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Numerical Investigation on the Influence of Shoring Stiffness on Slab Deflection with Consideration of Construction Phase Loading

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***Abstract* –** The construction phase of reinforced concrete buildings is critical, as temporary loads during shoring and reshoring can induce deflections that impact long-term serviceability. Traditional methods for evaluating these loads rely on assumptions of infinite shoring stiffness and uniform load distribution, which can lead to underestimation of deflections, especially when concrete creep is not considered. This research proposes a finite element modeling (FEM) process, integrating shoring stiffness, time-dependent concrete properties and concrete creep to simulate the load-deflection behavior of multi-story reinforced concrete buildings from the construction phase to the application of the service load. The aim is to study the influence of shoring system stiffness on load distribution and slab deflection. The proposed methodology, implemented in a standard FEM software, is then applied on a typical building for construction phase schemes including one level of shore and one, two and three levels of reshoring. The influence of stiffness variations is studied. It was found that accounting for the stiffness of shoring systems is essential for reliable assessment of slab deflections during the construction phase.

***Keywords*:** Shoring and reshoring, Construction phase, Construction loads, Multi-story buildings, Deflection, Stiffness, Finite element modeling.

1. Introduction

The construction of multi-story reinforced concrete buildings usually relies on temporary shoring systems to support slabs during the construction phase. This temporary structure transmits the load of newly cast slabs and live loads from construction activities to one or more lower slabs. The shoring system plays a crucial role in maintaining the stability of the structure and preventing excessive slab deflections, which can lead to serviceability issues if the shoring system or sequences are inadequate.

Over the years, numerous studies employing analytical methods, experimental investigations, and numerical approaches have been conducted to evaluate load transfers during construction phase. However, these studies have primarily focused on assessing the magnitude and distribution of construction loads, with limited attention given to their long-term effects [1]. This paper presents a review of existing methods for the evaluation of construction loads as well as the estimation of slab deflection. A numerical finite element investigation is then conducted to assess the influence of shoring stiffness on load distribution and slab deflection during the construction phase. It focuses on construction systems involving shoring and reshoring, which are the most widely used because of their economic advantages [1-2].

2. Literature review

2.1. Evaluation of construction loads

Given the critical nature of the construction phase, many studies have aimed to determine load distribution during construction. Among those studies, the simplified method developed by Grundy and Kabaila [3] is widely recognized for its simplicity and effectiveness in estimating construction loads. This method calculates a load ratio, R, at each stage, defined as the ratio of the load supported by the slab to the slab's self-weight. The method relies on four main assumptions: a) Slabs exhibit elastic behavior, neglecting creep and shrinkage effects; b) foundations are infinitely stiff; c) Shores are infinitely stiff compared to slabs; d) Load distribution from shores is uniformly distributed.

Several authors have examined the impact of these assumptions on load distribution during construction. Studies considering the relative stiffness of slabs and concrete creep have shown good correlation with results predicted by the simplified method [4-5]. However, studies incorporating shoring system stiffness reveal a significant influence on load distribution [6-10]. Finite element analysis (FEA) further emphasizes the limitations of assuming infinitely stiff systems and the impacts of integrating realistic material and structural properties of shores.

2.2. Analysis of deflections due to construction loads

Slab deflection during construction has received less attention than construction load evaluation, possibly due to the complexities of analyzing two-way slabs deflection and time-dependent properties of concrete. Motter and Scanlon [11], proposed an analytical method that addresses short-term and long-term deflections on bidirectional slabs during construction using cross-beam analogy method. Graham and Scanlon [12], combined a FEA model to estimate instantaneous deflections with an analytic method to calculate long-term deflections in order to determine total deflections due to construction loads. Aguinaga-Zapata and Bazant [5] developed a numerical model to analyze forces in shoring/reshoring systems and determine long-term deflections. While these methods account for time-dependent concrete properties, they assume an infinitely stiff shoring system and a uniform distribution of load during construction.

The main study that has used FEA to analyze structures during the construction phase is the one conducted by Alvarado et al. [13]. The authors modeled both permanent and temporary structures to evaluate deflections during construction sequences. Their study emphasized the importance of considering construction loads in structural design and identified the reshoring system as having the most impact on long-term deflection and represented a framework for further developments of construction loading numerical simulations.

3. Methodology

3.1. Assumptions and finite elements modeling

To study the influence of considering shoring stiffness on load distribution and deflection during construction phase, the proposed methodology consists of modeling the structure considering shoring/reshoring system as infinitely stiff, on the one hand, and considering its finite stiffness, on the other. In the first model, the elements of the temporary structure are not modeled, and the load distribution is considered as uniform, unlike the system including the stiffness of the formwork system. The common additional assumptions are the following: a) slabs have linear elastic behavior with finite stiffness that varies with time; b) columns are linear elastic with finite time-dependent stiffness; c) foundations are infinitely stiff; and d) creep deformations are considered.

The study employs a finite element model developed in SAP2000. Key model elements include:

- Slab: 2D thin-shell element with 4 nodes, each having 6 degrees of freedom. Slab thickness is constant, and material properties vary over time.
- Formwork: 2D thin-shell element with fixed characteristics.
- Columns and Shores: 1D frame elements with 2 nodes and 6 degrees of freedom. Mechanical properties are time-dependent for columns but fixed for shores.
- Foundation: incompressible supports under columns and shores.

The mesh of the slab and formwork is based on the position of the shores, reshores and columns to ensure appropriate load transmission. Additional mesh points are added to capture deflections at critical locations and a subdivision is also applied.

3.2. Evaluation of construction loads

When the shoring system is considered as infinitely stiff, the load assessment can be done by the simplified method. According to this method, the construction load can be expressed as [12]:

$$W_C = 1{,}1 * R * W_D + W_{CL}/N \quad (1)$$

Where W_D is the self-weight of the slab. W_{CL} is the construction live load; ACI 347.2R-17 [2] recommend considering a minimum construction live load of 2.4kN/m² when casting is not motorized, or 4.8kN/m² otherwise. N is the number of levels of the support system, R is the load ratio evaluated by the simplified method extended to shoring/reshoring system [14]. For a system with N support levels, $R = 1$ when the lowest level is connected to the foundations or to the stripping of the newly cast levels and $R = 1 + 1/\text{N}$ to the casting of new levels.

When the shoring system finite stiffness is considered, it undergoes deformations during the loading cycles, and the distribution of loads between the different slabs is no longer uniform, but proportional to the stiffness of each element of the system. Analytical and numerical studies having shown that it is not possible to define a single factor to take this stiffness into account [6], only a modeling of all the elements of the structure with their characteristics makes it possible to determine the distribution of loads during construction.

Furthermore, for an assessment of deflections up to the application of the maximum service load, it is suggested to apply a sustained load after the removal of the reshores to take into account the installation of the permanent structure elements and construction activities. In accordance with Motter and Scanlon [11], we will consider that these loads are:

$$W_{Sus} = W_D + W_{SDL} + 0.1W_{LL} \tag{2}$$

$$W_{max} = W_D + W_{SDL} + W_{LL} \tag{3}$$

Where W_{Sus}, W_{SDL}, W_{LL} and W_{max} are respectively the sustained load from the end of the construction cycle until the application of the maximum load, the additional dead load, the live load of the final structure and the maximum load of the structure considered applied five years after the construction cycle.

3.3. Deflection analysis

Deflection calculation in SAP2000 is performed using linear finite element analysis. In this approach, the slab stiffness EI is assumed constant, and the reduction in stiffness due to cracking is not considered. To account for this reduction, the effective inertia I_e should be used. For simplicity, this study assumes that I_e is a fraction of the gross moment of inertia I_g, as:

$$I_e = \alpha I_g \tag{4}$$

In this study, the value of $\alpha = 0{,}6$ is considered from construction to the application of the maximum load. Indeed, Motter and Scanlon [11] suggested, during the construction phase, for the calculation of deflection by the cross-beam analogy method to consider $\alpha = 0{,}4$ for the column strips, and $\alpha = 0{,}8$ for the central strip. Since the finite element calculation does not involve subdividing the slab into two strips, it seems reasonable to consider the average of the two values.

The time-dependent parameters considered include the concrete's strength, elastic modulus, and creep. These parameters are calculated in accordance with ACI 209.2R-08 [15] using the following formulas:

$$f'_{ct} = \frac{t}{a + bt} f'_c \tag{5}$$

$$E_c(t) = 0.043\gamma_c^{1.5}\sqrt{f'_{ct}} \tag{6}$$

$$\phi(t, t_0) = \frac{(t - t_0)^{0.6}}{10 + (t - t_0)^{0.6}} \phi_u \tag{7}$$

Where: f'_{ct} is the concrete strength at date t in MPa, f'_c the concrete's specified 28-days strength in MPa, γ_c is the unit weight of concrete in kg/m^3, t is time in day from casting. Coefficients a and b depend on cement type and curing method and are usually 4 and 0,85 respectively, $\emptyset(t, t_0)$ the creep coefficient and $\emptyset_u$ is the coefficient of ultimate creep after a long loading period It can take the mean value of 2.35 for standards conditions or be modified by corrector factors as factors that account for the duration of the loading, the age of the concrete when the load was applied, the humidity, for non-standards conditions [15].

3.4. Simulation of construction process

In SAP 2000, the simulation of the construction process can be done using the non-linear load case named "STAGED CONSTRUCTION", which allows to perform an evolutionary calculation of the structure according to the construction stages defined by the user. Thus, the stages and durations are first defined, then the operations to be performed are associated to each stage.

In the shoring/reshoring concept, it is assumed that a few days after a slab is cast, the concrete develops sufficient strength to support its self-weight without significantly compromising the stability of the structure. This allows the formwork to be removed and reused for the upper level. However, this strength remains insufficient for the slab to carry, in addition to its self-weight, the load of the newly cast slab above. Reshores are therefore installed beneath the striped slab to assist in distributing the loads from the new slabs. These sequences and loads involved can be summarized in fig. 1 for a system with one level of shore and two levels of reshore.

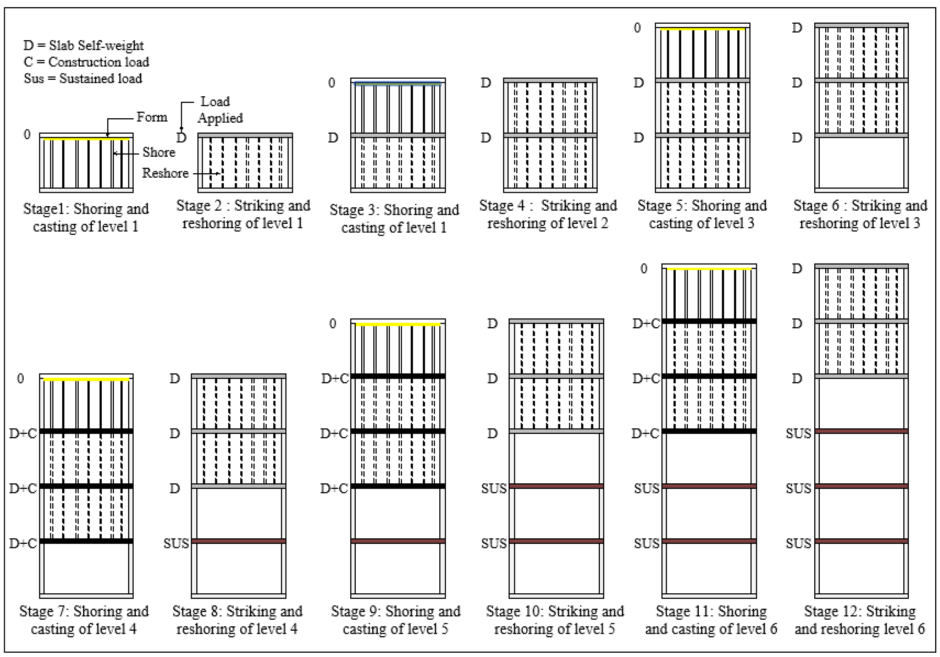


Fig. 1: Construction stages in a one level of shoring and two levels of reshoring system [16]

To implement these sequences, loads defined in section 3.2 were subdivided into simple load patterns. When the shoring system is considered infinitely stiff, the construction load C remains constant at all stages and can be obtained from equation 1 and the number of level required to analyze the deflection history is $n = 2N$ as suggested by Foula et al. [16]. When the system is not infinitely stiff, load distribution is automatic and only the construction live load is applied when a new slab is cast. The stages defined for the purpose of this study are limited to a case of a $n = 10$ stories building.

For the infinite stiffness model (IS), the system with one level of shoring and one level of reshoring required 13 stages, while systems with two and three levels of reshoring required 18 and 23 stages, respectively. In the finite stiffness model (FS), the system with one level of shoring and one level of reshoring involved 35 stages. Systems with two and three levels of reshoring required 36 and 37 stages, respectively. Table 1 summarized the keys operations implemented in those construction load cases.

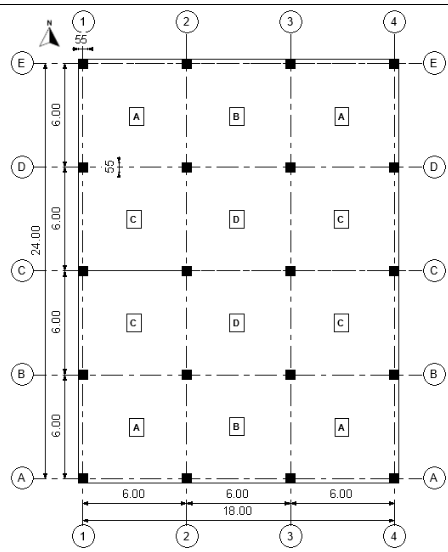
Table 1: Definition of construction stage operations

Designation	Duration	Operations in IS model	Operations in FS model
Construction levels $1 \leq i \leq N$	d	- Add story i ;	- Add story i ; - Load story i, Load pattern: Dead, coefficient 1; - Load story i, Load pattern: CL, coefficient 1
Stripping levels $1 \leq i \leq N$	0	- Load story i; Load pattern: Dead, coefficient 1;	-Remove form i; -Load story i, Load pattern: CL, coefficient -1
Reshoring levels $1 \leq i \leq N$	c-d		- Add reshore i ;
Construction levels $N+1 \leq i \leq n$	d	- Add story i; - Load story $i-1\ to\ i-N$; Load pattern: C, Coefficient 1;	- Add story i ; - Load story i, Load pattern: Dead, coefficient 1; - Load story i, Load pattern: CL, coefficient 1
Stripping levels $N+1 \leq i \leq n$	0	-Load story i, Load pattern: Dead, coefficient 1; - Load story $i-1\ to\ i-N$, Load pattern: C. Coefficient -1; - Load story $i-N$, Load pattern: SDL, coefficient 1; - Load story $i-N$, Load pattern: Live, coefficient 0.1;	-Remove Form i; -Load story i, Load pattern: CL, coefficient -1 -Remove Reshore $i-N$; - Load story $i-N$, Load pattern: SDL, coefficient 1; - Load story $i-N$, Load pattern: Live, coefficient 0.1;
Reshoring levels $N+1 \leq i \leq n-1$	c-d		-Add structure: Reshore i ;
Removing reshores levels $N+1 \leq i \leq n$	c+d	- Load story $i-1\ to\ i-N$, Load pattern: SDL, coefficient 1; - Load story $i-1\ to\ i-N$, Load pattern: Live, coefficient 0.1	
On year after construction	$365 - c(2N + 1$	No operation required	
Before the maximum load	1460		
At the application of maximum load	0	Load story $i-1\ to\ i-N$, Load pattern: Live, coefficient 0.9	

4. Application

4.1. Presentation of the study case

The developed methodology was applied to a typical building. Fig 3 shows the plan view of the structure as well as the characteristics of the structure. The formwork system considered is based on a real model commonly used in the construction of multi-story reinforced concrete buildings. The stiffness of this system is considered as practical stiffness and is referred to as K in the following sections.



- Building: 10-story reinforced concrete building;
- Slab: flat slab without drop panels;
- Clear Height: $H = 3{,}00m$;
- Column: $550mmx550mm$;
- Slab thickness: $h = 200\ mm$;
- Concrete: $f'c\ =\ 30\ MPa, \lambda =\ 24\ kN/m3$;
- Construction live load: $W_{CL} = 2{,}4\ kPa$;
- Structure live load: $W_{LL} = 2{,}4\ kPa$;
- Superimposed dead load: $W_{SDL} = 1{,}5\ kPa$;
- Construction cycle : $c = 7\ days$;
- Stripping cycle: $d = 5\ days$;
- Shore: Steel $E = 210GPa$, section $56x2mm$;
- Formwork: Modular metal panel of own weight $0{,}8KN/m^2$and dimensions $1{,}20mx2{,}4m$;

Fig. 2: Plan view of a typical slab floor for the study case and parameters

4.2. Results and discussions

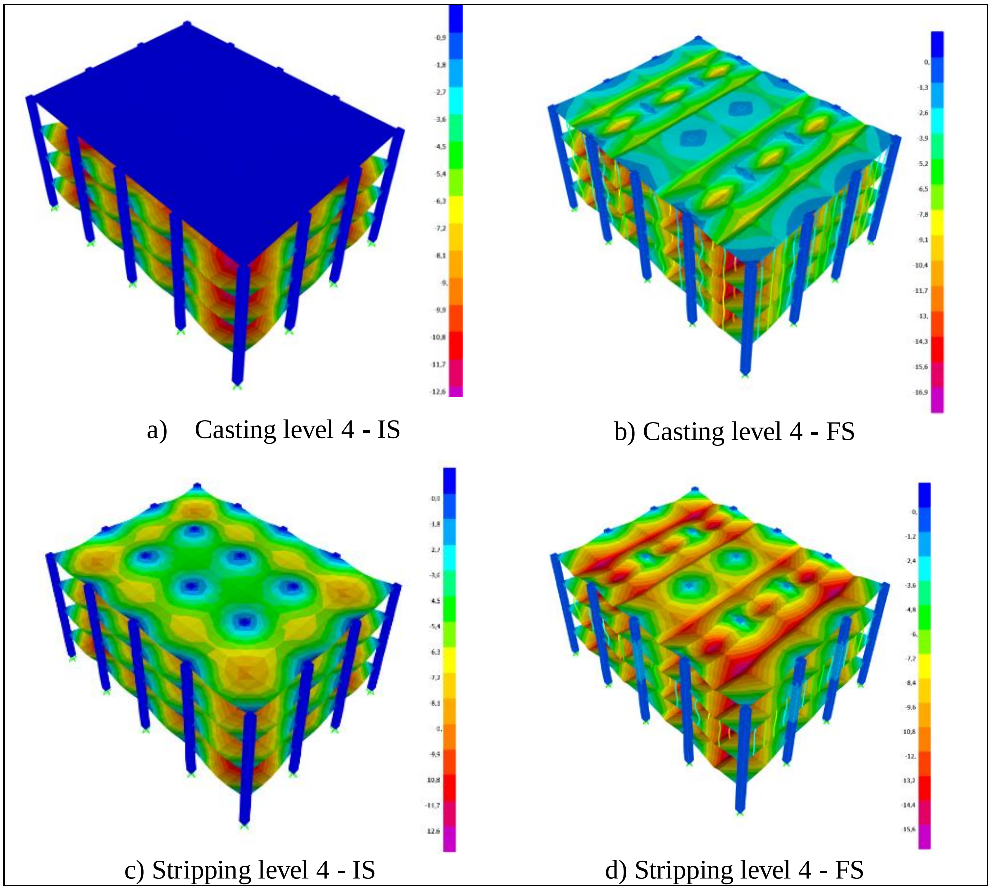
Fig. 3 presents the evolution deflections in the casting and stripping phases of level four for the system with one level of shoring and 2 levels of reshoring. In fig. 3.a (IS) and fig. 3.b (FS), the slab is cast and while there is no deflection in the IS model, there are some deflections in the slab with finite stiffness of shoring/reshoring system. In fig. 3.c (IS) and fig. 3.d (FS), shores and forms are removed, and in both cases, slabs deflect due to self-weight. We can also notice a decrease in the deflections of lower slabs, which is consistent with the removal of the load of the newly cast slab on the lower slabs. These observations are consistent with the operation of the slabs during the construction phase.

In order to study the influence of the variation of the stiffness, we varied the stiffness by varying the modulus of elasticity of the shores and we also created a load case with a higher density of the shores (1,2mx1,2m). Fig. 4 compares the evolution of defections of the corner slab A during the construction, and from the construction to the application of the maximum service load for the system of one level of shoring and two levels of reshoring.

In all cases analyzed, assuming infinite stiffness results in deflections that are lower than those calculated when the system's actual stiffness is considered. This aligns with the observation that ignoring shoring system stiffness underestimates construction loads, particularly in the critical slab with the weakest characteristics within the support system [9], [13]. The discrepancy becomes more pronounced as the stiffness of the shoring system decreases.

For the systems studied, deflections decrease when stiffness increases and vice versa. However, the intensity of these variations depends on the intervals. Between 0.75K and 1.5K, the deflection is relatively stable, suggesting that in this range, stiffness increase has a limited effect on deflection reduction. Conversely, for lower stiffnesses (from 0.25K to 0.75K), differences increase significantly.

For equivalent stiffness (case 1.5K and case 1.5K (1.2x1.2)), a more uniform shore distribution results in lower deflections, approaching those observed when assuming the shoring system is infinitely stiff. This highlights the critical role of the uniform load distribution assumption in the accuracy of results obtained through the simplified method.



a) Casting level 4 - IS

b) Casting level 4 - FS

c) Stripping level 4 - IS

d) Stripping level 4 - FS

Fig. 3: Evolution of deflections during casting and stripping of level 4.

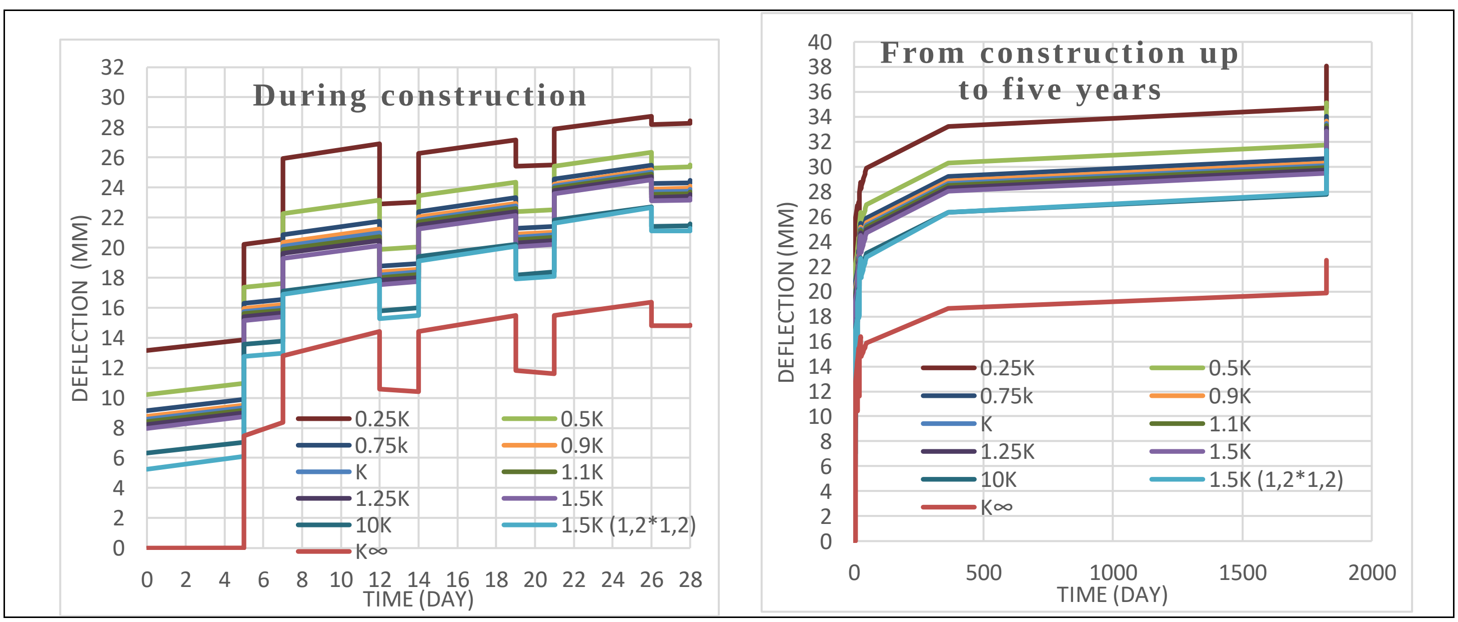


Fig. 4: Influence of stiffness variation.

4. Conclusion

This study introduces a finite element modeling approach developed to predict slab deflections in multi-story reinforced concrete buildings during construction phase. The approach integrates stiffness of shoring/reshoring system, time-dependent properties of concrete as well as creep. The methodology has been applied on a typical building to asset the effects or the shoring system stiffness on load distribution and slab deflections. It has been shown that shoring stiffness has an important impact on slab deflection during construction and should be considered by designers to ensure safety and performance of the structure. The study also highlights the importance of considering construction loads when evaluating slab deflections. This approach enables improved assessment of both short-term and long-term deflections and evaluation of its impact of the structure's serviceability.

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