Proceedings of the 9th International Conference on Civil Structural and Transportation Engineering (ICCSTE 2024)
Chestnut Conference Centre - University of Toronto, Toronto, Canada – June 13-15, 2024
Paper No. 234
DOI: 10.11159/iccste24.234

Finite Element Analysis of Slab Deflection Due To Construction Loads

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Abstract – The construction phase of multi-story reinforced concrete buildings is considered as a critical phase in a building's lifespan. Construction loads are likely to create additional deformations in the slabs, altering their serviceability. Therefore, it is crucial to understand how loads are distributed during construction and to estimate their effect on slab deflection at an early stage in the design process. In this paper, a finite element modeling process is developed to simulate the construction phase of a multi-story reinforced concrete building. The construction scheme involves the use of the shoring and reshoring system to transfer the load of newly cast floors to lower slabs. The model is employed to analyze the effects of construction loads on short-term and long-term slab deflection. The proposed modeling process takes into account construction sequences as well as time dependent properties of concrete. The modeling process is validated by comparing the model results to those of a case study from literature, which involved field measurements of slab deflections during the construction of a 28-story reinforced concrete building in Canada.

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

1. Introduction

The construction phase of multi-story reinforced concrete buildings is considered as a critical phase in a building's lifespan, [1-6]. Indeed, although this phase represents only a small fraction of a building's lifespan, more than 50% of building failures occur during this phase [6]. The delicacy of this phase is due to a principal factor: the transmission to slabs that have not reached their design strength, of loads exceeding their service load by the shoring system. These loads are likely to create significant deformations in the slabs, altering their serviceability and, in some cases, leading to structural failure. Therefore, it is crucial to understand how loads are distributed during construction and to estimate their effect on slab deflection at an early stage in the design process.

Over the years, numerous studies including analytical, numerical and experimental approaches have been carried out to determine the extent of load distribution during construction and its effects on slab deflection. Among these studies, the most widespread and widely used is that carried out by Grundy and Kabaila [7]. The authors developed a simple analytical method for determining, at each stage of construction, the distribution of loads on each slab. The method, later named the simplified method, involves determining a load ratio R at each stage, defined as the ratio between the load supported by the slab and the slab's self-weight. Since the simplified method is based on assumptions that are not necessarily accurate such as the assumption of infinite stiffness of the shoring system, many other authors carried out more detailed studies to explore the implication of those assumptions on load distribution during construction [8-10]. While the main findings of these studies indicated that the simplified method tends to overestimate props loads and underestimate slab loads, the distribution of loads did not significantly differ from the values predicted by the simplified method. Moreover, experimental results demonstrate a degree of consistency between the actual distribution of loads during construction and the results predicted by the simplified method [3]. As such, the simplified method remains a valuable tool for practical applications in structural analysis and construction planning.

Regarding deflections due to construction loads, Graham and Scanlon [11] developed an analytical model for estimating the long-term deflection of slabs that includes the construction loads, based on the determination of multiplier coefficients for instantaneous deflection. Motter and Scanlon [2] proposed an analytical procedure for calculating deflections due to construction loads, including concrete creep and variation in slab rigidity. On the other hand, the finite element method is considered more accurate approach for calculating deflection in slabs [5]. Considering the widespread use of the shoring and reshoring system in construction, primarily due to economic considerations, it becomes imperative to develop straightforward yet comprehensive modeling approaches to accurately predict deflections within this system, ensuring that service deflections comply with prescribed standards. Within this context, this study aims to develop a finite element modeling approach to simulate the construction phase using the shoring and reshoring system in order to determine deflections caused by construction loads. While the shoring and reshoring system may involve one or more levels of shoring, this study will focus on construction schemes incorporating a single level of shoring. By focusing on this aspect, the study seeks to provide valuable insights into quantitative assessment of the impact of construction loads on short-term and long-term slab deflections.

2. Methodology

2.1. Assumptions

The following assumptions are considered in the present study: a) slabs and columns have elastic behavior with variable stiffness; b) The shoring and reshoring system is infinitely stiff compared to the slabs; c) The distribution of props is such that the load can be considered uniformly distributed; d) The foundation is infinitely stiff; and e) concrete creep is taken into account.

2.2. Construction load

Considering the above assumptions, the construction load can be determined by the simplified method applied to the shoring/reshoring system as presented in ACI 347.2R-17 [3]. Using this method, the maximum construction load W_{con}, sustained load after the construction cycle W_{Sus} and service load W_{max} are estimated respectively [12] :

$$W_{con} = k_1 * k_2 * R * W_D + \frac{W_{CL}}{N} \tag{1}$$

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

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

Where k_1 is the factor for taking into account the weight of the formwork, generally set equal to 1.1; k_2 the factor that takes into account the variation in slab relative stiffness, set equal to 1 in this study since the evolution of slab stiffness is already consider; W_D is the slab self-weight; W_{CL} is the construction live load due to casting activities. CSA S269.1-16 [13] and ACI 347.2R-17 [3] recommend considering a minimum construction live load of 2.4kN/m² when pouring is not motorized, or 4.8kN/m² otherwise; $W_{SDL}$and W_{LL} are respectively the superimposed dead load and the live load of the structure; R is the maximum load ratio evaluated by the simplified method. In a system with 1 level of shoring and N-1 levels of reshoring, the maximum load ratio for each slab is:

$$R = 1 + \frac{1}{N} \tag{4}$$

2.2. Modeling and simulation of the construction process

In ETABS software, the "Nonlinear Staged Construction" load case allows to perform an evolutionary calculation of the structure following user-defined sequences. This load case can be used to simulate the construction process for deflection analysis. To utilize this feature effectively, it is essential to master the different phases of construction, understand the various tasks performed in each of these phases, and consider different loads applied.

In shoring and reshoring system, each level is cast after a predetermined number of days, known as the casting cycle and designated as "c". It is assumed that after a certain number of days, denoted as "d", the concrete has acquired sufficient strength to support its own weight. Consequently, the formwork and props are removed, allowing the slab to deflect under its own weight and support itself. Subsequently, reshoring props are installed to bear the additional loads that will be imposed when a new slab is poured. Consequently, reshoring carries no load upon installation. Assuming an infinitely stiff foundation and shoring system, as long as the reshoring are connected to the foundation, the slabs bear their own weight upon removal of the formwork, and the loads of the new casted slabs are entirely transmitted to the ground. Once the reshoring level is removed from the ground, each time a new slab is poured, the load will be evenly distributed between the lower slabs and removed when the slab is stripped.

To simulate those sequences, each cycle can be divided into two stages: a) shoring/casting stage where construction load is added; b) striking/reshoring stage where self-weight is applied on slabs and thus removed from lower slabs. Then, construction load defined in equation (1) can be divided into two loads patterns. Slab self-weight (D) and construction load defined as:

$$CONST = 1.1 * R * W_{slab} + \frac{W_{CL}}{N} - W_{slab} \tag{5}$$

Figure 1 shows the construction sequence and applied loads for a system with one level of shoring and two levels of reshoring. To simulate the effect of removing the construction load, another load pattern opposite to construction load pattern (DeCONST.) can be created and added on lower slab when dead load is applied to the newly poured slab.

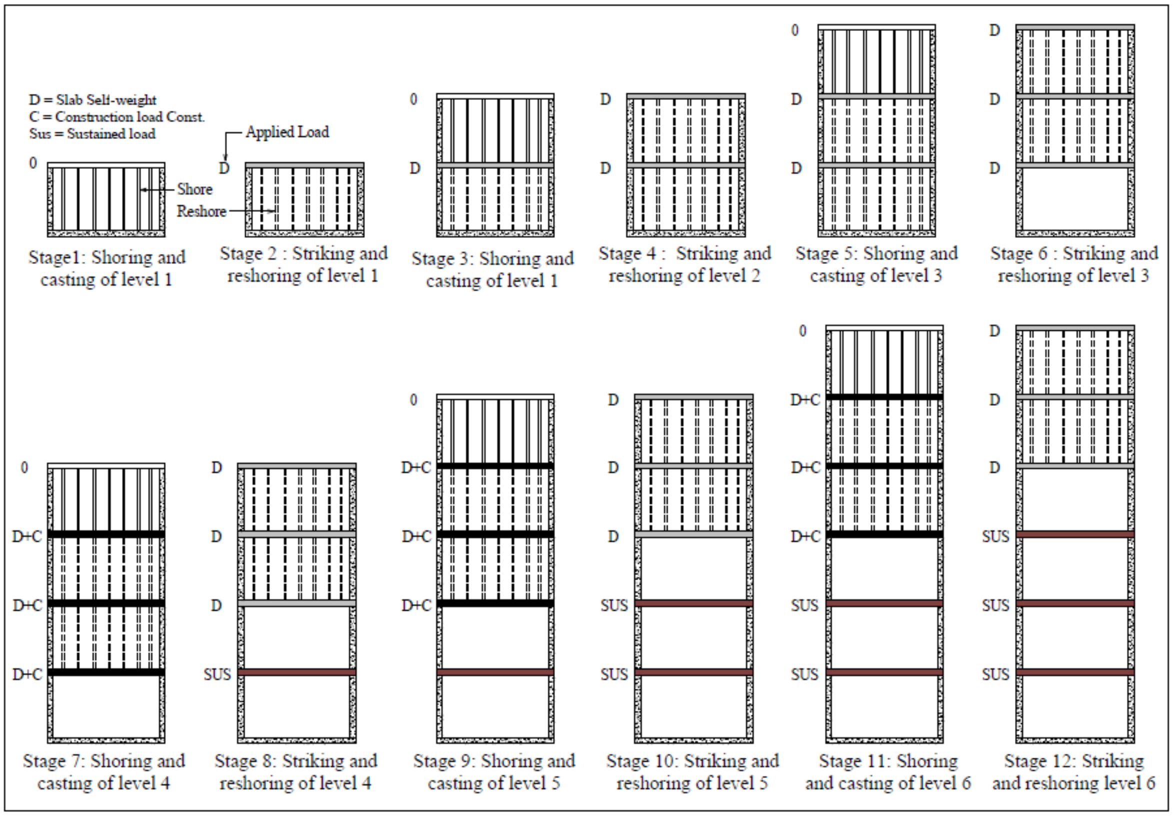


Figure 1: Construction sequence involving one level of shoring and two levels of reshoring.

In a system with one level of shoring and N-1 levels of reshoring, the evolution of construction load converges when the reshores are removed from the ground level (pouring of level N+1) and the most critical slab is the slab with the lowest compressive strength (Slab N). Thus, it is sufficient to model a number of levels required to obtain the most critical deflection. As in figure 1, in a system with one level of shoring and N-1 levels of reshoring, it takes N constructions cycles to cast level N and additional N cycles to remove the reshoring from the slab. Therefore, to study the load/unload history in the system; the building model can be limited to 2N levels.

To implement these construction sequences in ETABS, corresponding duration and the operations involved in each construction sequence for a system with one level of shoring and N-1 levels of reshoring have been defined. Table 1 resume the main steps and operations.

Table 1: Operations to be entered in ETABS for every stage.

Designation	Duration	Operations
Shoring and casting of levels $1 \leq i \leq N$	d	- Add structure: Story i ;
Striking and reshoring of levels $1 \leq i \leq N$	c-d	- Load structure: Story i, Load pattern: Dead, coefficient 1;
Shoring and casting of levels $N+1 \leq i \leq 2N$	d	- Add structure: Story i; - Load structure: Story $i-1$ to $i-N$; Load pattern: CONST, Coefficient 1;
Striking and reshoring of levels $N+1 \leq i \leq 2N$	c-d	-Load structure: Story i, Load pattern: Dead, coefficient 1; - Load structure: Story $i-1$ to $i-N$, Load pattern: DeCONST. Coefficient 1; - Load structure: Story $i-1$ to $i-N$, Load pattern: SDL, coefficient 1; - Load structure: Story $i-1$ to $i-N$, Load pattern: Live, coefficient 0.1;
Removing of reshore of levels $N+1 \leq i \leq 2N$	c+d	- Load structure: Story $i-1$ to $i-N$, Load pattern: SDL, coefficient 1; - Load structure: Story $i-1$ to $i-N$, Load pattern: Live, coefficient 0.1
On year later	365	- No operation required
Service	5 years	Load structure: Story $i-1$ to $i-N$, Load pattern: Live, coefficient 0.9

2.3. Time dependent properties

The "time-dependent properties" option in ETABS material definition tab enables user to define time dependent function or simply assign values to the coefficients for a specific standard. For this study, Concrete time dependent properties are defined as recommended in CSA A23.3-19 [14] and ACI 209-R08 [15]. The following expressions are used to compute those properties:

$$f'_{ct} = \frac{t}{a+bt} f'_c \tag{6}$$

$$E_c(t) = \left(3300\sqrt{f'_{ct}} + 6900\right) * \left(\frac{\lambda_c}{2300}\right)^{1,5} \tag{7}$$

Where: f'_{ct} is the concrete compressive strength at date t in MPa, f'_c the concrete's specified 28-days compressive strength in MPa, λ_c is the volume mass of concrete in kg/m^3, t is time in day, not greater than 28 days. Coefficients a and b depend on cement type and curing method [14].

For deflection due to concrete creep, the creep coefficient $\emptyset(t, t_i)$ at time t due to a load applied at the initial time t_i is calculated according to ACI 209-R08 [15] as follows :

$$\emptyset(t, t_i) = \emptyset_u k_t k_{ac} k_h k_{vs} k_a k_s k_{ta} \tag{8}$$

Where: $\emptyset_u$ is the coefficient of ultimate creep after a long loading period, with a recommended value of 2.35 [16] ; coefficients k_t, k_{ac}, k_h , k_{vs}, k_a, k_s, and k_{ta}, represent respectively the corrective factors that take into account the duration of the loading, the age of the concrete when the load was applied, the humidity (concrete cure condition), the ratio between the volume and the surface of the concrete, the slump, the percentage of fine elements, and the percentage of voids. The last 4 parameters are the project parameters and the first 3 factors are given by:

$$k_t = \frac{(t-t_i)^{0.6}}{10+(t-t_i)^{0.6}} \tag{9}$$

$$k_{ac} = \begin{cases} 1{,}25t_i^{-0.118}\ for\ moist\ cure \\ 1{,}13t_i^{-0.094}\ for\ steam\ cure \end{cases} \tag{10}$$

$$k_h = 1.27 - 0.0067H \tag{11}$$

Where H is the humidity percentage. This factor must be taken into account when the humidity percentage is greater than 40%, otherwise is assume equal to 1 [16].

3. Application

3.1. Presentation of the case study building

Slabs deformation measurements program was completed for a 28-story reinforced concrete building, located in downtown Edmonton, Alberta as reported in [17]. The measurements were surveyed during the construction phase and approximately one year after construction. The construction process used involved one level of shoring and three levels of reshoring, with an average casting cycle of seven days and a striking cycle of three days. Floor slabs were cambered 15 mm at bay centers. Measurements were taken on each lower slab directly after stripping the formwork from the upper level. Figure 2 shows a plan view of a typical floor.

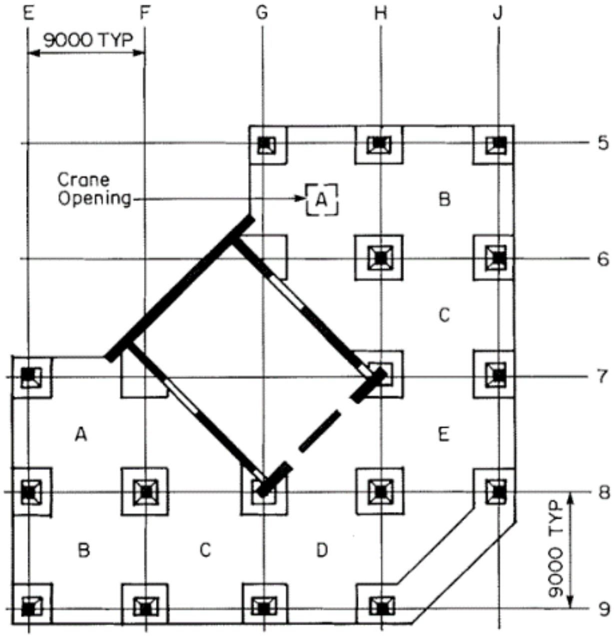


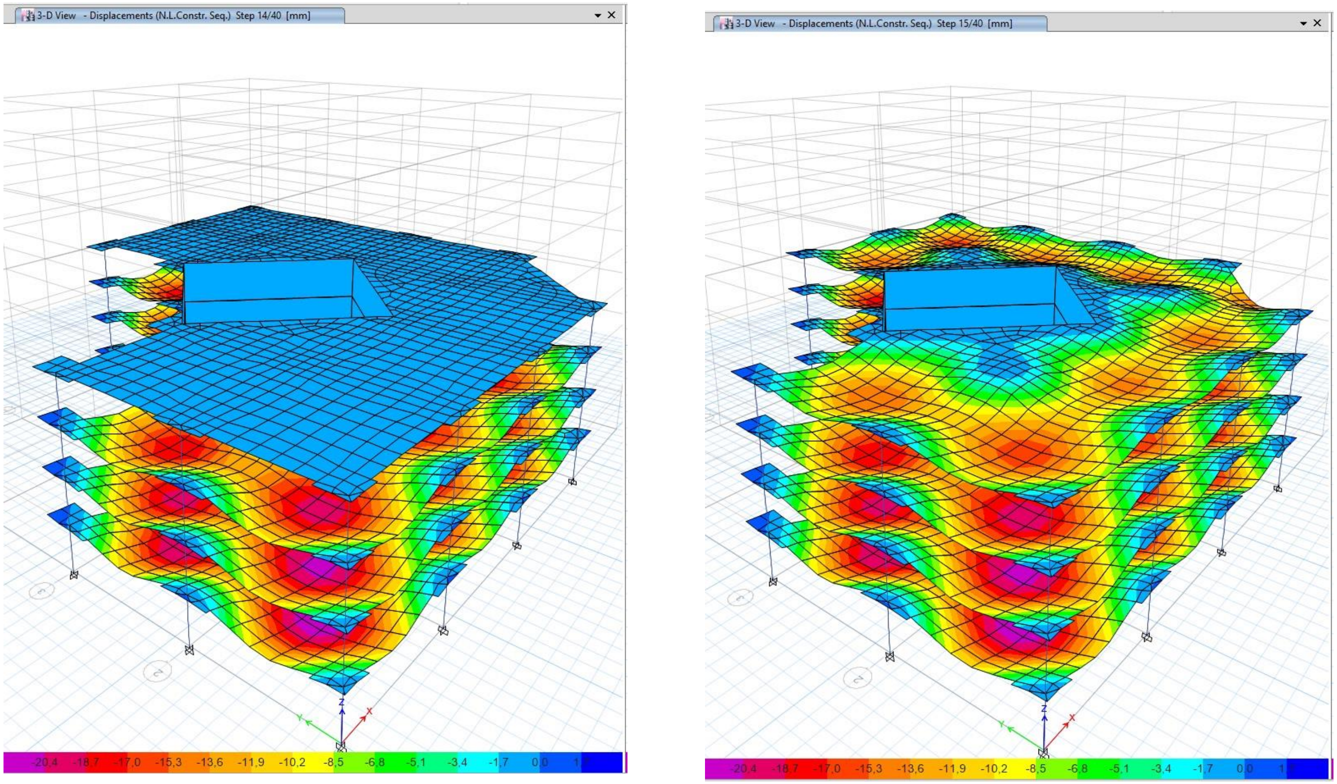
Figure 2 : Floor plan of experimental study [17]

The report of the field study provided mid-panel deflections of slab A to E from stories 8 to 20 during construction and approximately one year after construction. Those deflections increase with time as predicted. However, there is considerable variability between the deflection values of similar slabs taken over the same period. In fact, the coefficient of variation ranges from 17.5% to 57.1%. This variability of data is common in deflection measurement studies as observed [18].

3.2. Results and discussions

The case study building was modeled on ETABS using the methodology described above. Since measurements taken from slab level 8, the lowest shoring level was already removed from the ground and each slab was assumed to the maximum construction load. This slab corresponds to level 4 (N=3+1) of the model.

Figure 3 shows the deflections of the pouring and stripping stages of slab 4. In the first figure, it can be seen that the lower slabs are already deformed, while the newly poured slab is not deformed. In the second picture, the slab has deformed under its own weight. This describes the expected behavior of the slabs during construction using shoring and reshoring system.



a)

b)

Figure 3: Finite element model deflections (in mm) of slabs after casting (a) and stripping (b) of level 4.

Figure 4 shows the short-term deflection (during construction) and Figure 5 shows the long-term deflection (from construction to one year) for slabs A and B. Both figures includes the results based on the finite element model prediction as well as the observed data points from the report [17]. The figures demonstrate a good correlation between the computed results of the finite element analysis and the measured deflection data. Indeed, the finite element model results closely approximate the mean values of the field measurements for the studied slabs.

Furthermore, these results highlight the importance of considering construction loads when analyzing the deflection of reinforced concrete slabs. Early loading of the slab during construction induces deformations, which increase over time, due to creep and other construction activities, as evidenced by the deflections observed at one year. This conclusion aligns with the findings of Motter and Scanlon's study [2], which indicated that neglecting construction loads could result in an underestimation of service deflection by up to 50%.

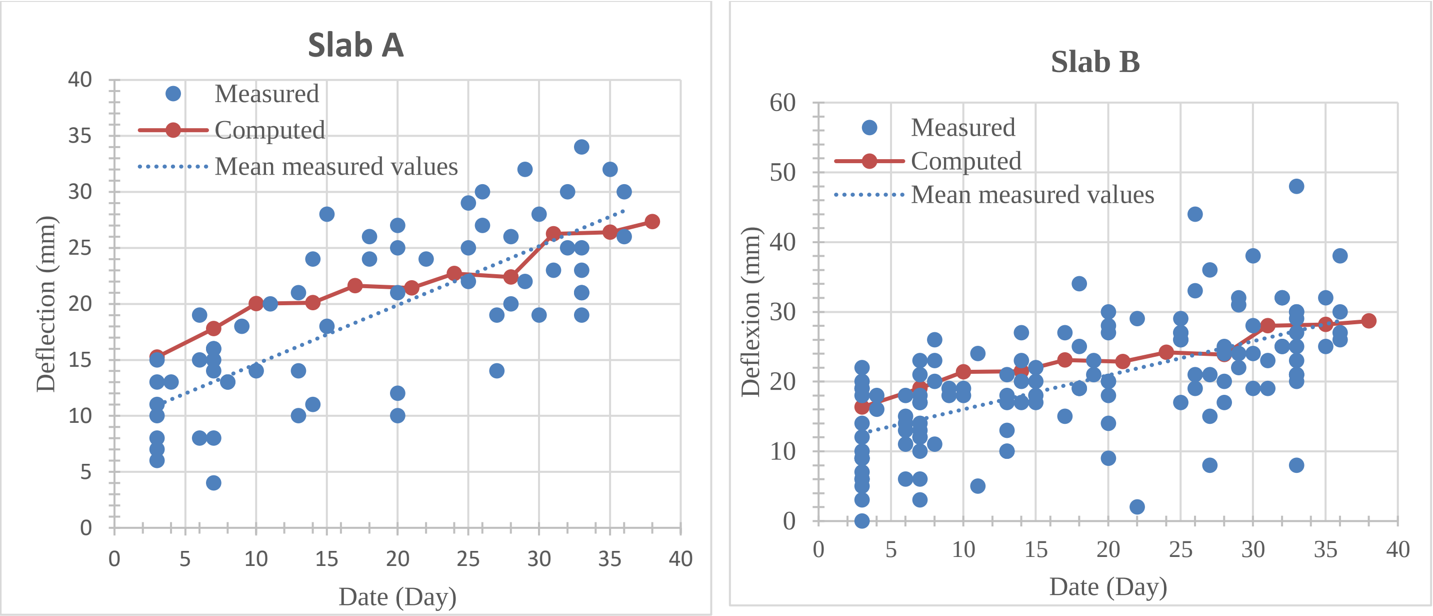


Figure 4: Comparison of short-term deflection of numerical model with experimental result of slabs A and B

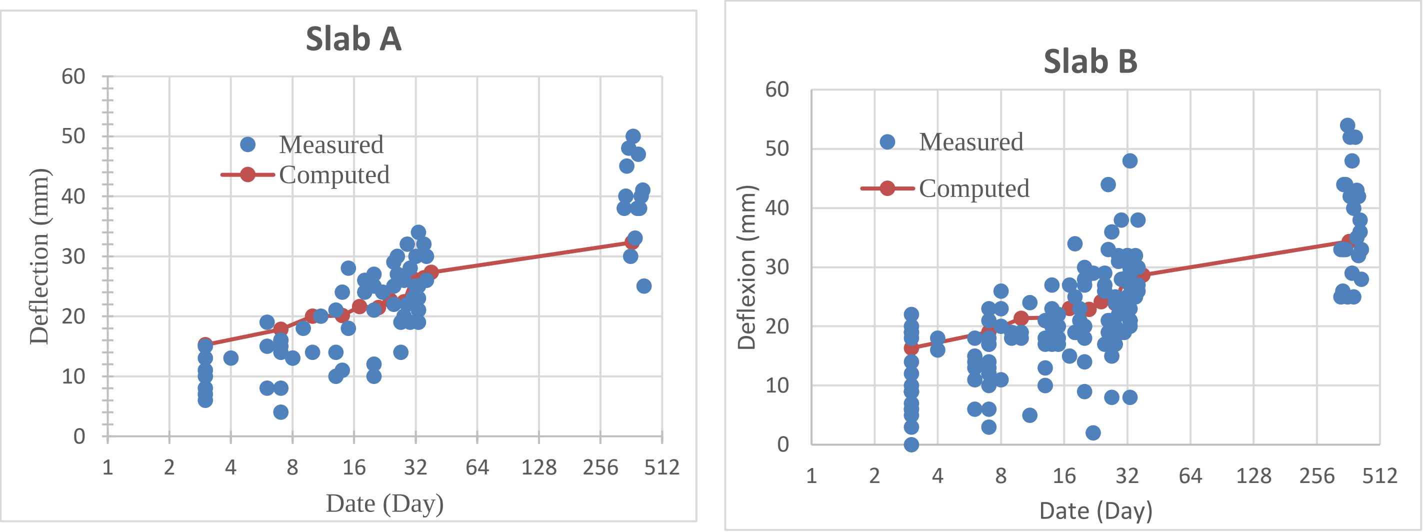


Figure 5: Comparison of long-term deflection of numerical model with experimental result of slabs A and B

4. Conclusion

A finite element modeling approach has been developed and validated for the estimation of the reinforced concrete slabs deflections with consideration of construction loads in multi-story buildings. This approach took into account time-dependent properties of concrete and creep. The finite element model was applied to a case study and comparative assessment of computed and measured deflections was conducted. Despite variability in field measurements, the mid-span deflections obtained through the finite element model closely approximated the mean values observed in the field.

The study also underscores the significance of accounting for construction loads when assessing slab deflection. As a result, this process can be adopted to promptly evaluate short-term and long-term deflections of concrete slabs, thereby reducing the risk of excessive deflection that could affect the structure's serviceability.

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