the deflection at the slab midspan is calculated. Slab deflections of column strip and middle strip are decided as follow by moments of column strip and middle strip

$$\delta = \frac{5}{48}\frac{l_n^{\,2}}{E_c I_g}\left[M_m + 0.1\left(M_1 + M_2\right)\right] \tag{1}$$

Where l_n is a length of clear span in the direction that moments are being determined, E_c is a modulus of elasticity of slab concrete, and I_g is the moment of inertia of the gross concrete section about the centroidal axis. M_m is the midspan moment per unit width in each strip, and M_1, and M_2 are end moments per unit width.

Deflection in the slab at midspan is calculated by overlapping the deflection of equivalent beam of column strip and deflection of equivalent beam of middle strip as follow (Fig. 1)

$$\delta_{mp} = \delta_c + \delta_m \tag{2}$$

where δ_{mp} is the deflection in the slab at midspan, and δ_c and δ_m are the maximum slab deflection of the column strip and middle strip, respectively. δ_c and δ_m are calculated by Eq. (1). The incremental elastic deflection in each construction step is calculated by Eq. (1) and (2) depending on an increase of moment.

Considering the cracking effects, the slab deflection increases more than elastic deflection. If design conditions such as geometries and modulus of elasticity are given, elastic deflection δ_0 and inelastic deflection δ of slab can be defined as follows

$$\delta_0 = \frac{kwL^4}{E_c I_g} \quad \text{and} \quad \delta = \frac{kwL^4}{E_c I_e} \tag{3}$$

where k is a factor decided on geometries and end-supporting conditions of slab, w is an applied floor load, and L is a span length of slab. Elastic and inelastic deflections are represented by ratio between effective moment of inertia I_e and moment of inertia of gross concrete section I_g

$$\frac{\delta}{\delta_0} = \frac{I_g}{I_e} \tag{4}$$

If the effective moment of inertia of the slab section is calculated properly, slab deflection affected by concrete cracking can be calculated from elastic deflection. Also, since the modulus of elasticity of slab concrete changes in each construction step, the total elastic deflection in each construction step should be calculated by accumulating the increments of elastic deflections of the previous and current construction steps. The effective section stiffness degradation by cracking is affected by the total construction load applied in each construction step, and the accumulated elastic deflection value in each step is converted into the inelastic deflection by magnification as much as the effective section relative stiffness ratio $I_g/I_{e,i}$ of the relevant construction step

$$\delta_i = \left\{ \sum_{k=1}^{i} \Delta\delta_{e,k}\left(\Delta W_k, E_{c,i}\right) \right\} \times \frac{I_0}{I_{e,i}} \tag{5}$$

where $\Delta\delta_{e,i}$ is an incremental slab elastic deflection in step i calculated by the modulus of elasticity $E_{c,i}$, the moment of inertia of gross concrete section I_g, and the incremental load ΔW_i. The accumulated elastic deflection is converted to an inelastic deflection (δ_i) with an effective section stiffness ratio $I_g/I_{e,i}$ in the construction step i.

ACI-318 (2011) presents the equation of the effective moment of inertia, to consider the effective section stiffness degradation by cracking in the flexural members

$$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr} \tag{6}$$

where M_a is the maximum moment in the slab, and I_{cr} is the moment of inertia of the cracked section defined by the section properties and reinforcing bar ratio (Hwang *et al.* 2016). M_{cr} is the cracking moment of concrete

$$M_{cr} = \frac{0.63\sqrt{f_c'}\, I_g}{h/2} \tag{7}$$

where f_c' is the concrete strength and can be defined as $f_c'(t)$ at concrete age t in analyses considering construction sequences, and h is the slab thickness.

For simply supported flexural members, the effective moment of inertia can be calculated directly by substituting the maximum positive moment to Eq. (6). However, for continuously supported members, each effective moment of inertia for a negative moment in both ends and a positive moment at midspan is separately calculated, and the effective moment of inertia(I_{ea}) of the whole slab is then calculated as an average (ACI Committee 318 2011)

$$I_{ea} = \left[\left(I_{e1} + I_{e2}\right)/2 + I_{em}\right]/2 \tag{8}$$

where I_{e1} and I_{e2} are the values of effective moment of inertia for negative moment in both ends of continuous member, and I_{em} is the value of effective moment of inertia calculated by substituting the positive moment at midspan to Eq. (6). Shrinkage and creep due to sustained loads cause additional long-term deflections over and above immediate deflections that occur when loads are first placed on the slab. For additional deflection due to long-term effects, ACI-318 (2011) presents a multiplier λ_Δ, which accounts for the time-dependent effect of concrete and the effect of compression reinforcement in reducing long-term deflections

$$\lambda_\Delta = \frac{\xi}{1 + 50\rho'} \tag{9}$$

where ρ' is a compression reinforcement ratio at midspan of slab, and ξ is the time-dependent factor for sustained loads. The additional long-term deflection resulting from creep and shrinkage of slab can be determined by multiplying the immediate deflection caused by the sustained load considered, by multiplier λ_Δ.

3. Procedure of slab deflection calculation

Based on assumptions presented in "2. Design parameters affecting deflection of flat plate ", the procedure of slab deflection calculation can be summarized as follows:

1) Define the construction steps and calculate the construction load in each construction step by considering the floor construction cycle and the number of shored floors.

2) Calculate the moment M_i in each construction step. The moment per unit width for each location of the flat-plate is defined by the direct design method (ACI Committee 318, 2011)

$$M_i = \alpha\beta \frac{w_i l_n^2}{4} \tag{10}$$

where w_i is a construction load in step i, and α is a factor decided on each location of the flat plate and can be

Table 1 Moment factor of flat plate

Location		Column Strip	Middle Strip
Interior Span	Negative Moment	0.49	0.16
	Positive Moment	0.21	0.14
Exterior Span	Interior Negative Moment	0.53	0.18
	Positive Moment	0.31	0.21
	Exterior Negative Moment	0.26	0

defined as Table 1 (ACI Committee 318 2011).

β is a factor representing a moment redistribution in equivalent beams. When the slab stiffness is locally damaged by the construction load, moment redistributions occur and actual moment distributions are a little different from the elastic moment distributions. Representing the moment redistributions, in equivalent beams for column strip and middle strip of continuous slabs, it is assumed that the negative moment in continuous support is decreased when a tensile strain in longitudinal tension steel at the section for the moment under consideration, ε_t, is equal to or greater than 0.0075, and the positive moment in the equivalent beam where the negative moment is reduced is increased inversely by the reduced amount of negative moment (ACI Committee 318 2011)

$$\beta = (1-10\varepsilon_t) \geq 0.9 \quad \text{for interior negative moment with } \varepsilon_t \geq 0.0075 \tag{11a}$$

$$> 1.0 \quad \text{for positive moment in equivalent beam corresponding to Eq. (11a)} \tag{11b}$$

$$= 1.0 \quad \text{for otherwise moment} \tag{11c}$$

3) Calculate the incremental elastic deflections $\Delta\delta_{ce,i}$ and $\Delta\delta_{me,i}$ in each construction step. The elastic deflection is linearly related to the applied load and material stiffness. Therefore, the incremental elastic deflections in each construction step are calculated by substituting a construction load increment and modulus of elasticity in construction step into Eq. (1)

$$\Delta\delta_{ce,i} = \frac{5}{48}\frac{l_{cn}^{2}}{E_{c,i}\,I_g}\left[\Delta M_{cm,i} + 0.1\left(\Delta M_{c1,i} + \Delta M_{c2,i}\right)\right] \tag{12a}$$

$$\Delta\delta_{me,i} = \frac{5}{48}\frac{l_{mn}^{2}}{E_{c,i}\,I_g}\left[\Delta M_{mm,i} + 0.1\left(\Delta M_{m1,i} + \Delta M_{m2,i}\right)\right] \tag{12b}$$

where l_{cn} and l_{mn} are lengths of clear spans of equivalent beams for column strip and middle strip respectively. In the construction step i, $\Delta M_{cm,i}$ and $\Delta M_{mm,i}$ are incremental midspan moments in column strip and middle strip respectively, and $\Delta M_{c1,i}$, $\Delta M_{c2,i}$, $\Delta M_{m1,i}$, and $\Delta M_{m2,i}$ are incremental end moments in column strip or middle strip.

4) Calculate the effective moment of inertia ($I_{e,i}$) in each construction step by Eqs. (6) and (8), with the acting moment (M_i) calculated by Eqs. (10) and (11), and the compressive strength and cracking moment of concrete. Each of the effective moment of inertia $I_{ce,i}$ and $I_{me,i}$ of the column strip and midspan need to be calculated. Especially, the decreased effective section stiffness by the crack is not recovered even though the load is removed is assumed, and the effective moment of inertia $I_{e,i}$ should be always equal or less than the value of the effective moment of inertia of previous steps($I_{e,i\text{-}1}$) (See Fig. 2).

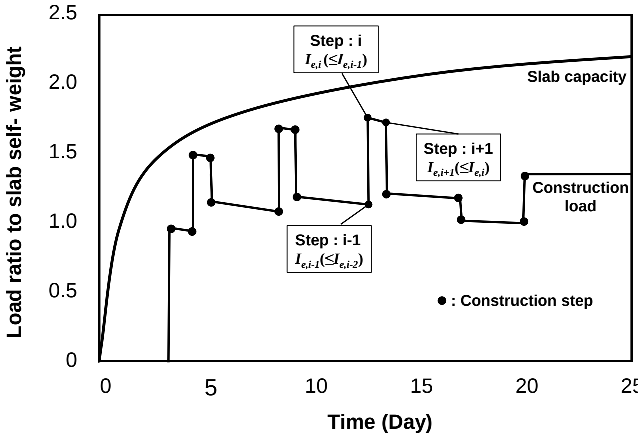


Fig. 2 Effective moment of inertia (I_e) according to construction step

5) Calculate the total elastic deflection ($\delta_{e,i}$) by accumulating the incremental elastic deflections ($\Delta\delta_{e,i}$) by Eqs. (12a) and (12b). The total elastic deflection $\delta_{ce,i}$ and $\delta_{me,i}$ of the column strip and middle strip are calculated

$$\delta_{ce,i} = \sum_{k=1}^{i}\Delta\delta_{ce,k} \quad \text{and} \quad \delta_{me,i} = \sum_{k=1}^{i}\Delta\delta_{me,k} \tag{13}$$

6) The total elastic deflection in each construction step is converted to the inelastic deflection with the effective moment of inertia ($I_{e,i}$) and the moment of inertia of gross concrete section (I_g)

$$\delta_{c,i} = \delta_{ce,i} \times \frac{I_{cg}}{I_{ce,i}} \tag{14a}$$

$$\delta_{m,i} = \delta_{me,i} \times \frac{I_{mg}}{I_{me,i}} \tag{14b}$$

7) The deflection $\delta_{t,i}$ in the slab at midspan in step i is calculated by the sum of the deflection of the column strip and middle strip according to the crossing beam method.

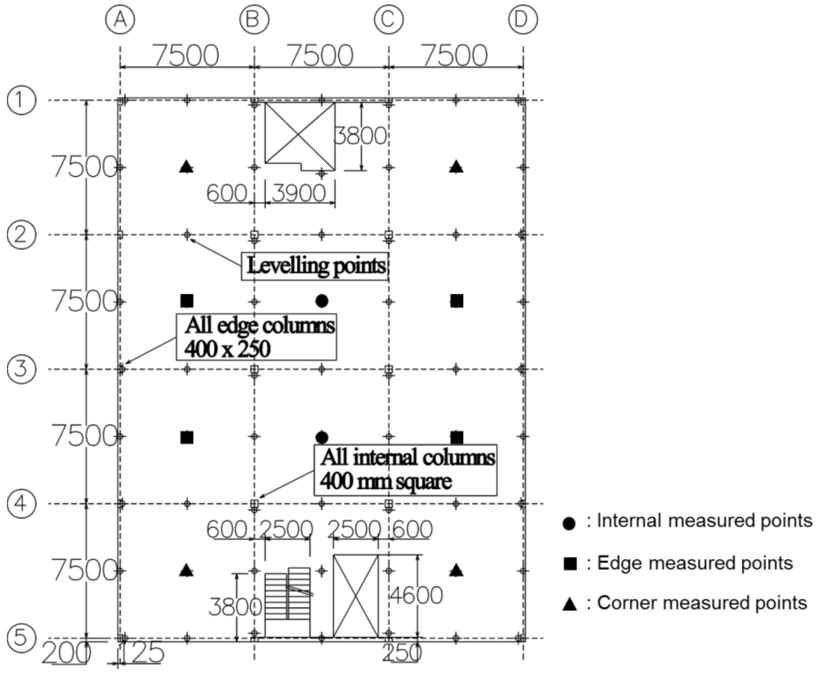
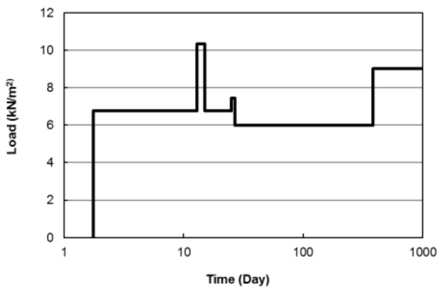
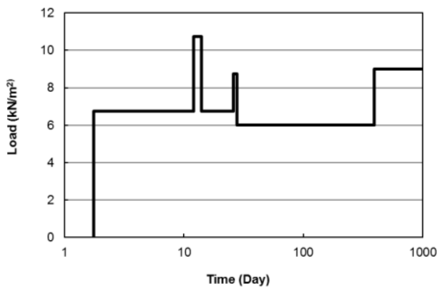


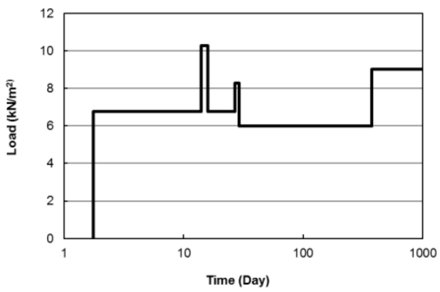
Fig. 3 Plan of Cardington in situ concrete building (Vollum *et al*. 2002)



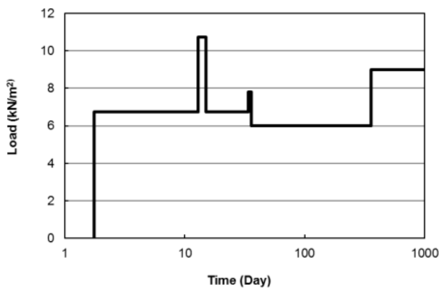
(a) 2nd floor slab



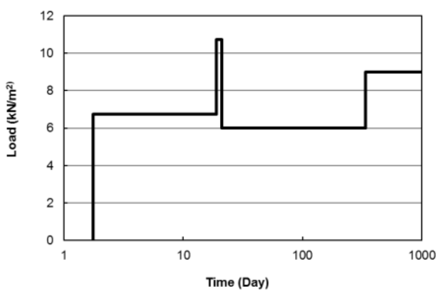
(b) 3rd floor slab



(c) 4th floor slab

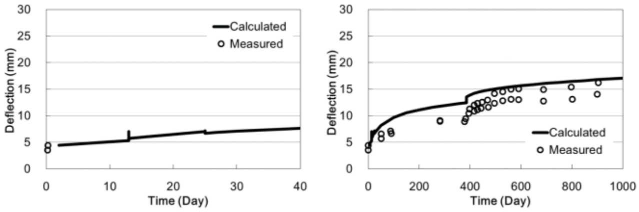


(d) 5th floor slab

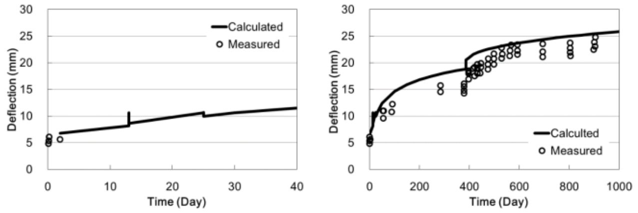


(e) 6nd floor slab

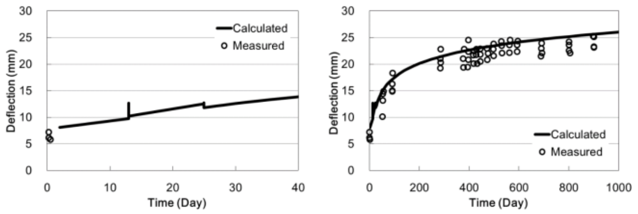
Fig. 4 Load History



(a) Internal slabs : short- and long-term deflections



(b) Edge slabs : short- and long-term deflections



(c) Corner slabs : short- and long-term deflections

Fig. 5 Comparisons of calculated and measured deflections for 2nd floor slab

$$\delta_{t,i} = \delta_{c,i} + \delta_{m,i} \tag{15}$$

8) Long-term deflection is calculated by accumulating incremental deflection ($\Delta\delta_i$) multiplied by long-term factor.

$$\delta_i = \sum_{i=1}^{n} \left\{ \Delta\delta_{t,i} \times \left(1 + \frac{\xi\left(t - t_i\right)}{1 + 50\rho'} \right) \right\} \tag{16}$$

Where ρ' is compressive reinforcement ratio in column and middle strip of slab, ξ is time dependent deflection factor for long-term displacement from design code (ACI Committee 318, 2011), and t_i is time when $\Delta\delta_i$ is generated by the load change.

9) Repeat process 2) - 8) in each construction step. When construction loads decrease, it is assumed that the deflection is elastically recovered

$$\delta_i = \delta_{i-1} + \left(\Delta\delta_{ce,i} + \Delta\delta_{me,i} \right) \tag{17}$$

where $\Delta\delta_{ce,i}$ and $\Delta\delta_{me,i}$ are elastic deflection increments in column strip and middle strip respectively from process 3), and have minus values meaning elastic recoveries of deflections since the applied load increments are minus values.

4. Verification

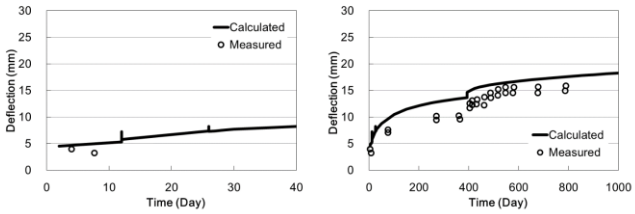
To verify the proposed deflection calculation method, the long-term deflections calculated by the proposed method were compared with the experimental results. Vollum *et al*. (2002) measured long-term slab deflections from the in-situ six-story building in which a floor system consists of 250 mm thick flat plates spanning 7.5 m in each direction (Fig. 3).

The slabs were shored with 2-story props and loaded at early concrete ages. Fig. 4 shows an idealized load-time history measure for each floor slab. The slab carried its self-weight of 6 kN/m^2 and a construction live load of 0.75 kN/m^2 when struck. Subsequently, the slab supported short-term loads of 10.14~10.74 kN/m^2 and 7.44~8.75 kN/m^2 respectively when the first and second upper slabs were placed. Table 2 presents the measured peak loads for each floor and the corresponding age of the slab concrete. One year after construction started, a superimposed dead load of 3 kN/m^2 was applied at floors 1 to 6.

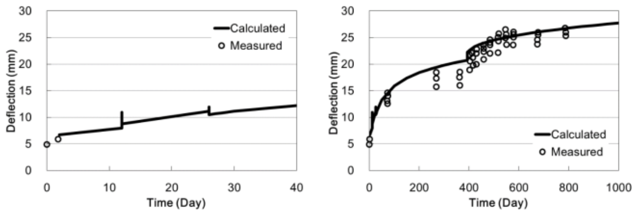
By the proposed method in "Procedure of slab deflection calculation", the maximum deflections for 2nd to 6th floor slabs were calculated with concrete properties and re-bar arrangement information presented by Vollum et al. (2002). Figs. 5-9 shows comparisons of calculated and

Table 2 Summary of slab construction load

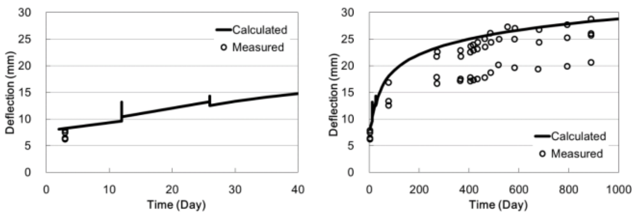
Floor i	Cast floor i +1 (days)	Load (kN/m^2)	Cast floor i +2 (days)	Load (kN/m^2)	Age at imposed loading of 3kN/m^2 (days)
2	13	10.34	25	7.44	386
3	12	10.74	26	8.75	393
4	14	10.27	27	8.29	374
5	13	10.73	34	7.80	359
6	19	10.14	-	-	337



(a) Internal slabs : short- and long-term deflections



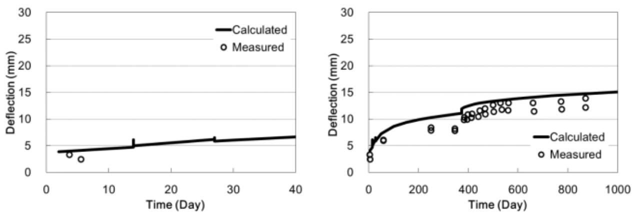
(b) Edge slabs : short- and long-term deflections



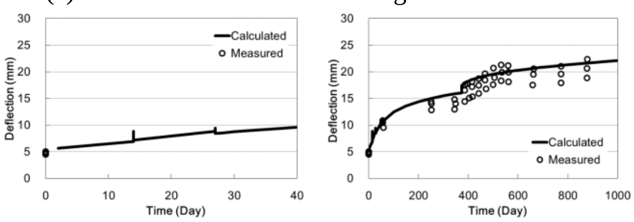
(c) Corner slabs : short- and long-term deflections

Fig. 6 Comparisons of calculated and measured deflections for 3rd floor slab measured deflections for 2nd to 6th floors by classifying as internal, edge, and corner slabs. For each floor slab, the deflections on 8 points - 2 points in internal slabs, 4 points in edge slabs, and 4 points in corner slabs - were measured as shown in Fig. 3. From measured data, some data deviations, that mainly result from the differences of opening locations in adjacent slabs and the construction time gaps from idealized construction sequences depending on slab locations even though on same floor, are observed, and the deviations in corner slabs are larger than those in internal and edge slabs.

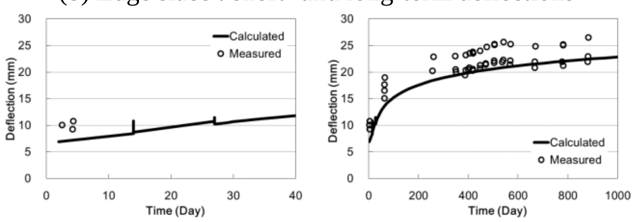
Figs. 5-9 compare separately the short-term deflections within 40 days after each slab was placed and long-term deflections to 1000 days. Due to differences in construction loading, re-bar arrangements, and concrete properties, there are significant differences in deflections between floors. Also, some differences between measured and analytical results are observed, especially in corner slabs, and those are because the proposed method cannot include the details of slabs and columns' layouts and constructions, for instance, the locations of slab openings and the slab deflections are calculated based on the elastic analysis results. In the slab with a local stiffness degradation due to construction load or irregular columns, the predictions of the proposed method may be a little different from the actual deflections. Table 3 presents critical stiffness reductions for each floor, and it shows that there is no stiffness reduction in middle strip of slab, but the stiffness of column strip is reduced to 68% of initial section stiffness. In more stiffness-reduced floors, 3rd and 5th floors, the larger differences between measured and analytical results are observed.



(a) Internal slabs : short- and long-term deflections

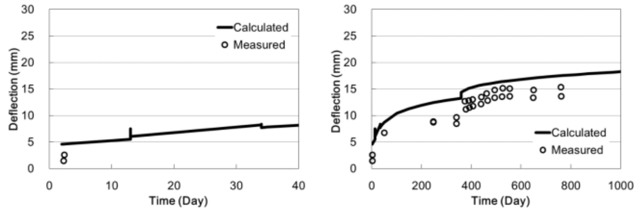


(b) Edge slabs : short- and long-term deflections

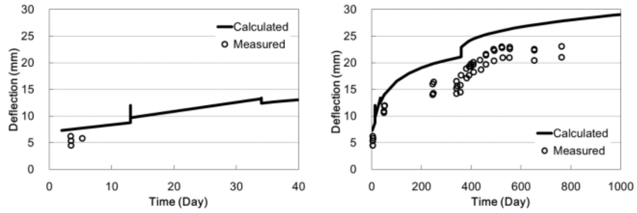


(c) Corner slabs : short- and long-term deflections

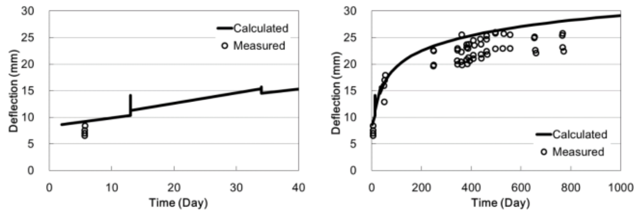
Fig. 7 Comparisons of calculated and measured deflections for 4th floor slab



(a) Internal slabs : short- and long-term deflections

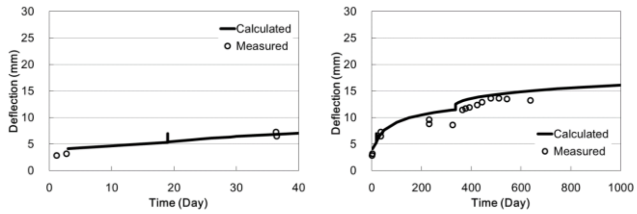


(b) Edge slabs : short- and long-term deflections

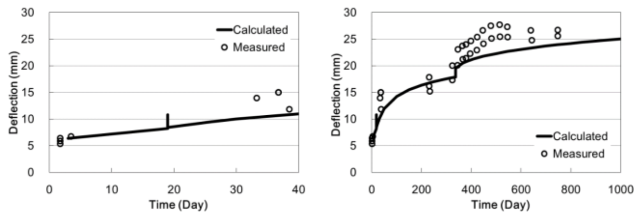


(c) Corner slabs : short- and long-term deflections

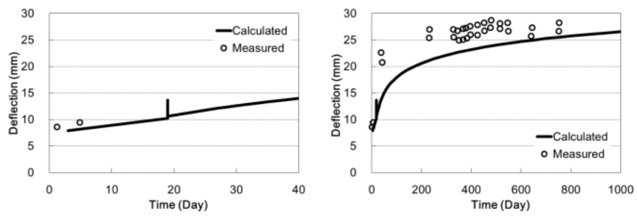
Fig. 8 Comparisons of calculated and measured deflections for 5th floor slab



(a) Internal slabs : short- and long-term deflections



(b) Edge slabs : short- and long-term deflections



(c) Corner slabs : short- and long-term deflections

Fig. 9 Comparisons of calculated and measured deflections for 6th floor slab

Although considering some differences between measured and analytical results, it can be concluded that generally, the calculated results by the proposed method agree well with the measured results for both of short-

Table 3 Critical stiffness reduction for each floor

Floor i	Location	Critical stiffness reduction day (days)	Corresponding Load (kN/m^2)	$[f_c'(t)/f_c']$ at critical day	$[I_e/I_g]$ at critical day	
					Column strip	Middle Strip
2	Internal	13	10.34	0.86	0.72	1.0
	Edge	13	10.34	0.86	0.79	1.0
	Corner	13	10.34	0.86	0.81	1.0
3	Internal	12	10.74	0.84	0.68	1.0
	Edge	12	10.74	0.84	0.76	1.0
	Corner	12	10.74	0.84	0.76	1.0
4	Internal	14	10.27	0.88	0.73	1.0
	Edge	14	10.27	0.88	0.85	1.0
	Corner	14	10.27	0.88	0.85	1.0
5	Internal	13	10.73	0.86	0.71	1.0
	Edge	13	10.73	0.86	0.73	1.0
	Corner	13	10.73	0.86	0.75	1.0
6	Internal	19	10.14	0.94	0.77	1.0
	Edge	19	10.14	0.94	0.88	1.0
	Corner	19	10.14	0.94	0.77	1.0

and long-term deflections. Despite the deflections were calculated not by finite element analyses but by simple calculations with some design and construction information, the changes of maximum deflections at all levels and locations were accurately predicted. Especially, for the almost cases, the calculated results formalize the upper bound, and the proposed method can be used as a reasonable tool in the practice.

5. Conclusions

In this study, the calculation procedure for simulations of short-term deflections in flat plates at construction stages and long-term deflections at service stages was proposed.

The calculations of deflections include the effects of construction load which changes with construction time and activities and the effects of concrete properties that the strength are time-dependently increased and the stiffness is degraded after cracking.

The proposed method implemented the simple calculation procedure in which the elastic deflections and the moments of flat plate are calculated respectively by the crossing beam method and by the direct design method, and then they are magnified in each construction step. The inelastic deflections are calculated by addressing the cracking effects and the long-term effects of concrete. Especially, stiffness degradation of the flat-plate by the cracks, which cannot be recovered by itself, is considered in the proposed method. The proposed method was verified by comparisons of the calculated deflections and the measured deflection from the in-situ six-story building. The comparison showed that the calculated results agree well with the measured results for both of short- and long-term deflections with various design and construction conditions. Since the maximum deflections of flat plates can be reasonably predicted not by finite element analyses but by using excel spread sheets with simple input, the proposed method can be practically useful in structural design and construction planning stages.

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