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ON THE USE OF EXPERIMENTAL TESTING IN RC BUILDING STRUCTURES UNDER CONSTRUCTION

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The current methods of building reinforced concrete (RC) structures have their origins in the first half of the 20th century. In the early stages, not a great deal of attention was paid to their behaviour under construction and not a lot was known about how loads were transmitted between shores and slabs. This meant that in the late 20th and early 21st centuries, there arose an interest in finding out how building structures behaved in the construction stage, and led to a large number of numerical and experimental studies being carried out. This paper gives a chronological account of the different experimental studies on the construction of RC building structures, together with a detailed research history of ICITECH, which in recent years has been a leader in this field, especially in the use of clearing (partial striking). This compilation of all the experimental studies sets out the objectives of each one, the results obtained, the advances achieved, and how each of them has contributed to the scientific community's present level of knowledge on the behaviour of buildings under construction. Another objective of this paper is to make readers aware of the advances that have made it possible for this knowledge to be effectively applied to the construction of new buildings.

Keywords: Slab, Shores, Loads, Concrete, Safety, Clearing, Partial striking, Reshoring, Formwork, Experimental studies.

1 INTRODUCTION

Shoring successive floors is the method most frequently used to build reinforced concrete (RC) building structures. This method consists of supporting the newly poured slabs, while keeping some of the lower floors totally or partially shored. The weight of the newly poured floor, plus any possible construction live loads, is thus distributed among one or more of the lower floors. Determining the real distribution of loads between shores and slabs is somewhat complicated and the only way to find out what actually happens is to carry out experimental studies. However, in the field of building the cost of carrying out full-scale experiments is not always affordable (BIA2004-02085, Alvarado *et al.* 2009). This is where numerical simulation can play an important role in finding out how structures behave without having to spend large amounts of money. It can also deal with a multitude of study cases which would otherwise be financially impossible. The main problem is encountered when it is required to prove that the results of the numerical models are close to reality, as this can only be confirmed by experimental studies that faithfully reproduce the real situation to calibrate and validate the numerical models (BIA2004-02085, Alvarado *et al*. 2009).

At this point, it is especially interesting to provide the reader with a brief summary of the state of the art of experimental studies on constructing buildings by the shoring of successive floors and is the main novelty of the paper. 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.

Section 2 contains a short description of the state of the art in the form of the experimental studies that have been carried out to date. Section 3 briefly describes the work of 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 in this field for the numerous experimental and theoretical studies it has performed. Finally, a series of conclusions are given in Section 4.

2 A BRIEF STATE OF ART OF EXPERIMENTAL TESTING IN RC BUILDING STRUCTURES UNDER 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 (1952) and especially by Grundy and Kabaila (1963), who developed simplified methods of calculating building structures constructed by shoring successive floors, the method which is still used today. The first experimental study was not carried out until 1974 by Agarwal and Gardner. Later, when interest arose in finding out exactly how loads were transmitted between slabs and shores, a number of experimental studies were carried out (Lasisi and Ng 1979, Ambrose *et al.* 1994, Rosowsky *et al.* 1997, Beeby 2001, Fang *et al.* 2001, Puente *et al.* 2007, Zhang *et al.* 2016).

2.1 Agarwal and Gardner (1974)

Agarwal and Gardner (1974) measured the loads in two buildings under construction in order to observe how loads were actually transmitted between shores and slabs and compared these loads with the expected theoretical loads by applying Grundy and Kabaila's simplified method (1963). Although they only found slight differences, they concluded that further studies including all the factors involved in the construction process would be necessary.

2.2 Lasisi and Ng (1979)

The experimental measurements obtained by Lasisi and Ng (1979) between the 7th and 11th floors of a building were also used to determine whether the simplified method developed by Grundy and Kabaila (1963), which was being used in the construction of all buildings, was valid. They concluded that there was a series of deviations that ought to be corrected and proposed a simple modification to the simplified method which consisted of considering the live construction loads during the concrete pouring phase.

2.3 Ambrose *et al.* (1994)

It is generally accepted that concrete acquires strength and its mechanical properties evolve during the curing process. Applying this phenomenon to building structures, Ambrose *et al.* (1994) wanted to find out how the loads were distributed between slabs and shores during curing, and measured the forces on the shores under a recently poured slab for 72 hours. During this time, they found that these loads became smaller, showing that the slab gradually assumed a larger percentage of the loads as it acquired stiffness.

2.4 Rosowsky *et al.* (1997)

Rosowsky *et al.* (1997) made a complete study of the load transmissions during shoring and striking of a building by simultaneously measuring the loads on the shores in different spans with different geometrical dimensions. The main conclusion they reached was that the loads on the shores were cyclical and tended to diminish with time. In this way, they showed that the variations of the loads on the shores are highly influenced by weather conditions and the gradual acquisition of stiffness by the concrete. They also concluded that the creep effect could be significant.

2.5 Beeby (2001)

Beeby (2001) extensively monitored shores during the construction of a seven-floor building and compared the loads measured with those expected according to Grundy and Kabaila (1963). They were led to conclude that the simplified method overestimated the shore loads, and consequently that the most recently poured slab that supported the shores for the next floor to be poured could be bearing heavier loads than those assumed in the calculations. Based on this study, they proposed a modification to Grundy and Kabaila’s simplified method (1963).

2.6 Fang *et al.* (2001)

Fang *et al.* (2001) made a broad experimental study of a building under construction and when they compared the results with those expected from Grundy and Kabaila’s simplified method (1963) they found differences of up to as much as 27.2%. They therefore proposed a new simplified method with which they found much smaller differences of up to 5.3%. They also confirmed that shore loads under newly poured floors tend to drop during concrete curing and that this variation is cyclical due to the influence of temperature.

2.7 Puente *et al.* (2007)

Puente *et al.* (2007) monitored shores in buildings to study the load transmitted between slabs and shores in successively shored floors. With the results obtained they were able to compare the experimental measurements with those that could be expected from various simplified calculation methods to find those that best fitted their measurements. They also analysed the influence of temperature on load transmission between slabs and shores and obtained variations of up to 3 kN in shore loads.

2.8 Zhang *et al.* (2016)

Zhang *et al.* (2016) monitored shores under newly poured slabs in three different buildings and confirmed that during curing the loads on the shores were reduced due to the increased stiffness of the slabs. They also found a peak load on the shores when the concrete was being poured. Their main conclusion was that loads during construction differed from those in service and should therefore be given different treatment in the calculations. They proposed a change in the code of the combination of loads during building work that allowed for these differences.

3 EXPERIMENTAL STUDIES CARRIED OUT BY ICITECH

This section describes the experimental studies carried out by a leader in research in this field, ICITECH. The first of these were done by Moragues *et al.* (1994). After the approval of a national project in 2004 (BIA2004-02085) and with the cooperation of a number of construction firms, a series of experimental studies were performed under controlled conditions (Alvarado 2009, Alvarado *et al.* 2009) and actual working conditions (Gasch 2012, Gasch *et al.* 2013 and 2015). The group is still working on improving construction processes by means of numerical simulation (Buitrago *et al.* 2015, Adam *et al.* 2017), developing simplified calculation methods (Calderón *et al.* 2011, Buitrago *et al.* 2016a and 2016c), obtaining optimal construction processes (Buitrago *et al.* 2016b) and developing experimental tests. These experimental studies are described below.

3.1 Moragues *et al.* (1994)

Moragues *et al.* (1994) monitored the shores in two buildings in order to study load transmission between slabs and shores in constructions using the habitual Spanish building system. They concluded that the maximum load on shores occurred in the first floor when all the floors were shored from the foundations upwards. However, the maximum load on the slabs was on the last one shored from the foundations upwards, when the number of slabs executed above it is the same as the sets of shores in use. They found the experimental values differed widely from those expected from Grundy and Kabila (1963).

3.2 Alvarado *et al.* (2009)

In order to study slab/shore load transmission using shoring and striking systems, Alvarado *et al.* (2009) constructed an entirely experimental three-storey building from which a large amount of information was obtained which has been used, and is still being used, as the basis for many further studies. Although they confirmed the different conclusions reached up to that time, the test was especially useful for its in-depth analysis of one of the technique most widely used in the Spanish construction industry and exported to the rest of the world: *clearing* or *partial striking*. The authors also used this in-depth study under controlled conditions to create a new simplified calculation method (Calderón *et al.* 2011), which is the latest and the one that best fits the experimental values (Gasch 2012, Gasch *et al.* 2013 and 2015, Buitrago *et al.* 2016b).

3.3 Gasch *et al.* (2012)

After the study by Alvarado *et al.* (2009) under highly controlled conditions, Gasch *et al.* (Gasch 2012, Gasch *et al.* 2013 and 2015) measured the forces on shores in three buildings under real working conditions, each of which was of a different type: flat-slabs, girderless hollow floor slabs and waffle slabs. In this way they were able to extrapolate the conclusions reached by Alvarado *et al*. (2009) to real cases and found that the simplified method that best fitted with the values they obtained was the one proposed by Calderón *et al.* (2011). They also made an in-depth study of the influence of temperature on slab/shore load transmission (Gasch *et al.* 2012), measuring both ambient temperatures and the temperature gradients in the slab concrete.

3.4 Current Work

ICITECH is still working along this research line in order to optimise construction processes using load limiters on shores. The load limiting concept, which is at present being patented, was first introduced by Buitrago *et al.* (2015). It is designed to improve safety during building work, make financial savings of between 30 and 40% in the cost of shoring and improve structural efficiency. The device is at present being used in a full-scale building under construction in the laboratory of ICITECH under controlled conditions before being put on the market.

4 CONCLUSIONS

This article includes a brief summary of the state of the art of experimental studies related to constructing buildings by the successively-shored floors method. 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 40 years of experimental 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.

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References

Adam, J. M., Buitrago, M., Moragues, J. J., and Calderón, P. A., Limitations of Grundy & Kabaila's Simplified Method and its Repercussion on the Safety and Serviceability of Successively Shored Building Structures, *Journal of Performance of Constructed Facilities*, 2017.

Agarwal, R., and Gardner, N. J., Form and Shore Requirements for Multi-Story Flat Slab Type Buildings, *Journal Proceedings*, 71(11), 559–569, 1974.

Alvarado, Y. A., 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].

Alvarado, Y. A., Calderón, P. A., Adam, J. M., Payá-Zaforteza, I. J., Pellicer, T. M., Pallarés, F. J., and Moragues, J. J., An Experimental Study into the Evolution of Loads on Shores and Slabs During Construction of Multistory Buildings using Partial Striking, *Engineering Structures*, 31(9), 2132–2140, 2009.

Ambrose, T. P., Houston, D. R., Fuhr, P. L., Devino, E. A., and Werner, M. P., Shoring Systems for Construction Load Monitoring, *Smart Materials and Structures*, IOP Publishing, 3(1), 26–34, 1994.

Beeby, A. W., The Forces in Backprops During Construction of Flat Slab Structures, *Structures and Buildings*, 146(3), 307–317, 2001.

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, *Research project - Spanish Ministry for Science and Technology*, 2004.

Buitrago, M., Adam, J. M., Alvarado, Y. A., Calderón, P. A., and Gasch, I., Maximum Loads on Shores During the Construction of Buildings, *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, Thomas Telford Ltd, 169(7), 538–545, 2016a.

Buitrago, M., Adam, J. M., Alvarado, Y. A., Moragues, J. J., Gasch, I., and Calderón, P. A., Designing Construction Processes in Buildings by Heuristic Optimization, *Engineering Structures*, 111, 1–10, 2016b.

Buitrago, M., Adam, J. M., Calderón, P. A., Alvarado, Y. A., and Moragues, J. J., Estimating Loads on Shores During the Construction of RC Building Structures, *Structural Concrete*, 17(3), 502–512, 2016c.

Buitrago, M., Alvarado, Y. A., Adam, J. M., Calderón, P. A., Gasch, I., and Moragues, J. J., Improving Construction Processes of Concrete Building Structures Using Load Limiters on Shores, *Engineering Structures*, 100, 104–115, 2015.

Calderón, P. A., Alvarado, Y. A., and Adam, J. M., A New Simplified Procedure to Estimate Loads on Slabs and Shoring During the Construction of Multistorey Buildings, *Engineering Structures*, 33(5), 1565–1575, 2011.

Fang, D. P., Zhu, H. Y., Geng, C. D., and Liu, X. La., On-Site Measurement of Load Distribution in Reinforced Concrete Buildings During Construction, *ACI Structural Journal*, 98(2), 157–163, 2001.

Gasch, I., 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].

Gasch, I., Alvarado, Y. A., and Calderón, P. A., Temperature Edfects on Load Transmission Between Slabs and Shores, *Engineering Structures*, 39, 89–102, 2012.

Gasch, I., Alvarado, Y. A., Calderón, P. A., and Ivorra, S., Construction Loads Using a Shoring–Clearing–Striking Process, *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, Thomas Telford Ltd., 2015.

Gasch, I., Alvarado, Y. A., Calderón, P. A., and Torres, B., Transmisión de cargas entre forjados y puntales en un edificio de forjado reticular de casetón perdido utilizando clareado, *Informes de la Construcción*, 65(530), 195–202, 2013.

Grundy, P., and Kabaila, A., Construction Loads on Slabs with Shored Formwork in Multistory Buildings, *Journal Proceedings*, 60(12), 1729–1738, 1963.

Lasisi, M., and Ng, S., Construction Loads Imposed on High-Rise Floor Slabs, *Concrete International: Design and Construction, ACI*, 1979.

Moragues, J. J., Catalá Alís, J., and Pellicer Armiñana, E., Mediciones en obra y análisis teórico de estructuras de edificación, de hormigón armado, durante el proceso de cimbrado consecutivo de forjados, *Hormigón y acero*, Asociación Científico-Técnica del Hormigón Estructural (ACHE), 1994.

Nielsen, K., Loads on Reinforced Concrete Floor Slabs and Their Deformations During Construction, *Final Report, 15*, Stockholm, 1952.

Puente, I., Azkune, M., and Insausti, A., Shore–Slab Interaction in Multistory Reinforced Concrete Buildings During Construction: An Experimental Approach, *Engineering Structures*, 29(5), 731–741, 2007.

Rosowsky, D. V., Philbrick, T. W., and Huston, D. R., Observations from Shore Load Measurements during Concrete Construction, *Journal of Performance of Constructed Facilities*, American Society of Civil Engineers, 11(1), 18–23, 1997.

Zhang, H., Reynolds, J., Rasmussen, K. J. R., and Ellingwood, B. R., Reliability-Based Load Requirements for Formwork Shores During Concrete Placement, *Journal of Structural Engineering*, American Society of Civil Engineers, 142(1), 4015094, 2016.