Computation of Post-Tensioned Slab Deflection under Construction Loads

Ah Sir Cho[1], Thomas Kang[2], Keenam Jeong[3], Yeong Wook Jo[4], and Byong Kap Jeon[5]

1) Ph.D. Student, Department of Architecture and Architectural Engineering, Seoul National University, Seoul, Korea. Email: pgulmark@snu.ac.kr
2) Associate Professor, Department of Architecture and Architectural Engineering, Seoul National University, Seoul, Korea. Email: tkang@snu.ac.kr
3) Structural Engineer, Total PS Co., Ltd., Seoul, Korea. Email: jkn@totalps.co.kr
4) Structural Engineer, Engineering & Construction Group, Samsung C&T Corporation, Seoul, Korea. Email: yeong.jo@samsung.com
5) Structural Engineer, Engineering & Construction Group, Samsung C&T Corporation, Seoul, Korea. Email: jbk21.jeon@samsung.com

Abstract:

In this study, deflections of post-tensioned (PT) slabs of a three-dimensional office building under construction loads were computed using a post-tensioning (PT) specialized computer program, ADAPT, and relevant theories. Typically a total of four floors of slabs are shored during the construction. The below three floors are already cast with concrete and partially hardened when fresh concrete is poured at the top level of these four floors. For the below three levels, post-tensioning of 15.2 mm diameter unbonded tendons is completed. The most below floor is subjected to largest construction load at its entire life, and may be vulnerable to severe cracking without PT. The reduced moment of inertia and elastic modulus of early-age concrete due to cracking (if cracked even with PT) may affect the long-term creep behavior of the floor significantly. The construction loads also include various loads of equipment, forms, self-weight of upper floors, and stored materials, as well as balancing uplift loads by PT. In the computer analysis, all the aforementioned conditions were considered carefully and computationally. The floor shoring was modeled using an elastic circular column, and its elastic modulus was input with actual values. The PT process and prestress losses due to wedge slip, friction, elastic shortening, etc. were simulated in the computer model. The construction loading and shoring/unshoring were taken into account. Finally, the model also reflected possible changes of the effective moment of inertia and elastic modulus at each construction step. The developed computational procedure helped predicting the deflection histories of PT slabs.

Keywords: Deflection, computer analysis, post-tensioned slab, construction loads, shoring, cracking.

1. INTRODUCTION

Slab deflection results in a variety of cracking problems and may lead to a serious damage or durability defect of the building if it occurs significantly in a short time. In the construction field, rearrangement or design modification of non-structural building materials might be needed due to the excessive deflection, especially for non-structural mechanical systems and finishing materials. With such changes, the performance cannot be made fully as planned, and the total construction time and cost would increase. For efficient construction, it is important to predict and control the deflections occurring during construction well. For example, the member could be designed to have a pre-camber or the prestressing is applied to the member using tendons. Compared to conventional reinforced concrete (RC) systems, the post-tensioning (PT) method is applied more effectively in long span structures as a lifting-up effect is created by tendons.

Jayasinghe (2011) predicted the deformation of PT beams and slabs over time. Rodriguez-Gutierrez and Aristizabal-Ochoa (2007) calculated the deflection of reinforced and prestressed concrete beams and compared with previous experiments. Hirsch (2009) suggested the method of long-term deflection prediction by using linear elastic analysis. There are several codes and researches that suggest how to calculate the deflection of slabs or analyze with their own program. In the case of post-tensioned (PT) building, relevant studies are still lacking. In this paper, a PT deflection analysis is performed using a commercial finite element analysis program.

2. MODELING

For the analysis of post-tensioned slab, a finite element analysis program ADAPT (ADAPT Corporation, 2015) was used. This is the program specially optimized for multi-story post-tensioned buildings, while other similar program such as SAFE (Computers and Structures, Inc., 2014) is capable of analyzing PT slab only for one story. Design codes for analysis were based on the ACI 2011 (ACI, 2011) and IBC 2012 (ICC, 2012).

2.1 Concrete

The target building is an office building constructed using the PT method. The plan view is shown in Figure 1.

This building is under actual construction. The slab was divided into 18 zones considering the column layout and each zone was named as shown in Figure 1. To take into account shoring over three stories, four stories were modeled. The top floor was defined as Nth floor and the floors below the top floor were labeled as N-1th, N-2th, and N-3th floor sequentially. Properties of concrete applied to the slab and columns of each layer are shown in Table 1. The design strength of the slab concrete was 35 MPa and that of columns was 30 MPa. The time of the initial deflection prediction was assumed to be the time immediately after pouring concrete for the Nth floor. At this time, poured concrete has low strength but normal weight which is the same as hardened concrete. Thus, in the analysis, the concrete strength (f'_c) of the Nth slab was 1 MPa. The columns of Nth floor were assumed to have 18 MPa because it would be partially hardened. The concrete elastic modulus (E_c) was then automatically determined by the strength in the ADAPT program (Aalami, 2011). For all concrete members, the unit weight of 2400 kg/m^3 and creep coefficient of 2.0 were applied.

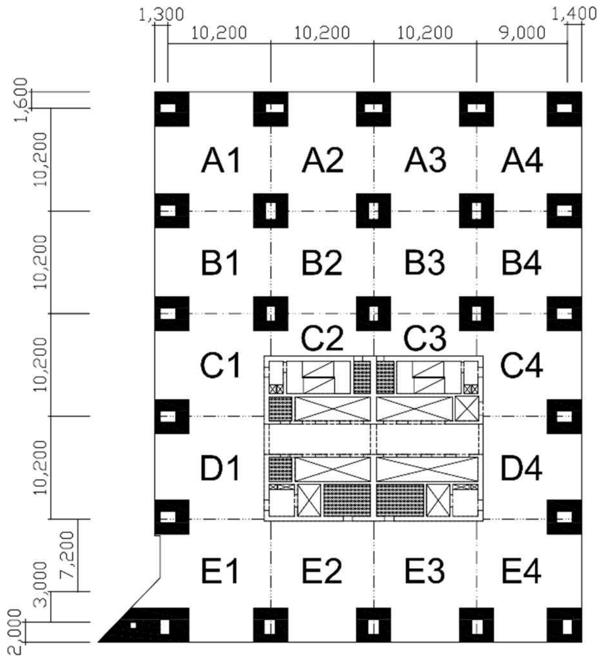


Figure 1. Slab dimension and zoning

Table 1. Material properties of shoring

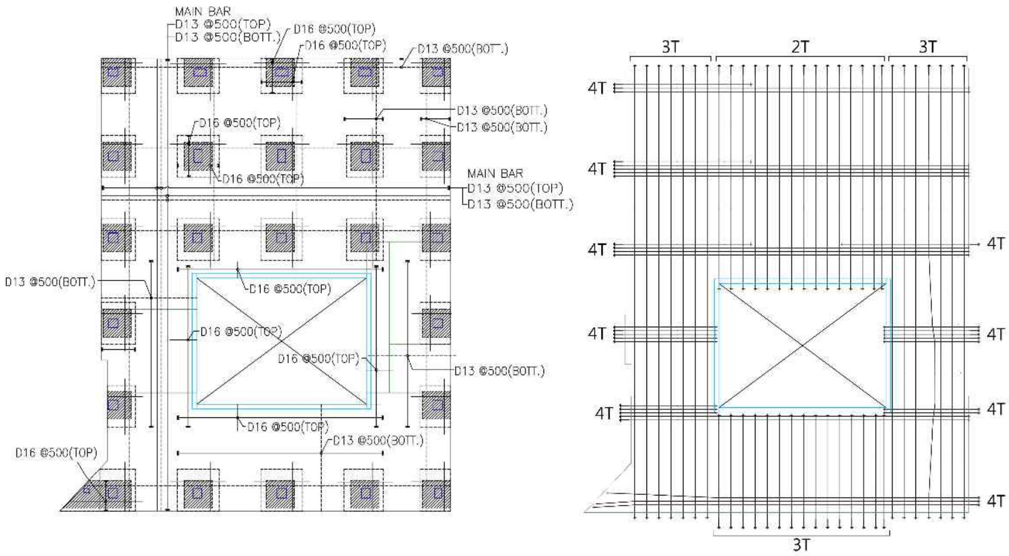
	Floor	f'_c (MPa)	Unit Weight (kg/m^3)	Type	E_c (MPa)	Creep Coefficient
Slab	N	1.00	2400.00	Normal	5026	2.0
	N-1	35.00	2400.00	Normal	29734	2.0
	N-2	35.00	2400.00	Normal	29734	2.0
	N-3	35.00	2400.00	Normal	29734	2.0
Column	N	18.00	2400.00	Normal	21323	2.0
	N-1	30.00	2400.00	Normal	27528	2.0
	N-2	30.00	2400.00	Normal	27528	2.0
	N-3	30.00	2400.00	Normal	27528	2.0

f'_c = concrete strength at 28 days; E_c = elastic modulus of concrete.

2.2 Reinforcement and Post-Tensioning

Steel reinforcing bars and PT tendons were arranged as shown in Figure 2. The tendons were banded horizontally in one direction, centered the column, and distributed in the other principle direction. The main longitudinal re-bar was SD400 D13 bar (diameter = 13 mm) with a specified yield strength of 400 MPa. The yield strength of re-bars used in the field was generally larger than the specified strength; thus, a value of 460 MPa was applied in the analysis.

For post-tensioning, 15.2 mm diameter unbonded tendons have the ultimate tensile strength of 1860 MPa were used. In the analysis, the same ultimate tensile strength was used and the yield strength was assumed to be 1700 MPa. The modulus of elasticity was set equal to 200,000 MPa for both the reinforcement and the PT tendon.



(a) Reinforcement (b) PT tendon

Figure 2. Reinforcement and PT tendon arrangement drawing

2.3 Shoring

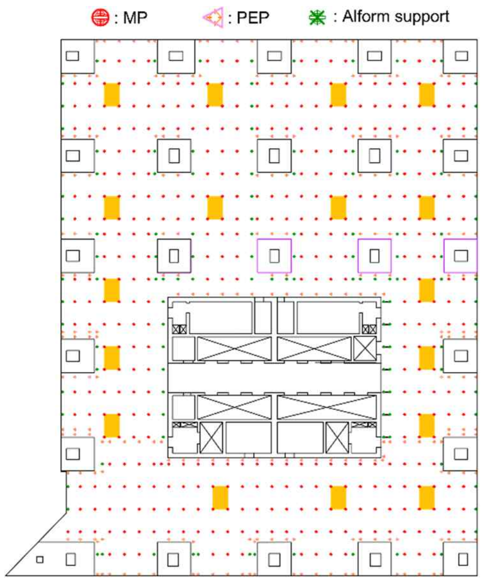


Figure 3. Shoring plan (red dot: MP, green dot: PEP & red arrow: AS)

Shores were installed over the three floors and each floor had three kinds of shores; Multiprop (MP), PERI Euro prop (PEP), and Aluminum form support (AS). They were spread all over the slab as shown in Figure 3. Their material properties applied in the analysis are indicated in Table 4. The MP plays a role to reduce the deflection at the center of each slab section. The largest number of the shoring used was PEP which is designed to resist total loads transmitted from upper stories. The AS is commonly used for supporting only the formworks, but in the analysis it was assumed as a prop because it shores up the drop panel.

In the ADAPT analysis, the prop was modeled as an axial member with two hinge ends and circular section having 100 mm diameter, and its unit weight was calculated by dividing the weight by the assumed volume. The main material of MP was steel while PEP and AS were made of aluminum. The elastic moduli of MP and PEP/AS of 200,000 MPa and 70,000 MPa were input in the program, respectively. The stiffness of each member was automatically calculated according to the modulus of elasticity during the analysis.

Table 2. Material properties of shoring

Shoring	Quantity (EA)	f_u	Weight (kg/EA)	Unit Weight (kg/m^3)	E	Creep Coefficient
MP	68	1583.45	18.8	626.83	200,000	2.0
PEP	339	193.97	19.2	613.77	69,999	2.0
AS	204	193.97	17.9	585.04	69,999	2.0

f_u = assumed strength; E = elastic modulus

2.4 Load

Load combinations shown in Table 3 were applied in the analysis. In order to consider the most basic service load, all factors for each load were defined as 1.0. Reinforced concrete (RC) with post-tensioning has only the weight of concrete and construction load, and the prestressing effect was accounted for as additional PT upward load. When the concrete was poured on the Nth floor slab, all the tendons up to the floor of N minus one floor ((N–1)th floor) were assumed to be post-tensioned. Before concrete hardens nothing can be placed on the slab, so Nth floor slab was subjected to only the self-weight for both the RC and PT systems.

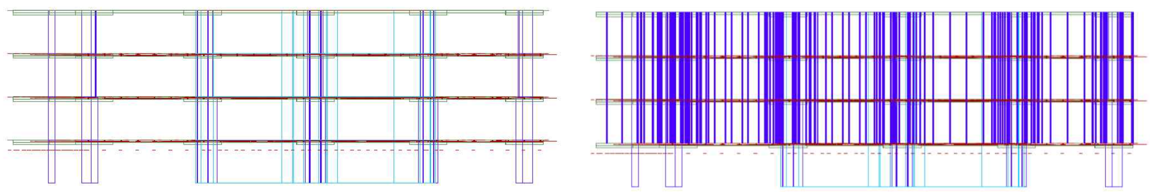
Table 3. Load combination

Floor	RC	PT
N	1.0 SW	1.0 SW
N–1	1.0 SW + 1.0 LL	1.0 SW + 1.0 LL + 1.0 PS
N–2	1.0 SW + 1.0 LL	1.0 SW + 1.0 LL + 1.0 PS
N–3	1.0 SW + 1.0 LL	1.0 SW + 1.0 LL + 1.0 PS

SW = self-weight; LL = live load; PS = Prestressing.

2.5 Final Model

Applying for aforementioned conditions and information, analysis models are created by using ADAPT as shown in Figure 4.

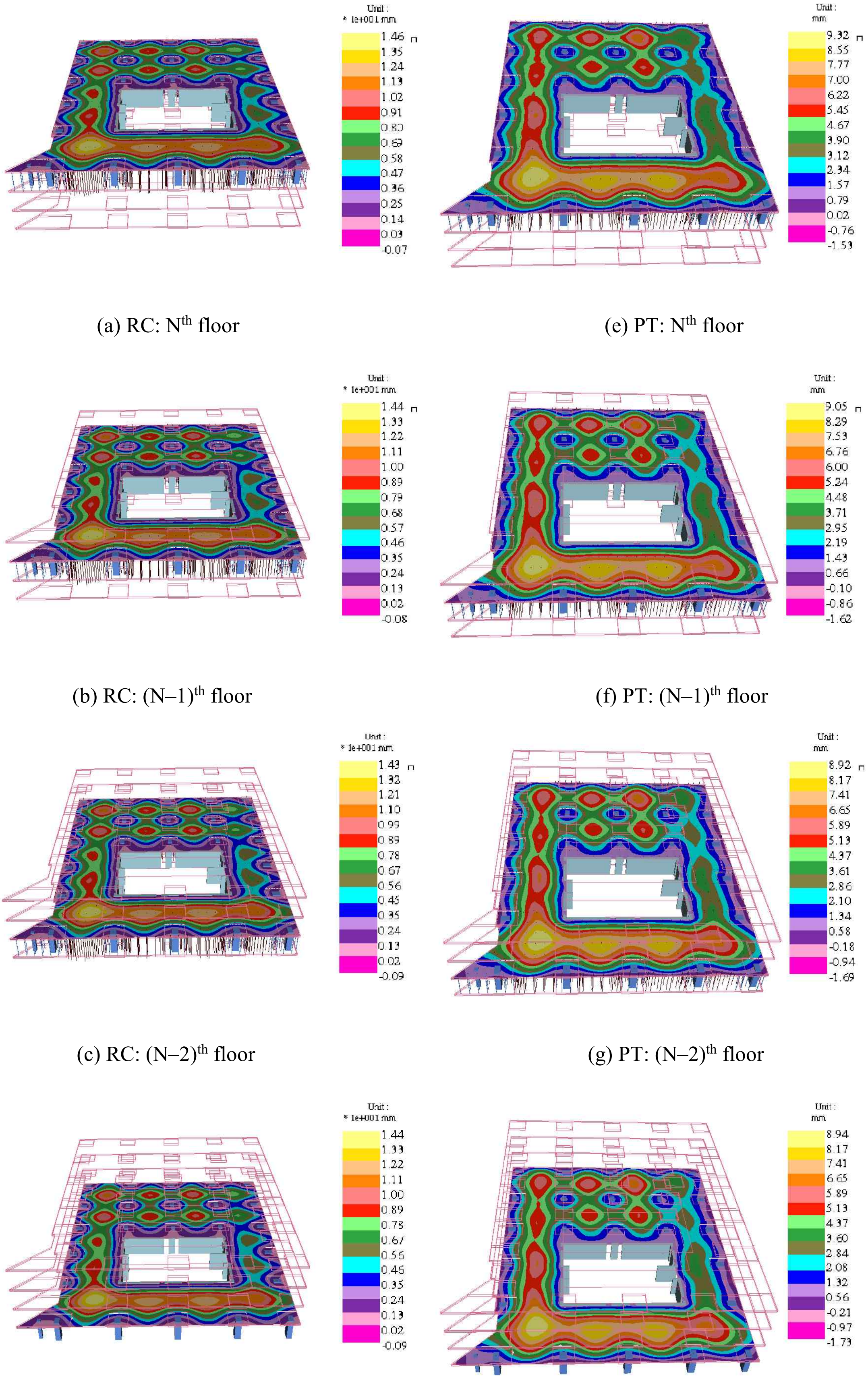


(a) Without shoring (b) With shoring

Figure 4. Slab and shoring modeling

3. RESULTS

The analysis results on the deflection occurring in the RC and PT slabs are shown in Figure 5, with the maximum deflection of each floor indicated in Table 4. Both RC and PT slabs showed a similar pattern in all floors. Maximum deflection occurred in the panel of E1. Also, in the panels of E2 and E3 second and third larger deflections occurred in order. Maximum deflections in the panels of A1 ~ A3 are larger than those of B1 ~ B3. This means that the more deflection occurred near the perimeter of the building. At the locations of A4, B4, C4, and D4, relatively smaller deflections were expected. One reason might be that the widths of these slabs were smaller than those of A1, B1, C1, and D1 panels. The other reason could be that they were substantially away from the E1 panel, the slab most vulnerable to deflection.



(a) RC: Nth floor

(e) PT: Nth floor

(b) RC: (N–1)th floor

(f) PT: (N–1)th floor

(c) RC: (N–2)th floor

(g) PT: (N–2)th floor

(d) RC: (N–3)th floor

(h) PT: (N–3)th floor

Figure 5. Slab deflection contour

In the computer analysis, there was little difference in each floor deflection, unlike the anticipation that the deflection would be the largest in the most below floor without shoring at the time of concrete pouring on N^{th} floor in proportion to the magnitudes of loads. In the analysis, the deflection of N^{th} floor was the largest and the deflections were slightly reduced for $(N–1)^{th}$ or $(N–2)^{th}$ floor, but it was almost the same. The almost same deflections were likely due to the slabs linked with shores, enabling the slabs to move. The deflection of N^{th} slab resulted from not only its own weight but the push-down force from the $(N–1)^{th}$ slab through the integrated shoring system. Also $(N–2)^{th}$ and $(N–3)^{th}$ floors' weights are related to the deflections of its own floor and other floors in a similar way. Slabs of each floor were connected with the props and these shoring members acted as elastic links so that all the members contributed to the stiffness and associated deflection in the analysis. Thus, the difference in deflection between the floors was not considerable.

For the PT structure, the deflection was reduced significantly as compared to the RC structure. Uplift forces by prestressing decreased the deflection. In the analysis, it can be surmised that uplift behavior of upper slab also affected the deflections of lower slabs through the integrated props.

Table 4. Maximum deflection (Unit: mm)

Floor	RC	PT
N	14.6	9.32
N–1	14.4	9.05
N–2	14.3	8.92
N–3	14.4	8.94

4. CONCLUSIONS

In this paper, 4-story part of a post-tensioned concrete building was designed using the post-tensioning-specialized finite element program, ADAPT. For comparison, the same building without post-tensioning forces was also analyzed. Through the analysis, both reinforced and post-tensioned structures were found to have similar aspects, which include the fact that the maximum deflection occurred at the largest slab panel, except that the maximum deflections were 14.6 mm and 9.32 mm in RC and PT slabs, respectively. The post-tensioning effect decreases about 37% in deflection. Unlike the common anticipation, the deflections for all four stories were similar. This tendency was due to the connection between the shoring and the slabs in the analysis. The props were integrated to the slab as an elastic member. The prediction method needs to be further improved. Even so, the computer analysis takes into account the construction loads such as the accumulated upper floor weights, the post-tensioning effect, and the shoring effect reasonably well. Additionally, the model also reflected possible changes of the effective moment of inertia and elastic modulus at each construction step. The developed computational procedure helped predicting the deflection histories of PT slabs during the construction.

ACKNOWLEDGMENTS

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