Limitations of Grundy & Kabaila's simplified method and its repercussion on the safety and serviceability of successively shored building structures

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Abstract

One of the most critical stages for a structure's safety is precisely its construction process, and this problem is even more acute in buildings with reinforced concrete structures. These structures are usually built by shoring successive floors, so that the most recently poured floor rests on the lower floors by means of shores. It is therefore vitally important to have calculation tools available to estimate the loads to which the shores and slabs are subjected in each stage of construction. A number of calculation methods have been proposed to date, of which the one proposed by Grundy & Kabaila in 1963 is the best known and most frequently used. This paper analyses the limitations of Grundy & Kabaila's method by means of a parametric study of FEM simulations, which found a large number of situations in which this method presented unsafe results as regards the estimated loads on the slabs. In many situations, therefore, applying this method could gravely affect a building's in-service behavior and durability. The paper's final objectives are to make the reader aware of the limitations of Grundy & Kabaila's method and the need to use the more refined methods now available to estimate the loads on shores and slabs in reinforced concrete buildings under construction.

Keywords: Building; Slab; Shores; Loads; Concrete; Safety; Durability

1. Introduction

Shoring successive floors is the method most frequently used when building reinforced concrete (RC) structures. This method consists of supporting the newly poured slabs on the last floor cast, while keeping some of the lower floors either 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. Total or partial striking of the shores on the lower floors means they can be re-used for the subsequent pouring of upper floors.

Being aware of how the loads are actually transmitted between slabs and shores is a crucial aspect in establishing safe construction processes. In fact, a large number of studies have been carried out to date on how these loads are transmitted. Advanced models have been used to carry out numerical studies (Alvarado et al. 2010; Buitrago et al. 2015; Huang and Liu 2014; Kwak and Kim 2006; Moragues et al. 1996). Calculation methods have also been proposed (Aguinaga-Zapata and Bazant 1986; Beeby 2001; Buitrago et al. 2016a; Buitrago et al. 2016b; Calderón et al. 2011; Duan and Chen 1995; El-Shahhat and Chen 1992; Fang et al. 2001a; Fang et al. 2009; Grundy and Kabaila 1963; Liu et al. 1985; Mosallam and Chen 1991; Nielsen 1952; PJ 1967), ranging from Grundy & Kabaila's traditional method (1963), the best known and most frequently used so far, to the latest proposal by Calderón et al (2011). A number of studies have also used the experimental approach (Agarwal and Gardner 1974; Alvarado et al. 2009; Fang et al. 2001b; Gasch et al. 2013; Moragues et al. 1994; Rosowsky et al. 1997; Zhang et al. 2016) and reflect the present level of interest in determining exactly how loads are transmitted during a building's construction.

All these studies emphasize the importance of the safety measures to be taken in building works. Many studies (Carper 1987; Epaarachchi et al. 2002; Hadipriono and Wang 1987; Kaminetzy and Stivaros 1994) agree that one of the most critical stages for a building's safety is precisely the construction stage. In a building under construction, the loads supported by the slabs can exceed their design loads (Grundy and Kabaila 1963) and this factor, together with the possible failure of the shores that support the slabs, can lead to critical situations. Some instances of buildings that have collapsed while under construction include 2000 Commonwealth Avenue (Boston, USA) in 1971 and the Skyline Plaza (Fairfax County; USA) in 1973, described in detail in (Carino et al. 1983; King and Delatte 2004; Schellhammer et al. 2013). The OSHA (Occupational Safety & Health Administration) also looked into (OSHA 2008) the collapse of a building under construction planned to be used as a car park in Jacksonville, USA, in 2007. A more recent example occurred in Mallorca (Spain) in 2015, in which the failure of the shores in a building under construction caused two deaths and a considerable amount of material damage (Diario de Mallorca 2015).

All these examples show that if a floor collapses, the dynamics of the impact on the lower floors can cause a progressive collapse of all the other floors. It is also clear that an exhaustive knowledge of the construction phase is an absolute necessity in order to avoid accidents during this period. Although the number of such accidents is relatively low, considering the number of buildings constructed, apart from the accidents involving deaths, the conditions of buildings after construction should also be considered. Incorrect calculation of the loads transmitted between slabs and shores can cause cracking and excessive deflection in slabs during building works. When both these factors are joined together in early-age concrete they compromise the safety of the building in both the short and long-term (Almeida-Prado et al. 2003).

The correct estimation of loads on shores and slabs, together with allowing sufficient time for each building operation, should therefore be given priority. For this, as will be explained in Sections 3 and 4, it is of vital importance to know exactly when such an over-simplified method such as that of Grundy & Kabaila (G&K) can or cannot be applied. Grundy & Kabaila (1963) proposed their method in 1963, which, as it was found to be quick and easy to apply, quickly became generally accepted and has remained so to the present time. The basic principles of the method, which will be detailed in depth in Section 4, are based on the assumption of a shoring system having infinite stiffness. Being aware of this method's limitations will allow us to specify when more precise and up-to-date methods should be used to increase safety levels in buildings under construction and ensure their behavior in the medium and long-term.

The principal novelty of this paper lies in its compilation and synthesis of the common practice in calculating and building structures by means of shoring successive floors. Familiarity with this practice allows us to discuss and analyze common errors committed when calculating the building process. In the worst case, these errors can compromise the safety or the behavior of the building in service. This paper presents for the first time an exhaustive compilation of the existing calculation methods and analyzes the possible effects of the incorrect use of a simplified method (G&K) when designing the construction process.

The paper is structured as follows: Section 2 describes some details of the construction of RC building structures, the habitual building processes and their evolution up to the present time. Section 3 includes a compilation of the methods formulated to date to estimate the loads transmitted between slabs and shores in buildings under construction. Section 4 deals with a parametric study of an actual building that includes the most commonly used building practices when shoring successive floors. In this section a comparison is also made of the results of a finite elements method (FEM) simulation and those from the most popular classical method at present in use, G&K's method (1963) and it includes a discussion of when this method can be safely applied without risks to the structure and when its application could cause problems. Finally, Section 5 gives the study's most important conclusions.

2. Different procedures used in the construction of buildings with RC structures

In the construction of buildings by the system of shoring consecutive floors, one or more floors are shored in order to transmit the load of the newly poured slabs to the floors beneath.

Each of the shored floors is involved in two or more shoring operations; placing the first set of shores to support the new floor and striking are two essential operations. When the slab is able to bear its own weight, live loads under construction and possible loads coming from the upper shored floors, the shores can be removed. Intermediate operations such as clearing or reshoring can also be included.

Clearing consists of removing more than half, but not all, the shoring system's components a few days after pouring. This operation achieves, firstly, the partial unloading of the system, since its stiffness is reduced, and secondly the load on the slabs increases slightly. After clearing, each shore takes on a greater load due to its larger tributary area below the slab.

Reshoring involves removing all the shores under the slab a few days after pouring and re-installing them in such a way that they can resist any future load increases. In this stage of the construction process, the shores are completely unloaded and the slabs assume all the loads placed on them. After replacing the shores, both the shoring system and the slabs assume their share of the loads transmitted from the upper floors.

To sum up, clearing makes each shore absorb a higher load, while the loads are reduced on the newly-poured slabs to less than they would be if reshoring were used. At present, the normal practice is to use one of these intermediate processes, since they free a large part of the shoring material (formwork, straining pieces and shores) for re-use on the succeeding floors. In many cases building times can also be reduced. These different operations can be combined in the following ways: shoring/striking (SS), shoring/clearing/striking (SCS), and shoring/reshoring/striking (SRS) (Alvarado et al. 2010). Figure 1 shows a scheme of the use of these three processes up to the shoring of the third floor in a building with two consecutively shored floors. As can be seen in Figure 1, apart from the shores necessary in each process, SCS and SRS need only half the formwork required for SS, since all the formwork is recovered when clearing and reshoring.

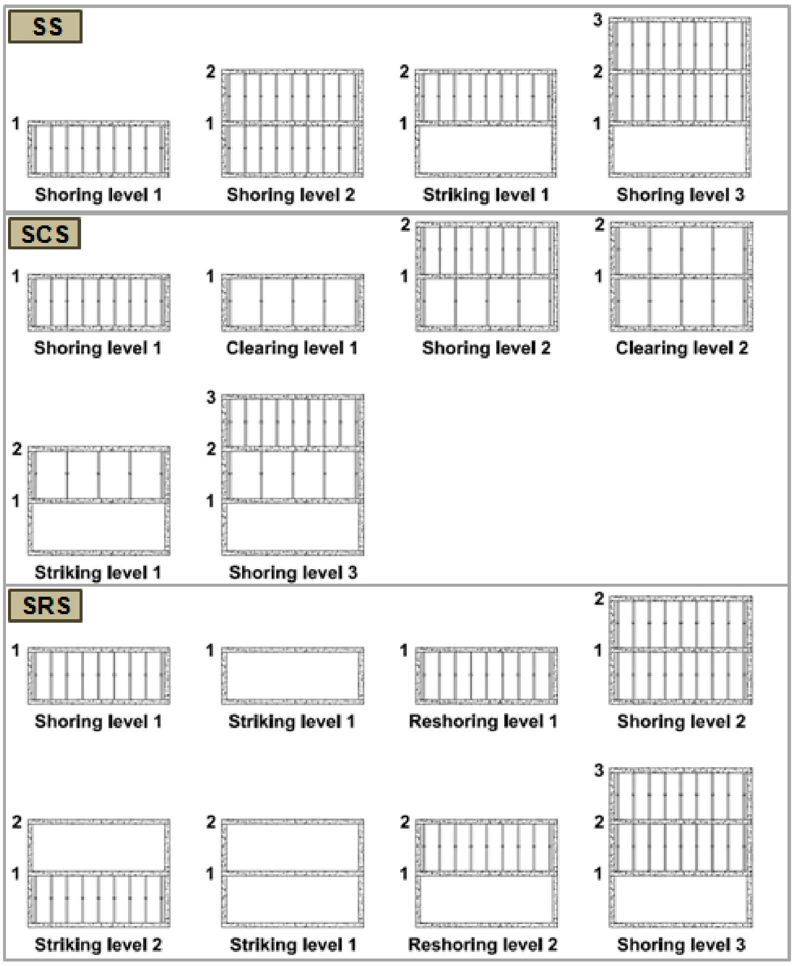

Fig. 1. Construction processes most often used at present: shoring/striking/ (SS), shoring/clearing/striking (SCS) and shoring/reshoring/striking (SRS).

Fig. 2. Building under construction in Sabadell (Barcelona, Spain) in 2010 with three consecutively shored floors, two of which have been cleared and one is still completely shored.

As can be seen in Figure 2, the successive shoring of floors is the current norm. The improvements that have been introduced now mean that it is possible to obtain a detailed analysis of the building processes in order to keep a close watch on a building's safety and durability aspects, as can be seen from the large number of studies that have been published on the subject (see e.g. Section 1) and the different calculation methods that have been proposed (see Section 3). The superficial treatment of structural calculations should now be out of the question, as should the use of outdated shoring systems. To show how these systems have been improved, Figure 3 contains photos of two buildings under construction in the 80s and 90s in which wooden and not vertical shores were used. In comparison, as can be seen in Figure 2, systems with steel components and ensuring a vertical position of shores are currently used.

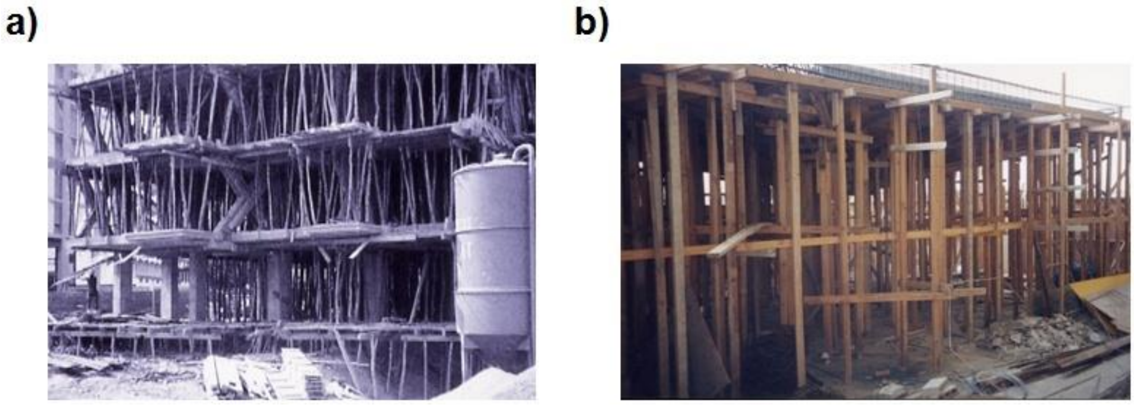

Fig. 3. Views of buildings supported by wooden shores: a) in Valencia (Spain) in the 1980s and b) in El Calafate (Argentina) in the late 90s.

3. A review of the simplified methods of estimating the transmission of loads between slabs and shores

Although a number of different methods have been proposed to estimate slab/shore load transmission during the different construction phases of RC structures cast in situ, only a few of them are actually used in practice. This section offers for the first time an exhaustive compilation of all the proposals of this type so far published.

The first of these proposals was published in 1952 by Nielsen (1952). Some years later, in 1963, Grundy & Kabaila (1963) proposed their method, which, as it was found to be quick and easy to apply, quickly became generally accepted and has remained so to the present time. The basic principles of the method, which will be explained in Section 4, are based on the assumption of a shoring system having infinite stiffness. Many authors (Alvarado et al. 2009; Beeby 2001; Calderón et al. 2011; Duan and Chen 1995; Fang et al. 2001b; Liu et al. 1985; Moragues et al. 1996; Mosallam and Chen 1991; Stivaros and Halvorsen 1990) subsequently pointed out that this latter hypothesis leads to overestimating the loads on shores and seriously underestimates those on slabs during the different construction phases.

In 1967, Taylor (1967) extrapolated G&K's method to the reshoring case, but it was not until 1985 when Liu et al (1985) proposed a method based on 2 and 3D, which for the first time considered shores to have finite stiffness and allowed for different boundary conditions in the slabs (internal, end or corner spans). Liu et al's method additionally considered the evolution of slab stiffness with time and assumed that columns were undeformable. Aguinaga & Bazant (1986) developed a new method that took into account the effect of concrete creep. Sometime later, in 1991, Mosallam & Chen (1991) proposed a further method that assumed all G&K's hypotheses besides the evolution of slab stiffness and calculated slab/shore loads at the beginning and end of each construction phase. This they considered necessary due to the importance of the evolution of stiffness during this period and its effect on the loads transmitted between slabs and shores.

In 1992, El-Shahhat & Chen (1992) proposed performing a two-part analysis: a) in the casting phases they used Liu et al's method, and b) for reshoring and striking they used the compatibility of displacements between slabs and shores at the points at which the slab was supported by shores in order to determine the load transmitted between these elements. Seeking to improve on G&K's method and avoiding the need to apply complex structural engineering software, in 1995 Duan & Chen (1995) proposed a one-dimensional analysis of each span, as in G&K's method, in addition to the compatibility of slab/shore displacements. Its main hypotheses were: 1) shores are finitely stiff, 2) slab stiffness varies with time, 3) the model is incremental, i.e. it allows for construction by phases and considers the accumulation of loads and displacements, and 4) slab deformability is modified by a factor that considers different boundary conditions.

In 2001, Beeby (2001) suggested two methods of obtaining the loads between slabs and shores. First, he directly provided the value of the loads that should be considered for slabs and shores according to the construction phase. Secondly, to get a more precise idea of the loads transmitted, he established a calculation method for obtaining the loads on the shoring system, based on G&K's method and assuming finitely stiff shores and variable slab stiffness. Also in 2001, Fang et al (2001a) developed a method that considered a 2-D multilayer structure of slabs interconnected by shores, regarded as a time-dependent structure. Besides adopting Duan & Chen's hypotheses, they considered that slab stiffness varied significantly during curing and that the loads were redistributed, especially in newly-poured slabs. In 2009, Fang et al (2009) reformulated their method for application to a 1-D system.

Finally, in 2011, Calderón et al (2011) proposed a new method that not only adopted Duan & Chen's hypotheses, but added the following: 1) mean slab deformation coincides with mean shore deformation and 2) slab deformability, considering different boundary conditions (internal, intermediate or corner spans), is estimated by the Equivalent Frame Method devised by Scanlon & Murray (1982). Buitrago et al (2016a; 2016b) recently published two different reformulations of Calderón et al's method. The first, and simplest (Buitrago et al. 2016a), was to estimate the load on the shore at the point in the slab has the highest deformation, and the second (Buitrago et al. 2016b), for the first time using simplified methods, was to estimate the load on each shore in each construction phase. Table 1 briefly summarizes all the calculation methods proposed to date, including the number of citations received in *Scopus* and *Google Scholar* in order to show indirectly their different levels of popularity among the academic community.

Table 1. Simplified methods proposed to estimate transmission of loads between slabs and shores in successively shored floors.

Authors	Year	Country	Citations in Scopus[a]	Citations in Google Scholar[b]
Nielsen	1952	Sweden	9	46
Grundy & Kabaila	1963	Australia	61	201
Taylor	1967	Australia	- (**)	18
Liu et al	1985	USA	42	101
Aguinaga & Bazant	1986	Spain-USA	8	25
Mosallam & Chen	1991	USA	15	35
El-Shahhat & Chen	1992	USA	19	44
Duan & Chen	1995	USA	13	37
Beeby	2001	UK	7	12
Fang et al	2001a	China	15	24
Fang et al	2009	China	3	9
Calderón et al	2011	Spain	10	18
Buitrago et al	2016a	Spain	1	1
Buitrago et al	2016b	Spain	0	0

[a]Data accessed on 05/07/2016.
[b]No data found.

As already mentioned, for its simplicity and ease of application, G&K's method developed in 1963 is still the method most frequently used. In its time, this calculation tool, which provided a practical approach to a complex problem with the means available fifty years ago, was a big step forward in shoring successive floors. However, times have now changed, new calculation methods are available, more is known about materials, and the improvements in construction aspects in recent years have encouraged research groups to produce new proposals that better define the actual behavior of a building under construction (Beeby 2001; Buitrago et al. 2016a; b; Calderón et al. 2011; Duan and Chen 1995; El-Shahhat and Chen 1992; Fang et al. 2009, 2001a; Liu et al. 1985; Mosallam and Chen 1991).

4. Use of Grundy & Kabaila's method and its limitations

As has already been stated in the previous sections, G&K's method is the best known and widely used at the present time to estimate the loads on shores and slabs in buildings with consecutively shored floors. It is noteworthy that this method first appeared in 1963 and was one of the first serious attempts to achieve a practical and simple approach to the complex problem of building RC structures.

In this section the different construction processes are analyzed in a specific building under construction to determine the situations in which G&K's method can be applied and thus point out its limitations. First, the method itself is described and then the building considered and its modeling by FEM. The building's construction will be simulated, some of whose parameters will be varied, and then the results obtained will be analyzed to establish the method's limitations.

4.1. Grundy & Kabaila's Method

This method assumes the following initial hypotheses:

a) shores are infinitely stiff
b) foundations are infinitely stiff
c) the loads of shores on slabs are uniformly distributed
d) all the slabs have the same flexural strength, regardless of the age of the concrete
e) the effects of shrinkage and creep are ignored

With these hypotheses, the transmission of loads between slabs and shores is established according to individual building operations. For example, the load coefficients of shores and slabs for the different processes can be seen in Figure 4 (SS, SCS and SRS) for a building with two consecutively shored floors. The load coefficient is defined as the ratio of the load received by each element (slab or shoring system) with respect to the load applied to each floor, so that when the slab or shoring system assumes a load value equal to the load applied to a floor, the load coefficient is equal to one. For the different building operations and construction processes, the same system is used as that in Figure 4, which consists of:

- When shoring, the weight of the newly cast slab is shared equally among the lower slabs. This situation can be seen in the shoring of Level 3 in all the construction processes.
- In striking operations, for SS and SCS, the load assumed by the shores removed from under the slab is equally distributed among the upper slabs, as in the striking of Level 2 in SS and SCS.
- In reshoring, which first requires a striking operation, the slabs assume the total load applied. The shores are then repositioned to contribute to supporting the loads of the subsequently cast floors (see SRS process in Figure 4).
- Clearing operations do not introduce any variations in the transmission of loads between slabs and shores, since the method considers the shores to be infinitely stiff. Due to this consideration, the fact that, for example, half the shores have been removed can be ignored, since the remaining shores are also considered to be infinitely stiff. This is the reason why the load coefficients in SS and SCS coincide in Figure 4.

- In all the processes, since the foundations and shoring systems are considered to be infinitely stiff, this means that the slabs do not assume any loads until the striking of Level 1 (see Fig.4).

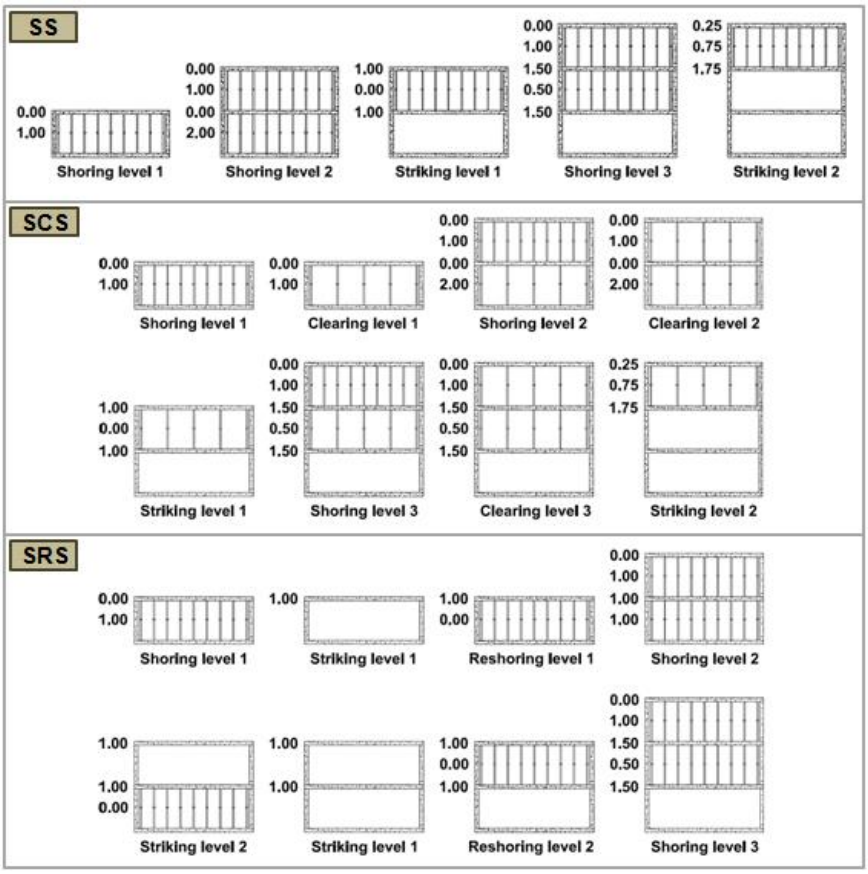

Fig. 4. Load coefficients in slabs and shores according to Grundy & Kabaila's method for SS, SCS and SRS processes on two consecutively shored floors

4.2 Finite elements model

The building considered for the study of the different construction processes was made up of three floors of RC flat slabs 0.25 m thick (which implies a self weight of 6.25 kN/m^2). Floor to ceiling height is 2.75 m, columns are separated by 6.00 m and there is a cantilever of 1.80 m. This building was erected on the campus of the Technical University of Valencia for purely experimental purposes. An SCS process of two consecutively shored floors was used for its construction. A view of the building under construction can be seen in Figure 5.

The finite elements method (FEM) was used to model the building in ANSYS 15 (2014). BEAM188 type elements were used for columns and formwork support beams, LINK180 type for shores and SHELL181 for formwork and slabs. The evolving calculation of the structure was also considered in which each construction stage had different geometric characteristics and mechanical behavior of the materials. The computation of each stage took as the starting point the loads and deformations exerted on the structure in the previous stage. The numerical simulation was verified with the results obtained from the experimental building (Alvarado et al. 2010), so that the model can be considered a faithful representation of its actual behavior. A fuller description of the building and its model can be found in Alvarado et al (2009, 2010). Figure 5b shows a view of the building during the construction stage given in Figure 5a.

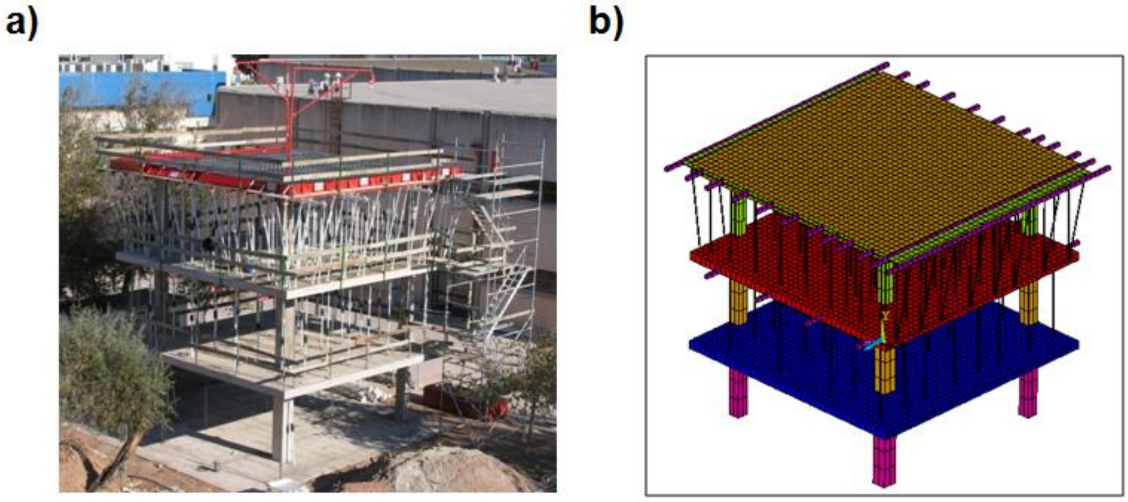

Fig. 5. Building used to study the different cases: a) under construction and b) the finite elements model

4.3 Construction stages and parameters analyzed

In order to make a thorough analysis of the suitability of G&K's method, in this section the construction stages normally used for this type of structure are considered: i.e. SS, SCS and SRS of two and three consecutively shored floors. The number of days allowed for each operation is not especially relevant, since the FEM results are compared with those of G&K's method under the same conditions, with the usual values for the different operations. Clearing was carried out after three days and reshoring after seven. As previously mentioned, when reshoring, the slabs must be able to bear the loads applied to them, so that reshoring is usually performed after a longer period than clearing. The building cycle consists of a new slab being poured every week (7 days) for the cases of SS and SCS, and every 8 days for SRS, one day after reshoring.

The clearing and reshoring operations and the different parameters considered will now be described. The usual practice when clearing (Alvarado et al. 2009, 2010) is to remove 50% of the shores. When reshoring, in order to keep costs to a minimum, not all the shores are replaced, i.e. some are reserved for use on successive floors. The shores are usually redistributed every $1m^2$, $1.5m^2$ or $2m^2$. In the case study described here, they were placed at $0.86m^2$, $1.20m^2$, $1.80m^2$ and $3.00m^2$ intervals, which covers the usual range. Table 2 gives all the factors and values considered in each of the cases analyzed. The factors include the SS, SCS and SRS construction stages, the distribution of the shores on shored, cleared or reshored floors, and the number of consecutively shored floors (two or three).

Finally, the applied loads considered during the construction of the building were as follows: the self-weight of the structure (6.25 kN/m^2) and a live load of 1.5 kN/m^2 to allow for the weight of shoring, workers and materials. Although there is no recognized international standard for live loads, which can vary between 1.0 and 2.4 kN/m^2, a value 1.5 kN/m^2 is considered adequate according to the existing studies and recommendations (Steering Committee of Concrete 2014).

Table 2. Analyzed construction processes

Construction process	Distribution of shores (s^a)		Consecutive shored floors
SS	Shored floor:	1s/0.86m^2	2shored
			3shored
SCS	Shored floor:	1s/0.86m^2	1 cleared +1shored
	Cleared floor:	1s/2m^2	2 cleared +1shored
SRS	Shored floor:	1s/0.86m^2	1reshored+1shored
	Reshored floor:	1s/0.86m^2	2reshored+1shored
	Shored floor:	1s/0.86m^2	1 reshored + 1 shored
	Reshored floor:	1s/1.20m^2	2 reshored + 1 shored
	Shored floor:	1s/0.86m^2	1 reshored + 1 shored
	Reshored floor:	1s/1.80m^2	2 reshored + 1 shored
	Shored floor:	1s/0.86m^2	1 reshored + 1 shored
	Reshored floor:	1s/3.00m^2	2 reshored + 1 shored

[a]s = shore

4.4 Results and limitations of Grundy & Kabaila's method

The reliability of G&K's method was assessed by the results obtained from the FE model. This was done by comparing G&K's values for the loads on the slabs with the values obtained from the FEM. The loads on the shores were not analyzed, since they are generally overestimated in G&K's method, due to their assumption that shores have infinite stiffness. The estimated values for the loads on shores would therefore be on the safe side and would not involve any risks for the shores themselves. The analysis therefore focused on the slabs, due to the risk of possible damage to them during construction arising from G&K's mistaken estimation of the loads applied to them. As has been described in Section 3, this method habitually underestimates the loads acting on the slabs, which implies risks to the safety of the structure under construction and to its behavior in service.

The comparison between loads on shores obtained by G&K's method and those obtained from the FEM are shown in the form of graphs in Figures 6, 7, 8 and 9. Each point in these graphs represents the load on a slab during a given construction stage. The load estimated by the FEM is given on the horizontal axis and G&K's estimations are shown on the vertical axis. The further the points are from the 45º line, the greater the error. The points under the 45º line show when the loads estimated by G&K's method are lower than those given by the FEM, and thus are the points at which the structure's safety and in-service behavior are compromised.

The dashed lines in the figures represent different percentages of load deviations with respect to the FEM (15%, 30%, 45% and 60%). Each of the points shown in Figures 6, 7, 8 and 9 also gives the age of the concrete in the slab. Regardless of the construction stage and level of the slab under study, it should be remembered that excessive loads applied to early-age concrete can reduce safety during construction and gravely affect the building's in-service performance and durability. For this reason, only the age of the concrete of the slab under study is provided in the label of each point in the graphs.

In Figure 6, the results of the SS operations on 2 and 3 consecutive floors are compared. It can be seen that many of the points are quite far from the 45º line, showing a considerable degree of error, with deviations of over 30% in estimating loads on slabs during the construction. It can also be seen that the errors are greater in the case of 3 consecutively shored floors, with 23.1% of the estimates more than 60% out, while only 7.7% of the estimates for 2 consecutively shored floors are above this threshold.

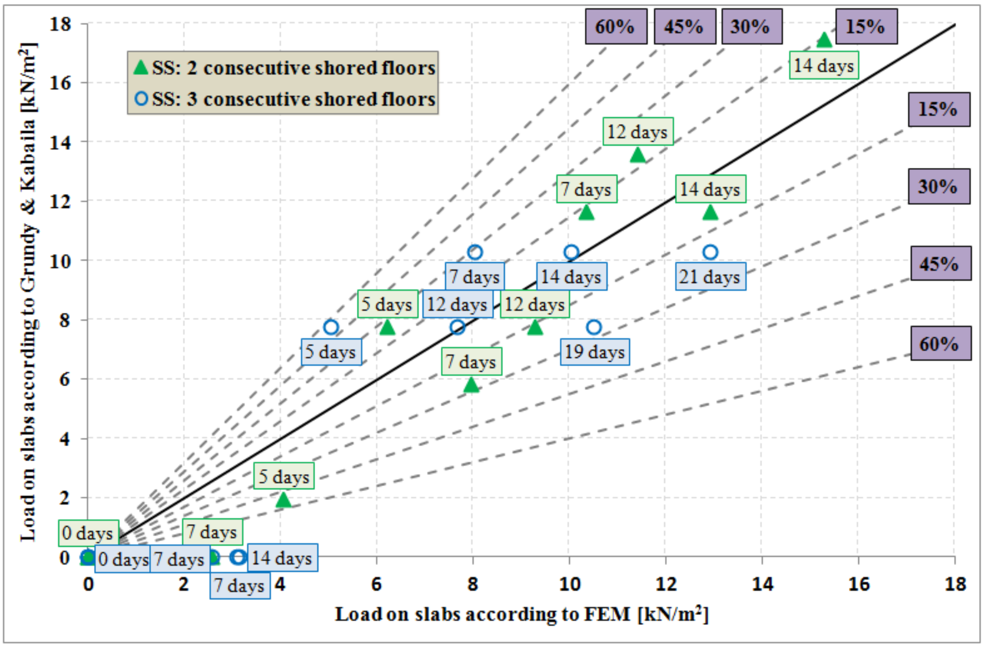

Fig. 6. Fitting of values of loads on slabs obtained from G&K's method and FEM results for SS operations on 2 and 3 consecutively shored floors

Figure 7 compares the results of SCS on 2 (1+1) and 3 (2+1) consecutively shored floors. As in the SS case, many of the results deviate from the 45º line. The points at which G&K's method estimates null loads in very early-age concrete slabs should be noted. These points could have to stand up to 5.83 kN/m^2, which is almost the entire slab's self-weight. As already mentioned, these situations are extremely dangerous when a building is under construction and can affect its in-service performance and durability. It can also be seen that the errors in the 3 consecutive shored floor case are greater than in the 2 consecutive shored floor case. 47.4% of the estimates are more than 60% out in the former, while the errors over the threshold are 26.3% in the latter. When the SCS and SS results are compared, the errors are higher in the former, mainly due to the fact that in clearing operations G&K's fundamental hypothesis that considers shores to be infinitely stiff is no longer valid.

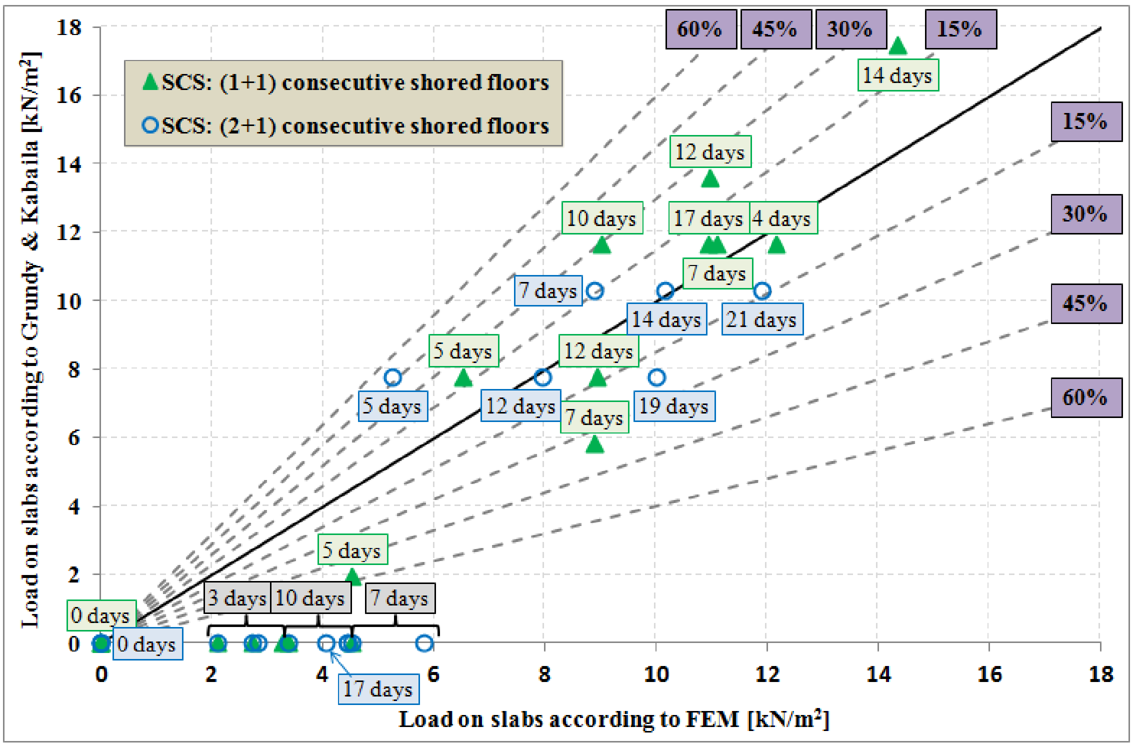

Fig. 7. Fitting of values of loads on slabs obtained from G&K's method and FEM results for SCS operations on 2 and 3 consecutively shored floors

Figure 8 compares the results of SRS operations on 2 (1+1) consecutively shored floors. As mentioned above, reshoring is performed a few days after pouring the slab, in which process the slabs have to bear all the forces applied to them. Although this situation appears to be adequately dealt with in G&K's method, in the casting operations in this method, the weight of the newly poured slab is shared equally among the lower floors. However, far from being equally distributed among the lower floors, this mainly depends on the stiffness of the shoring system and on the different stiffnesses of the different slabs, attributable to the different ages of the concrete. This means that the estimates of the loads on slabs in casting operations by G&K's method are erroneous, and furthermore, this error is made in slabs whose concrete is in the age of eight days.

It can also be seen in Figure 8 that, as happened in SCS operations, on reducing the number of shores per m^2 the error is even greater, given the doubtful validity in these cases of the infinitely stiff shores hypothesis that G&K's method assumes. In the four cases analyzed in Figure 8, there is only one estimate of loads on slabs by G&K's method with an error over 15%. However, when reshoring involves distributions of less than one shore every 1.20 m^2, the errors are more than 20%. In the authors' view, exceeding this error threshold nowadays is absolutely unacceptable, given the existence of improved simplified estimation methods that are better able to predict load transmissions between slabs and shores.

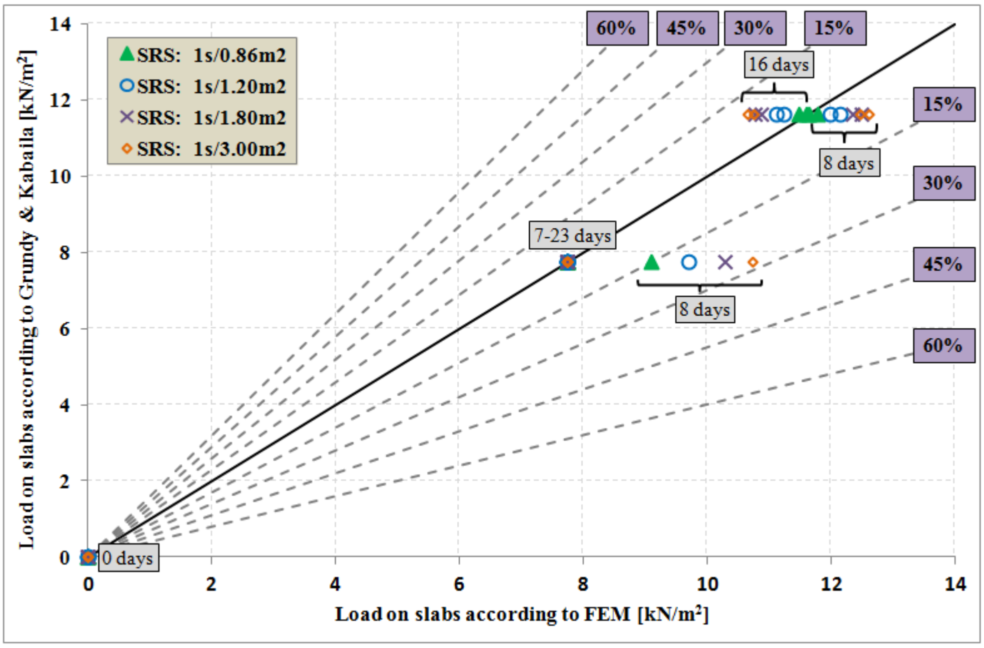

Fig. 8. Fitting of values of loads on slabs obtained by G&K's method and FEM results for SRS operations on 2 consecutively shored floors

Figure 9 compares the results of SRS on 3 (2+1) floors, which can be interpreted in a similar way to those for the SRS case on 2 floors. The peculiarity of this case lies in the larger errors made, with two estimates above the 15% error threshold. It should be noted that these errors were made with only eight days old (corresponding to the construction cycle).

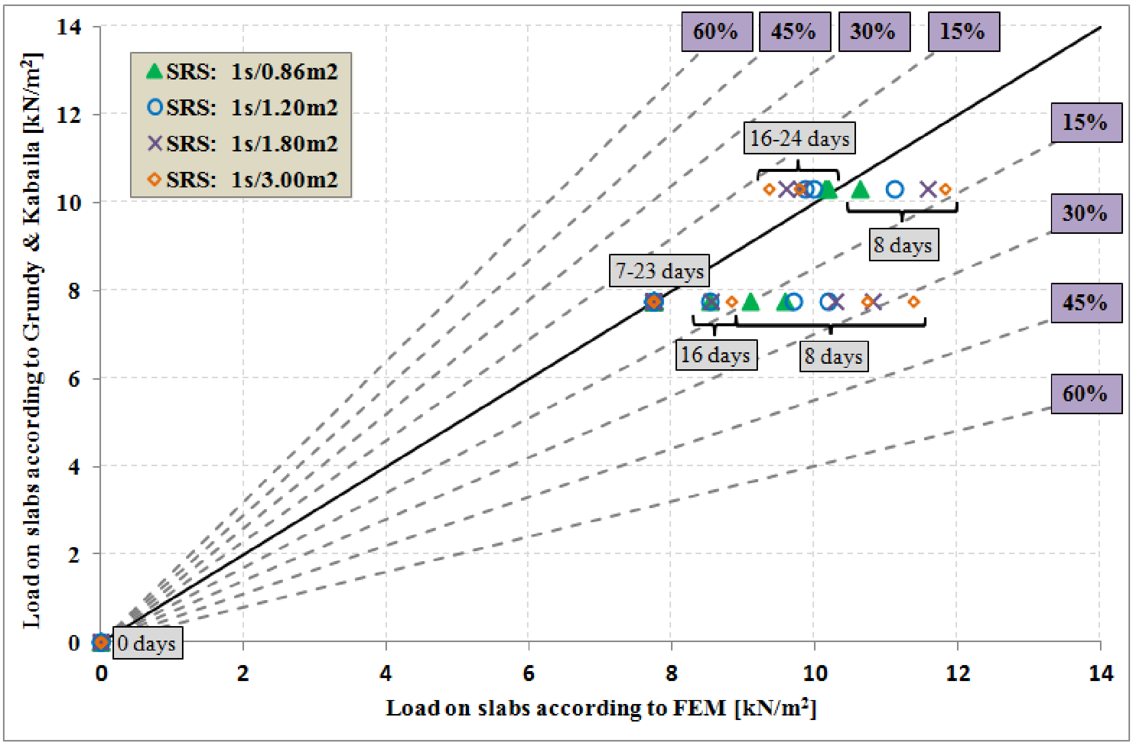

Fig. 9. Fitting of values of loads on slabs obtained by G&K's method and FEM results for SRS operations on 3 consecutively shored floors

Table 3 gives, for the cases analyzed the percentage of estimates of loads on slabs by G&K's method within the different error thresholds (less than 15%; between 15% and 30%; between 30% and 45%; between 45% and 60%; and over 60%).

In Table 3 it can be seen that G & K's method generally provides worse predictions of loads on slabs for three consecutively shored floors and that a large number of estimates present unacceptable errors higher than 30%, or even 60% in processes that include clearing and no intermediate operations. In fact, in the worst case (SCS on 3 consecutively shored floors), almost half the estimates by G&K's method have errors higher than 60%. For operations with reshoring, G&K's method is generally less than 30% out.

In the authors' opinion, for the simplicity and ease of application of G&K's method, only SRS processes with 1 or more shores per 1.20m^2 slab area can be accepted as valid, as the estimates of loads on these slabs are less than 20% out. However, in all other cases it is inadvisable to apply this method, which often predicts loads on slabs which are unsafe. The use of more up to date methods (see Section 3) is strongly recommended to avoid inaccurate estimates of the loads on slabs in these cases, and thus avoid risks to the structural integrity of the building. Another aspect to be borne in mind has to do with the post-construction state of the structure, due to the possible appearance of cracks or excessive and unforeseen deformation, which could affect its in-service behavior and durability.

Table 3. Percentage of estimates of loads on slabs of each construction stage analyzed within the different error thresholds defined.

Construction process	Error thresholds				
	< 15%	15%<Error<30%	30%<Error<45%	45%<Error<60%	> 60%
SS (2)	53.8%	30.8%	0.0%	7.7%	7.7%
SS (3)	46.2%	23.1%	0.0%	7.7%	23.1%
SCS (1+1)	42.1%	21.1%	5.3%	5.3%	26.3%
SCS (2+1)	36.8%	10.5%	0.0%	5.3%	47.4%
SRS (1+1) 1s/0.86m^2	93.3%	6.7%	0.0%	0.0%	0.0%
SRS (1+1) 1s/1.20m^2	93.3%	6.7%	0.0%	0.0%	0.0%
SRS (1+1) 1s/1.80m^2	93.3%	6.7%	0.0%	0.0%	0.0%
SRS (1+1) 1s/3.00m^2	93.3%	6.7%	0.0%	0.0%	0.0%
SRS (2+1) 1s/0.86m^2	87.5%	12.5%	0.0%	0.0%	0.0%
SRS (2+1) 1s/1.20m^2	87.5%	12.5%	0.0%	0.0%	0.0%
SRS (2+1) 1s/1.80m^2	87.5%	12.5%	0.0%	0.0%	0.0%
SRS (2+1) 1s/3.00m^2	87.5%	6.3%	6.3%	0.0%	0.0%

5. Conclusions

This paper contains a review of the habitual calculation of the processes involved in constructing RC building structures cast in situ. In order to detect possible deficiencies in the methods used to calculate these processes, an exhaustive compilation was made of the existing calculation methods. Since G&K's method is the best known and most widely used at the present time, an analysis was made of possible situations in which its application may not be advisable, taking into account the different parameters of the different construction stages: type of construction process, distribution of shores on slabs, and number of consecutively shored floors.

For the analysis, the reference framework used was the finite elements method applied to the construction of a building. A comparison was made of the results obtained by G&K's method with those obtained from the FEM. Follow conclusions can be summarized of this comparison:

- There are unacceptable errors in the slabs load estimates done by G&K's method. These errors, in comparison to FEM estimates, are higher than 30% in SS processes, SCS processes and SRS process with 3 consecutive shored floors where only one shore every three square meters is re-installed.
- There are a lot of high errors, higher than 60 %, in the SS processes and SCS processes.
- SCS process is the worst process for applying G&K's method. The main hypothesis considered by G&K's method takes shores as elements with infinite stiffness, which is not valid for the clearing process where about half of shores are removed and the stiffness of the shore system is consecutively reduced.

The conclusions drawn from this comparison were that, due to the simplicity and ease of use of G&K's method, construction processes that include reshoring may be acceptable with a distribution of one or more shores per 1.20 m^2 slab area. Only in this way can this method be generally applied, as it gives estimates of loads on slabs with errors of less than 20%. For reshoring operations (SRS) with less than one shore per 1.20 m^2, in processes with no intermediate operation (SS) or processes that include clearing (SCS) its use is not recommended, as it could compromise the safety of the building under construction and have serious consequences for its durability and behavior in service.

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] and also to the GeneralitatValenciana [GV/2015/063].

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