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Construction of RC building structures: ICITECH's experience during the last 30 years

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Abstract (150 – 200 words)

This paper contains a summary of the experience obtained by ICITECH’s researchers at the *Universitat Politècnica de València* in the last thirty years of investigating reinforced concrete (RC) building structures under construction. During this period ambitious experimental campaigns and advanced computational simulations have been carried out, and new analytical methods have been formulated to assess slab-shore load transmissions in buildings under construction. From all these campaigns the following main conclusions can be derived: 1) the importance of considering construction processes when planning building projects; 2) the use of analytical methods to evaluate construction processes adapted to the current requirements of efficiency and sustainability; and 3) the need to improve the robustness of temporary shoring or propping structures. Improving the construction sector necessarily involves the implementation of the above measures in buildings under construction and the use of new monitoring and inspection technologies for the construction processes applied.

Keywords chosen from ICE Publishing list
Buildings, Structures & Design; Concrete Structures; Temporary Works.

1. Introduction

The construction of RC building structures and the different processes used to construct them have been widely studied since the mid 20th century (Buitrago *et al.*, 2018b). The method of shoring or propping successive storeys is usually by shoring the last two, three or four floors (Grundy & Kabaila, 1963; Adam *et al.*, 2017). This method allows new slabs to be poured while the newly created loads are shared out between a number of lower floors, which during the construction process may have to support higher loads than those they were designed to resist in their service life, at a time when the lower floors concrete's mechanical characteristics are still below their design level.

From a safety point of view, the fact of receiving high loads combined with the early age of the concrete on the lower floors creates a high-risk situation that is usually greater than any likely to occur in the building's service life and has been the cause of a significant number of historical failures and collapses (Feld, 1974; Hadipriono & Wang, 1987; Kaminetzy & Stivaros, 1994; Peng *et al.*, 1996; Epaarachchi, Stewart & Rosowsky, 2002; Yates & Lockley, 2002; Epaarachchi & Stewart, 2004; Fang *et al.*, 2004; Uzoegbo & Harli, 2010; Yuan & Jin, 2011; Zhang, Rasmussen & Ellingwood, 2012; Kaminetzky, 1976; Buitrago *et al.*, 2018c; Schellhammer, Delatte & Bosela, 2013). This document considers failures as a malfunction of the performance of the structure (e.g. Serviceability Limit States; SLS) whereas collapses are limited to those cases of major failures resulting in debris (e.g. exceeding Ultimate Limit States; ULS). Figure 1(a) shows the possible reasons for structural failures during construction. It can be seen that in first place, with a frequency of 33%, the most common cause of failure is collapse of the shoring or propping system (Buitrago *et al.*, 2018c), which has been known to lead to the collapse of the entire structure, as occurred in the Skyline Plaza in Virginia (Schellhammer, Delatte & Bosela, 2013), or failure in the service and durability conditions with excessive deflections and cracking, which can affect the short- and long-term behaviour of the structure (Adam *et al.*, 2017). Figure 1(b) gives an example of a case in which the shores were buckled but without causing the structure to collapse, while Figure 1(c) shows a slab with excessive deflections and cracking.

The aim of the line of investigation, started by ICITECH's researchers 30 years ago and summed up in this paper, is to improve the safety of RC building structures under construction and involves diverse topics designed to cover the construction industry's current needs as regards shoring and formwork, as well as other questions that so far have not been resolved by the scientific community. The research has opened up new areas that had not been studied previously, such as the particular type and widely used construction process known as partial striking or clearing, studies of the robustness of temporary shoring structures, and establishing mitigation measures against the risk of progressive collapse of buildings under construction. Throughout the years the research has been accompanied by in-depth experimental campaigns and computational simulations that finally formed the knowledge base on which the analytical methods and simplified construction process calculations (described in the following sections) were developed to facilitate the work of practitioners and improve the safety of buildings under construction.

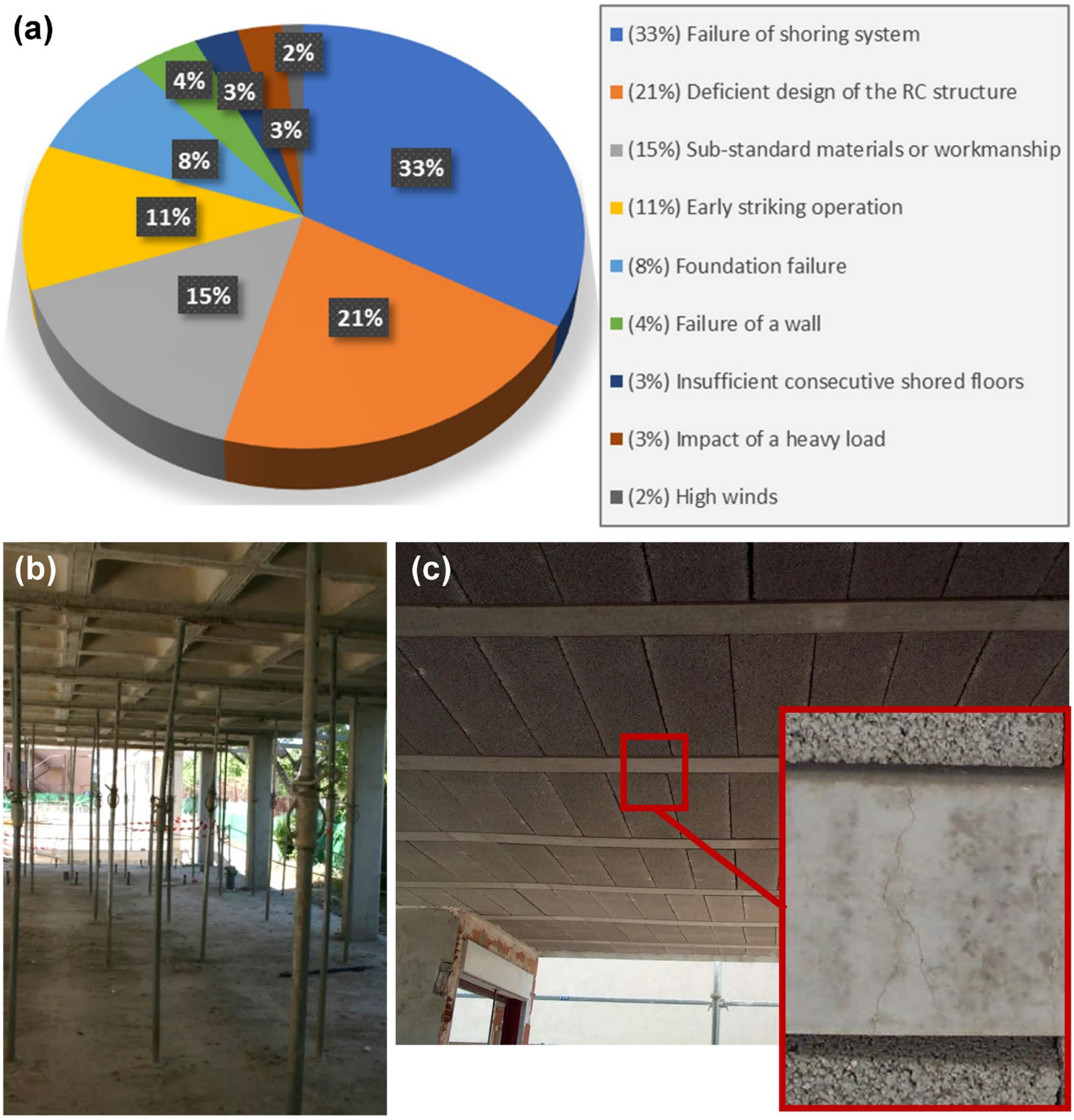


***Figure 1**. Failures*

2. Tests and computational modelling

Figure 2 shows a series of photos of some of the most important tests carried out, while Figure 3 gives the associated computational modelling studies. In the beginning, towards the end of the 1980s, a study was made of the evolution of the mechanical properties of different types of early-age concrete in a variety of environments in order to determine the structural response of buildings in different construction phases. Then, in the early nineties, the shores used in a clearing or partial striking system in actual construction sites were monitored (Moragues, Catalá & Pellicer, 1994) to estimate the real transmission of loads between slabs and shores in order to compare the results with those obtained by computational simulations (Moragues, Catalá & Pellicer, 1996) and simplified calculation methods such as that by Grundy & Kabaila (1963).

After 2004 the work on this line of research intensified, and from 2004 to 2008 a full-scale RC building structure was constructed for purely experimental purposes. This building had 3 single-bay floors with cantilevers on two sides. The main purpose of the experimental study was to analyse the transmission of loads between slabs and shores in a clearing or partial striking system (Alvarado *et al.*, 2009). Figure 2 contains a photo of the building during the pouring of the third floor, which was totally shored, while the second had been cleared. This study also served to validate a finite element model (see Figure 3) and extend the analysis to other types of construction processes (Alvarado *et al.*, 2010).

In the next stage, between 2008 and 2012, a variety of real buildings under construction with flat-slabs, waffle slabs or girderless hollow floor slabs using clearing or partial striking were monitored (Gasch *et al.*, 2013, 2015) and the effects of temperature were analysed in uniform increments or in the form of a gradient on the distribution of loads between slabs and shores (Gasch, Alvarado & Calderón, 2012).

In the final period, from 2012 to 2018, work was done on studying the robustness of temporary shoring structures and mitigating the risks of the collapse of the entire shoring system or even of the entire building (Buitrago, Sagaseta & Adam, 2018). During this time the new load-limiter (LL; see Fig. 2) device was developed (Buitrago *et al.*, 2015, 2018a) and validated in an application to a full-scale RC building test (Buitrago *et al.*, 2021). The device was later patented (Calderón *et al.*, 2017) and put on the market (Encofrados J. Alsina S.A., 2020) and its effectiveness in mitigating the risks of progressive shoring system collapse was confirmed by computational simulations (Buitrago, Sagaseta & Adam, 2020). The load limiter works as a structural fuse to control and limit the load a shore/prop can bear. To limit the load, the LL activates a plastic mechanism with the formation of three hinges at a design limit load, so permitting: (i) the shore/prop to have small vertical deflections: (ii) the limitation of the load of this shore-LL unit and (iii) a transfer of the excessive loads to the neighbouring shores/props via the slabs.

***Figure 2**. Tests.*

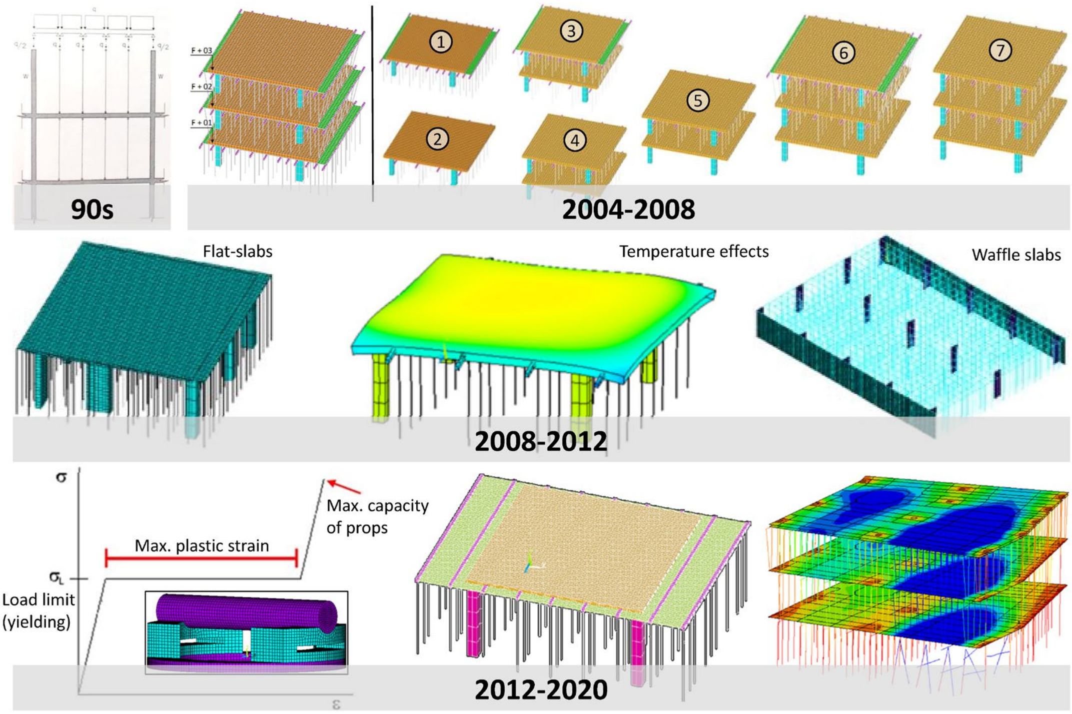


***Figure 3**. Computational modelling.*

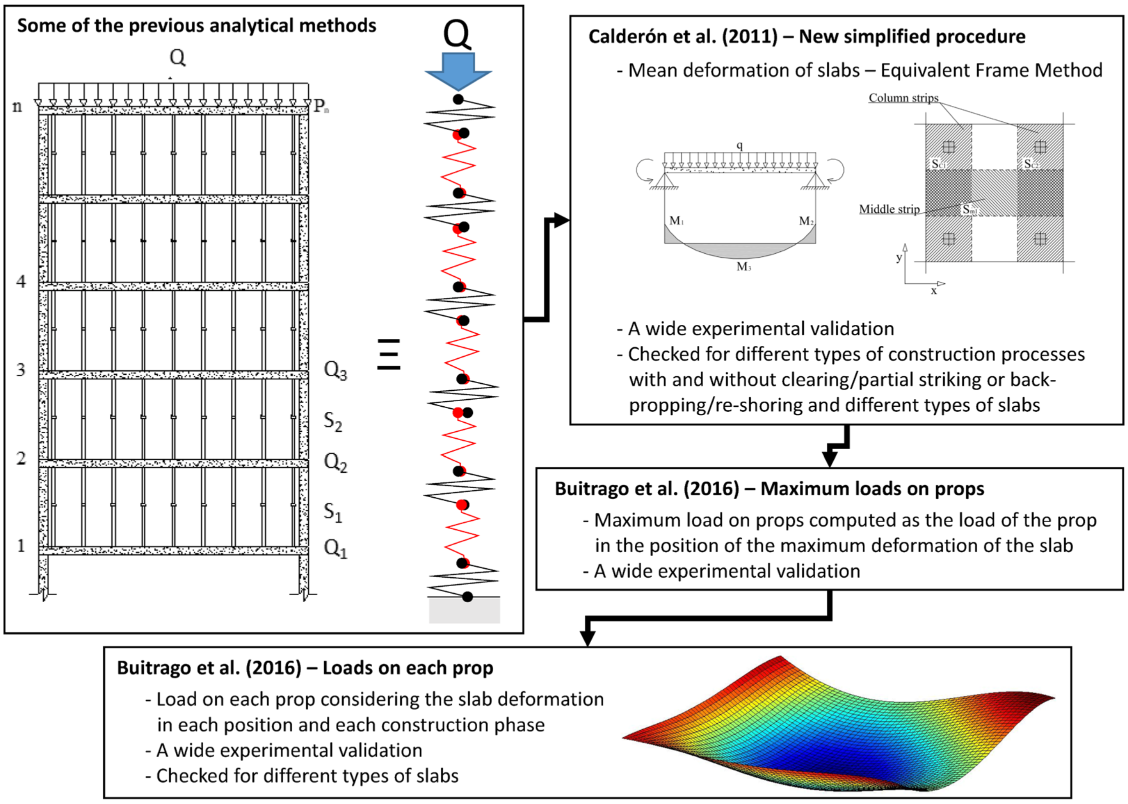
3. Analytical methods

Analytical methods have traditionally been used to make the calculation of complex phenomena easier, especially those with simplified procedures. This is also the case of the construction procedures based on shoring a number of successive floors. Some of the most frequently used methods are those by Grundy & Kabaila (1963), Duan & Chen (1995) and Fang et al. (2001), who simplified all the construction stages into a one-dimensional model of springs arranged in a series to represent the behaviour of individual bays (see Figure 4). However, these methods left a lot of room for improvement and in most cases were not experimentally validated, or were not developed to be applied to certain construction processes such as clearing or partial striking (Adam *et al.*, 2017; Buitrago *et al.*, 2018b). In order to cover these needs, analytical calculation methods were developed in the line of research that was begun more than 30 years ago to estimate slab-shore load transmission and could be adapted to all the existing construction processes. These new analytical methods are based on the whole range of knowledge generated throughout a period of many years in the experimental and computational simulation fields. Figure 4 shows the sequence and briefly describes each of the analytical methods so far developed within the framework of the present line of research.

Calderón, Alvarado & Adam (2011) first developed a new simplified method that significantly improved on its predecessors by considering the actual boundary conditions of individual bays with the help of the Equivalent Frame Method (EFM). In this way the computed mean slab deformation was more realistic and provided better correlation against the experimental results. This simplified method is now being used by formwork manufacturers (e.g. Encofrados J. Alsina S.A. (2020)), is beginning to be recommended in building codes (e.g. Guideline for EHE-08 (2014)) and has been used to design optimal building processes (Buitrago *et al.*, 2016b).

Buitrago et al. (2016a) later proposed a modification to Calderón, Alvarado & Adam's method (2011) to obtain the maximum load on shores, computed as the load on the shore placed in the position of maximum slab deformation.

In the same year, Buitrago et al. (2016c) proposed a second modification to determine the load on individual shores by simplified methods. Before developing this method, the 3D problem was always oversimplified by using 1D analysis, whereas this new method considers the 3D effects. This method was validated by the experimental results from different types of slabs.



Some of the previous analytical methods

Calderón et al. (2011) – New simplified procedure

- Mean deformation of slabs – Equivalent Frame Method
- A wide experimental validation
- Checked for different types of construction processes with and without clearing/partial striking or back-propping/re-shoring and different types of slabs

Buitrago et al. (2016) – Maximum loads on props

- Maximum load on props computed as the load of the prop in the position of the maximum deformation of the slab
- A wide experimental validation

Buitrago et al. (2016) – Loads on each prop

- Load on each prop considering the slab deformation in each position and each construction phase
- A wide experimental validation
- Checked for different types of slabs

Figure 4. Analytical methods.

4. Conclusions

This paper sums up more than 30 years' experience in researching RC building structures in the ICITECH laboratories at the *Universitat Politècnica de València*, including extensive experimental campaigns together with the formulation of new analytical methods to evaluate load transmissions between slabs and shores in buildings under construction. This has allowed us to cover the needs of both the private sector and the scientific community and might also have produced an important impact on the safety of structures and society as a whole. Some recent statistics (Buitrago *et al.*, 2018c) showed that an average of 12.4 collapses are reported every year, involving 2.6 floors each. In addition, an average of 76 deaths and 133 injuries are reported every year. By using the research outputs (new methods to estimate the transmission of loads and load limiters), a 47% of the causes of these collapses could be avoided (see Figure 1), such as those referring to: (i) failure of the shoring system, (ii) early striking operation, or (iii) insufficient consecutive shored floors. Among the main conclusions reached are the importance of using analytical methods to assess the latest construction processes and the need to improve the robustness of temporary shoring structures.

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