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Analysis of the effect of shoring on the behaviour of reinforced concrete slabs

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HIGHLIGHTS

- Effects of the shoring system on the behaviour of reinforced concrete slabs.
- Stresses and deformations induced by the construction stage.
- Thermo-mechanical analysis of reinforced concrete at early ages.
- Parametric study involving the spacing and the withdrawal sequence of a shoring system.
- Finite element analysis using ADINA.

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ABSTRACT

The purpose of this work is to study the influence that the construction stage has on the distribution of stresses and strains in solid slabs. To that purpose, a numerical simulation framework for thermo-mechanical analysis has been implemented and deployed, with due account to the evolution of concrete properties at early ages. This framework was then used to simulate the behaviour of several alternative procedures to define the shoring system and scheduling that can be adopted in the construction phase, with the aim of identifying the best practices to control and reduce the residual stresses attained during the construction stage, which may in turn be responsible for less-than-optimum cracking behaviour in service.

The results obtained confirmed that, for the particular case under study, delaying the shoring removal until concrete has reached its 28-day characteristic strength corresponds in fact to the best practice as it reduces the stresses and prevents cracking of the slab in the first 28 days. However, it was also seen that other more ambitious practices, leading to an early withdrawal of the shoring (before 28 days), are also perfectly acceptable in terms of stresses and deformations in the slab under study. Only in premature withdrawal schemes (before 7 days) the likelihood of early cracking is more significant, and so these situations can in fact demand a sophisticated study of stress history to adequately take into account the influence of the initial stresses on the service life behaviour of the slab.

1. Introduction

The usual strategies adopted for the design of reinforced concrete slabs in ordinary building structures generally consider the structure with its final shape, as well as the mechanical properties of concrete at 28 days, and the loading conditions that are predictable to occur after the beginning of the actual operation of the building (i.e. post-construction). However, in some quite specific design situations, as in the case of bridges to be built using the balanced cantilever method, more detailed analyses are made, explicitly taking into account the cumulative stresses and behaviour of the reinforced concrete structure throughout the construction stage [1–3].

In fact, there is currently insufficient information for designers about the consideration of the construction process in the structural behaviour of reinforced concrete structures. This lack of information is further extended to the insufficient understanding of design criteria for the shoring system, from the point of view of the supported concrete (particularly the spacing between shores,

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types of shoring, number of floors to be simultaneously shored, among others), and the proper definition of the construction cycles (time between casting and removal of the shoring system) [4].

During the construction process of buildings, a recently cast concrete slab is initially supported by props that either extend directly to the ground, or to underlying existing floors, until it acquires adequate mechanical properties (e.g. strength and stiffness) to support all its loads, i.e. until it becomes self-bearing. During the construction process, the loads that act on the slabs are frequently of a different nature and intensity when compared to the in-service actions predicted at the design stage that solely considers the in-service conditions. In fact, according to Prado [5], it is very common that the loads that act on a structure during construction exceed the loads considered in the structural design, with the aggravating circumstance of acting at early ages, well before the reference age of 28 days. This situation is particularly severe in residential and commercial buildings, as in this type of constructions, the live loads are relatively small when compared to the self-weight of the structure. Thus, the structure is subjected to an already significant part of the total project load in the early stages of construction.

Another important component in structural analysis during the constructive phase is the shoring and formwork system itself. Its correct design and the knowledge of the influence of this system on the behaviour of reinforced concrete structures are of great importance for the safety, durability and cost of the works. An incorrect analysis and design of the formwork and shoring system can lead to serious consequences, which include the advent of unpredicted action-effects on the structures, the increase of the risk of unacceptably large concrete cracking, major deformations over time and a significant increase of the possibility of collapse of the structure. In fact, many of the collapses that are observed in structures are due to problems occurred at the construction stage [6]. These collapses can have several causes, such as the collapse of the shores (caused by excessive loading) or of the concrete structure (mainly in the early ages when it has not reached its characteristic strength), unpredicted loads that act on the structure, and errors associated with premature withdrawal of the shores, when concrete has not yet reached the required strength.

The purpose of this paper is to study the influence that the construction stage has on the increase of the likelihood of premature cracking and on the distribution of stresses and strains in slabs before and after complete removal of the shoring system. This work intends to determine whether the current practices of slab shoring are in fact the best solution to reduce residual stresses and cracking of the slab before and after complete withdrawal of the shores. It is also intended to evaluate the consequences of adopting alternative systems and sequences of withdrawal of the shores, where for example the shores are removed in earlier ages or the number of props that sustain the slab is significantly reduced.

In order to perform the intended analyses, a numerical model was initially created to simulate the thermal behaviour of concrete, taking into account all the phenomena involved in the heat transfer process between the concrete slab and the environment, as well as the exothermic chemical reactions that occur in concrete at early ages. Subsequently, a mechanical numerical model was developed, with due account for the evolution of the mechanical properties of concrete since casting (according to the equivalent age concept), with particular attention to relevant phenomena such as creep and shrinkage.

Finally, based on the thermo-mechanical numerical model, a sensitivity study was performed with the aim of determining how the stresses and strains in the slab vary over time according to the variation of given parameters, such as the spacing between props and the plan and date of withdrawal of the shores.

2. Case study (base model)

As mentioned above, the aim of this work is to study the stress and strain distributions in a slab during the construction stage, according to several alternative possibilities of propping placement and scheduling. For this purpose, a 'base model' was initially developed, in which a set of parameters for the shoring system has been assumed, attempting to match a typical situation found in ordinary buildings. Based on this model, the impact of several factors on the behaviour of the structure at early ages was assessed, as outlined in chapters 4 and 5 of this article.

In this subsection, the conditions assumed in the base model are described, namely the geometry of all the elements of the model, the type of material used, the actions and the combinations of loads and the shoring removal plan over time considered in the base model.

The geometry of the base model (also referred as 'model 1') comprises a 6 m square slab of reinforced concrete with 0.20 m thickness, related to an office building. This thickness was pre-designed according to the relation L/30 (where L is the centre to centre distance between the supports) for two way reinforced concrete slabs, forwarded in EN1992-1 [3]. The slab has edge beams 0.25 m width and 0.50 m height (which corresponds to the relation L/12) and four corner columns with a cross-section of 0.25 m $\times$ 0.25 m. The height of the columns is 3 m.

In order to support the loads that act on the structure at the early ages and its self-weight at a time when concrete still does not have enough stiffness/strength to be self-bearing, a shoring system, made of wooden planks (which support the slab), secondary and primary beams (used to support the wooden planks) and steel props (which support the entire weight of the shoring system and all the loads that act on the slab during the construction phase), was included in the thermal and mechanical simulations.

In model 1, the secondary beams are spaced by 0.5/0.6 m and placed transversally to the primary beams, which are spaced by 1.5 m. Props are spaced by 1.5 m in the X direction and by 1.5 m in the Y direction. Table 1 shows the mechanical properties of the steel (S235 strength class according to EN 1992-1 [3]) and wood (C18 strength class according to EN 338-2003 [7]) that compose the shoring system and Table 2 lists the cross-sections considered for the shoring elements.

A reference concrete that is typical in Portuguese RC buildings was considered (C25/30), with the following composition: (i) sand-765 kg/m^3 (ii) granite-1085 kg/m^3 (iii) cement CEM I 42.5R-240 kg/m^3 (iv) fly ash-105 kg/m^3 (v) superplasticizer-3.2 kg/m^3 (vi) water-162.5 kg/m^3. Based on this composition, several thermal properties of concrete were estimated and used in the thermal analysis, namely the total heat of hydration (which is based on the type of cement) and the specific heat (which is based on a weighted average of the specific heat of concrete constituents-cement, aggregates and water). The Poisson's coefficient was assumed as 0.2, whereas the coefficient of thermal expansion (CDT) was 10×10^{-6} °C^{-1}. Both these parameters were assumed constant. However, it should be noted that especially the value of the CDT endures variations during the very early ages after con-

Table 1
Mechanical properties of the shoring system elements.

	Steel (S235)	Wood (*pine pinaster*)
Modulus of elasticity-E (GPa)	210	9
Yield strength-f_y (MPa)	235	-
Poisson's ratio-ν	0.3	0.3
Density-ρ (kN/m^3)	77	3.8
Coefficient of thermal expansion-α_T (°C^{-1})	1.20E−05	3.00E−06