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Short- and long-term deflections of RC building structures influenced by construction processes

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Abstract. This paper analyzes the influence of the construction process on short- and long-term deflections on a reinforced concrete structure poured on-site by a portable industrialized system. A parametric analysis was carried out by the Finite Elements Method (FEM) that considered: a) type of construction process with reshoring or clearing (partial striking); b) the number of successively shored floors and c) the number of shores used on each floor. All three factors were especially important for the values of short- and long-term deflections, which were highest in the reshoring processes with the lowest number of successively shored floors and the lowest number of shores per floor. Deflections obtained were compared with the limits laid down by ACI 318-14 and as calculated by this code's simplified method. The long-term deflections were seen to be almost double than those obtained by applying the ACI 318-14 code's simplified method and in some cases these deflections were above the established limits. It can thus be concluded that the load history of a building under construction should be taken into account in order to satisfy a structure's in-service conditions and durability.

Keywords: clearing; construction process; creep; deflection; industrialized system; shores; shoring; striking

1. Introduction

The usual procedure in constructing buildings is to shore successive floors. The shores thus not only support the newly-poured floors but also distribute the loads of the new slab to the lower floors. One or more floors may thus be shored simultaneously, according to the capacity of the lower floors to support the weight shared among the different slabs. The shores removed from the lower floors can be reused for the new floors as the building gets higher.

When speaking of industrialized systems, these are generally associated with mass production, mechanization, standardization and prefabrication (Essays 2013), which imply speeded up processes. In building construction, the most frequently used industrialized system consists of a structure formed by walls and slabs joined together monolithically. The shoring used for this type of building is commonly known as a portable industrialized system and consists of wooden, steel or aluminum formwork to allow the simultaneous construction of both walls and slabs. On each floor, the formwork is supported by one or several lines of shores, which form the slab shoring. For example, in the particular case of Colombia, according to the report written by Aguirre Patiño (Aguirre 2012), the industrialized system is the second most used system for building.

Given the speed of industrial systems, the high mechanical demands placed on the concrete mean it is not advisable to use conventional concrete (Díaz 2004). It is essential that the concrete used in this type of construction should contain accelerators so that its strength can be developed at an early stage, as this is crucial for the structure to be able to support the loads without the help of shoring, which after a few days can be re-used for the higher floors. In buildings made with conventional concrete, the shores can be removed (if the slabs can support the loads placed upon them) after about five days (Alvarado 2006). However, in industrialized systems, this time is reduced to a maximum of 24 hours. In addition, striking times often depend on the builder's experience or on the shore manufacturer's recommendations. National and international codes and recommendations, such as ACI 347.2R-05 (2005), mostly agree on the general criteria for estimating the times of the different construction phases, although they also emphasize the requirement of ensuring that the construction process does not have a negative effect on the structure and place all the responsibility for this on the builder.

It is important to point out that the critical construction operation in industrialized systems consists in removing the shores one day after pouring the concrete, when it has to be able to support its own weight plus any possible

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construction live loads (Lin 2007). The experience of years has shown that a significant percentage of concrete building collapses occur in the construction phase, as has been pointed out by Eldukair and Ayyub (1991), Kaminetzky and Stivaros (1994), Epaarachchi *et al*. (2002). Even though a very small number of the total buildings actually collapse, high deflections and cracks in young concrete can seriously affect the life of the structure and its in-service behavior. In this regard, it is generally acknowledged that the long-term creep deflections of concrete loaded at an early age are at least several times higher than the elastic deflections, as can happen in the construction of buildings (Aguinaga and Bazant 1986, Fang *et al*. 2009).

Many proposals have been made for simplified and advanced methods of estimating and calculating load transmissions between slabs and shores during the construction phase, e.g., Duan and Chen (1995), Moragues *et al.* (1996), Huang *et al.* (2004), Fang *et al.* (2009), Alvarado *et al.* (2010), Calderón *et al.* (2011), Gasch *et al.* (2014). However, most of the studies carried out did not consider the effect of creep or the influence of the construction process on long-term deflections. Only Aguinaga and Bazant (1986), Liu and Chen (1987), Lee *et al.* (1991), Duan and Chen (1995), Fang *et al.* (2009), Kang *et al* (2013) allowed for the effect of creep on the transmission of loads between slabs and shores in the construction stage. Furthermore, only Aguinaga and Bazant (1986), Duan and Chen (1995), Kang *et al.* (2013) analyzed the relationship between the construction process used and long-term deflections in the building's serviceability stage. Except for these three studies, up to the present time no detailed study has been carried out on the influence of the different types of building methods on long-term deflections.

2. Objectives, novelty and content of the study

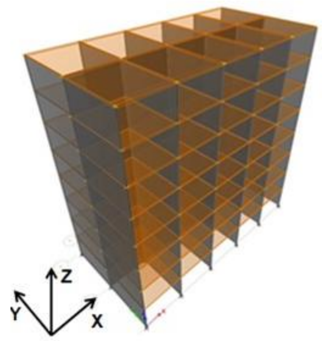
The main objective of the present work is to study the influence of the construction processes on short- and long-term deflections and to discover whether these deflections have a significant negative effect on the serviceability stage and durability of the structure.

The novelty of this work lies in its analysis of how the most frequent building processes used in RC building structures influence short- and long-term deflections of the slabs. This analysis was carried out, for the first time, with advanced calculation methods and focused on the specific case of portable industrialized construction systems. By analyzing variations in the loads on the slabs, according to the construction process employed, the aim was to improve and reflect on the conventional designs of portable industrialized systems, in order to ensure that the process had no negative effects on the life and behavior of the structure in its serviceability stage.

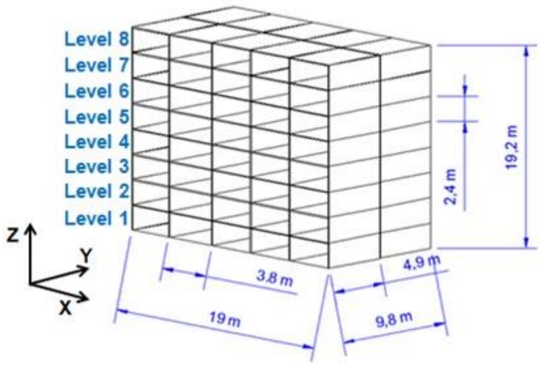
The study is divided as follows: Section 3 describes the FE model developed to study the influence of different construction processes on short- and long-term deflections, including the considered hypotheses, the used materials, loads during construction and serviceability stages, the different construction processes, and the parametric analysis carried out. This analysis considered variations in the different parameters of the construction processes in order to study the different cases generally applied in practice. Section 4 gives the results of the short- and long-term deflections in the different cases analyzed. Section 5 evaluates and compares the deflection values obtained in the different cases: Section 5.1 compares short-term deflections during construction with short-term deflections in the serviceability stage. Section 5.2 compares the long-term deflections of the different cases with the maximum deflections laid down by the ACI 318-14 Code (2014) and Section 5.3 compares the long-term deflections obtained with those obtained from the simplified method proposed in ACI 318-14 (2014). Finally, conclusions are given in Section 6.

3. The finite element model

In order to observe the influence of the construction process on slab deflections, a finite elements model was developed of a typical 8-floor RC structure, consisting of monolithically joined slabs and walls. Each floor was made of a 19×9.8 m^2 slab supported by a wall in direction X and 6 walls in direction Y. Slabs and walls were 10 cm and 8 cm thick, respectively. The defined geometry and the adopted number of floors, as shown in Fig. 1(a), allowed a large number of different building processes and operations to be studied. The building dimensions can be seen in Fig. 1(b).



(a)



(b)

Fig. 1 The considered building: (a) Finite Elements Model, and (b) dimensions

Table 1 Loads considered in the FE model.

	Dead load (kN/m^2)	Live load (kN/m^2)
Design loads	7.0	1.8
Construction loads	4.7	2.4

As constructing a building is an evolutionary process in which the support given by shores to the slabs, the characteristics of the concrete in slabs and walls and the number of floors to be built all tend to change over time, we used the ETABS modelling program (2013), which allows these variations to be considered.

Below we describe the considered hypotheses, the used materials, the applied loads, the types of finite elements considered and the parametric analysis carried out for the purpose of studying the influence of different construction processes on short- and long-term slab deflections.

3.1 Considered hypotheses

Following previous studies (Alvarado *et al*. 2010, Gasch *et al*. 2012, Buitrago *et al*. 2015) and including the effect of creep in the concrete, the hypotheses considered in the FE model were as follows:

- Linear elastic behavior of concrete in slabs and walls, with variations of stiffness with time;
- Formwork boards and shores with linear elastic behavior and finite stiffness;
- Infinitely stiff foundations;
- Effects of creep as in ETABS (2013);
- Shrinkage and temperature variations in the different structural elements were not considered.

3.2 Materials

The FE model considered the mechanical characteristics of concrete wall and slab, steel shores and wooden formwork. The two types of concrete, typically used in portable industrialized systems, were considered: one for walls, with a compressive strength of 28 MPa, 28-day elasticity modulus of 25,000 MPa; another for slabs, with compressive strength of 21 MPa, 28-day elasticity modulus of 22,200 MPa. Their mechanical properties and their evolution during the construction of the building were obtained from Castro-Garrido *et al.* (2016). Steel shores were 2.4 m long with an elasticity modulus of 210,000 MPa. Wooden formwork boards were 50 mm thick with an elasticity modulus of 10,000 MPa.

3.3 Loads

The loads adopted in the FE model were obtained from ACI 347-14 code (2014). In addition to the self-weight of the walls, dead and live loads were applied to slabs (see Table 1). Due to the long-term deflection considered in this study, both the construction and design loads were considered.

3.4 Types of finite elements

2-D elements such as slabs, wooden formwork and walls were modelled as SHELL-type elements, formed by 4 nodes with 6 degrees of freedom per node (translations and rotations in *X*, *Y* and *Z* direction). Shores were modelled as FRAME-type elements. The union of shores and slabs and the actual behavior of these elements only permit vertical deformation. In the modelling, applying the RELEASES option (ETABS, 2013), this FRAME-type element only admits vertical displacements, complying with the actual behavior.

When modelling the different considered scenarios, it was also necessary to use the NONLINEAR STAGE CONSTRUCTION (ETABS 2013) option, which allows the different structural elements to be modified with time. This makes it possible to consider the evolution of the material properties and the building's geometry in the different construction phases, and also a non-linear geometric calculation to allow for the accumulation of loads and deformations in the evolutionary phase of the construction of the building.

3.5 Construction processes considered

For each floor, two or more shoring operations are normally considered. Shoring and striking are essential operations: the first to support the freshly poured slab and the second is performed when the slab has enough strength to resist to the loads applied on it. However, it is very common to use additional intermediate operations such as clearing and reshoring.

Clearing consists of removing more than 50% of the shores a few days after pouring to partially unload the shoring system, due to reduced stiffness, in exchange of an increase in the load assumed by the slabs themselves. Reshoring consists of removing all the shores a few days after pouring and re-installing them in such a way that they can support future load increases. In this case, the shores are totally unloaded and the slabs assume the entire load applied to them in this stage. Both operations allow: a) large part of the material to be swiftly recovered (formwork and shores) for re-use in successive floors; and b) to reduce building times. The different operations can be combined as follows: shoring/striking (SS), shoring/clearing/striking (SCS), and shoring/reshoring/striking (SRS). Since one of the intermediate operations is normally used, in the present study SCS and SRS were considered. Fig. 2 gives a scheme for these two processes up to the shoring of Level 3 in a building with two consecutively shored floors.

In the case studied in this work, the construction process followed consisted first of the pouring of the walls, followed by the slabs, at a rate of a new floor every 4 days and carrying out an intermediate operation every 0.67 (2/3) days.

3.6 Parametric analysis

A parametric analysis was carried out to study the influence of construction processes on short- and long-term deflections, considering different aspects susceptible to variation in the most common processes.

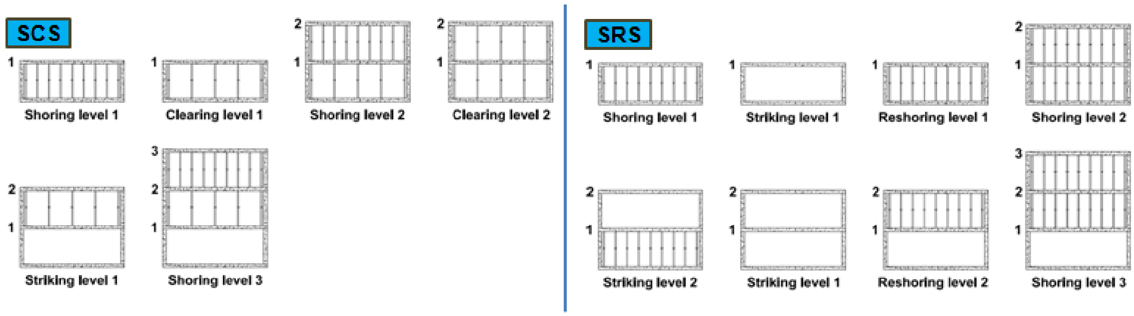


Fig. 2 Construction phases up to the shoring of Level 3 for SCS and SRS of a building with 2 consecutively shored floors

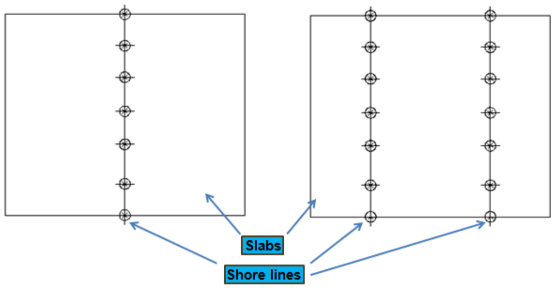


Fig. 3 Plan view of a slab with (a) a single line of shores and (b) double line of shores

Firstly, as has already been mentioned, the SCS and SRS processes were considered; then, the different conditions of slab support by the shoring system are taken into account: one case with a single line of shores and another with two lines, after clearing or reshoring had been carried out. The layouts related to such two cases can be seen in Fig. 3. Finally, two, three and four successively shored floors were also considered. All these cases gave a total of 12 different situations, as can be seen in Fig. 4.

4. Results

This section deals with a comparison of the results of the different models of both short- and long-term deflections, with the aim of determining the influence of the deflections produced in the construction phase on long-term deflections. The results were also compared with the conventional simplified deflection control method according to ACI 318-14 (2014), in which the construction process is not included in calculating long-term deflections. The aim was to find out whether the amount of the loads on slabs during construction could have a negative effect on the life and behavior of a structure in service condition and to make recommendations on including or excluding the construction process when calculating long-term deflections or even give preference to a specific construction process.

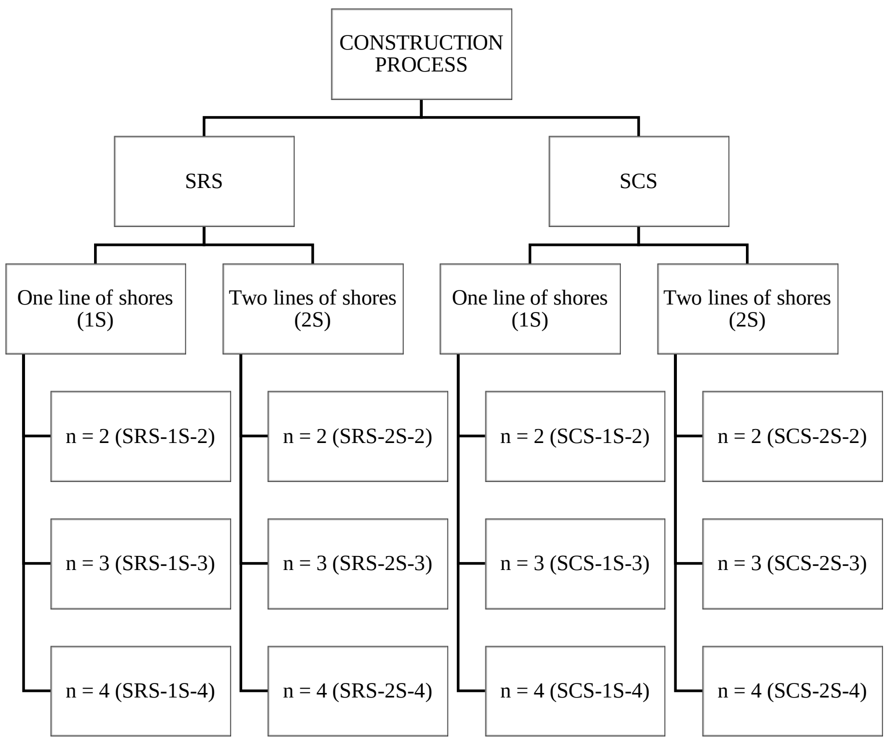


Fig. 4 Cases studied

Table 2 Analysis of variance for maximum instantaneous deflection

Source	Sum of Squares	*Df*	Mean Square	*F*-Ratio	*P*-Values
MAIN EFFECTS					
A: Construction Process	5.03107	1	5.03107	177.25	0.0000
B: Consecutive shored floors	0.870317	2	0.435158	15.33	0.0028
C: Shore lines	0.221408	1	0.221408	7.80	0.0268
RESIDUAL	0.198692	7	0.0283845		
TOTAL (Corrected)	6.32149	11			

Fig. 5 Comparison of maximum short-term deflections of the 12 cases analysed

4.1 Short-term deflections

To compare the results of the different cases in terms of deflection, the maximum registered deflection in any building operation and any slab was used. This parameter gives an idea of the loads put on the slabs by the process and enables the most unfavorable point of the whole process to be identified as regards short-term deflections. Fig. 5 shows the maximum short-term deflections obtained for the different cases.

An ANOVA was carried out in order to decide whether or not the different factors in the cases studied had a significant effect on short-term deflections, with the help of Statgraphics (2013), considering maximum short-term deflection as the dependent variable, and three factors: type of construction process, number of successively shored floors, and number of shore lines. The results are given in Table 2 which shows the different parameters used in an ANOVA (Sum of squares, degrees of freedom -*Df*-, mean square, *F*-Ratio and *P*-Values).

The most important parameter for this study is *P*-Value which shows the importance of each factor in the results, in this case, the importance of each factor in the maximum instantaneous deflection. Since the *P*-values are less than 0.05, these factors have a statistically significant effect on maximum instantaneous deflection at the 95.0% confidence level.

Firstly, the type of construction process is the factor with the most effect on maximum instantaneous deflection. In Fig. 5 it can be seen that these deflections obtained in the SRS process are greater than those in SCS (maximum deflection obtained in SRS was 12.1 mm, while in SCS it was 10.6 mm). This was as expected, as in SRS when all the shores are removed, the slab has to bear all the load applied a few days after pouring. In contrast, in SCS, only 50% of the shores are taken away and so the deflection is less. This was the reason for the difference of 1.5 mm between the two types of construction process.

Secondly, it can also be said that the number of consecutively shored floors has a significant effect on maximum instantaneous slab deflection: the higher the number of floors, the lower the maximum instantaneous deflection. The reason for this is that the loads are distributed among a higher number of shored floors, so that the slabs bear less of the load and thus suffer less deflection. In SRS the greatest difference in maximum instantaneous deflection among cases of different numbers of consecutively shored floors is 0.90 mm, while in SCS the greatest difference is 0.66 mm, both by considering the same number of shore lines.

As regards the number of shore lines, maximum instantaneous deflection was less affected, but not to a significant extent, as can be seen in Table 2. In SRS the greatest difference between 1 and 2 shore lines in maximum instantaneous deflection is 0.3 mm by considering the same number of consecutive shored floors, while in SCS it is 0.4 mm, being higher in the case of a single shore line. This leads to the conclusion that the fewer the lines of shores, the higher the maximum instantaneous deflection recorded in the slabs.

4.2 Long-term deflections

In order to calculate long-term deflection, the "creep" option was activated in ETABS (2013). This evaluates creep in the different concrete elements, considering, among others, the geometry of the elements, mechanical characteristics of the different concrete types, and the relative ambient humidity. The objective measure for this data was taken as the average humidity recorded in Colombia, as would have been done in any other country.

Fig. 6 Comparison of maximum long-term deflections (10 years) of the 12 cases analyzed

Fig. 6 gives the maximum long-term deflections (10 years) for each case. It can be seen that those for SRS are higher those for SCS.

Following the method described in Section 4.1, an analysis was made to determine whether or not the different parameters

Table 3 Analysis of Variance for maximum long-term deflection

Source	Sum of Squares	*Df*	Mean Square	*F*-Ratio	*P*-Values
MAIN EFFECTS					
A: Construction Process	52.0833	1	52.0833	7056.45	0.0000
B: Consecutive shored floors	3.095	2	1.5475	209.66	0.0000
C: Shore lines	0.27	1	0.27	36.58	0.0005
RESIDUAL	0.0516667	7	0.00738095		
TOTAL (Corrected)	55.5	11			

of the cases analyzed had a significant effect on long-term deflections. An ANOVA was used for this, with the help of Statgraphics (2013), considering maximum long-term deflection (10 years) as the dependent variable and the three factors (type of construction process, number of consecutively shored floors, and 1 or 2 lines of shores) as the independent variables. The results are given in Table 3. Since the P-values are less than 0.05, these factors have a statistically significant effect on maximum long-term deflection at a 95.0% confidence level.

From the analysis of the results, it can be said that the greatest calculated maximum difference in long-term deflections between the SRS and SCS construction processes was found to be 4.4 mm. It should be noted that creep is determined by the period and intensity of a load on a concrete element. This means that if the load on an element is increased at an early age it will suffer greater creep deflection, so that the construction process that imposes the heaviest penalties on young concrete structures is SRS, unlike the SCS process, whose load values are lower.

As occurred with maximum instantaneous deflections, higher maximum long-term deflections were found in the SRS than the SCS processes. As can be seen in Fig. 6, the highest value of maximum deflections in SRS is 17.1 mm, while in SCS it is 13.1 mm.

As regards the number of consecutively shored floors, the higher the number of floors the lower the maximum long-term deflections, in all cases. The largest reduction in an SRS case was 1.1 mm, whereas was 1.4 mm in SCS, both by considering the same number of shore lines.

The number of shore lines was found to be a significant factor though with a lower influence: the greatest difference between cases in long-term maximum deflection was 0.3 mm for SRS and 0.4 mm for SCS by considering the same number of consecutive shored floors.

5. Evaluation of the obtained short- and long-term deflections

In order to assess the deflections, this section is divided into three sub-sections to compare, firstly, maximum instantaneous deflections under construction with those found in service; secondly, maximum long-term deflections with the limits laid down by ACI 318-14 (2014); and

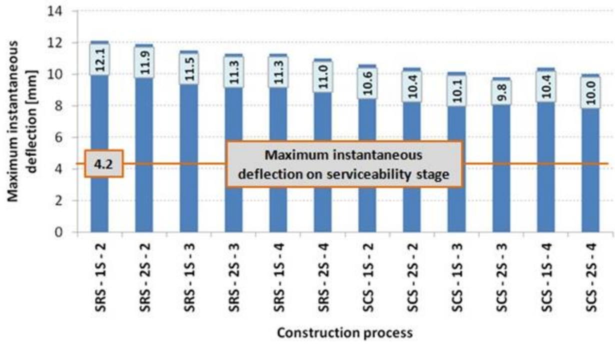


Fig. 7 Maximum instantaneous deflections of the 12 construction processes compared with those obtained in the structure's serviceability stage

finally, maximum long-term deflections with the same deflections as calculated by ACI 318-14's simplified method.

5.1 Comparison of maximum instantaneous deflections obtained under construction with those obtained in the serviceability stage

The control of slabs deflections is obtained for the serviceability limit state, i.e., for design loads only, with a safety factor equal to 1.0. It should also be remembered that the structure's load history is not taken into account in the control of instantaneous deflections. This procedure was used to calculate maximum instantaneous deflection with the help of the FEM used in the study.

The maximum instantaneous deflections of each model and those calculated by the conventional calculation method can be seen in Fig. 7.

It can be seen that the maximum instantaneous deflection in service, 4.2 mm, is considerably lower than that obtained for each of the construction processes analyzed. This aspect underlines the fact that the deflections suffered in the construction phase were significantly higher than those predicted for the building in service, which means that the construction phase is more critical than the in-service stage as regards deflections.

5.2 Comparison of long-term deflections obtained from FEM with the limits laid down by ACI 318-14

A comparison between the maximum deflection laid down by ACI 318-14 and long-term maximum deflections of each numerical model of the different construction processes can be seen in Fig. 8. The maximum deflections given are at structural ages of 3 months, 6 months, 1 year, 5 years and 10 years. It is also given the limit laid down for the control of long-term deflections by ACI 318-14 (2014) for a value equal to L/240, which presents a value of 15.83 mm.

As can be seen in Fig. 8, the maximum long-term deflections with the SRS construction process tend to be close to or exceed the code's limit. SRS processes with two consecutive shored floors exceed the limit after 1 year. Those that use 3 consecutive shored floors tend to exceed

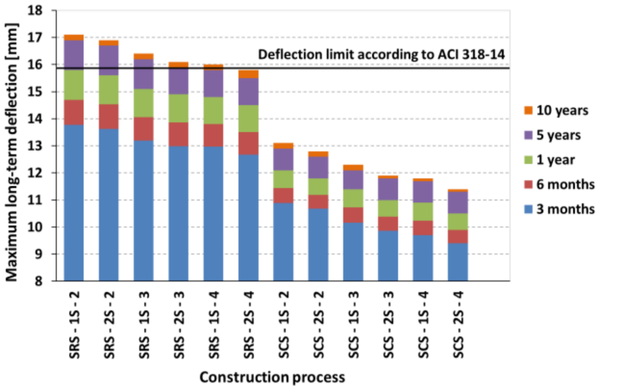


Fig. 8 Maximum long-term deflections of the 12 construction processes analyzed and the limit laid down by ACI 318-14

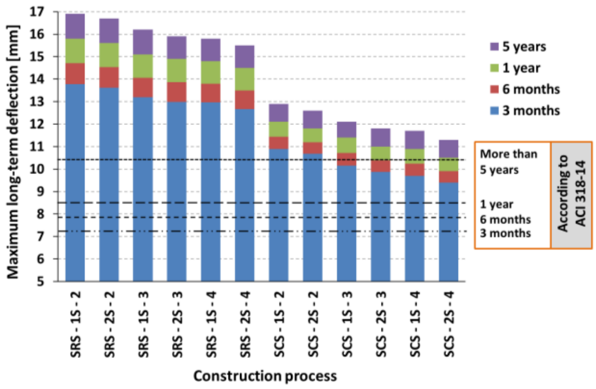


Fig. 9 Comparison of maximum long-term deflections of the 12 construction processes analyzed with those obtained by the simplified method in ACI 318-14

the limit after around 5 years of age. The use of 4 consecutive shored floors has less effect on the structure, since only the process with a single line of shores exceeds this limit after about 10 years of age. However, all the values calculated either exceed the limit or come pretty close to it, except for the SCS construction process, which presents maximum long-term deflections below that laid down by ACI 318-14. It should be noted that, although variations in the number of consecutive shored floors or lines of shores used in clearing affect maximum deflections, these values are still considerably lower than the limits set by the code. Fig. 8 also shows that the construction process has a stronger influence than the number of successively shored floors or the number of shore lines.

5.3 Comparison of maximum long-term deflections obtained by FEM with those obtained by the simplified method proposed by ACI 318-14

Fig. 9 contains a comparison of maximum long-term deflections obtained by FEM at structural ages of 3 months, 6 months, 1 year and 5 years and the same deflections at the same ages as calculated by Branson's proposed method (1977) in ACI 318-14 (2014) and described in detail in ACI 435R-55 (2003). According to the simplified procedure, without considering compressed reinforcement, the increased deflection due to creep should be computed from instantaneous deflection under permanent loads (3.1 mm), affected by a factor that depends on the age at which the long-term deflection is obtained. This factor has values of 1.0 for 3 months 1.2 for 6 months, 1.4 for 1 year and 2.0 for 5 or more years. Considering deflection of a structure due to design live loads of 1.1 mm, long-term deflection of the structure is therefore: initially, 4.2 mm; for 3 months, 7.3 mm; for 6 months, 7.9 mm; for1 year, 8.5 mm; and for 5 or more years 10.4 mm.

Fig. 9 shows that the deflections obtained in the cases studied exceed those computed by the simplified method proposed by the code, at all ages. These large differences are due to the fact that ACI 318-14 (2014) calculates long-term deflections according to those calculated for the in-service stage and does not take into account those that occur during construction. On one hand, for the SCS processes, even though the long-term deflections calculated by the simplified method are lower respect to those calculated by the advanced method, the differences are less than 50%. On the other hand, as can also be seen in Fig. 9, maximum long-term deflections obtained for SRS are around twice (almost 100% higher) than those calculated by the simplified method. It should be remembered that the long-term creep deflections of concrete loaded at an early age are at least several times higher than the elastic deflections. It is therefore extremely important to take the structural load history under construction into consideration, according to the different parameters of the construction processes, to make proper allowance for the durability and conditions of the structure in service.

6. Conclusions

This study analyzed the influence of the construction process on short- and long-term deflections by advanced calculation methods applied to the construction of RC buildings cast on-site by portable industrialized systems. A parametric analysis was carried out on a series of construction processes, including: type of construction process (SCS or SRS), number of consecutively shored floors (2, 3 or 4), and number of shore lines installed (1 or 2). The three factors considered were found to be of special importance for the values of both short- and long-term deflections. A comparison of the values of these deflections (allowing for the loads supported by the structure in the construction phase) was also made with the deflection limits and long-term deflections calculated by the simplified method proposed in ACI 318-14 (omitting the structural load history during construction). From the results of the study, the following conclusions can be drawn:

- The SCS construction process has less influence on slab deflections than SRS, due to the fact that the slabs in the latter process have to support the total load, self-weight and construction live loads, at a very early age. According to the results obtained, the difference in maximum instantaneous deflection between the SCS and SRS processes is within 9% and 15%, being greater for SRS processes.

• For the SCS process the maximum long-term deflections were seen to increase by approximately 30% over instantaneous deflections. This percentage was higher, approximately 41%, for the SRS construction process.
• The instantaneous deflections determined by FEM, taking the construction phase into consideration, exceed by more than 100% this deflection calculated for the structure's in-service stage, without taking the construction phase into account. This indicates that the construction phase is more critical than the service stage as regards deflections.
• In most SRS processes, maximum long-term deflections exceed the limit (L/240) laid down in ACI 318-14. However, the same deflections in SCS do not exceed this limit, with values between 20% and 30% mm below the code's limit.
• The deflections calculated for 3, 6 and 12 months and 5 years or over, applying Code ACI 318-14's simplified method, are considerably lower than those obtained by FEM, considering the construction process.

Therefore, allowing for the construction process is crucial for both short- and long-term deflections, obtaining much larger deflections than those obtained by simplified calculation methods. This conclusion highlights the need to consider the construction process in the conventional design of the industrialized systems studied, to reduce its effect on the structure's long-term response and durability.

The present work is the first step in a study of the construction process chosen for portable industrialized systems on long-term deflections, in which the structural concrete elements were considered to have linear elastic behavior. In the authors' opinion, in future work it will be important to allow for the real behavior of the concrete elements, taking cracking into consideration and analyzing the deterioration and durability of the structure in service.

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