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Additional Information

Stage of construction: An essential consideration in designing RC building structures

Stage of construction: An essential consideration

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Abstract

This paper analyses the potential influence of the construction process on the serviceability stage of the structure of reinforced concrete (RC) buildings. For this, a number of cases of buildings erected by habitual construction processes were simulated by a finite elements model (FEM), including and excluding the construction process. The Shoring-Clearing-Striking method (SCS) was seen the least harmful to the long-term behaviour, but even so maximum loads during construction exceeded the design loads. On the other hand, Shoring-Reshoring-Striking (SRS) procedure had construction loads similar to the design loads but worse long-term behaviour. In view of the results obtained, it is of the utmost importance to consider the construction phase when designing building structures. Some practical recommendations are given to improve the consideration of the construction process in the design as well as to take into account the long-term behaviour of structures due to load history during construction.

Keywords: building design; construction process; loads on slabs; long-term deflections; one-way slabs; shores; short-term deflections.

1. Introduction

As building structures are designed bearing in mind their final state, all types of loads have to be considered and the dimensions have to be adequate for both the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS). However, the building process includes various phases that are not usually considered either in the calculations or in the design. The construction process is generally only decided on after the design has been completed, and it is only then that the loads on the slabs under construction are calculated, usually by simplified methods (1), and the decision is made as to whether or not they are acceptable. However, this procedure involves three main problems: 1) the most frequently used simplified method is that of Grundy & Kabaila (2), which has been strongly criticised by many authors (1,3–9); 2) only a rough calculation is made of the loads on slabs, leaving out the consequences of this early loading of the structure for in-service conditions and durability of structures (reduced stiffness of slabs, cracking and excessive deflections); and 3) thought is seldom given to changing the design, even if this is recommended

for the construction phase, either by simply modifying the slab reinforcement or both the reinforcement and the geometry.

Many authors have identified the construction phase as being of critical importance for the structure's safety (6,7,10,11) and even though many structures have collapsed while actually being built, the cause is rarely investigated or published in specialised journals (12–15). This means that if the construction phase is understood to be critical for the structure then it is essential to consider it in the design phase.

Although concrete shrinkage and creep has been widely studied in concrete engineering, only a few authors (16–21) have considered these effects in the transmission of loads between slabs and shores in buildings under construction. Although all agree that shrinkage and creep do not have a great impact on slab/shore load transmission, not a great deal of attention has been paid to the fact that slabs are subjected to high loads at an early stage in their lives. Only Aguinaga & Bazant (16) and Duan & Chen (19) have analysed the relationship between the construction process selected and its effects on the long-term deflections of the structure in its serviceability stage. Both the above studies found that long-term creep deflections of young concrete loaded during the construction of a building are at least several times higher than the elastic deflections. Apart from these two proposals from 1986 and 1995, since then no in-depth studies have been made on the possible influence of the construction process on long-term behaviour of the structure.

The main objective of this paper is thus to make clear the importance of considering the building's construction phase in the initial design in order to increase safety during construction and improve in-service conditions and durability. Its novel contribution consists of showing the result of ignoring the construction process in the design stage by comparing the results of including and excluding this process in the design of multi-storey buildings. Even though two-way systems are a bit more common, one-way slabs are used in this work because they are still being widely applied for both tall and small buildings and its study is perhaps more interesting because of the reduced studies carried out on this system. Anyway, general conclusions obtained from this study can also be extended to two-way systems. Another objective of this paper consists of giving some practical recommendations to easily and correctly consider the construction stage in the design of buildings and the effects of the early loading of slabs in the long-term behaviour of structures.

A 3D finite element (FE) model of a building is used in Section 2 to calculate with precision the transmission of loads between slabs and shores during the most common construction processes. This section 2 describes the FE model used for both in-service stage and construction stage, the different types of construction processes considered and the parametric analysis carried out to study the most common procedures to build a building structure. Section 3 shows the results and discussion in terms of short- and long-term deflections and loads on slabs during construction. Finally, conclusions, some practical recommendations and future lines of research are shown in Section 4.

2. FE model of a building

A typical building with frames (columns and beams) and one-way joist slabs was used as the reference for the study. The floors consisted of six 6x5m bays, each with a surface area of 180m², including end, corner and internal bays, an aspect with a strong influence on the construction phase (5). There were eight 3m-high floors, which made it possible to study closely the behaviour of buildings under construction, including the phases in which the shoring was not connected to the foundations. Figure 1 shows a view of the structure modelled in ETABS (22). The photo in Figure 2 shows an example of the type of slab and a detail of the cross-section used for the study. As it can be seen, apart from columns and main beams, slabs are composed of thin plates with stiff joists only in one direction. Both elements of slabs working together produce the one-way flexural behaviour.

The dimensions of columns, beams and slabs were determined by those of the structure needed in the serviceability stage, whose geometric characteristics can be seen in Table 1.

2.1. Simulation of the building to obtain the results of its in-service stage

The behaviour was simulated of the definitive structure of a building (see Fig.1) whose design had not included the factors involved in its construction phase. Neither its construction process nor its loading history under construction were therefore taken into account, as is the usual case when buildings are designed. By means of this and subsequent simulations (See Section 2.2) that did consider the construction process, this study analyses the consequences of omitting the construction phase from the building's design. Non-linear geometrical behaviour of the structure was considered together with the linear behaviour of the materials. For the first approach of this study, the reduced stiffness of slabs due to cracking is not considered

because of the linear behaviour of materials and because cracking should be avoided during construction and non-extensive during in-service stage. Actually, no study, and no simplified calculation method either, has considered this reduced stiffness of the slabs during construction; neither for the study of the influence of construction processes on in-service conditions of structures.

The creep effect was considered as in ETABS (22) using the parameters proposed by the Model Code (23), which doesn't include the analysis procedure that could take into account principles of equilibrium and compatibility explained at Balázs et al. (24). Details of the materials, the building's in-service design loads and the types of elements used are given below. Shrinkage in the different structural elements were not considered.

2.1.1. Materials

The materials used in the building structure and their properties were as follows:

- Concrete with an average compression strength of 28 MPa and the mechanical properties as defined in Model Code (23).
- Reinforcement steel with a yield strength of 420 MPa and elasticity modulus of 200,000 MPa.

2.1.2. Design loads

The loads considered for the structure's service stage were self-weight plus dead, live and seismic loads. For a building with the characteristics defined above, these loads are enough for the design geometry and the definition of the different structural components. Table 2 gives a summary of the gravity loads on the different floors. The spectrum used to consider seismic loads has been obtained according to the NSR-10 (25).

2.1.3. Types of Finite Elements

2-D elements such as slabs 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). Columns, beams and joists were modelled as FRAME-type elements, formed by 2 nodes with 6 degrees of freedom per node. Slabs were considered with the rigid diaphragm hypothesis by means of DIAPHRAGM option from ETABS (22).

2.2. Simulation of the building to obtain the results of the construction phase.

In order to include the construction phase in the design of a building, a series of additional hypotheses were taken into account in relation to the different materials used for shoring and the construction loads. Details of these aspects and of the types of finite elements used in simulating this phase are given below.

2.2.1. Considered hypotheses

Following previous studies (1,26–28) and including the effect of creep in the concrete, the considered hypotheses in the stage of construction were as follows:

- Linear elastic behaviour of concrete in slabs, columns and beams with variations of stiffness with time.
- Formwork boards, straining pieces and shores with linear elastic behaviour and finite stiffness.
- Infinitely stiff foundations.
- Effects of creep as in ETABS (22) using the expressions proposed by the Model Code (23).
- Shrinkage and temperature variations in the different structural elements were not considered.

2.2.2. Additional materials

The mechanical properties of the materials used for shoring were:

- Steel shores with an elasticity modulus of 210,000 MPa.
- Metal straining pieces with an elasticity modulus of 210,000 MPa.
- Wooden formwork boards with an elasticity modulus of 10,000 MPa.
- The mechanical properties of the concrete as defined in Section 2.1.1 varied with time in accordance with Model Code (23).

2.2.3. Construction loads

The possible construction loads that appear during the building phase are different to those in the service phase, because live loads must be considered besides the self weight of the structure and the dead weight of the shoring. These live loads include building workers, overloading during the concreting phase, stored materials, etc. The following were included in the study:

- Self-weight of the structure: 3.87 kN/m².
- Dead loads of the shoring system: 0.50 kN/m².
- Live loads: 2.40 kN/m² (Minimum live load according to ACI 347-04 (29)).

2.2.4. Additional Types of Finite Elements

When simulating the construction process, the new elements introduced must be considered such as shores, straining pieces and formwork boards, besides a cumulative evolutionary calculation of the different elements to simulate their geometric changes during the different construction phases.

2-D elements such as formwork boards 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). Steel shores and straining pieces were modelled as FRAME-type elements, formed by 2 nodes with 6 degrees of freedom per node. The actual behaviour of shore elements only permits vertical deformation. In the modelling, applying the RELEASES option (22), this FRAME-type element only considers vertical displacements, complying with the actual behaviour.

When modelling the different scenarios considered, it was also necessary to use the NONLINEAR STAGE CONSTRUCTION option (22), 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 stages, 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.

The simulation of some of the different construction phases is shown in Figure 3.

2.2.5. Different construction processes considered

For each floor two or more shoring operations are considered. Shoring and Striking (SS) are essential operations, the first to support the freshly poured slab, and the second is performed when the slab has enough strength to resist the loads applied to it. However, it is very common to use additional intermediate operations such as clearing and reshoring. Clearing (C) consists of removing more than half, but not all, the shoring system's components a few days after pouring. Reshoring (R) involves removing all the shores under the slab a few days after pouring and re-installing them in such a way that they can resist any future load increases. At present, the normal practice is to use one of these intermediate processes, since they leave free a large part of the shoring material (formwork, straining pieces and shores) for re-use on the succeeding floors. In many cases building times can also be reduced. These different operations can be combined in the following ways: Shoring / Striking (SS), Shoring / Clearing / Striking (SCS) and Shoring / Reshoring / Striking (SRS). A complete description of the different processes can be found in Adam et al (1). The present study included this three most widely used construction methods.

The shore distribution in each phase can be seen in Figure 4. In SS, all the shores marked with red and green circles are installed (Fig.4a). The distribution of shores along the main beams in this process (SS) can be seen in Figure 4b. In SRS, the same system is used, except that in reshoring only the shores marked in red are re-installed (see Fig.4a). In this building process (SRS) the shores are not re-installed under the main beams. Shore distribution in SCS can be seen in Figure 4c. The shoring of the beams is considered to be the same as in the previous processes (see Fig.4b). In the clearing operation more than 50% of the shores and formwork boards are taken away. The resulting distribution can be seen in Figure 4d.

2.2.6. Parametric analysis

A parametric analysis was carried out in order to determine whether or not the construction phase should be considered when designing a building with one-way slabs, including the SS, SCS and SRS processes, with 2 or 3 consecutively shored floors and new operations every 3 or 7 days. A total of twelve numerical models were processed and almost all the habitual construction procedures used in this type of building were included. The different models can be seen in Figure 5.

3. Results and discussion

In this Section, different results are shown and discussed with and without considering the construction stage in the design of building structures. Results are shown in the follow terms: short-term deflections (Section 3.1), long-term deflections (Section 3.2) and loads on slabs (Section 3.3). Loads on slabs during construction compared with the design load of them give an idea of which is the level of load the slabs have to bear during construction. Short- and long-term deflections, as a first approach remembering the linear behaviour of materials, give an order of magnitude of which is the influence of considering the construction process and how the different construction processes affect to these results. In this way, the aim of this section is to show the large importance of considering the construction stage in the design of RC building structures.

3.1. Short-term deflections

The maximum short-term deflections in slabs and beams obtained from the different simulation models can be seen in Figures 6 and 7 respectively, which give the results of ignoring (conventional design) and considering the construction process in the design of the structure.

The maximum short-term deflections in slabs (see Fig. 6) of the conventional model is significantly lower (6.4mm) than that obtained when the structure was being built, which clearly shows that the structure was subjected to worse conditions than those that could be expected in its serviceability stage. No large differences were observed between the different construction processes, although the maximum short-term deflection for SRS was slightly higher.

In the case of the main beams (see Fig. 7) there is an even bigger difference between maximum short-term deflection of the models that ignored the construction process and those that did consider it. Only in the SCS processes, the maximum short-term deflection of the conventional model is about half that of the value when the construction process was considered. For SS and SRS the maximum short-term deflection is substantially higher and was up to four times higher than the conventional model in the SRS-3D simulation, which clearly shows that the SCS construction process puts the least deflection on the structure in terms of maximum short-term deflection.

3.2. Long-term deflections

The maximum long-term (5-year) deflections obtained in slabs and main beams can be seen in Figures 8 and 9, respectively, with the results of the models that ignored (conventional design) and considered the different construction processes (see Fig.5). Also shown are the long-term deflection-limits according to ACI 435-95 (30) for the cases: 1) when slabs are supporting or attached to non-structural elements likely to be damaged by large deflections ($L/480$); and 2) when slabs are supporting or attached to non-structural elements not likely to be damaged by large deflections ($L/240$).

The maximum long-term deflection in slabs (see Fig. 8) of the conventional model is considerably lower (10.3mm) than that obtained when the construction process is considered. No great differences were observed between the construction processes themselves, although the SRS maximum long-term deflection is slightly higher. As in the short-term deflections (Section 3.1), these results clearly show that the structure was subjected to high loads with early-age concrete. This indicates that ignoring the construction process in the design phase, as is the usual practice, long-term deflection is clearly underestimated, which could have serious consequences for the structure.

In fact, as can be seen in Figure 8, even though the conventional model complies with the long-term deflection limit according to ACI 435-95 (30), the other models are much higher than the limit. The different

models, in general, even exceed the limit in the case when no damage is expected to non-structural elements, which shows that ignoring the construction process in designing the structure of a building can lead to serious consequences in its in-service conditions and durability.

In the case of the main beams (See Fig.9) the difference between the maximum long-term deflection of the model that ignores the construction phase and those that consider it is even greater. Only in the SCS processes, the maximum long-term deflection of the conventional model is around half that calculated when considering the construction phase. In SS and SRS maximum long-term deflection is considerably higher, and is up to four times higher than the conventional model in the SRS-3-3D simulation. Therefore, SCS is clearly the construction process that makes the smallest demands on the structure in terms of maximum long-term deflections. Indeed, in the case of the main beams, all the SCS processes comply with the limits laid down in ACI 435-95 (30), unlike SS and SRS, in which only SS-2-3D and SRS-2-3D are below it. However, even though some processes do comply with these limits, as the construction process is usually ignored in the design phase (conventional design), the serviceability and durability conditions of the main beams in this case would be affected just the same.

3.3. Loads on slabs

In successively shored floors it is very important to estimate slab/shore load transmissions in order to know the loads on both shores and slabs during construction. Slabs can receive very high loads from the accumulated loads on higher successively shored floors. In fact, the construction stage is generally the most critical phase due to the accumulated loads on slabs on higher floors and the early age of the concrete. Table 3 compares the maximum loads found on slabs per surface unit in all the cases studied, with the slabs' design load per surface unit, together with age of concrete and the slab and construction phase involved. The loads are given for the characteristic combination with no load safety factors, which are used for testing structural serviceability limit states (SLS).

As seen in Table 3, the maximum load on slabs is higher than the design load for the SS and SCS processes, which means the serviceability and durability conditions could be seriously affected if the construction phase is not considered in the design phase. In the case of SRS processes, in which the maximum slab load is slightly below the design load, the loads are exerted on concrete only 6 to 14 days old and this could also affect the in-service conditions.

4. Conclusions, recommendations and future lines of research

This paper describes an analysis of the effect of considering and ignoring the construction process when designing an RC structure by studying the short- and long-term deflections and the loads on the slabs during construction. The influence of the type of construction process employed was also studied. From the results obtained, the following conclusions can be drawn:

- The SCS process generally produced the least deflection and thus is the one that demands least from the structure in terms of short- and long-term deflections.
- SRS generated the highest deflections, since the slab had to support its own weight at an early age during intermediate reshoring, permanently deforming the structure and worsening long-term deflections.
- In SS and SCS, the maximum load on slabs during construction exceeds the design load. This would affect the structure's serviceability and durability conditions.
- In SRS, although the maximum load on slabs during construction is similar to the design load, it should be remembered that this load is transmitted to the slabs while the concrete is still very young.

It should therefore be emphasised that it is essential to consider the construction phase when designing a structure to avoid seriously affecting the structure's in-service conditions (comfort, short- and long-term deflections and cracks), durability (cracks in early-age concrete due to overloaded slabs) and safety (loads on slabs possibly higher than the design loads).

Practical recommendations for designers (construction, consulting and formwork companies) and also for the scientific community consist of:

1. It is essential the consideration of the construction stage in the design of RC building structures. Otherwise, in-service conditions or durability could be highly affected. Additionally, whether the construction stage recommends some changes (reinforcement, geometry) in the RC structure, they can be done in the design phase.
2. It is not recommended the use of general cases or oversimplified methods, such as Grundy & Kabaila's method (2), to estimate the load transmission between shores and slabs. Nowadays, the

use of newest simplified methods such as those proposed by Duan & Chen (3), Fang et al (4), Calderón et al (5) or Buitrago et al (6,7) should be recommended.

3. Scientific community are encouraged to develop or modify the newest simplified methods to include, not only the calculation of the load transmission between slabs and shores, but also the effects of this early loading of slabs on the long-term behaviour of the structure. In the analysis procedure, it should also be included those aspects that adheres to principles of equilibrium and compatibility (24,31,32).

The present work is the first step in the study of the effect of the construction process in RC buildings, considering linear elastic concrete behaviour. The authors of the study consider it important to include the non-linear behaviour of the concrete elements in a future line of work, in which even greater differences can be expected in terms of deflections than those obtained here.

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Figure Captions:

1. *Model of type of building considered in the study.*
2. *a) Example of one-way joist slab and b) Slab cross-section used in the study.*
3. *Model of the building in different construction phases.*
4. *Distribution of shores in the different building processes.*
5. *Building procedures studied to determine their influence on the structure's in-service conditions.*
6. *Maximum instantaneous slab deflection with and without considering the construction stage in the design of building structures.*
7. *Maximum instantaneous beam deflection with and without considering the construction stage in the design of building structures.*
8. *Maximum long-term slab deflection with and without considering the construction stage in the design of building structures.*
9. *Maximum long-term beam deflection with and without considering the construction stage in the design of building structures.*

Table 1. Geometric properties of columns, beams and slabs.

Element	Dimensions [m]
Columns	0.50x0.50
Beams	0.35x0.50
Joists	0.10x0.25
Separation between joists	1.00
Compressive deck layer	0.05

Table 2. Slab design loads.

Floor	Self-weight [kN/m ²]	Dead load [kN/m ²]	Live load [kN/m ²]	Total load [kN/m ²]
Floors from 1 to 7	3.87	5.84	1.80	11.51
Floor 8	3.87	3.17	1.80	8.84

Table 3. Maximum loads on slabs during the construction stage.

Construction process	Stage of construction	Level	Age of concrete [days]	Maximum Load [kN/m ²]	Design Load [kN/m ²]
SS-2-3D	Casting level 4	2	6	13.40	11.51
SS-2-7D	Casting level 4	2	14	13.47	11.51
SS-3-3D	Casting level 6	3	9	13.61	11.51
SS-3-7D	Casting level 6	3	21	13.68	11.51
SCS-2-3D	Casting level 3	2	6	12.32	11.51
SCS-2-7D	Casting level 3	2	14	12.39	11.51
SCS-3-3D	Casting level 4	3	6	11.64	11.51
SCS-3-7D	Casting level 4	3	14	11.71	11.51
SRS-2-3D	Casting level 3	2	6	11.03	11.51
SRS-2-7D	Casting level 3	2	14	11.07	11.51
SRS-3-3D	Casting level 4	3	6	10.56	11.51
SRS-3-7D	Casting level 4	3	14	10.60	11.51

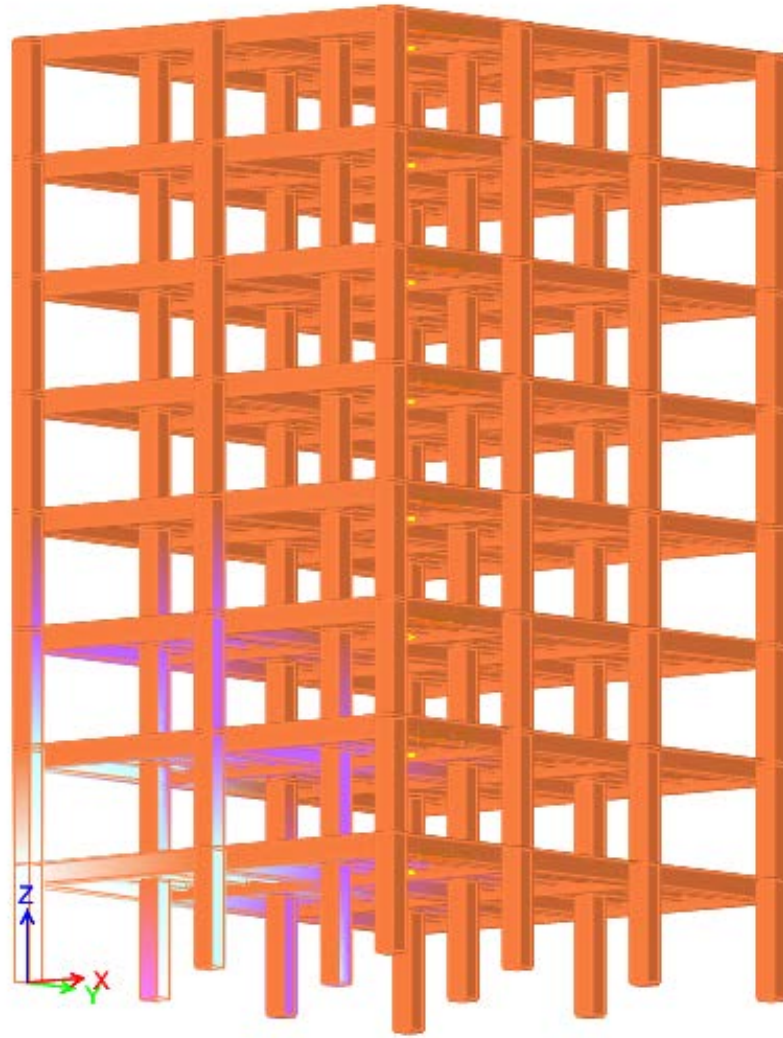
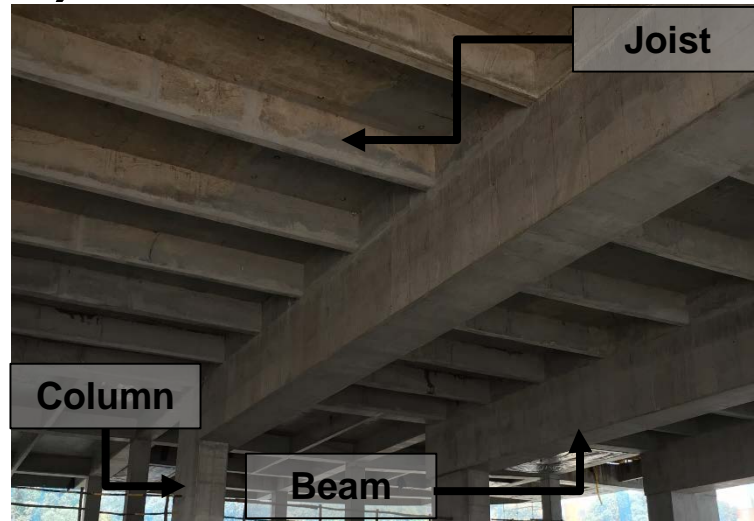


Fig. 1 Model of type of building considered in the study.

a)



b)

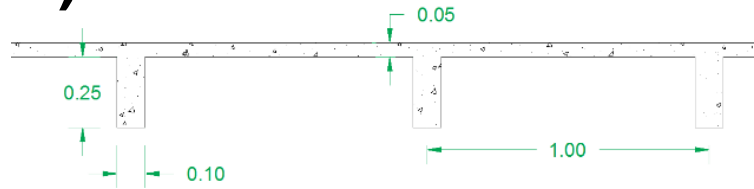


Fig. 2 a) Example of one-way joist slab and b) Slab cross-section used in the study.

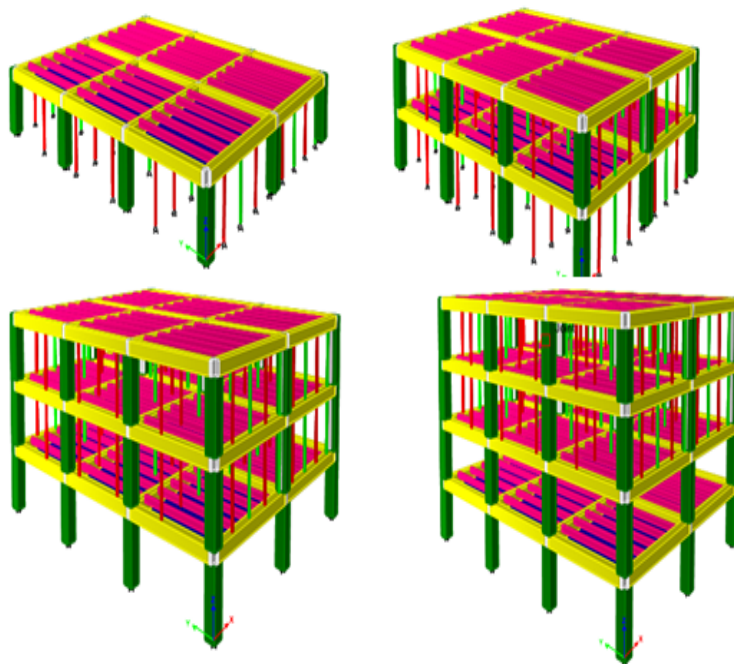
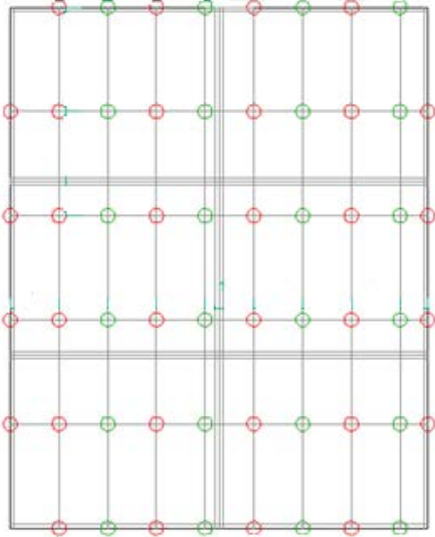


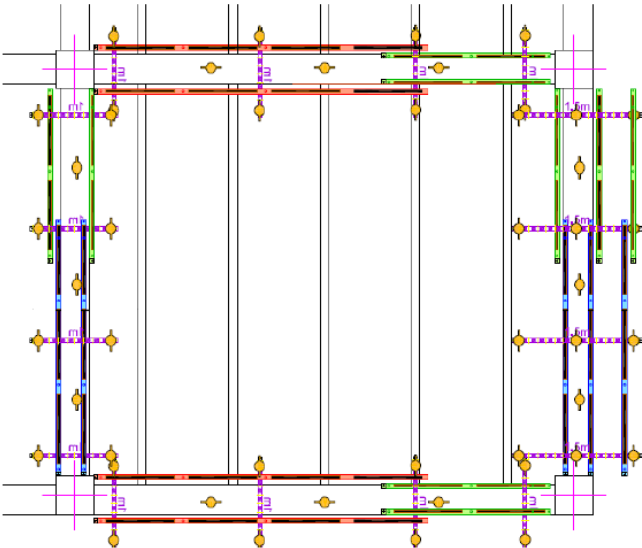
Fig. 3 Model of the building in different construction phases.

a) Shoring on slabs (SS/SRS)

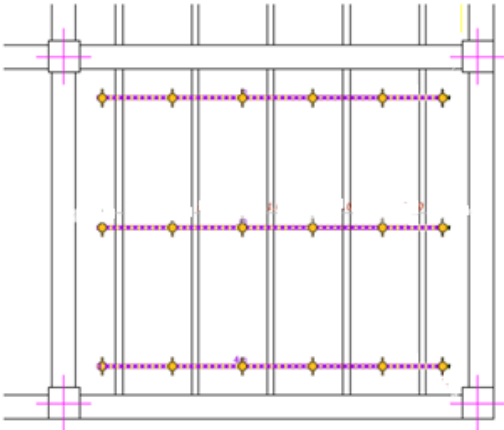


○ : Reinstalled shores in a reshoring operation

b) Shoring on beams (SS/SCS/SRS)



c) Shoring on slabs (SCS)



d) Clearing on slabs and beams (SCS)

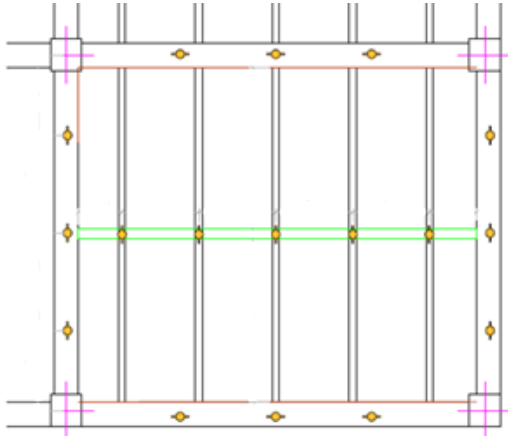


Fig. 4 Distribution of shores in the different building processes

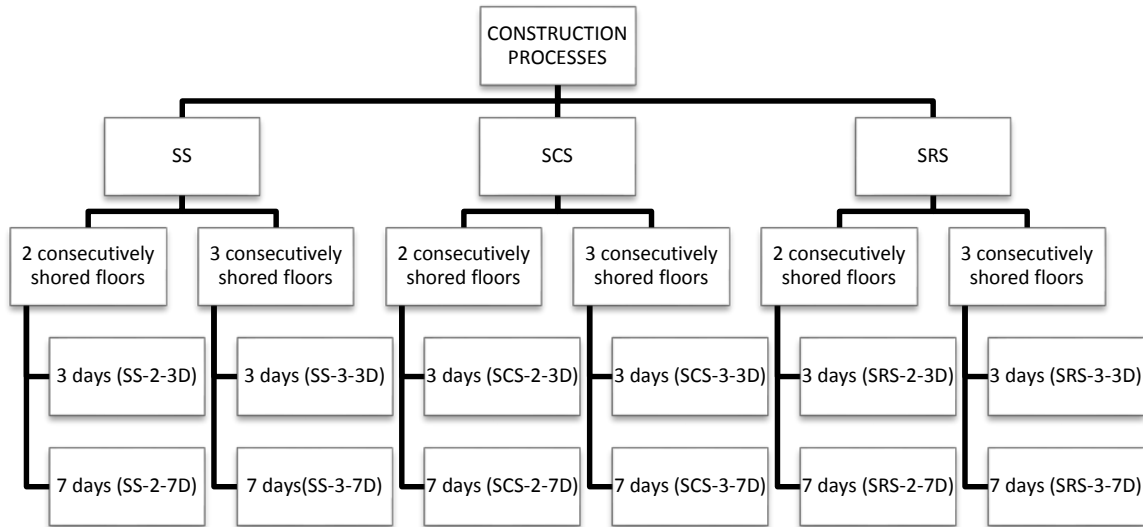


Fig. 5 Building procedures studied to determine their influence on the structure's in-service conditions

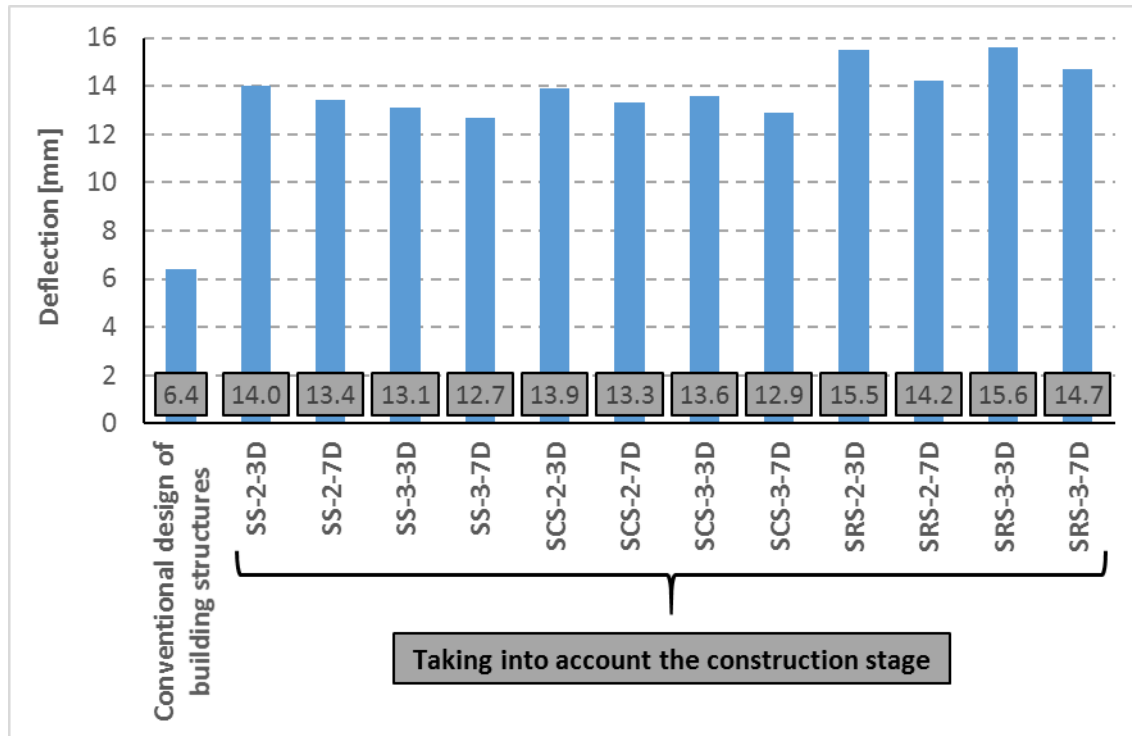


Fig. 6 Maximum instantaneous slab deflection with and without considering the construction stage in the design of building structures.

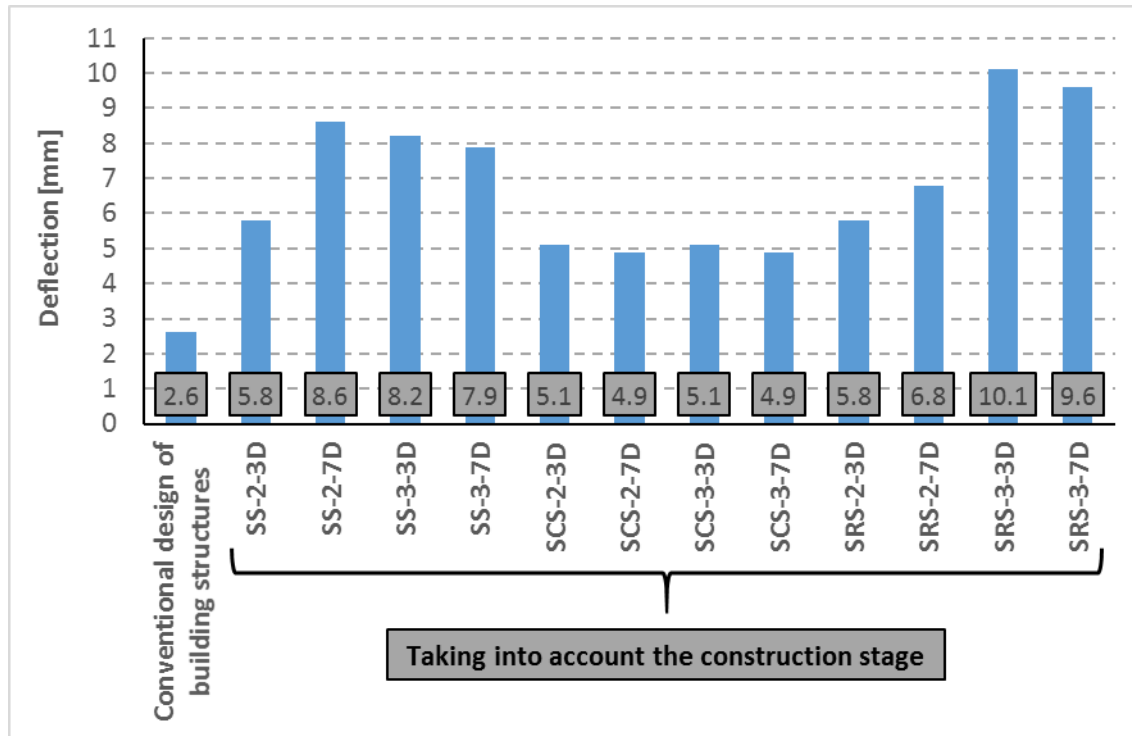


Fig. 7 Maximum instantaneous beam deflection with and without considering the construction stage in the design of building structures.

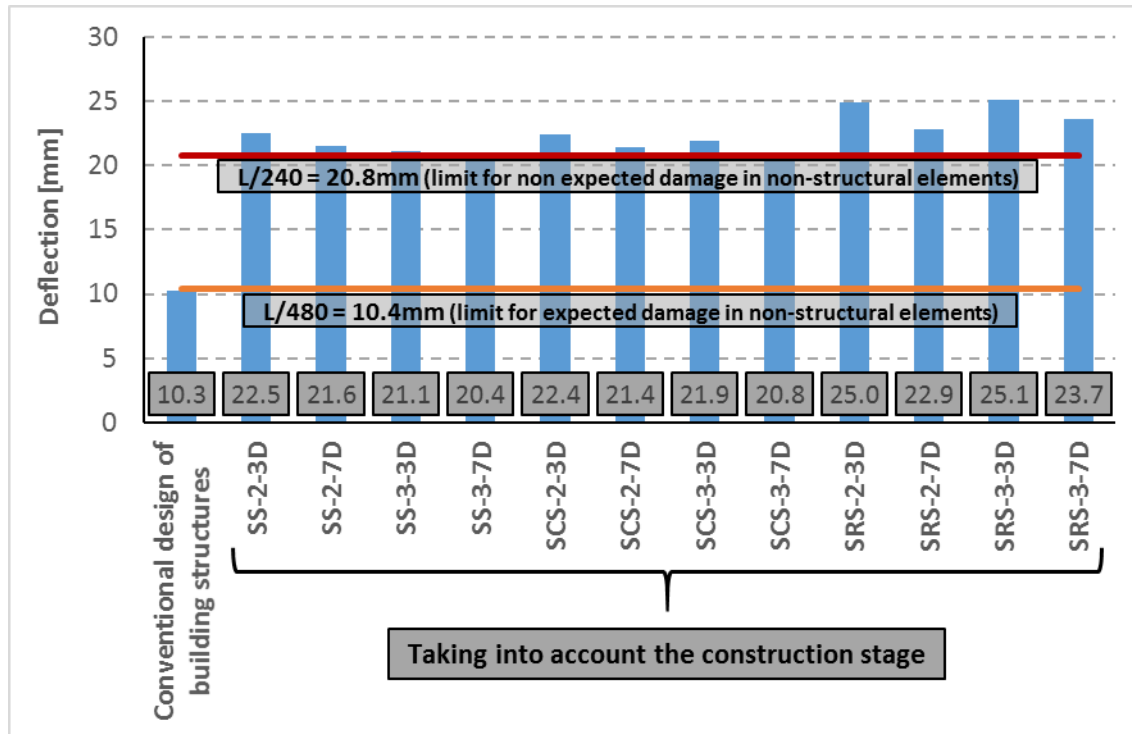


Fig. 8 Maximum long-term slab deflection with and without considering the construction stage in the design of building structures.

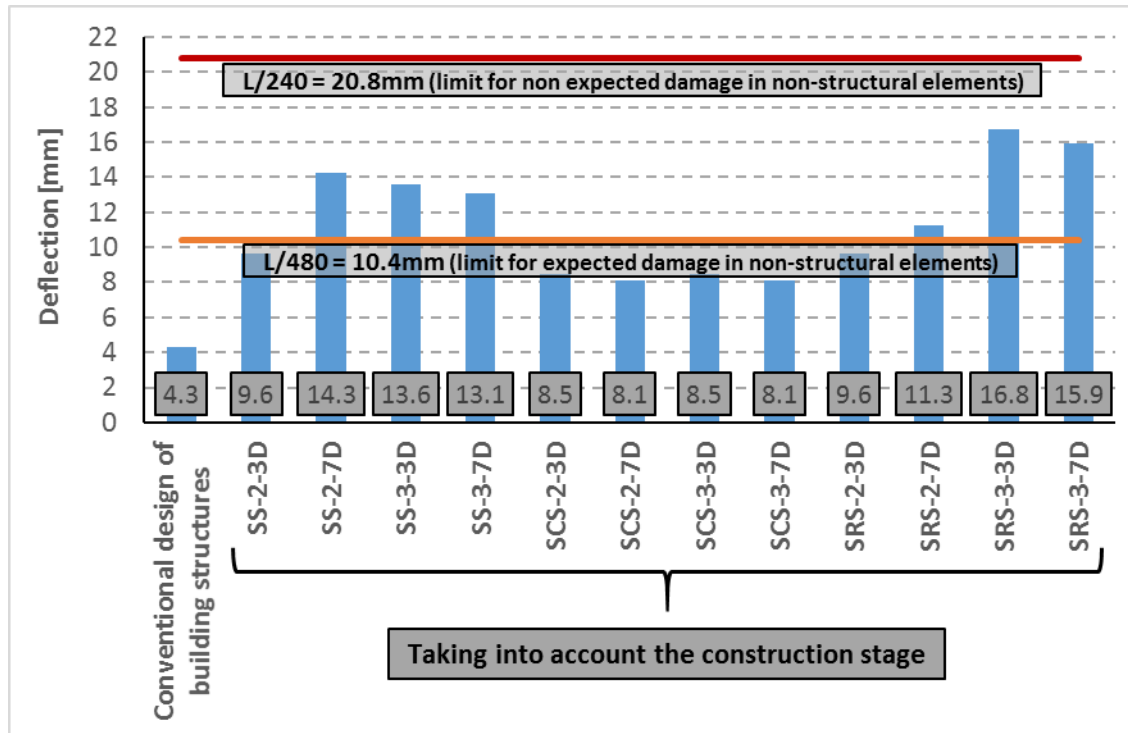


Fig. 9 Maximum long-term beam deflection with and without considering the construction stage in the design of building structures