Title: **Sequential Analysis of Flat-Slab Construction and Its Impact on Construction Cycle**

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He is currently involved in the construction of the Burj Dubai, slated to be the tallest building in the world.

Sequential Analysis of Flat-Slab Construction and Its Impact on Construction Cycle

This presentation is based on a paper by Seung-Chang Lee, Jae-Yo Kim, Jung-Keun Oh, and Ahmad Abdelrazaq, all of the Samsung Corporation (Engineering & Construction). Dr. Lee and Mr. Abdelrazaq will present the paper.

Extensive studies and research have been performed to evaluate flat-plate/flat-slab system behavior during construction and the resulting short-term and long-term behaviors of the system. Present material technologies, especially as they relates to high-performance concrete (HPC), may have some influence on the construction sequence of these systems. Proper precautions in practice may influence the behavior positively, especially as it relates to cracking and stiffness control because of HPC use.

This presentation will discuss the purpose of the paper, which was to study the behavior of flat-plate slab system behavior when utilizing HPC during construction and its impact on long-term performance. Through the study, a construction sequence analysis was performed that took into account the effect of slab strength and stiffness during construction cycle, prop member stiffness, and the cracking effects on the long- and short-term behavior of flat-plate construction.

This study is necessary to optimize the shoring method of high-rise building system with flat-plate floor construction as it may influence a typical floor construction cycle in a high-rise building.

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Ahmad Abdelrazaq works with the Samsung Engineering & Construction as a vice president and technical advisory. He leads and directs a group of engineers in all aspects of structural engineering, from planning and feasibility studies to construction. He has extensive experience in the design of buildings, ranging from low-rise to ultra high-rise, as well as long-span structures. His experience includes working on completed U.S. and award-winning international projects, including Jin Mao Tower in Shanghai; Tower Palace III in Seoul, Korea; the Millennium Park Project in Chicago; and Hotel De Artes in Barcelona, Spain.

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This study is necessary to optimize the shoring method of high-rise building system with flat-plate floor construction as it may influence a typical floor construction cycle in a high-rise building.

Sequential analysis of flat slab construction and its impact on construction cycle

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Abstract

Extensive studies and research have been performed on the evaluation of flat plate and flat slab system behavior during construction. Construction sequence tends to influence the short term and long term behaviors of these systems, especially as it relates to serviceability conditions and in some occasion to strength related issues. Present material technologies, especially as it relates to high performance concrete (HPC), may have positive influence on the construction sequence and planning of these systems. Proper precautions in construction practice nowadays is required as it may influence the behavior positively and improves the serviceability behavior, especially as it relates to cracking and stiffness control because of the use of HPC.

The purpose of this paper is to study the behavior of flat plate slab system behavior when utilizing high performance concrete during construction and their impact on the long term performance of these systems. Through this study, several construction sequence analyses were performed that take into account the effect of slab strength and stiffness development during construction cycle, shoring member stiffness and the cracking effects on the long and short term behavior of flat plate construction. This study was performed to study different shoring methods of a high-rise building system with flat plate floor construction as it may influence a typical floor construction cycle in a high-rise building structure and its overall impact on the construction schedule.

Keywords; flat plate, high performance concrete, sequence analysis, shoring member, cracking

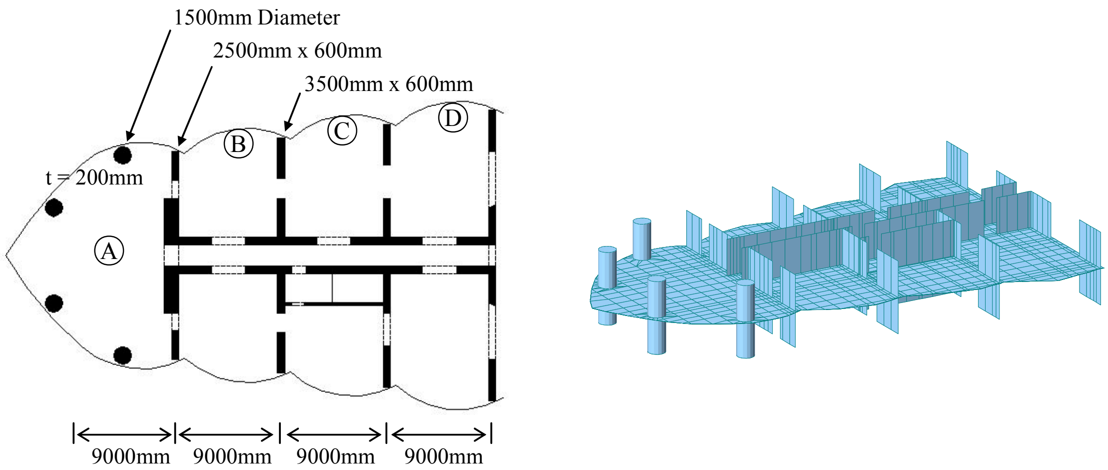
Introduction

Present building codes provide guidelines for slab thickness in flat plate/flat slab construction. These guidelines are based on assumptions related to normal concrete with strength equal to or less than 35Mpa, and experiences related to slab construction sequence and its impact on the immediate long term deflection of these systems. These guidelines are provided to help engineers select the minimum slab thickness without going through the extensive calculations that these systems may require. Moreover, the codes also allow the engineer to reduce these thicknesses as long as the engineer performs structural calculation to verify the serviceability requirements. Present use of a) high performance concrete with high strength, stiffness and durability, b) high performance computer power, and c) sophisticate computer program with many analytical and design capabilities allowing engineers to exceed the span to depth ratios while satisfying the serviceability requirements. While this analysis and design approach is logical it will impose significant demands on the construction sequence and planning, which in turn require the contractor to keep up with these technologies and thus impose high quality control program during construction in order to ensure that the design and analysis assumptions are achieved. Thus, the construction of these projects requires careful planning in construction method and the curing methods so that a) early cracking (due to shrinkage) are minimized. b) overload on the youngest slabs are avoided, and the process of shoring / pre-shoring / re-shoring is balanced to verify proper load distribution among the slabs participating in the construction cycle.

The purpose of this paper is to present a summary of the analytical studies of a typical bay in a prominent high-rise residential tower. This study includes 1) the effect of high performance concrete on the design of flat plate construction, 2) the impact of construction sequence on the behavior of the slabs, 3) a summary of the different shoring schemes considered to control the slab cracking, deflection and to prevent the early aged slabs from being overloaded because of the construction sequence, and 4) finally a summary of the analytical study of the construction sequence that takes into account the load distribution in the slabs as a function of the slab strength development, axial stiffness of shoring members and cracking effects.

Impact of high performance concrete on the slab deflection

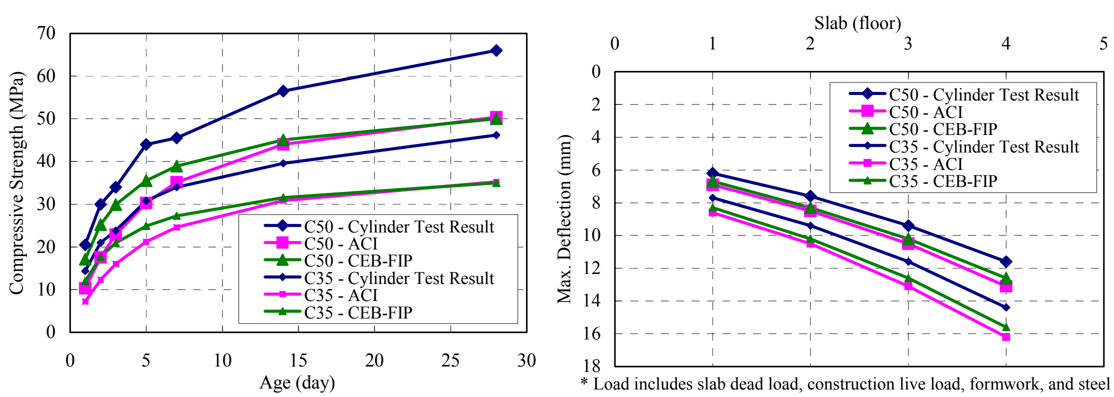
The floor framing system of typical bays of a prominent high-rise residential tower consists of two-way flat plate construction as shown in Figure 1.   The floor framing system consists of 200 mm two-way flat plate construction that is bounded by high performance reinforced concrete (C80) walls on 3 sides (essentially fixed at 3 sides) in the typical cell and very large high strength reinforced concrete columns at the nose areas, which exceeds the span/depth limits specified in ACI code.   However the 3-dimensional finite element analysis was performed that takes into account the effect of high performance concrete (C50) characteristics, including early strength development, high stiffness, high durability etc. and the cracking resistance.   The structural analysis model indicated that the slab serviceability requirements can be achieved because of using high performance concrete. **Table 1** and **Figure** 2 depicts a summary



(a) 4-bay plan (b) Typical 3-D analysis model

Figure 1. Typical partial framing plan of a high-rise building tower and 3-D structural analysis model

of the slab deflection, including cracking and long term effects, at the critical areas utilizing high performance concrete C50(50Mpa) and normal concrete C35(35Mpa). **Table 1** also shows that the slab deflection using C50 concrete is smaller than that of C35 normal concrete. The long term deflection multiplier utilized here are in accordance with the ACI code. The long term deflection values for high performance concrete could be lower than those shown in Table 1. **Figure 2** compares the strength development characteristics of C50 concrete vs. C35 concrete based on the model code and the actual concrete testing. The lower slab deflections realized by using HPC is related to utilizing with higher concrete resistance to cracking, higher modulus of elasticity, lower shrinkage and creep effects, and higher durability.



(a) Concrete strength development (b) Maximum elastic defection

Figure 2. Variation of maximum elastic deflection vs. concrete strength development

Table 1: Summary for maximum deflection on a typical 4-bay slab system (unit: mm)

			High Performance Concrete (C50: 50MPa)				Normal Concrete (C35: 35MPa)			
			A	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Deflection by elastic analysis	Δ_{DL}		5.2	2.9	2.7	3.3	6.2	4.4	4.1	4.9
	Δ_{DL+SDL}		7.3	4.5	4.2	5.2	8.7	7.1	6.6	8.1
	$\Delta_{DL+SDL+LL}$		9.0	5.6	5.2	6.4	10.8	8.8	8.4	10.2
Deflection with cracking	Δ_{DL}		6.4	5.5	3.9	5.1	8.2	5.8	5.3	6.8
	Δ_{DL+SDL}		11.6	8.6	8.0	10.5	15.5	11.7	11.3	14.4
	$\Delta_{DL+SDL+LL}$		16.0	13.4	12.8	17.1	21.2	16.3	16.4	20.1
Deflection with cracking and long term effect	Δ_{DL}	**6month**	13.0	11.3	8.0	10.3	15.7	11.9	10.8	13.9
		1 year	14.1	12.2	8.6	11.2	17.0	12.9	11.8	15.1
		2 year	15.5	13.4	9.5	12.3	18.5	14.1	12.9	16.6
		3 yeas	16.4	14.2	10.0	13.0	19.5	14.9	14.0	17.4
		4 year	16.9	14.6	10.3	13.4	20.1	15.4	14.1	18.0
	Δ_{DL+SDL}	**6month**	22.2	17.5	16.4	21.5	29.7	23.9	23.1	29.4
		1 year	24.0	19.0	17.8	23.3	32.1	25.9	25.1	31.9
		2 year	26.2	20.1	19.5	25.6	35.1	28.5	27.5	35.1
		3 yeas	27.6	22.0	20.6	26.9	36.8	30.0	29.0	36.9
		4 year	28.5	22.7	21.3	27.8	38.0	31.0	30.0	38.2
	$\Delta_{DL+SDL+0.25LL}$	**6month**	24.3	19.9	18.8	24.8	32.5	26.3	25.7	32.3
		1 year	26.3	21.2	20.4	26.9	35.0	28.5	27.9	35.1
		2 year	28.7	23.7	22.4	29.5	38.3	31.3	30.6	38.5
		3 yeas	30.2	25.0	23.6	31.1	40.2	33.0	32.2	40.6
		4 year	31.1	25.8	24.4	32.2	41.5	34.1	33.3	42.0

Impact of slab construction sequence on the slab behavior

Several preliminary shoring options were considered for a typical cell area in order to limit the slab overload during construction as shown in **Figure 3**. While some of the temporary shoring options shown in this **Figure 3** are valid and could provide better behavior, deviation from the traditional construction method was considered risky because of the potential impact on the construction schedule, therefore the options shown in **Figure 3**, were considered practical and within the capabilities of the local skilled labor. Option 3 provided a rigid support at the free edge of the slab during the construction stage, thus significantly reducing the deflection. **Figure 4** provides the elastic deflection summary of slab during construction for each of the schemes considered. The analysis method utilized takes into accounts the construction sequence and the accumulation of loads in the slabs, effects of shoring stiffness, and concrete strength development with time. The shoring members were modeled as compression only members. Table 2 provides a summary of the shoring member forces under different loading conditions. Based on the various scheme considered, options 3 and 5 were considered the most effective schemes in controlling the slab deflection behavior in a typical cell area, but they require special shoring. Therefore, option 4 may be considered the most effective option in limiting the slab deflection and forces within the allowable limits, and in controlling the maximum shoring forces.

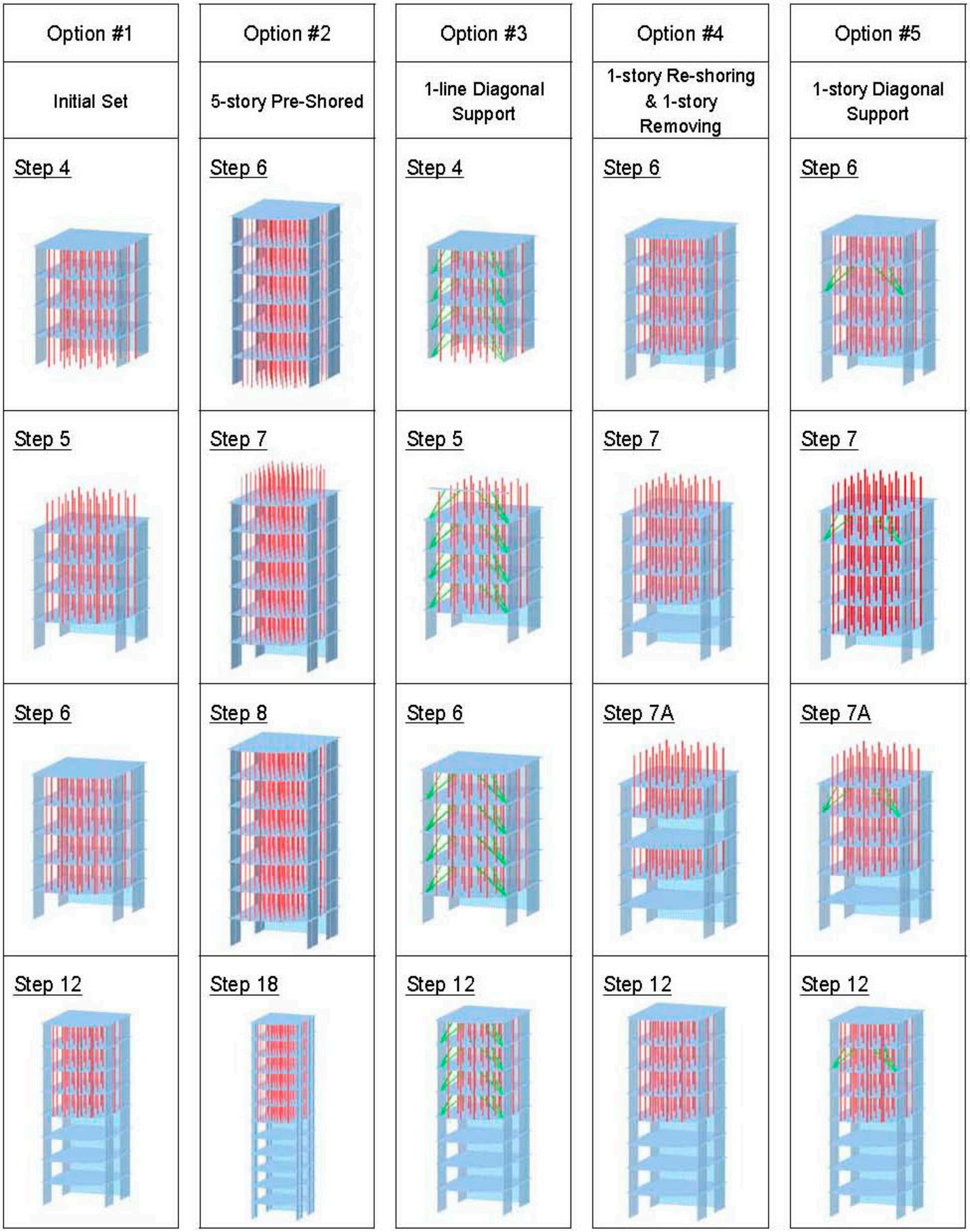
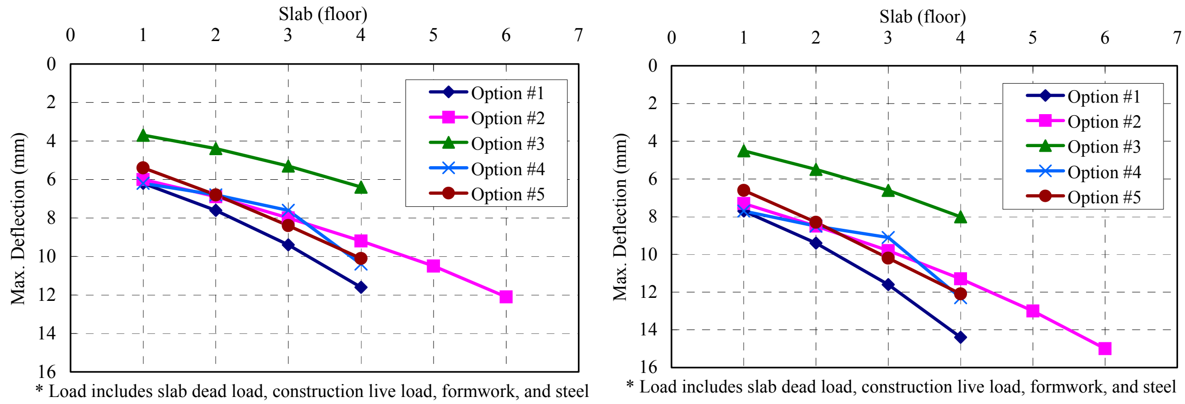


Figure 3. Various options of construction schemes



(a) High performance concrete (b) Normal concrete

Figure 4. Maximum slab elastic deflection during construction depending on concrete strength

Table 2. Maximum Shoring Forces

	Location	Force (kN)
Option #1	5th Slab	37
Option #2	7th Slab	51
Option #3	5th Slab	38
Option #4	5th Slab	27
Option #5	4th Slab	54

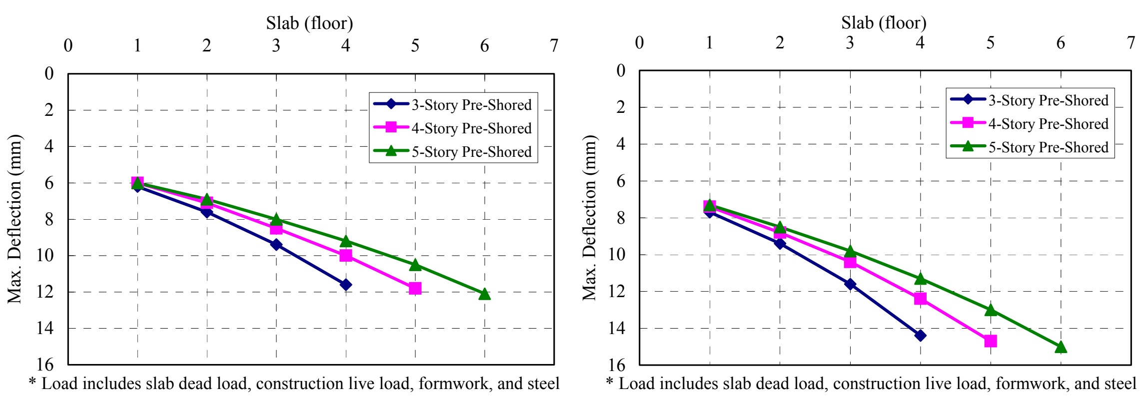
Parametric study

The intent of this study is to compare the behavior of flat plate construction staged analysis using HPC (C50) to that of normal concrete (C35) for the same slab boundary conditions. The staged analysis is performed to evaluate the effects of the following four parameters. 1) concrete strength, 2) shoring method and sequence of construction, 3) number of pre-shored stories, 4) slab thickness. These slab deflection and shoring forces were compared for each of the scheme and summarized as below.

Concrete strength development

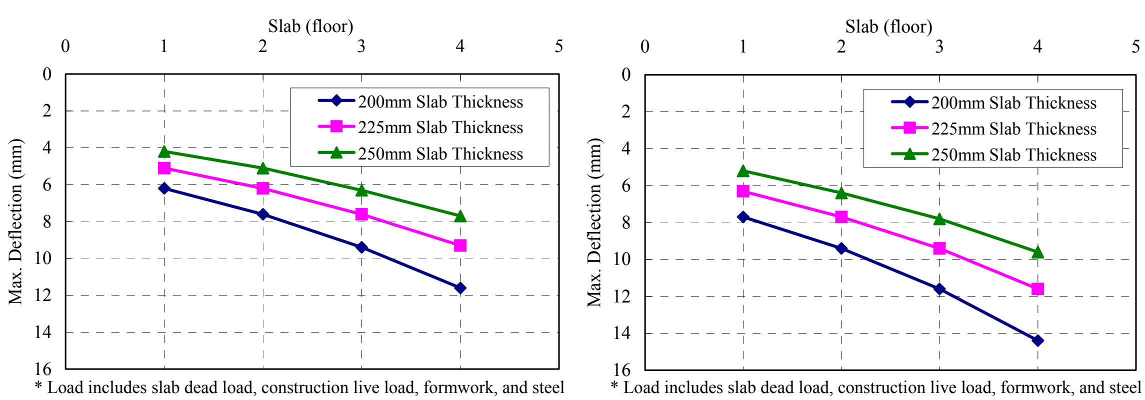
Early strength development plays an important role in controlling the slab behavior during construction, especially when utilizing high performance concrete in hot climate. Monitoring the strength development of high performance concrete on site and in the laboratory plays a major role in deciding the optimum slab construction methods and formwork activities. Figure 2 compares the actual concrete strength development of the high performance concrete that is intended to be utilized for the project as a base for this study. C50 (50Mpa) concrete strength development is compared to other model design codes, (Kosmatka 2002) ACI and CEB-FIB, strength development. The concrete strength development by testing is different from that of the model codes (ACI or CEB-FIP). Using the actual test results is usually preferable as it reflects the actual concrete characteristics and the environmental conditions. Therefore, for the purpose of this study, the actual concrete strength development is utilized. Figure 4 shows that one line of edge diagonal shoring provides for the most effective method of reducing the slab deflection and forces. However, this option may have impact of the shoring system design and construction cycle. Utilizing option 3 could be considered a very effective option to be utilized for normal concrete, especially for the 200mm slab that is spanning 9 meter between the walls, mostly acting as one way system for part of the slab between the boundary walls.

As shown in **Figure 5**, increasing the number of shoring increases the maximum deflection and forces in the slabs slightly, and it increases the shoring forces, however, it delays the time when the maximum deflection and forces occur in the slabs. Increasing the number of shoring economical impact has to be balance against increasing the concrete strength since increasing the number of shoring may not be economical. Comparison of slab construction method for option 1 and option 4 were also evaluated using both HPC and normal concrete. **Figure 7** shows that slab re-shoring is an effective solution in limiting the slab deflection, slab design forces under construction, and shoring forces. The design of re-shoring system member properties can be changed with members that are lighter, but with higher capacity, thus reducing the number of re-shoring members needed.



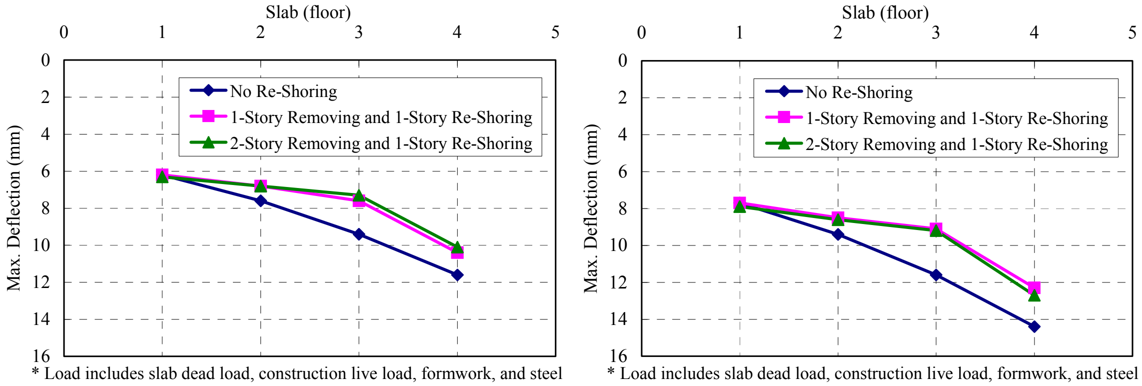
(a) High performance concrete (b) Normal concrete

Figure 5. Variation of maximum elastic deflection under the number of pre-shored story



(a) High performance concrete (b) Normal concrete

Figure 6. Maximum elastic deflection under the variation of slab thickness



(a) High performance concrete (b) Normal concrete

Figure 7. Variation of maximum deflection by re-shoring scheme

The effect of increasing the slab thickness was also considered in this study. A summary of the slab thickness effects on the slab deflection, design forces, and shoring loads, was evaluated for construction option 1and option 2 utilizing both high performance and normal concrete. As shown in **Figure 6**, the 200mm slab is considered effective and economical with high performance concrete, but the slab thickness would need to be 225 to 250 for normal concrete.

Conclusions

Further research is needed to evaluate the slab deflection limits when utilizing high performance concrete. Span/depth ratio limits guides present in model codes may be exceeded and they do not necessarily take into account the effect of boundary conditions, utilization of high performance concrete, and construction sequence, but they do provide good guidelines for providing upper limits on member sizes that are loaded with ordinary normal conditions and use. High performance concrete with good quality control may have advantages in controlling the serviceability conditions of concrete structures under both temporary and permanent building loading conditions, and thus it may result in overall economical design, especially in high-rise building construction. The parametric studies performed for slabs with high performance and normal weight concrete indicates that thinner slabs can be achieved as long as due diligence is performed during the design and construction stages, and careful construction planning is performed, especially as it relates to concrete strength development, proper curing, and impact of the environmental condition on concrete strength development. In addition, the slab construction method needs to evaluated in order to achieve the most economical form work system and construction method.

The study of the flat plate construction for the system presented herein indicates that the optimum method of controlling the slab behavior can be related to the following, 1) the use of high performance concrete with early strength development, high modulus of elasticity, and lower creep and shrinkage coefficients, 2) utilize re-shoring method, option 4, as a base for the construction sequence since it utilizes simple construction and construction that is easily understood by the local labor, 3) and the potential for utilization of non traditional shoring system, such as option 3, as long as it does not influence the construction cycle. Finally the most effective method of construction is the one that is simple, and that takes into account the capabilities and the readily available skilled labor, while utilizing present material and construction technologies.

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