2nd International **Conference on Recent Advances in Nonlinear Models** – Design and Rehabilitation of Structures
CoRASS 2017
H. Barros, C. Ferreira, José M. Adam and Norb Delatte (Eds)

MODELLING OF RC BUILDING STRUCTURES DURING CONSTRUCTION

MANUEL BUITRAGO[χ], PEDRO A. CALDERÓN[†], JUAN J. MORAGUES[‡] AND JOSE M. ADAM[*]

[χ]Concrete Science and Technology Institute (ICITECH)
Universitat Politècnica de València
Camino de Vera s/n, 46022 Valencia, Spain
E-mail: mabuimo1@upv.es

[†]Concrete Science and Technology Institute (ICITECH)
Universitat Politècnica de València
Camino de Vera s/n, 46022 Valencia, Spain
E-mail: pcaldero@upv.es

[‡]Concrete Science and Technology Institute (ICITECH)
Universitat Politècnica de València
Camino de Vera s/n, 46022 Valencia, Spain
E-mail: jmorague@upv.es

*Concrete Science and Technology Institute (ICITECH)
Universitat Politècnica de València
Camino de Vera s/n, 46022 Valencia, Spain
E-mail corresponding author: joadmar@upv.es

Keywords: finite element method, shoring, RC buildings, construction.

Summary. This paper deals with the specific case of reinforced concrete buildings constructed by the habitual system of successively shored floors, in which new slabs are poured while one or more of the lower floors are either fully or partially supported on shores. In this situation it is no easy task to determine exactly how the loads are distributed among the floors interconnected by the shoring. Numerical simulation can provide valuable information on structural behaviour at a very reasonable cost and can also deal with many other types of study whose cost would otherwise be unacceptable.

This paper provides a chronological history of numerical models used by different authors to determine load transmissions between slabs and shores in reinforced concrete buildings under construction from the beginning of the 20th century up to the latest models developed at the Polytechnic University of Valencia. The main aim of this paper is to keep the reader informed on the state-of-the-art of numerical studies on the construction of RC buildings with successively shored floors by a first-hand account of the advances and improvements available for application to the construction of buildings. However, neither must we forget the historical studies carried out in the past that are the basis of the latest advances.

1 INTRODUCTION

Shoring of successive levels of floors is the most common construction method for RC building structures. This method consists of pouring the fresh concrete of a new floor when this or more lower floors are totally or partially shored. Self-weight of new poured slabs, in addition to possible live loads during construction, are then distributed between slabs connected by the shoring system. It is no easy to know how loads are transmitted between slabs and shores. Numerical simulation is at this point really important to know the behaviour of structures without using a great amount of money, as it could be the construction of experimental test in real or reduced scale [1-2]. It also allows studying multiple cases which, on the other hand, would be impossible because of large cost of experimental tests.

The main novelty of this conference paper consists of providing the reader with a brief state-of-art of numerical studies about the construction of buildings using the shoring of successive floors technique. The reader can thus learn at first hand the available tools and advances made with the aim of encouraging him to put them into practice in order to improve building methods.

A brief description of the state-of-art about numerical modelling of RC building structures during construction from the second half of the 20^{th} century to date is presented in Section 2. Section 3 briefly describes the numerical models carried out by the Concrete Science and Technology Institute (ICITECH) of the Polytechnic University of Valencia (Spain), which in recent years has become a leader in the research of this field for the numerous numerical, experimental and theoretical studies it has performed. Finally, a series of conclusions are given in Section 4

2 STATE-OF-ART IN NUMERICAL SIMULATIONS OF RC BUILDING STRUCTURES DURING CONSTRUCTION

When RC buildings began to be constructed in situ in the first half of the 20th century, no information was available on the transmission of loads between the different floors and the shoring during the construction process. The first theoretical studies were undertaken by Nielsen [3] in 1952 and especially by Grundy & Kabaila [4] in 1963, who developed simplified methods of calculating building structures constructed by shoring successive levels of floors. This simplified method is still used today. Grundy and Kabaila’s simplified method [4] mainly considers: an infinitely stiff shoring system, same stiffness for different slabs and no changes in the concrete mechanical properties during time. Many authors have justified that these hypothesis are no longer valid, more with the currently advances in simplified methods [5]. However, Grundy and Kabaila’s simplified method is one of the most used calculation method. From 1963 to date several authors [6–10] started numerical studies about how loads are transmitted between slabs and shores. Following, a brief description of each of them is given.

2.1. Liu et al (1986)

Liu et al [6] improved the theoretical model proposed by Grundy and Kabaila [4] with a 3D model and the following hypothesis:

- Linear behaviour of shores and slabs (considering its stiffness variation during time) is considered.

- Different slabs boundary conditions were taken into account: one single bay, a continuous bay in all directions and a continuous bay only in one direction.
- The foundations are assumed to be of infinite stiffness.

Comparing their results with those expected by Grundy and Kabailas's method, Liu et al concluded that their method is adequate to predict loads on slabs and shores during the construction process. However, they considered the use of a corrector factor (1.05-1.10) which allows taking into account the influence of different and not considered aspects.

2.2. Stivaros and Halvorsen (1990)

The use of the Equivalent Frame Method (EFM) was proposed by Stivaros and Halvorsen [7] to estimate the load transmission between slabs and shores. This methodology was firstly proposed in 1970 by ACI Committee 311 as a design method of RC structures. A 2D model of the structure was proposed with the following assumptions:

- Linear behaviour of shores is considered with an equivalent stiffness equal to the total shore stiffness of those shores located in one row of shores of the equivalent frame.
- A simple support (as hinges) is considered for slab and shores connection.
- Foundations are assumed to be of infinite stiffness.
- Different boundary conditions were taken into account: isolated bay and a group of three bays.
- Slabs were modelled as beams, with a length equal to the span between columns and a depth equal to the depth of the slab.
- Columns were considered as beams with the actual cross-section.

Differences greater than 5% were found comparing their results with those expected by Grundy and Kabaila's [4] and Liu et al's [6] methods. They also noticed that slabs boundary conditions should be considered to avoid important mistakes in the estimation of loads on slabs and shores.

2.3. Mosallam and Chen (1991)

Mosallam and Chen [8] developed a 2D model to estimate load transmission between slabs and shores during the construction process and to compare its results with the Grundy and Kabaila's simplified method [4] and the Liu et al's model [6]. Generally speaking, although the vertical deformation of columns is considered, this model is similar to Liu et al's model. The following conclusions were obtained from the studies carried out:

- The stiffness of the foundation has a very small influence in the slab load estimation, whereas it is important in the shore load estimation.
- Slabs boundary conditions have a little influence on the slab load estimation, even though this is not true for the maximum shore load.
- The influence of the slab stiffness is reduced.
- The actual stiffness of shores has a great effect on the shore load.
- The evolution during time of concrete mechanical properties has a big impact on the load distribution between slabs and shores.

2.4. Kwak and Kim (2006)

In 2006, Kwak et al [9] developed a numerical model in which the time-dependent behaviour of a RC building structures during construction was accounted. This model considered: a) geometric and material (cracking and yielding of the reinforcement) non-linearities, b) creep and shrinkage, and c) variation of concrete properties during time. They used a 2D model with the addition of the actual stiffness of columns and different types of construction processes. They concluded that, whether concrete mechanical properties during time are not considered, results would be on the safe side on slabs but on the unsafe side on shores.

2.5. Díaz (2008)

Díaz studied the influence of different parameters of construction processes on the load transmission between slabs and shores with a SAP2000 model. He also studied the minimum age when striking operation can be done. Diaz, in addition to the different hypothesis stablished by other authors, considered that each concrete slab must have the same elastic modulus, except the new poured slab whose elastic modulus is considered 0 because of the fresh concrete. Within other conclusions, Diaz highlighted that shores should be removed from the center of the bay to the columns. Otherwise, shores located in the center of the bay might collapse.

3 NUMERICAL MODELS CARRIED OUT AT POLYTECHNIC UNIVERSITY OF VALENCIA

This section describes the numerical models carried out by the Concrete Science and Technology Institute (ICITECH) of the Polytechnic University of Valencia (Spain), which in recent years has become a leader in the research of this field. The beginning of this research started in the second half of the 20th century by Moragues et al [11-12]. Following, and with a Spanish project in 2004 [1] and the collaboration of some private companies, numerical studies and experimental tests were carried out under controlled conditions [13–15] and under real conditions [16–19]. Currently, our group continues working in construction process optimization through numerical simulation [5,20], with new simplified method [21–23], obtaining optimum construction processes [24–26] and developing new experimental tests [2]. Following subsections give details about the numerical studies carried out.

3.1. Moragues et al (1994-1996)

Moragues et al [11] monitored two buildings with the aim of registering loads on shores during a construction process performed with a common technique called clearing or partial striking which was widely known in Spain and nowadays is extended around the world (reader can find a detailed description of the most common construction techniques in Adam et al [5]). The actual differences in loads found during the construction of these two buildings with those expected by Grundy and Kabaila's simplified method [4] motivated the development of a 2D model in SAP2000 [12]. Finally, Moragues et al concluded that more studies were necessary taking into account aspects such as deformation during the construction process, cracking of an early-age concrete and the influence in the load transmission between slabs and shores of creep, shrinkage or changes in temperatures.

3.2. Alvarado et al (2009-2010)

Alvarado et al [15] developed a 3D model with an evolutionary calculation. The objective of this evolutionary calculation is to simulate the actual construction process, from the first day to the last one, and to consider the evolution of concrete mechanical properties during time. The hypothesis adopted for the model were the following:

- Elastic and linear behaviour of slabs and columns, considering the stiffness variation during time.
- Elastic and linear behaviour of shores, formwork boards and joists considering its actual stiffness.
- Foundations are assumed to be of infinite stiffness.
- Creep and shrinkage of concrete elements were not considered. Changes in temperatures of different elements of the structure were not considered either.

ANSYS package [27] was used with the following types of elements: SHELL63 for slabs and formwork boards, BEAM44 for columns and joists and LINK1 for shores. Birth and death option and MPCHG command are allowed for these elements to take into account the evolutionary calculation. Both options are able to considerer different elements on different construction stages and also to change the concrete mechanical properties during time. The FE model consisted of an evolutionary structure where geometry (shores, joists and formwork boards) and material properties (concrete) were changeable during time.

Different load steps were carried out to do an evolutionary calculation in ANSYS. A load step consists of calculating the structure with that geometry and those material properties of each of the different construction stages. Once the first load step is solved, the second load step starts with those stresses and strains got from solving the first step. So the evolution of the structure in the FE model is carried out with as load steps as construction stages a building has. Birth and death options and MPCHG command are used in ANSYS to simulate this evolution. Birth and death option consists of activating and deactivating some elements of the structure. EKILL command deactivates elements reducing the stiffness of the considered element, multiplying it by a small factor. Equally, loads attached to killed elements are 0. On the other hand, EALIVE command is used to activate elements. This command recovers the stiffness and loads of the pre-killed elements. Finally, MPCHG command allows considering the evolution of the concrete elastic modulus during time. This command changes the assigned material of those selected elements.

A FE model comprises 3 phases. The first phase consists of defining the types of elements, material properties, geometry, mesh and the applied loads. Everything is defined in this phase: slabs, columns and the temporary structure. Figure 1 (left) shows the complete FE model once the first phase is finished. The second phase consists of solving the different load steps regarding the different construction stages. Figure 1 (right) shows each of the studied load steps of this case. Results were really fitted [13] to the experimental results in the analysis performed in the third phase (analysis). Alvarado et al concluded that the employed methodology using a FE model is strongly recommended to simulate construction processes of RC building structures during construction.

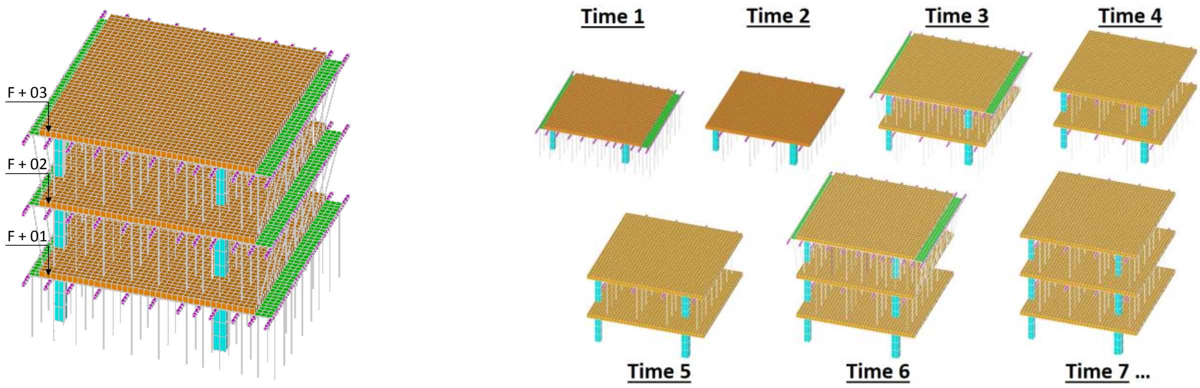

Figure 1. FE model (left) and the studied construction stages (right).

3.3. Gasch et al (2012)

In 2012, Gasch et al [16] followed the employed methodology by Alvarado et al [14]. They performed 3 FE models with 3 different kinds of RC building structures. They analysed, simulated and monitored 3 real buildings with flat-slabs [19], girderless hollow floor slabs [18] and waffle slabs [20]. They also numerically studied with a FE model [17] the ambient temperature effect over the slabs for both uniform increase of temperature and temperature gradients during the construction of the 3 real RC building structures. Other authors had already developed the experimental study about the importance of temperature effects on the load transmission between slabs and shores showing that temperature effects is one of the aspects with more influence. However, this experimental study included, for the first time, the gradient temperature through slabs cross-section and its numerical study using the FE method. Thanks to this numerical study, we know how temperature affects to the load transmission, why it occurs or what the consequences are. For instance, the temperature gradient causes upwards or downwards deflections on slabs inducing less or more loads on shores respectively. For temperature gradients of only 1ºC, load per surface unit on shores changed between 0.13kN/m^2 and 0.34kN/m^2, values which represent a 2% and a 6% of the slab self-weight respectively. Experimentally, temperature gradients as far as 10ºC were registered, showing that the changes of shore loads might represent between 20% and 60% of the slab self-weight.

3.4. Buitrago et al (2015)

In 2015, Buitrago et al [20] introduced a new concept: load limiter on shores. The load limiter was born because of the necessity of increasing safety during construction due to the registered accidental events [5,22,23,26] and the main cause of collapse: overloads on shores [26]. Load on shores are limited to their allowable load when load limiters are installed on shores. If this allowable load is reached, load limiters are able to maintain this allowable load without increasing or decreasing it. Thus, any shore could have a load greater than its allowable load.

Buitrago et al [20] proved its technical and economic viability introducing these load limiters in those numerical models previously developed by Alvarado et al [14] and Gasch et al [16]. Figure 2 shows the construction of the building during casting of the second in a real picture (left) and in the FE model (right). Figure 3 represents ground-floor loads that shores would receive immediately after the casting of the second floor, without load limiters (left) and with load limiters of 16 kN (right).

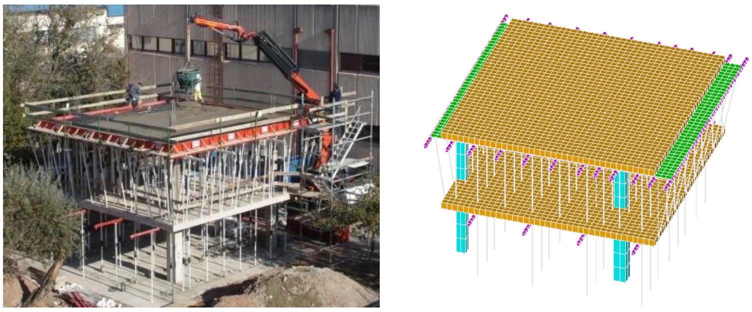

Figure 2. Building under construction during the castif of the second slab (left) and its numerical simulation (right).

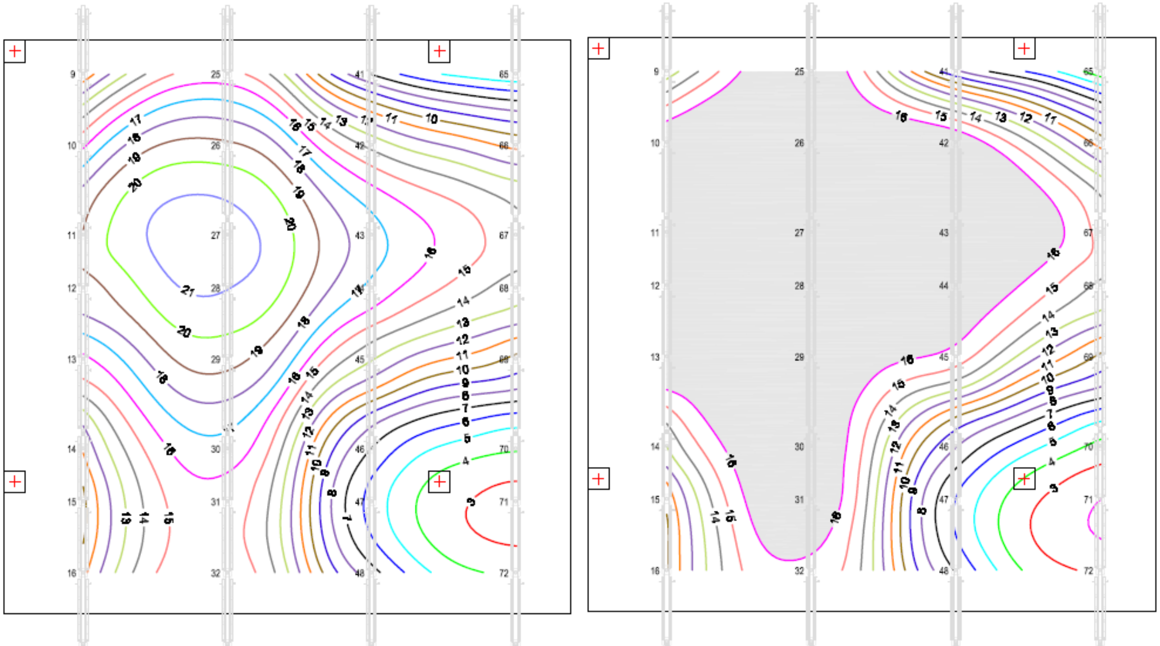

Figure 3. Loads on ground-floor shores without load limiters (left) and with load limiters of 16 kN (right)

As it can be seen, maximum loads on shores when load limiters are not installed are greater than 21 kN, whereas when load limiters of 16kN are installed (more economic shore), every shore under the shaded area is working on its allowable load (16kN), being any shore below its allowable load and taking advantage of the shore resistance of shoring system.

3.5. Currently

Currently, ICITECH is still working on load limiters: its design, fabrication and testing its suitable behaviour. In fact, this device is currently being involved in a protection process (Patent nº P201730339 in the Spanish Patent and Trademark Office on 15th March 2017) so it cannot be shown any images or results.

At the same time, another research line that is now recently opened is the study of the progressive collapse of RC building structures during construction with implicit solvers in ANSYS (Figure 4 left) [28] and with explicit solvers in LS-DYNA package (Figure 4 right) [29]. This last approach is suitable to better consider the dynamic aspects which dominate during the progressive collapse of a structure.

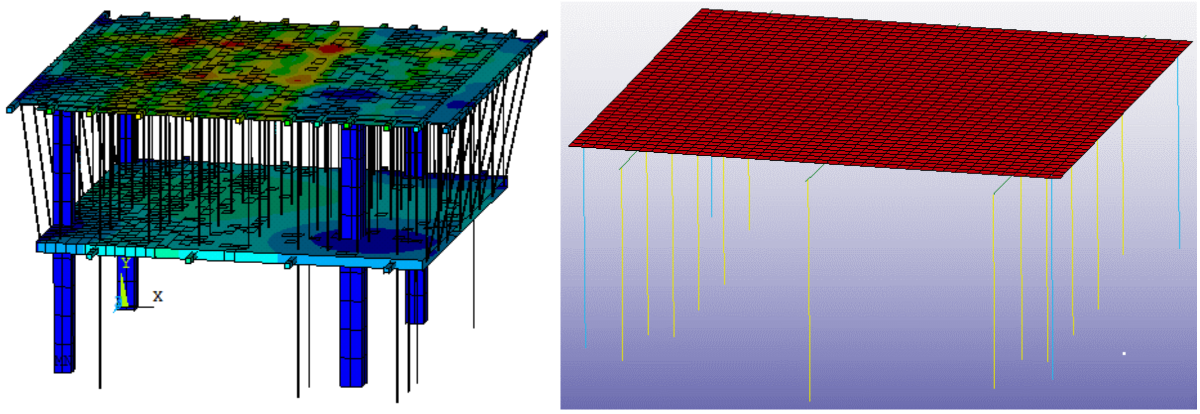

Figure 4. Numerical simulation of the progressive collapse of the shoring system due to a local shore failure: in ANSYS [28] (left) and in LS-DYNA [29] (right).

4 CONCLUSIONS

This paper shows a brief state-of-art regarding the performed numerical studies in the construction of RC building structures using the shoring of successive levels of floors technique. The aim was to give the reader a first-hand account of the tools and advances at present available, encourage their application and thus help to make better building structures. After more than 60 years of numerical studies, it can be seen that these techniques have been substantially improved and that the knowledge of construction processes has been expanded to such an extent that is no longer necessary to go on using techniques created in the mid 20th century to solve this type of problem. In fact, internationally, the FE method is nowadays widely applied and it has allowed calculating construction processes with precision, efficiently and with a better fit to the experimental data.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to the Spanish Ministry of Education, Culture and Sport for funding received under the FPU Program [FPU13/02466], to the GeneralitatValenciana [GV/2015/063] and also to private companies Levantina, Ingeniería y Construcción S.L. and Encofrados J. Alsina S.A. for their invaluable cooperation.

REFERENCES

[1] BIA2004-02085, “Estudio experimental y numérico de la construcción de forjados de hormigón in situ mediante procesos de cimbrado, clareado y descimbrado de plantas consecutivas,” *Res. Proj. - Spanish Minist. Sci. Technol.*, 2004.

[2] M. Buitrago, J. M. Adam, P. A. Calderón, and J. J. Moragues, “On the use of

experimental testing in RC building structures under construction," in *Proceedings of the Ninth International Structural Engineering and Construction Conference*, 2017.
[3] K. Nielsen, "Loads on reinforced concrete floor slabs and their deformations during construction," *Final Report, 15,* Stockholm, 1952.
[4] P. Grundy and A. Kabaila, "Construction Loads on Slabs with Shored Formwork in Multistory Buildings," *J. Proc.*, vol. **60**, no. 12, pp. 1729–1738, Dec. 1963.
[5] J. M. Adam, M. Buitrago, J. J. Moragues, and P. A. Calderón, "Limitations of Grundy & Kabaila's simplified method and its repercussion on the safety and serviceability of successively shored building structures," *J. Perform. Constr. Facil.*, vol. **31**, no. 5, 2017.
[6] X. L. Liu, W. F. Chen, and M. D. Bowman, "Shore-Slab Interaction in Concrete Buildings," *J. Constr. Eng. Manag.*, vol. **112**, no. 2, pp. 227–244, Jun. 1986.
[7] P. C. Stivaros and G. T. Halvorsen, "Shoring/Reshoring Operations for Multistory Buildings," *Struct. J.*, vol. **87**, no. 5, pp. 589–596, Sep. 1990.
[8] K. H. Mosallam and W.-F. Chen, "Determining Shoring Loads for Reinforced Concrete Construction," *Struct. J.*, vol. **88**, no. 3, pp. 340–350, Mar. 1991.
[9] H.-G. Kwak and J.-K. Kim, "Determination of efficient shoring system in RC frame structures," *Build. Environ.*, vol. **41**, no. 12, pp. 1913–1923, Dec. 2006.
[10] J. Díaz, "Criterios técnicos para el descimbrado de estructuras de hormigón," PhD Thesis. Universidad Politécnica de Madrid, 2008. [In Spanish]
[11] J. J. Moragues, J. Catalá Alís, and E. Pellicer Armiñana, "Mediciones en obra y análisis teórico de estructuras de edificación, de hormigón armado, durante el proceso de cimbrado consecutivo de forjados," *Hormigón y acero*, vol. **190**, pp. 83–91, 1994. [In Spanish]
[12] J. J. Moragues, J. Catala, and E. Pelicer, "An Analysis Of concrete Framed Structures During The Construction Process," *Concr. Int.*, vol. **18**, no. 11, pp. 44–48, Nov. 1996.
[13] Y. A. Alvarado *et al.*, "An experimental study into the evolution of loads on shores and slabs during construction of multistory buildings using partial striking," *Eng. Struct.*, vol. **31**, no. 9, pp. 2132–2140, Sep. 2009.
[14] Y. A. Alvarado, "Estudio experimental y numérico de la construcción de forjados hormigonados in situ mediante procesos de cimbrado, clareado y descimbrado de plantas consecutivas.," PhD Thesis - Universitat Politècnica de València. 2009. [In Spanish]
[15] Y. A. Alvarado, P. A. Calderón, I. Gasch, and J. M. Adam, "A numerical study into the evolution of loads on shores and slabs during construction of multistorey buildings. Comparison of partial striking with other techniques," *Eng. Struct.*, vol. **32**, no. 10, pp. 3093–3102, Oct. 2010.
[16] I. Gasch, "Estudio de la evolución de cargas en forjados y estructuras auxiliares de apuntalamiento durante la construcción de edificios de hormigón in situ mediante procesos de cimbrado, clareado y descimbrado de plantas consecutivas.," PhD Thesis - Universitat Politècnica de València. 2012. [In Spanish]
[17] I. Gasch, Y. A. Alvarado, and P. A. Calderón, "Temperature effects on load transmission between slabs and shores," *Eng. Struct.*, vol. **39**, pp. 89–102, Jun. 2012.
[18] I. Gasch, Y. A. Alvarado, P. A. Calderón, and B. Torres, "Transmisión de cargas entre forjados y puntales en un edificio de forjado reticular de casetón perdido utilizando clareado," *Inf. la Construcción*, vol. **65**, no. 530, pp. 195–202, Jun. 2013. [In Spanish]

[19] I. Gasch, Y. A. Alvarado, P. A. Calderón, and S. Ivorra, "Construction loads using a shoring–clearing–striking process," *Proc. Inst. Civ. Eng. - Struct. Build.*, vol. **167**, no. 4, pp. 217–229, May 2015.

[20] M. Buitrago, Y. A. Alvarado, J. M. Adam, P. C. Calderón, I. Gasch, and J. J. Moragues, "Improving construction processes of concrete building structures using load limiters on shores," *Eng. Struct.*, vol. **100**, pp. 104–115, 2015.

[21] P. A. Calderón, Y. A. Alvarado, and J. M. Adam, "A new simplified procedure to estimate loads on slabs and shoring during the construction of multistorey buildings," *Eng. Struct.*, vol. **33**, no. 5, pp. 1565–1575, May 2011.

[22] M. Buitrago, J. M. Adam, Y. A. Alvarado, P. A. Calderón, and I. Gasch, "Maximum loads on shores during the construction of buildings," *Proc. Inst. Civ. Eng. - Struct. Build.*, vol. **169**, no. 7, pp. 538–545, Jan. 2016.

[23] M. Buitrago, J. M. Adam, P. A. Calderón, Y. A. Alvarado, and J. J. Moragues, "Estimating loads on shores during the construction of RC building structures," *Struct. Concr.*, vol. **17**, no. 3, pp. 502–512, Dec. 2016.

[24] M. Buitrago, J. M. Adam, P. A. Calderón, and J. J. Moragues, "Automatic design of building construction processes by simulated annealing. A measure to improve sustainability, time, financial and computational costs," in *Proceedings of the Second International Conference on Concrete Sustainability (ICCS 16)*, 2016, pp. 191–202.

[25] M. Buitrago, J. M. Adam, Y. A. Alvarado, J. J. Moragues, I. Gasch, and P. A. Calderón, "Designing construction processes in buildings by heuristic optimization," *Eng. Struct.*, vol. **111**, pp. 1–10, Mar. 2016.

[26] M. Buitrago, J. J. Moragues, P. A. Calderón, and J. M. Adam, "Structural failures in cast-in-place RC building structures under construction," in *Handbook of Materials Failure Analysis with Case Studies from the Construction Industries*, 1st ed., A. S. H. Makhlouf and M. Aliofkhazraei, Eds. Butterworth-Heinemann, Elsevier, 2017.

[27] ANSYS 15.0, "Theory reference. ANSYS Inc." Theory reference. ANSYS Inc., 2014.

[28] D. Di Palma, "Measures to minimize the risk of progressive collapse of reinforced concrete building structures during construction. Application at buildings with flat slabs," Máster Thesis. Polytechnic University of Valencia, 2017.

[29] LSTC, "LS-DYNA theory manual." Lawrence Software Technology Corporation, Livermore, California, 2012.