Load transmission between slabs and shores during the construction of RC building structures - A review

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Abstract

Shoring successive floors is at present the most frequently used technique when constructing reinforced concrete (RC) building structures. This technique allows the recently poured slabs to be supported by the lower slabs by means of shores. Considering the particular characteristics of shoring successive floors, it is very important to be able to estimate how loads are transmitted between shores and slabs in order to maintain adequate structural safety and avoid situations of risk or even collapse in buildings under construction. The transmission of loads from shores to slabs during all the construction stages is a complex phenomenon and has been the subject of numerous studies, especially in recent years. The research carried out to date has included experiments on full-scale buildings and the development of advanced numerical models, the estimation of the loads acting on slabs during construction, the definition of simplified calculation methods to estimate loads on slabs and shores during building construction and estimating the appropriate construction times taking into account the evolution of the mechanical properties of early-age concrete. This paper was conceived in order to give an answer to: 1) advances in the field of constructing RC building structures, 2) the growing interest of the scientific community, and 3) the need for the structural and construction engineering sector to have the tools available to increase the safety and design of building construction processes. The paper is unique in the field of RC building structures in that it is the widest, most complete and most ambitious review carried out to date and includes the most important advances in the study of slab-shore load transmissions. This work will be of interest

to researchers who wish to go deeper into the field of building construction, and to more experienced professionals who require all the up-to-date information in a single document. However, engineers, architects and builders could also find the paper an excellent guide that will help them to improve their daily work in the field of designing and constructing buildings.

Keywords*: Building, Slabs, Formwork, Shores, Construction, State-of-the-Art*

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1. Introduction

Shoring successive levels of 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. This construction method allows the option of choosing from a number of variations, each one involving different operations on each floor: shoring/striking (SS), shoring/clearing/striking (SCS) or shoring/reshoring/striking (SRS). A scheme of the operations in these three variants can be seen in Fig. 1 up to the shoring of the third floor, with two successively shored floors. The shoring and striking operations are always present to support the new slab and remove the shores at the right time, respectively, although intermediate operations, such as clearing or reshoring, can also be used. Clearing (or partial striking) consists of removing more than 50% of the shoring components, without completely striking the slab, a few days after pouring. On the other hand, reshoring consists of removing all the shores under the slab some days after pouring and re-installing them to help support subsequent load increases. One or other of these intermediate operations is often used, thus recovering a large proportion of the materials (formwork boards, joists and shores) for later use in building the upper floors.

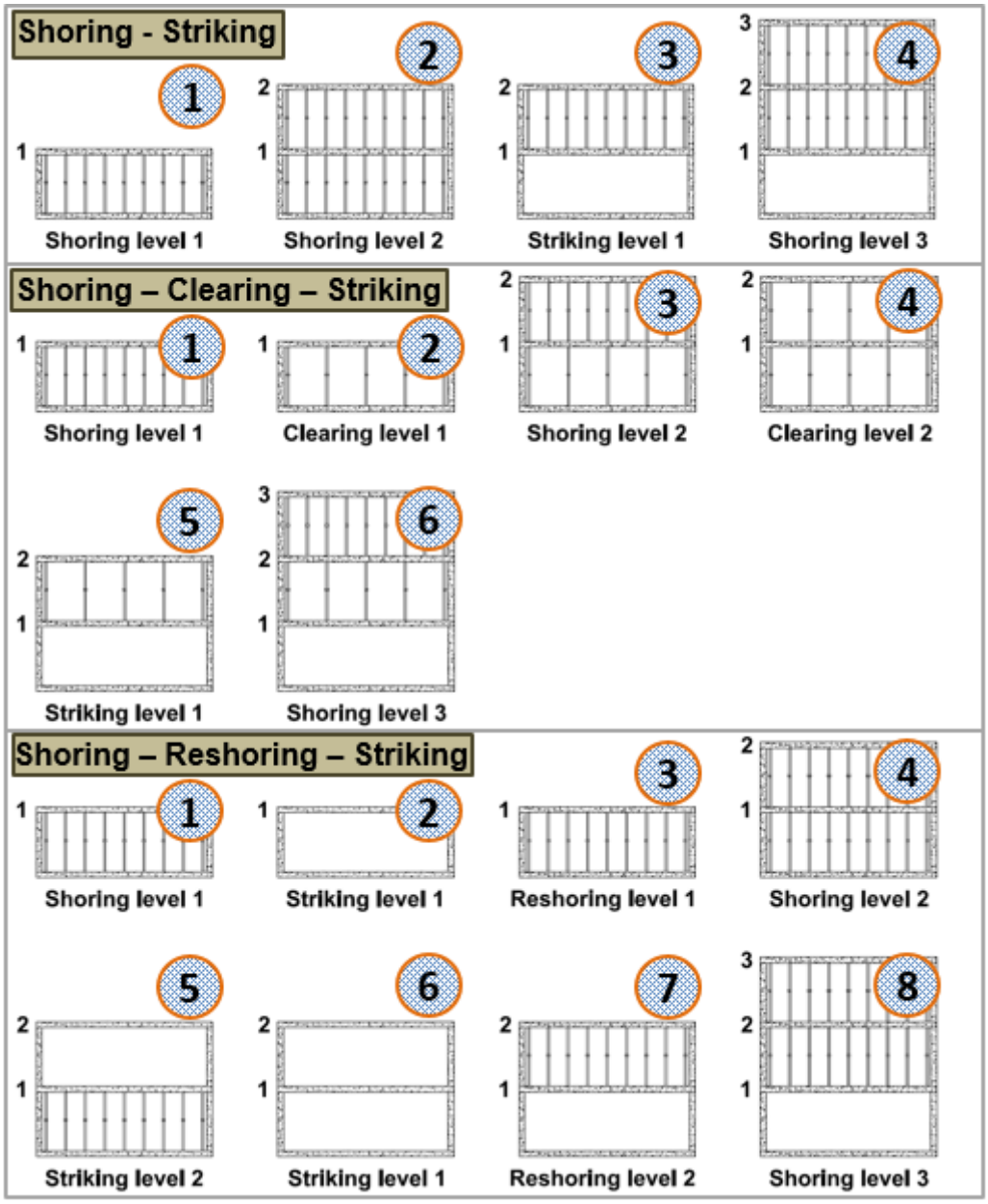

Fig. 1. Types of construction processes most often used: shoring/striking (SS), shoring/clearing/striking (SCS) and shoring/reshoring/striking (SRS).

Discovering how the loads are transmitted between shores and slabs in a building under construction is quite a complex problem and has been studied by many authors. Although experimental studies are the only way to really know how these loads are transmitted, full scale experimental tests are extremely costly and are not be justified in most cases. In situations like this, numerical studies come into their own, as they can be used to simulate the behaviour of a building under construction, without the need to use expensive resources. They can also be used

to study many other cases that would otherwise be impossible due to their excessive cost. In addition, the calculation methods, especially the simplified methods, can be used by professional engineers and practitioners, thus transferring the knowledge generated by researchers to the actual construction of building structures.

This paper presents an ambitious review, including all calculation methods, experimental and numerical studies carried out to date that analyse and determine slab-shore load transmissions during the construction of RC building structures. The review gives the present state of the topic, promotes the application of recent developments and indicates where future research should lead. Due to the scope and magnitude of the work involved, the paper is expected to be of use to research groups in the field of RC building structures, as well as to engineers and architects in their day-to-day design and construction of building structures.

The paper is organised as follows: Section 2 explains the importance of knowing the magnitude and distribution of the loads generated during construction. Section 3 reviews all the approaches to estimating slab-shore load transmissions during the construction of RC building structures so far proposed. Section 4 offers an extensive collection of all the experimental studies performed. Section 5 gives a selection of numerical studies, divided into: those that study load transmissions without including the effects of temperature, shrinkage and creep (Section 5.1); those that do consider shrinkage and creep (Section 5.2); and those that include temperature (Section 5.3). Finally, Section 6 offers the conclusions drawn from the review and suggests some lines of work-research which will need to be dealt with in the future.

2. The importance of being aware of the magnitude and distribution of existing loads during the construction of a building

Through the years there have been a large number of accidents and collapses of building structures under construction. Different authors have collected and highlighted the main causes of these collapses and their possible mitigation measures. Some of the most important include: Feld [1] in 1974, Carper [2], and Hadipriono & Wang [3] in 1987, Eldukair & Ayyub [4] in

1991, Kaminetzy&Stivaros[5] in 1994 and Khudeira [6] in 2010. More recently, Buitrago et al [7] made an exhaustive review of the structural failures reported in such accidents between 2012 and 2017, together with an extensive compilation of the causes of the collapses and mitigation measures for the existing risks.

One of the most important and widely studied aspects of reducing the risk of failure or collapse of buildings under construction is the magnitude and distribution of the dead and live loads that may be found. Both the magnitude and spatial distribution of live loads have a higher degree of associated uncertainty and, in fact, live loads have received most attention from the scientific community. In 1994 Karshenas & Ayoub [8,9] developed a stochastic model to determine the correct uniformly distributed load that must be applied to produce the same effect as the actual live loads. In the same year Rosowsky et al [10] analysed how different concrete placement patterns affected the loads on the structure. In 1998 Kothekar [11] monitored the loads on shores during and after pouring in order to study the magnitude of the dead and live loads. Later, in 2002 Rosowsky & Stewart [12] developed a probabilistic model to determine the loads under construction considering peak loads, probabilistic distributions and live loads (constant, material stacking and move-in loads). In 2002, Zhang et al [13] made a statistical analysis of live loads with the aim of recommending an appropriate value for the construction phase, while in 2007 Peng et al [14] studied the spatial distribution, form and time dependence of loads on a shoring system in different configurations. In 2011, Zhao et al [15] studied the variations recorded in dead loads and recommended standard values for the live loads. Between 2011 and 2015 Xi et al [16–18] measured the loads on the shoring system during the construction of buildings and proposed statistical methods of determining and considering dead and live loads. In 2016, Zhang et al [19] measured the loads on the shores of three buildings under construction and statistically determined and characterized the magnitudes of the loads received by the shores before and after pouring of the concrete.

In spite of the effort involved in all these studies, the most important international standards and codes [20–23] have traditionally established, and still lay down today, different and variable

criteria as regards: a) magnitude of live loads during construction, and b) load factor of the dead and live loads. In view of the disparity of these criteria, the importance of the magnitude of design loads plus the quantity of failures and collapses that have actually occurred, many authors have studied the reliability and safety of building structures under construction. Webster [24], in 1980, proposed a method of determining the reliability of multi-storey flat slab structures during construction. A few years later in 1987 Ellingwood [25] studied the effects of errors in the design and construction phases on the reliability of building structures under construction. In 1992, Mosallam & Chen [26] applied an analytical method to test the adequacy of slabs and shores during construction. In 2002 and 2004 Epaarachchi et al [27,28] developed a probabilistic model to estimate the likelihood of building structures collapsing under construction with a large number of variables (number of consecutively shored floors, construction cycle, concreting workmanship, concrete grade, number of floors in the building and human errors). Also in 2004, Fang et al [29] developed a method of calculating the probability of structural failure of buildings during construction, based on previous models and Monte Carlo simulations. Later, in 2011, Yuan & Jin [30] proposed a model to analyse the reliability of structures under construction, bearing in mind that shoring is a time-dependent supporting system also affected by human errors. A year later, Zhang et al [31] analysed the reliability of buildings under construction using previously published shore load surveys. In 2013, Rubio-Romero et al [32] analysed the safety conditions of shoring systems during the construction of 105 buildings. In 2016 Zhang et al [19] assessed the reliability of temporary shoring structures designed by the allowable stress design and limit state design and proposed an optimal load combination for dead and live loads. Recently, Buitrago et al [7,33,34] and Di Palma [35] stressed the importance of safety during building work and how it could be improved by fitting load limiters to shores.

The transmission of loads between slabs and shores depends on many variables (time-dependent geometry and mechanical properties of permanent and temporary structures). Many authors have focused on determining exactly how these loads are transmitted, since it is

considered to be a crucial aspect for the correct design of both permanent and temporary structures. Below, the review deals with these aspects in greater detail, dividing the studies into: a) methods of estimating load transmission between slabs and shores during the construction of RC building structures, b) experimental studies and c) numerical studies. Figure 2 shows the distribution of the papers in this field indexed in Scopus and Web of Science. The research groups responsible for these publications belong to: Australia, Brazil, Canada, China, Portugal, South Korea, Spain, Sweden, USA and the United Kingdom. In all these countries the studies carried out were transformed into published papers. Figure 2 gives precisely the numbers of papers published in each country, while Figure 3 shows their evolution. Interest in the subject (slope of the curve) can be seen to have increased from about halfway through the 20th century up to the present time.

Fig. 2. Regional distribution of research on load transmission between slabs and shores.

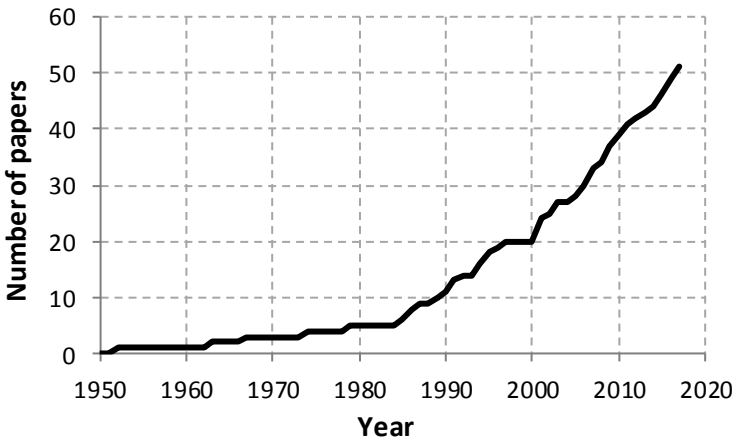

Fig. 3. Accumulated number of published papers.

3. Methods of estimating load transmission between slabs and shores during the construction of RC building structures

Diverse methods of estimating slab-shore load transmissions during the construction of RC building structures have been proposed up to the present time. Nielsen [36] in 1952 and Grundy & Kabaila [37] in 1963 made the first theoretical studies developing simplified methods for the design of the construction of building structures by means of consecutively shored floors. The method of Grundy & Kabaila [37] was hailed as revolutionary and after its publication quickly became the most widely used method, since it was fast and easy to apply. The most important hypothesis on which it was based was that the shoring system was infinitely stiff. Later, other authors [38–46] showed that this hypothesis led to overestimating the loads on shores and underestimating those on slabs during the various construction phases. In 1967 Taylor [47] extrapolated Grundy & Kabaila's method to the reshoring case.

It was not until 1986 that Liu et al [48] proposed a method that considered: a) shores as elements of finite stiffness, b) differing boundary conditions in the slabs (internal, end and corner bays), c) time-dependent stiffness of slabs, and d) the non-deformability of columns. In the same year Aguinaga & Bazant [49] developed a new method that considered the phenomenon of concrete shrinkage. Later, in 1991, Mosallam & Chen [40] proposed another method in which the loads transmitted between slabs and shores was calculated twice for each

operation, at the start and end of each construction phase, given the time-dependent stiffness of slabs. A year later, El-Shahhat & Chen [50] proposed a method that divided the analysis into two parts: a) using Liu's method for the pouring phase, and b) considering the compatibility of displacements between slabs and shores to determine the load transmitted from one element to another.

In 1995, Duan & Chen [41] developed an improved and more complex method that could make a one-dimensional analysis of each bay in a building with the following hypotheses: a) compatibility of displacements exists between slabs and shores, b) shores as elements of finite stiffness, c) slab stiffness varies with time, d) the model is incremental, i.e. it allows for construction in phases, considering the accumulated loads and displacements, e) slab deformability is modified by a factor that considers the different boundary conditions.

In 2001, Beeby [43] proposed two simplified methods of obtaining the loads transmitted between slabs and shores: a) taken directly from the author's load value proposed for slabs and shores, according to the construction phase involved, or b) by a new calculation method to obtain the load on the shoring system, based on Grundy & Kabaila's simplified method but assuming shores as elements of finite stiffness and time-dependent stiffness of slabs. Also in 2001, Fang et al [51] developed a method that considered a 2-D multilayer structure of slabs interconnected by shores regarded as a time-dependent structure. As an additional hypothesis to those of Duan & Chen [41], they considered variations in slab stiffness during concrete curing, re-distributing the stresses especially on the newly poured slabs. Fang et al [52] re-formulated their method in 2009 to work with a one-dimensional method. In 2003 Prado et al [53] proposed a new method similar to Duan & Chen's, although simpler, to analyse the slab-shore load distribution. In 2005 Kajewski [54] proposed a modification of Grundy & Kabaila's simplified method to allow for post-tensioned slabs. In 2011 Park et al [55] developed a frame model considering shore stiffness, different boundary conditions and concrete cracking.

Finally, in 2011 Calderón et al [46] developed a new method that, besides Duan & Chen's hypotheses, considered the following: mean slab deformation coincides with mean shoring

system deformation, and b) slab deformability considering the different boundary conditions (internal, end and corner bays) is evaluated by the "Equivalent Frame Method" defined by Scanlon and Murray [56]. Among many other applications, this method has been used to obtain optimal construction processes [57,58]. Buitrago et al [59,60] recently proposed two different reformulations of the method proposed by Calderón et al. The first [59] is the simplest and can evaluate, besides slab-shore load transmissions, the load on the shore over the maximum slab deformation point. The second [60], for the first time, also allows the load to be calculated on each shore in each building operation. Table 1 contains a summary of all the proposed calculation methods formulated up to the present time.

Table 1. Methods.

References	Year	Country
Nielsen [36]	1952	Sweden
Grundy & Kabaila [37]	1963	Australia
Taylor [47]	1967	Australia
Liu et al [48]	1986	USA
Aguinaga & Bazant [49]	1986	Spain-USA
Mosallam & Chen [40]	1991	USA
El-Shahhat & Chen [50]	1992	USA
Duan & Chen [41]	1995	USA
Beeby [43]	2001	UK
Fang et al [51]	2001	China
Prado et al [53]	2003	Brazil
Kajewski [54]	2005	Australia
Fang et al [52]	2009	China
Park et al [55]	2011	South Korea
Calderón et al [46]	2011	Spain
Buitrago et al [59]	2016	Spain
Buitrago et al [60]	2016	Spain

4. Experimental studies

The first experimental study was carried out by Agarwal & Gardner [61] in 1974. Two buildings under construction were monitored to observe how loads were transmitted between slabs and shores. The deviations between the mean and the loads estimated by Grundy & Kabaila's simplified method [37] were quite small in the two specific cases studied.

In 1979 the experimental measurements obtained by Lasisi and Ng [62] in the 7th to 11th floors of a building also served to confirm the validity of Grundy& Kabaila's method. The results showed a series of deviations, which, according to Lasisi & Ng, ought to be corrected by

a small modification to the simplified method, considering the construction live loads during the pouring phase.

It is widely accepted that concrete progressively acquires strength and that its mechanical properties evolve during the curing process. Applying these conditions to the construction of building structures, in 1994 Ambrose et al [63] observed the load distributions between slabs and the shoring system during curing. They fitted sensors to some shores below a newly poured slab to record their loads for a period of 72 hours, during which time the loads were seen to decrease, showing that the slab assumed higher load percentages as its stiffness increased.

In 1994 Moragues et al [64] installed sensors on shores in two buildings to study slab-shore load transmissions, considering building processes with clearing for the first time. The results showed that: a) maximum load on shores occurs on the ground floor with the maximum number of shored floors down to the foundations; b) maximum load on slabs occurs on the last slab to be shored down to the foundations with the maximum number of shored floors above it; and c) the values estimated by Grundy & Kabila's method were far removed from the experimental results, which indicated that this method ought not to be used at least when clearing is included in the processes.

In 1997 Rosowsky et al [65] made a complete study of load transmissions by recording the loads on shores in geometrically different bays. The load measured on the shores presented a cyclical variation with a tendency to reduce with time. These variations showed that: a) the loads on slabs and shores are greatly influenced by weather conditions, and b) the slab concrete acquires stiffness with time and thus gradually unloads the shores.

In 2001 Beeby [43,66] performed an extensive measurement campaign on shores during the construction of a 7-storey building. When the results were compared with those obtained from Grundy & Kabaila's simplified method it was found that the latter overestimated the loads on the shores. Based on this experimental study, Beeby proposed a new method (described in Section 3). In the same year Fang et al [44] made an in-depth study of a building under construction. When the results measured were compared with those estimated by Grundy &

Kabaila's method, very high deviations of up to 27.2% were found. According to the authors, the formulation of a new calculation model (Fang et al [51], see Section 3) reduced the differences to values below 5.3%. This study also confirmed that: a) during curing there is a tendency for loads on shores to reduce beneath a newly poured slab, and b) these loads vary cyclically due to the influence of temperature.

In 2003 Vollum [67] compared the loads registered on shores in two buildings with estimations made by a finite elements model and Beeby's predictions. To allow for slab cracking during construction, Vollum recommended reducing the concrete elasticity modulus when estimating loads on shores.

In 2007 Puente et al [68] fitted sensors to shores in two buildings to study how loads were transmitted from slabs to shores on consecutively shored floors. The comparison of the experimental results with those of various simplified calculation methods identified the methods that made the best predictions. In the same year Azkune et al [69] analysed the influence of temperature on slab-shore load transmissions and obtained variations of up to 3kN in the load on a shore. In 2010 the same authors [70] made an experimental study of the possible overloads on shores during striking.

In 2009 Alvarado et al [45,71] constructed a three-storey building for entirely experimental reasons. A great deal of data was obtained from these tests that was used, and is still being used, to carry out further studies. An in-depth study was included of one of the most frequently used construction techniques in Spain and exported to the rest of the world: clearing or partial striking. The authors also took advantage of the experiment, carried out under strict control, to develop a new simplified calculation method [46] (see Calderón et al in Section 3), which is one of the latest techniques and also the one which gives the best fit with experimental measurements [57,72–74].

In 2011 Park et al [55] measured the loads on shores in a building under construction with the aim of fitting and validating the correct behaviour of their simplified method (see Section 3).

In 2012 Gasch et al [72–75] measured loads on shores under actual conditions in three buildings under construction, each one with different types of slab: flat-slabs, girderless hollow floor slabs and waffle slabs. This broad experimental study could be used to extrapolate the conclusions reached by Alvarado et al [45,71] to real cases and confirm that Calderón et al's simplified method [46] was the one that best fitted experimental results. The results obtained also showed that ambient temperature significantly affects the loads transmitted between slabs and shores [75]. The effect of temperature on these transmissions was due to: a) uniform changes in temperature with a clearly cyclical day and night component, and b) the strong influence of temperature gradients at different depths in the slab, causing it to rise or fall according to the type of gradient and thus affecting slab-shore load transmissions.

In 2014 Huang & Liu [76] studied the effect of day-night temperature variations by continuously measuring loads on shores and ambient temperature. The results were used to develop new structural models of RC structures during construction and develop new software for a safety analysis during construction considering temperature.

Finally, in 2016 Zhang et al [19,77] fitted sensors to shores under newly poured slabs in three different buildings and confirmed that loads on shores drop during curing as slab stiffness rises. They also recorded a peak load on the shores during pouring due to the live loads involved. The experimental study's main conclusion was that construction loads are of a different type to in-service loads and should therefore be considered differently in the design phase. As has been mentioned above (see Section 2), Zhang et al proposed a new load combination for construction phase to allow for these differences. Table 2 summarises the experimental studies carried out to date.

Table 2. Experimental studies.

References	Year	Country
Agarwal & Gardner [61]	1974	Canada
Lasisi & Ng [62]	1979	Canada
Ambrose et al [63]	1994	USA
Moragues et al [64]	1994	Spain
Rosowsky et al [65]	1997	USA
Beeby [43,66]	2001	UK
Fang et al [44]	2001	China
Vollum et al [67,78]	2002-2003	UK
Puente et al [68]	2007	Spain
Azkune et al [69,70]	2007-2010	Spain
Alvarado et al [45,71]	2009	Spain
Park et al [55]	2011	South Korea
Gasch et al [72–75]	2012-2015	Spain
Huang & Liu [76]	2014	China
Zhang et al [19,77]	2016	Australia

5. Numerical studies

The more advanced numerical studies did not start until the late eighties. Until then, the proposed simplified calculation methods (see Section 3) had provided estimates that were considered fairly close to the real loads. However, the first experimental studies (see Section 4) showed that slab-shore load transmission was a complex problem that needed to be analysed in greater detail. The numerical studies performed to date are divided into: a) those that studied slab-shore load transmission without considering the effects of temperature, shrinkage or creep, and b) those that considered shrinkage and creep, c) those that considered temperature. Table 3 contains a list of the numerical studies carried out.

Table 3. Numericalstudies.

References (Load transmission)	Year	Country
Liu et al [38,79]	1985-1989	China-USA
Stivaros & Halvorsen [39]	1990	USA
Moragues et al [42]	1996	Spain
Kajewski [54]	2005	Australia
Kwak & Kim [80]	2006	Korea
Díaz [81]	2008	Spain
Alvarado et al [71,82]	2009-2010	Spain
Gasch et al [72–74]	2012-2015	Spain
Buitrago et al [33]	2015	Spain
Adam et al [83]	2017	Spain
References (Creep and shrinkage effects)	Year	Country
Aguinaga & Bazant [49]	1986	Spain-USA
Liu & Chen [84]	1987	China-USA
Mosallam & Chen [40]	1991	USA
Lee et al [85]	1991	China-USA
Duan & Chen [86]	1995	USA
Kwak & Kim [87]	2006	Korea
Xi et al [88]	2007	China
Fang et al [89]	2009	China
References (Temperature effects)	Year	Country
Fang et al [89]	2009	China
Gasch et al [75]	2012	Spain
Huang & Liu [76]	2014	China
Simavorian et al [90]	2017	Portugal

5.1. Load transmission without considering temperature, creep or shrinkage effects

Towards the end of the eighties Liu et al [38,79] developed a 3-dimensional numerical model with the following hypotheses: a) elastic shore and slab behaviour, b) time-dependent stiffness of slabs, c) different boundary conditions of slabs (continuous in all directions, continuous in one direction and isolated), d) non-deformable columns, and e) infinitely stiff foundations. The results obtained showed that Grundy & Kabaila's simplified method was suitable for predicting loads in the construction process, although a coefficient from 1.05 to 1.10 could be used to conservatively correct the results of this simplified method.

Later, in 1990, Stivaros & Halvorsen [39] proposed the Equivalent Frame Method (EFM) to calculate slab-shore load transmissions by a 2-D model. The model hypotheses were: elastic shore behaviour, b) a simply supported slab-shore connection, c) infinitely stiff foundation, d) different boundary conditions (isolated bay and set of three bays), and e) slabs and columns considered as beam-type elements. The results showed differences over 5% higher than the results obtained from Grundy & Kabaila and Liu et al's simplified method. According to the

authors, to avoid serious errors it was also important and necessary to consider boundary conditions in the calculations.

One year later Mosallam & Chen [40] developed a 2-D model with the aim of comparing the results obtained from the Liu et al and Grundy & Kabaila's simplified model. In general, this model is similar to the one used by Liu et al, with the addition of considering possible vertical column deformation. The results obtained showed that: a) the stiffness of the foundation hardly affects the load on the slabs but does have an important effect on the loads on the shores, b) slab boundary conditions have a negligible effect on loads on slabs, but not on the maximum value of the load on shores, c) slab stiffness has little influence, d) considering the actual shore stiffness has a considerable effect on the load they receive, and e) the evolution of the concrete's mechanical properties significantly affects load distributions between slabs and shores.

In 1996, after carrying out an in-depth experimental study of slab-shore load transmissions (see Section 4) Moragues et al [42] developed their 2-D numerical model, whose results confirmed the conclusions obtained from the experimental study and showed that: a) Grundy & Kabaila's simplified method is not suitable for construction processes that include clearing, and b) it is necessary to analyse the deformations caused during the building process, possible cracking of early-age concrete and the possible influence of deformation due to shrinkage and temperature differences during the building process.

In 2005 Kajewski [54] carried out finite element (FE) models to study load transmissions between different post-tensioned slabs connected by shoring. The results gave the level of the load received by the slabs after post-tensioning, thus unloading the shores under the same slab by the same proportion. In 2006 Kwak & Kim [80] developed a numerical model to simulate the time-dependent behaviour of an RC structure taking into account the construction process and considering: a) geometric and material non-linearities (cracking and yielding of the reinforcement) and b) variation of concrete properties with time. Kwak & Kim used a 2D model similar to the one used by Liu et al, but also considering the actual stiffness of columns and different types of construction processes. The authors concluded that if the evolution of the

concrete's mechanical properties is not considered, conservative results are obtained for loads on slabs and those for the loads on shores are on the unsafe side.

In 2008 Díaz [81] studied the influence of different parameters on slab-shore load transmissions and the minimum age for striking the slabs with a model in SAP2000 [91]. In addition to the hypotheses formerly considered for the different models, Diaz assumed that all the concrete floors had the same deformation modulus, except the last one to be poured, whose modulus was considered to be null. Among other conclusions, Díaz argued that shores should be removed starting at the centre of the bay towards the columns in order to avoid shore overloads and unforeseen failures.

In 2009 Alvarado et al [71,82] developed a 3D FE numerical model, including an evolutionary calculation to consider the evolution of the concrete's mechanical properties with time. The hypotheses considered were: a) elastic linear behaviour of slabs, columns, shores, formwork boards and joists, b) time-dependent stiffness of slabs and columns, c) finite stiffness of shores, formwork boards and joists, and d) infinitely stiff foundation. This numerical model was validated by achieving results very close to the experimental values and thus showed that the 3D FE method could be used to simulate the construction processes of building structures.

Following the same method as Alvarado et al, in 2012 Gasch et al [72–74] simulated the construction of a three different buildings by the FE method. Real buildings with different types of slab were analysed: flat-slabs [74], girderless hollow floor slabs [73] and waffle slabs [72]. The results confirmed that in the cases studied the FE method gave very similar results to those obtained from experimental measurements.

In 2015 Buitrago et al [33] introduced the concept of a load limiter on shores. The load limiter concept arose from the need to reduce the safety problems that occurred when buildings were being constructed [7,34]. When fitted to shores, these devices keep the load on the shore below its allowable load. Buitrago et al [33] proved their technical and economic viability and introduced load limiters to the FE numerical models previously developed by Alvarado et al and

Gasch et al. This study analysed in depth how loads were transmitted between slabs and shores with load limiters and showed how their use had technical and economic advantages.

Finally, in 2017 Adam et al [83] used the FE method to study the limitations of Grundy & Kabaila's method, using Alvarado et al's previously developed method for the numerical simulation. When the results showed the limitations of the Grundy & Kabaila's method, the authors recommended that it be used only for reshoring processes (SRS) of one or more shores per 1.20m^2 slab area and that it should not be considered for SS or SCS processes.

5.2. Creep and shrinkage effects on load transmission

Apart from the numerical studies described in Section 5.1, some authors made numerical studies of the effects of shrinkage and creep on slab-shore load transmissions in building structures under construction. Those by Aguinaga & Bazant [49], Liu & Chen [84], Mosallam & Chen [40], Lee et al [85], Duan & Chen [86], Kwak & Kim [87], Xi et al [88] and Fang et al [89] all reached similar conclusions: shrinkage and creep have negligible effects on load transmissions between slabs and shores; the loads on shores and slabs are at similar levels whether or not the phenomena are considered.

However, even though the effects of shrinkage and creep are negligible on load transmission during construction, the authors also agree that they do have a strong influence on long-term deflections, since those of an early-age loaded concrete during the construction of a building are at least several times higher than the elastic deflections. Other authors who studied the consequences of early-age loaded concretes during construction on long-term deflections (Vollum et al [78], Hossain et al [92,93], Kang et al [94], Hwang et al [95] and Alvarado et al [96,97]) confirmed the conclusions reached and emphasised the importance of reducing cracking and the loads on slabs under construction.

5.3. Temperature effects on load transmission

Other authors made a careful study of the effect of temperature on slab-shore load transmissions; in 2009 Fang et al [89] studied the load fluctuations on slabs and shores due to

day and night-time temperature variations. According to the conclusions reached, changes in temperature can modify these loads by up to 31.6%.

In 2012 Gasch et al [75] studied the effect of ambient temperature on slabs by the FE method, considering both the uniform variations in day-and night-time ambient temperatures and, for the first time, the temperature gradients at different depths inside monitored slabs during the construction of actual buildings (see Section 4). The study was able to correctly determine how temperature affected load transmissions, the process by which it occurred, and its consequences: the temperature gradient at different depths in the slabs makes them rise or fall, loading and unloading the shores, respectively. For temperature gradients of only 1ºC, the load on the shores varied by between 2 and 6% of the slab self-weight. Experimentally, gradients of up to 10ºC were recorded, which could mean, therefore, load variations between 20% and 60% of the slab self-weight.

In 2014 Huang & Liu [76] developed new numerical models and new software to consider the effect of ambient temperature, with its respective day-and night-time variations, on slab-shore load transmissions; while in 2017 Simovarian et al [90] carried out thermo-mechanical analyses to study the influence of temperature, among other parameters, on the distribution of stresses and strains in flat-slabs during construction.

6. Conclusions and future research

This paper has offered a review of the present state-of-the-art of knowledge on the transmission of loads between slabs and shores during the construction of RC building structures, including all the advances in the topics of simulation and experimental tests and the different calculation methods available, with the aim of fomenting their application in practice and thus contribute to improving the construction phase of building structures. In a history of more than 60 years of studies, as the technique and knowledge of the construction of building structures have improved substantially and can easily be applied by building professionals, it

seems senseless at the present time to go on using the techniques of the mid-20th century to solve this type of problem.

The consideration of all the studies cited in this paper leads the authors to suggest some possible future lines of research:

- The development of new elements to increase the safety and robustness of temporary shoring structures to reduce risks and the numbers of failures and collapses during construction.
- The study and development of a tool that could automatically define the optimal building processes in terms of safety, cost and efficiency.
- Obtain an international consensus on the loads and load factors to be considered during the design of building structures during construction. It is clear from this review that both the studies and the international standards present widely differing criteria that need to be unified.

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Figure captions:

- Fig. 1. Types of construction processes most often used: shoring/striking (SS), shoring/clearing/striking (SCS) and shoring/reshoring/striking (SRS).
- Fig. 2. Regional distribution of research on load transmission between slabs and shores.
- Fig. 3. Accumulated number of published papers.