Evaluation of the redistribution of loads in the foundations of reinforced concrete structures from the computational modeling of the construction sequence

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Abstract. The aim is to analyze the loads on columns on a reinforced concrete building considering elastic behavior with instantaneous loading and gradual loading (construction in 3 stages). The finite element commercial program SAP2000 (version 15) with staged construction module was used. Time analysis is carried out subsequently, considering instantaneous loading and construction in 3 stages. Staged construction allows the consideration of creep and shrinkage of concrete. Concerning elastic analysis with instantaneous loading in 3 stages, it was found that a redistribution of loads on columns took place even when normal stress value is low. Therefore, the significant influence of the construction sequence on the redistribution of loads on reinforced concrete structures is highlighted. Further research is required to investigate the influence of masonry, coatings, occupancy overload and structural elements (especially beams and columns) of variable stiffness. No redistribution of loads was observed in the analysis carried out over time (creep and shrinkage). This result may be related to structural simplicity.

Keywords: foundations, reinforced concrete structures, construction sequence, soil-structure interaction.

1 Introduction

Until recently, the sizing of foundations and structures design was always carried out assuming that they had independent behavior, that is, effects of soil-structure interaction were ignored as shown in Fig.1.

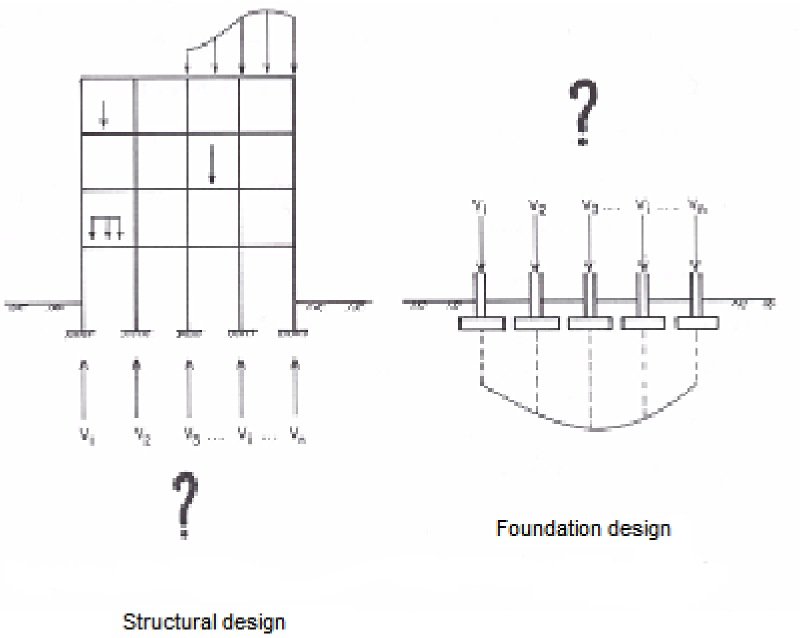


Figure 1. Conventional project designed until recently: the sizing of structure and foundation treated separately, Gusmão [1]

Given that recently there are so many sophisticated engineering calculation softwares some projects have been developed considering foundation-structure interaction. However, this interaction takes place accepting only the immediate deformations and displacements. Material creep is not taken into account for example.

According to Barata [2], soil-structure interaction mechanism is a very complex phenomenon and requires close coordination between structural and geotechnical engineers.

Soil-structure interaction depends on a number of factors such as the number of floors of the building, effect of the first floors, foundation layouts in floor plans, among others, and it is also related to mechanical effects. A redistribution of loads on structural elements occurs in general, especially on columns, with load transfer from the columns which tend to settle more to those that tend to settle less, consequently it is likely to standardize differential settlements.

Following Gusmão [1] and Gusmão and Gusmão Filho [3 and 4], many studies on soil-structure interaction are based on the hypothesis that there are not forces acting in the construction of the building. Considering the effect of height over structural stiffness, the authors mention that construction sequence plays a significant role on soil-structure interaction. They assumed a practical point of view to approach the issue based on some readings about settlements during the construction of buildings in the city of Recife. They observed absolute settlement increase due to the increase in load level. As the construction progressed, structural stiffness also increases tending to make uniform settlements and a redistribution of loads on columns.

Taking instantaneous and gradual loading, Brown and Yu [5] analyzed a flat structure using the methodology presented by Poulos (1975, apud Gusmão [1]) and a three-dimensional methodology using the computer program Focals presented by Fraser and Wardle [6]. Taking into account the interaction, an analysis of these cases showed that the effective stiffness of a building that is progressively under loading conditions during construction is about half that of the value in a building with instantaneous loading.

Fonte et al. [7] examined a fourteen-storey building, considering the influence of the construction process through a finite element computation program, the Building Information Modeling. Approaching settlement predictions, following the authors, the proposed model for instantaneous loading, soil-structure interaction aside, overestimates the differential settlements. The model that considers effects of the soil-structure interaction with instantaneous loading in turn underestimates the differential settlements because it is estimated to have higher stiffness than it actually does. Precise results were obtained through the models that consider the interaction effect and the gradual application of loads, hence increasing the structural stiffness.

Moura [8 and 9] also analyzed the effect of the construction sequence using the Interaction Module program for a nineteen-storey reinforced concrete building and observed a large influence of the construction effect on the redistribution of loads on columns.

Silva et al. [10] recently investigated the influence of the construction method on the redistribution of loads on reinforced concrete structures. Their results pointed out a significant relevance, determined by the dimensions of the construction and the need to make more detailed studies to improve the analysis as well.

This is the background for the development of this article. The influence of the construction sequence on soil-structure interaction over time is analyzed considering a low-rise reinforced concrete building (3 floors). Structures with instantaneous and gradual loading are compared. This study aims to provide elements on how to interpret results for more sophisticated structures, such as multi-storey reinforced concrete buildings with soil-structure interaction over time.

2 Structural modeling

The program SAP200 (version 15) [11] was used to conduct this study, which enables elastic and viscoelastic analyses. With this specific version 15, it was possible to consider creep and shrinkage of concrete material for example based on CEB-FIP [12].

Bar elements were used in the modeling of beams and columns of frames for a three-storey building. Plate elements were used for the slabs.

The structure is subjected to self-weight, that is, masonry, coatings and occupancy overload were not considered.

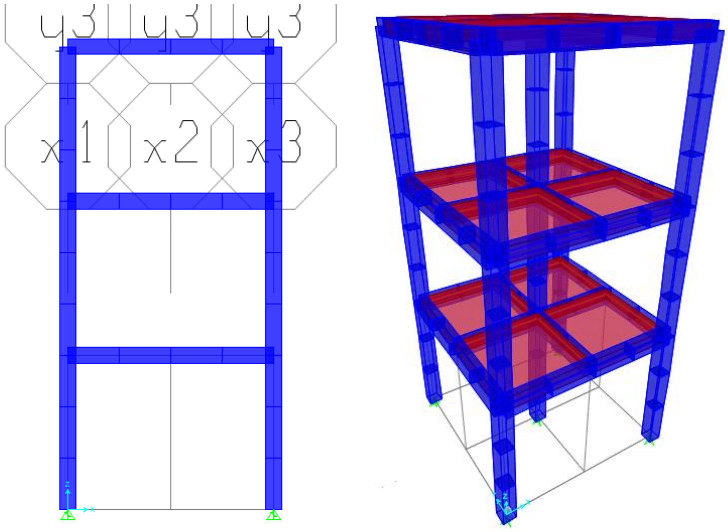
The building has 5 columns reaching the foundation level. The beams are 4 meters long. The ceiling height is 3 meters. The beams and columns cross-sections are equal to 30 x 30 cm. Slab thickness is 30 cm.

The weight of concrete is equal to 25 kN/m³ in the discretization of the structure. An initial tangent elastic modulus at 28 days with 25 GPa has been adopted. These values are based on Nunes [13].

Taking into consideration the properties of the concrete over time, including the analysis of creep and shrinkage of concrete material, coefficient to value of 0.25 which depends on the type of cement (hardening cement), 50% for the relative humidity and 0.15 for h (h = 2Ach/u, where Ach = cross-sectional area of the plain concrete column and u = section perimeter in contact with the atmosphere) were adopted. To analyze concrete shrinkage, the coefficient was 5 observing the type of cement (hardening cement) and 0 for the age of the concrete in days at the beginning of shrinkage. These concrete properties were adopted based on CEB-FIP [12].

With this specific version 15 it was possible to consider creep and shrinkage of concrete material for example. Therefore we used staged construction module. Besides allowing the staged construction, this module enables the consideration of some variation in concrete elastic modulus over time, in creep and shrinkage of the concrete based on CEB-FIP [12].

Figure 2(a) shows a front view (Y = 0) of the structure discretized in finite elements method and Fig. 2(b) shows the three-dimensional model with rigid supports.



(a) (b)

Figure 2. (a) Front view (Y = 0) of structure discretized in finite elements method with rigid supports and (b) three-dimensional model of the building

3 Normal stresses in columns – elastic model

Table 1 illustrates the normal stress in the peripheral (1, 3, 7 and 9) and central (5) columns of the elastic model with instantaneous loading and gradual loading (construction in 3 stages: 1st floor, 2nd floor and 3rd floor). The stiffness value is the same for all columns and beams.

Table 1. Normal stresses in columns – elastic model

Pilar	1	3	5	7	9	S	
Normal stress (kN)	99	99	192	99	99	587	Instantaneous loading
	94	94	213	94	94	587	Construction in 3 stages - gradual loading

Table 1 shows that the values of normal stress are low due to a particular feature of the study (structure is subjected to self-weight). Even when normal stress is low, a redistribution of loads on the columns takes place in case of staged construction – closer to reality. The central column (5) presents an increase in normal stress (around 11%), meanwhile the load decreases in the peripheral columns (around 5%). Therefore, it is relevant to examine the influence of the construction sequence on the redistribution of loads on reinforced concrete structures. Further research is required in order to include the influence of masonry, coatings, occupancy overload, structural elements (especially beams and columns) of variable stiffness and also focusing on the redistribution of loads on high-rise buildings.

4 Normal stresses in columns – time series analysis

Six situations are studied considering the loads derived from finite element modeling of two three-dimensional space frames (instantaneous and gradual loading) over time (for creep and shrinkage of concrete), as follows:

(i) Space frame with rigid supports and material subjected to creep;
(ii) Space frame with rigid supports and material subjected to creep and shrinkage;
(iii) Space frame with spring supports (k = 100 kN/m) and material subjected to creep;
(iv) Space frame with spring supports (k = 100 kN/m) and material subjected to creep and shrinkage;
(v) Space frame with spring supports (k = 1000 kN/m) and material subjected to creep;
(vi) Space frame with spring supports (k = 1000 kN/m) and material subjected to creep and shrinkage.

Figures 3 and 4 show normal stresses in corner and central columns for instantaneous loading respectively.

Normal stresses were normalized to normal stress at time equal to zero considering rigid supports and the elastic space frame in the eq. (1):

$$\nu = \frac{\mathrm{N(t)}}{\mathrm{N_e(t)}}. \tag{1}$$

Where:

ν = Normalized normal stress.
$N(t)$ = Normal stress at time t.
$N_e(t_0)$ = Normal stress in the elastic range at time t_0.

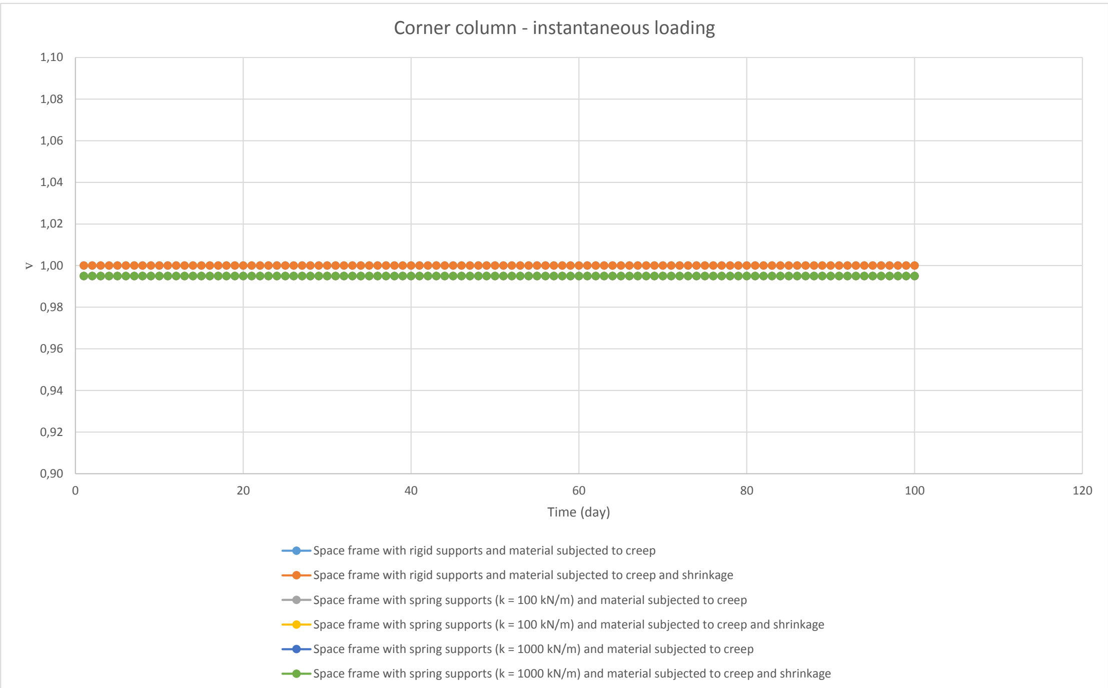


Figure 3. Normal stress in corner columns versus time for instantaneous loading

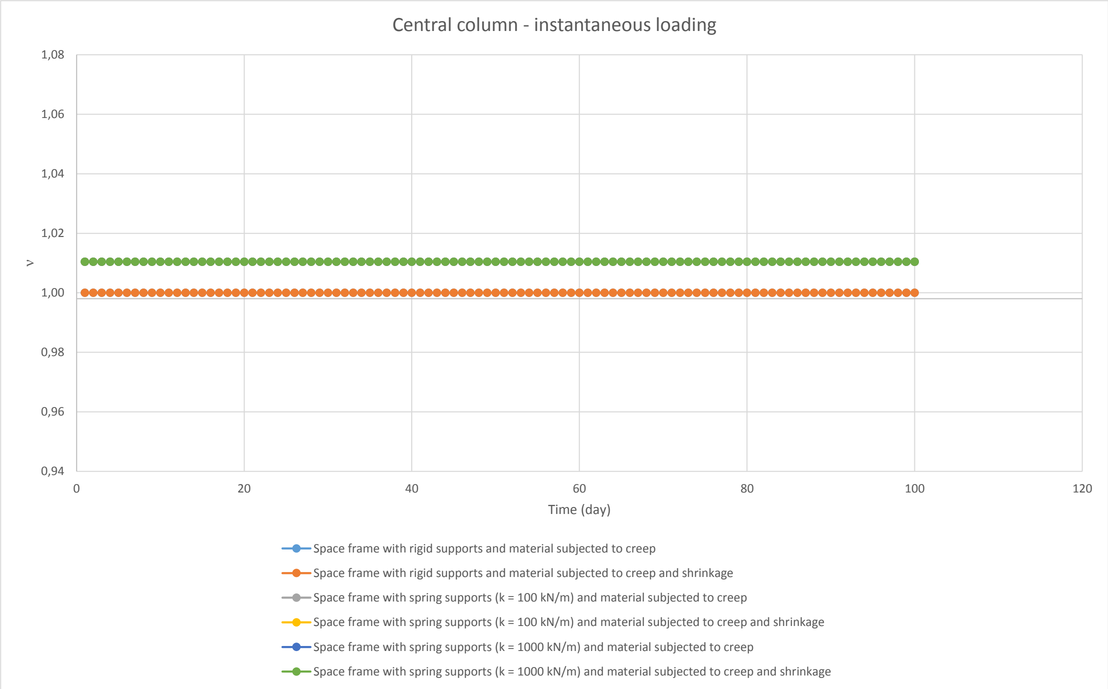


Figure 4. Normal stress in central column versus time for instantaneous loading

Figure 3 shows that corner columns present constant normal stress over time on all six situations focused here. No redistribution of loads was observed in the analysis carried out over time. This result may be related to structural simplicity (low stress values – from 99 to 192 kN, same stiffness for all structural elements and model symmetry).

For space frame with rigid supports and material subjected to creep, it is important to note that normal stress normalized to normal stress at time equal to zero show results equal to one. This is an expected outcome because the internal forces (tensions or internal forces at the sections) due to imposed load are not altered by creep according to Carneiro [14] and following the first Elastic-Viscoelastic Correspondence Theorem. At any time t the internal forces are those acting upon a body with the same geometric characteristics and binding features with the same loads but possessing elasticity.

Based on Fig. 4, it is possible to verify that central columns did not undergo load redistribution.

Figures 5 and 6 illustrate the normal stresses acting on the corner columns and central column for the staged construction respectively.

Normal stresses were normalized to normal stress at time equal to zero considering rigid supports and elastic space frames also through the Eq. 1.

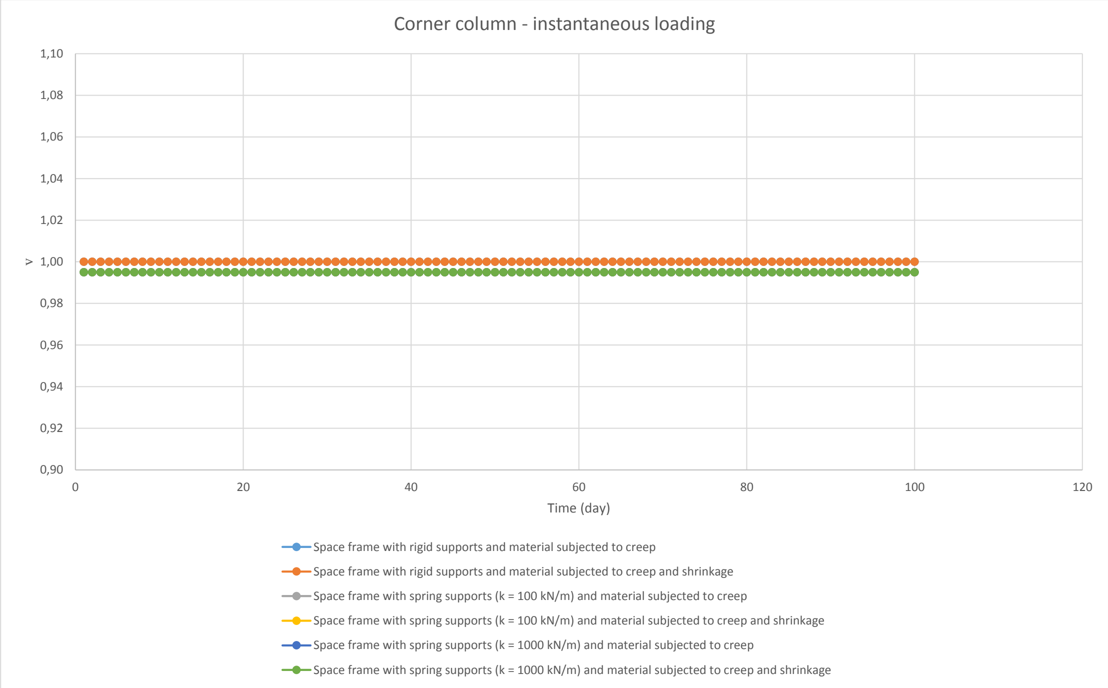


Figure 5. Normal stress in corner columns versus time for the 3 stages of loading situation

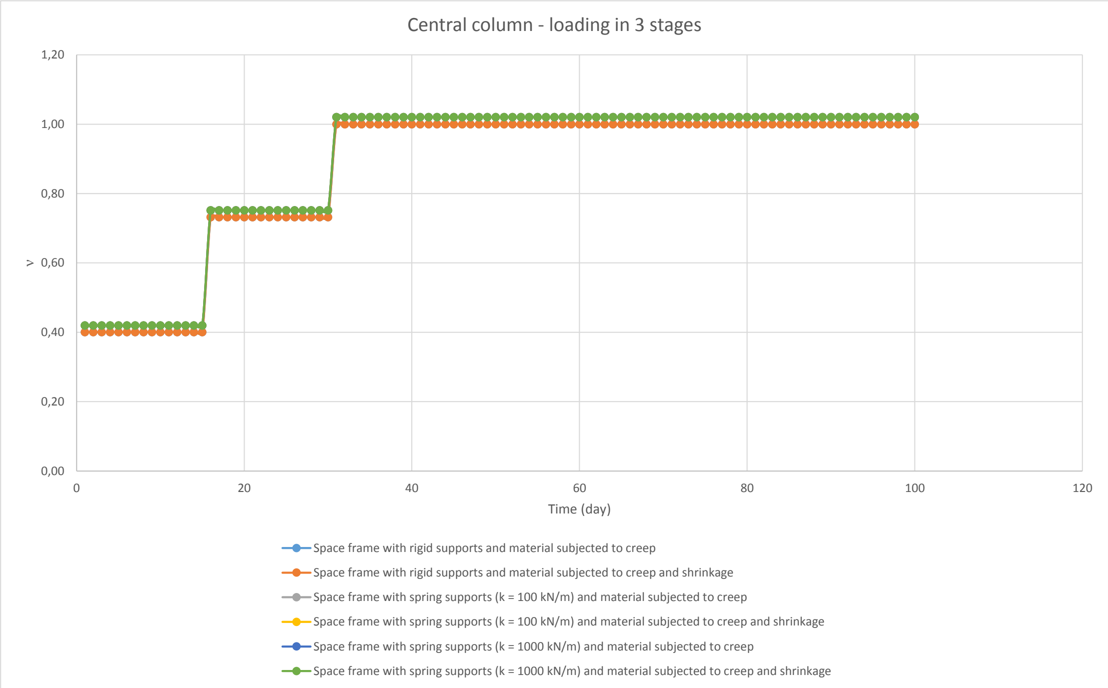


Figure 6. Normal stress in central column versus time for the 3 stages of loading situation

Figure 5 shows that loading in 3 stages occurs on corner column. At the last stage, the corner column presents constant normal stress over time on all six situations. No redistribution of loads was observed in the analysis carried out over time. As previously mentioned, this result may be related to structural simplicity (low stress values – from 99 to 192 kN, same stiffness for all structural elements and model symmetry).

For space frame with rigid supports and material subjected to creep, the first Elastic-Viscoelastic Correspondence Theorem was fulfilled.

Based on Fig. 6, it is possible to verify that central columns did not undergo load redistribution.

The effect of concrete shrinkage was almost negligible considering all the situations approached here.

5 Conclusions

The main conclusions are:

(i) Concerning elastic analysis with instantaneous loading and in 3 steps, it was found that normal stress value on columns is low due to a particular feature of the study, that is, the structure is subjected to self-weight. Even when normal stress is low, a redistribution of loads on the columns takes place in case of staged construction – closer to reality. Therefore, the significant influence of the construction sequence on the redistribution of loads on reinforced concrete structures is highlighted. Further research is required to investigate the influence of masonry, coatings, occupancy overload and structural elements (especially beams and columns) of variable stiffness.

(ii) No redistribution of loads was observed in the analysis carried out over time for both instantaneous loading and gradual loading in 3 stages. This result may be linked to structural simplicity (low stress values, same stiffness for all structural elements and model symmetry).

(iii) The first Elasticity-Viscoelasticity Correspondence Theorem, which establishes that the internal efforts (tensions or internal forces at the sections) due to imposed load are not altered by creep, was fulfilled.

(iv) The effect of concrete shrinkage was almost negligible considering all the situations approached here.

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