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Procedia Structural Integrity 5 (2017) 179–186

Structural Integrity Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Structural Integrity, ICSI 2017, 4-7 September 2017, Funchal, Madeira, Portugal

Simplified Assessment of the Effects of Columns Shortening on the Response of Tall Concrete Buildings

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Abstract

The constructive process as well as the time-dependent effects must be considered in the assessment of the response of complex concrete structures. For tall buildings, the adequate prediction of vertical elements shortening is required to determine its effects on other structural and nonstructural elements, usually overestimated by linear elastic analysis. Thus, simple numerical methods which make it possible to consider the most relevant aspects of the structural behaviour may be useful in the early stages of a project. In the research presented herein a simplified method, which considers the viscoelasticity of concrete as well as the construction sequence, was used. Its adequacy was assessed by comparison of the results for a tall concrete building with those obtained with a commercial software which incorporates a nonlinear staged construction analysis package. The good correlation between the obtained results indicates that the simplified method used may be applied to help make appropriate design choices.

Peer-review under responsibility of the Scientific Committee of ICSI 2017

Keywords: Tall buildings; Concrete; Time-dependent effects; Columns shortening; Constructive process.

1. Introduction

Over the years, buildings height has increased to economize on land area, and the construction of reinforced concrete (RC) high-rise buildings became popular. As a result, problems due to differential axial shortening of vertical

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elements have been observed and reported (Moragaspitiya et al., 2009a; Kurc and Lulec, 2011). The total column shortenings are rarely of practical interest. However, the effects of differential axial shortenings between vertical elements can lead to excessive deflection and unacceptable crack widths on horizontal elements. The former may additionally result in damage on nonstructural elements, such as façades, partitions, claddings and mechanical installations (Fintel et al., 1987). Furthermore, when vertical elements are rigidly connected through slabs or beams, relative vertical deformations can generate substantial internal forces (Pan et al., 1993; Kim et al., 2010), and significant redistribution of forces may be required at the ultimate limit states. Thus, the axial deformations of columns, both elastic and inelastic, require special consideration in the design and construction of tall building structures (Fintel et al., 1987).

It should be noted that linear elastic analysis often overestimates these effects, thus more complex analyses must be performed to prevent the exclusion of adequate structural solutions based on inadequate analysis. Several methods were developed to quantify the magnitude of the mentioned effects, making it possible to define competent design provisions and procedures (Moragaspitiya et al., 2010). The finite element method, combined with step-by-step integration methods, for example, is a reliable solution for the prediction of the time-dependent deformations. However, these procedures are often complicated and time-consuming, or do not capture the complexity of the problem, because they are limited to a few analysis parameters (Au et al., 2007; Huang et al., 2007; Moragaspitiya et al., 2009b; Kurc and Lulec, 2011). For early design stages, it is useful to use simple numerical methods, adequate for an engineering practice environment, which consider both the constructive process and the time-dependent response of concrete.

A simplified method to predict the internal forces due to axial shortening of columns was used in the research presented herein, making it possible to consider the more relevant parameters in the response assessment of concrete structures. The study reported now is intended to assess the adequacy of the simplified method used through the comparison of the results for a RC tall building with those obtained with SAP2000, using its nonlinear staged construction analysis package.

2. Axial shortening of concrete columns

The construction and loading sequence may be relevant for the analysis of complex structures, namely regarding the axial deformation of columns (CTBUH, 1980; Smith and Coull, 1991). During construction, dead loads are applied step-by-step. As indicated in Fig. 1, at the time of construction of a given level *N* there are *N*-1 previous load stages due to slabs concrete pouring, to which adds all subsequent load stages, owing to other installations, such as cladding and partitions, that occurred up to the time of construction of level *N*. Because each column segment undergoes elastic and inelastic deformations due to the different loads, axial shortening of columns is directly related to the construction sequence and its pace. At the design stage, an assumption of the loading history, as realistically as possible, is required to assess the differential shortening consequences.

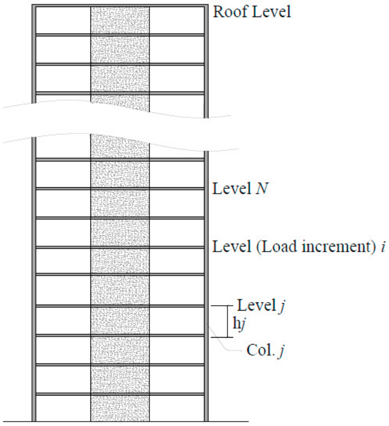

Fig. 1. Schematic of a multi-story building.

In the case of cast-in-situ RC structures, the deformations that occur prior to installing a slab are corrected through the levelling of the formworks of the horizontal components of the floor (Fintel et al., 1987). If accurate estimates of the vertical displacements are available, it is even possible to prescribe further corrective measures, eliminating long-term deformations. Nonetheless, it is not possible to avoid the structural effects of the resulting differential deformations.

The variation of the elasticity modulus with time may be of primary importance when time-dependent behaviour of concrete is considered. The ageing of the material is considered through the use of the concrete strength at the time of loading rather than the usual 28 days. The time-dependent Young's modulus used for determining axial shortenings may be obtained by the equation presented in NP EN 1992-1-1:2010, given by

$$E_{cm}(t) = \left(\frac{f_{cm}(t)}{f_{cm}} \right)^{0.3} \cdot E_{cm} \tag{1}$$

where E_{cm} and f_{cm} are the Young's Modulus and the compressive strength, respectively, at the age of 28 days. The tangent elasticity modulus $E_c(t)$ is obtained by multiplying $E_{cm}(t)$ by 1.05.

The loads are applied on the vertical elements at the loading stages, and the columns shortening results from both elastic and time-dependent deformations. Assuming that the axial stress of a column segment varies in small increments due to the loading cycles, the total axial strain at any instant t, due to a load applied at t_i, may be obtained by the sum of all strains which occur during that time interval, given by (Ghali et al., 2002)

$$\varepsilon_c(t) = \varepsilon_{ce}(t_i) + \varepsilon_{cc}(t, t_i) + \varepsilon_{cs}(t, t_i) \tag{2}$$

in which $\varepsilon_{ce}(t_i)$ is the elastic strain due to the load applied at time t_i. $\varepsilon_{cc}(t,t_i)$ and $\varepsilon_{cs}(t,t_i)$ represent the creep and shrinkage deformations, respectively. If the stress is constant over the time period from t_i to t, the total deformation $\varepsilon_c(t)$ is caused by two components: the shrinkage that takes place during the considered time period; the stress applied at t_i, $\sigma_c(t_i)$, in which case its contribution is a function of the Young's modulus and of the creep coefficient, $\varphi(t,t_i)$, which may be determined according to NP EN 1992-1-1:2010. Thus, the Equation in (2) can be rewritten as (Bažant, 1982; Ghali et al., 2002)

$$\varepsilon_c(t) = \sigma_c(t_i) \cdot \left(\frac{1}{E_c(t_i)} + \frac{\varphi(t, t_i)}{E_c(28)} \right) + \varepsilon_{cs}(t, t_i) \tag{3}$$

In this study, the columns shortening which occur before and after the casting of the slab of each level were calculated separately. This procedure made it possible to determine the deformations that are eliminated during the construction process and, therefore, do not contribute to the final displacements. Considering a segment j of a vertical element, the corresponding total shortening up to the construction of a level N has N-j loading cycles applied at instants t_i, with t_j equal to the time instant of the initial loading of the segment being analysed - the construction of the slab at level j. The mentioned shortening may be determined by the superposition of the deformations of each loading cycle. Thus, using the Equation in (3), the corresponding strain may be given, in a simplified manner, as

$$\varepsilon_j(t_N) = \sum_{i=j}^{N-1} \left(\sigma(t_i) \cdot \left[\frac{1}{E_c(t_i)} + \frac{\varphi(t_N - t_j, t_i)}{E_c(28)} \right] \right) + \varepsilon_{cs}(t_N - t_j, t_j) \tag{4}$$

Thus, for a given column, the total shortening which occurs before the construction of level N, eliminated by the construction process, may be obtained by

$$\delta_{c,N} = \sum_{j=1}^{N-1} \varepsilon_j(t_N) \cdot h_j \tag{5}$$

where h_j is the height of the segment j of the vertical element.

The long-term shortenings of each segment of a column were determined in a similar manner to what was considered for the construction shortenings. In this case, it is necessary to account for all the deformations that occur up to an instant T after the construction of the structure, with n loading stages. Thus, the long-term strains are given by

$$\varepsilon_j(T) = \sum_{i=1}^{n} \left(\sigma(t_i) \cdot \left[\frac{1}{E_c(t_i)} + \frac{\varphi(T - t_j, t_i)}{E_c(28)} \right] \right) + \varepsilon_{cs}(T - t_j, t_j) \tag{6}$$

The total long-term shortening of a vertical element is then computed in a similar manner to what is presented in the Equation in (5), resulting

$$\delta_{T,N} = \sum_{j=1}^{N} \varepsilon_j(T) \cdot h_j \tag{7}$$

The final values of the columns shortening of a level N at time instant T, $\delta_{f,N}$, are determined by the difference between the total vertical displacement of the column at the analysed level and the displacement eliminated by the constructive process, and is written as

$$\delta_{f,N} = \delta_{T,N} - \delta_{c,N} \tag{8}$$

The simplified method adopted uses the columns displacements obtained as described above to predict the shear and bending moment diagrams of the horizontal elements of each floor. These internal forces are then computed assuming that a differential shortening has the same effect on a horizontal element as a differential settlement of supports. Usually, on a concrete building, the differential shortenings are more substantial between columns and shear walls, given the more pronounced difference of mean axial strains. **Erro! A origem da referência não foi encontrada.** shows the simple beam model adopted in this study as well as the corresponding internal forces due to the differential settlement of the supports. The spring represents the flexural stiffness of the column at the beam-column joint.

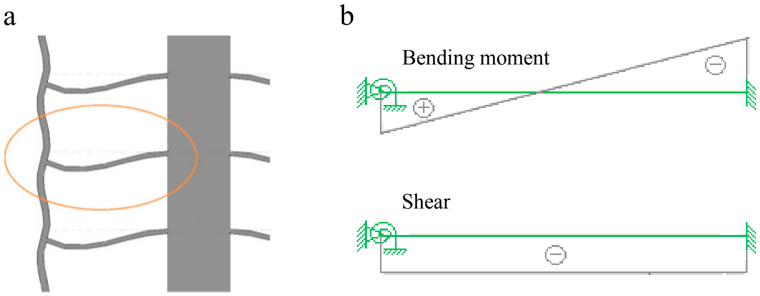

Fig. 2. (a) deformations due to the axial shortening of columns; (b) corresponding bending moment and shear diagrams.

On the determination of the internal forces of the beams, both age-adjusted and effective elasticity moduli were used. The former was used to estimate the stiffness values when assessing the effects of differential shortenings resulting from the loading cycles up to the construction of the level of the beam under analysis. The latter elasticity modulus was used in the assessment regarding the effects of the loads applied after the construction of the level under analysis. For a load introduced at t_i, the effective and age-adjusted Young's modulus at an age t may be estimated per the equations presented in CEB-FIP Model Code 90, given by

$$E_{c,eff}(t,t_i)=\frac{E_c(t_i)}{1+\dfrac{E_c(t_i)}{E_c(28)}\cdot\varphi(t,t_i)} \tag{9}$$

and

$$E_{c,adj}(t,t_i)=\frac{E_c(t_i)}{1+\chi\cdot\dfrac{E_c(t_i)}{E_c(28)}\cdot\varphi(t,t_i)} \tag{10}$$

In this study, the ageing coefficient, χ, was considered equal to 0.8.

3. Case study

A multi-storey building with 45 floors and total height of 135 m was used to assess the adequacy of the methodology described above. The building has a typical high-rise structural beam-column system, with a central core and a simple symmetrical plan, as shown in Fig. 3. The chosen building made it possible to perform a straightforward analysis of the results and to focus on the effects of differential shortening of vertical elements.

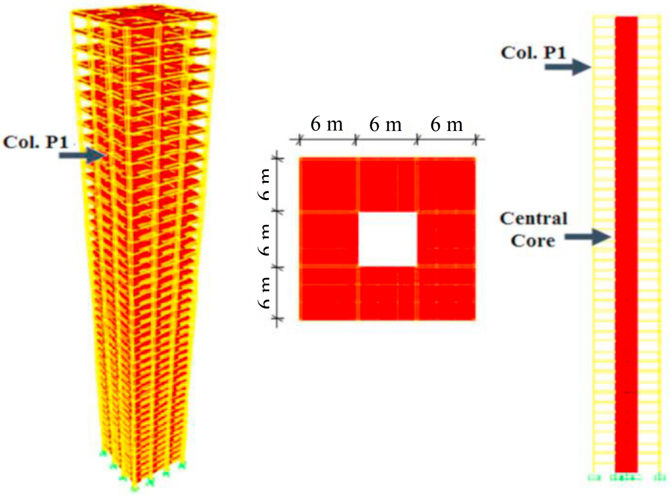

Fig. 3. 3D perspective, plan and elevation of the building analyzed.

The horizontal and vertical members are constructed with C30/37 and C60/70 concrete, respectively. The interior beams, which connect the core shear walls to the peripheral frame, have a 0.30×0.50 m^2 cross-section, while the exterior beams have 0.40×0.70 m^2 cross-section. Regarding the vertical elements, a continuous cross-section area of 1.00×0.40 m^2 was adopted for the columns, whilst the central core has 0.40 m thick concrete walls.

The stress values due to the axial deformations of the vertical supports obtained with the simplified method adopted were compared with the results of a 3D analysis using SAP2000 *Ultimate v.15.0*. This software makes it possible to consider the construction process and the time-dependent behaviour of the material, using a specific package called "Staged Construction", based on the input of the material properties which affect ageing, creep, and shrinkage parameters. These properties were computed per the constitutive laws recommended in CEB-FIP Model Code 90.

On both nonlinear analyses, floor construction and loading cycles of seven days were considered. The total permanent loads were considered to be imposed 14 days after the floor self-weight was applied. Moreover, the long-term results were determined for 10 and 30 years after the construction of the building.

4. Results

The validity of the simplified method used was assessed by comparison of its results with the values obtained with SAP2000. The study focused the differential axial shortening between the central core and the exterior column P1 (see Fig. 3) as well as the internal forces of the interior beams resulting from those displacements. If the structure presents adequate ductility, the problem here evaluated, regarding both internal forces and displacements, is a matter of serviceability limit states verification, thus service-level loads combination was considered in the assessment presented below.

The total columns shortening values at every five levels are shown in Fig. 4.

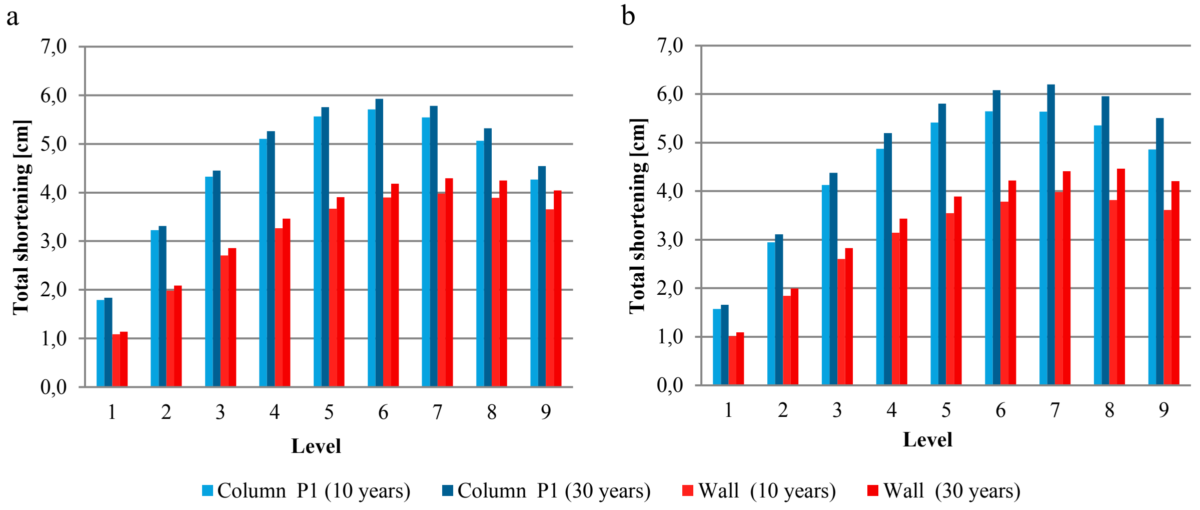

Fig. 4. (a) simplified method; (b) “Staged Construction”.

The similarities in the results of the simplified method and of the “Staged Construction” analyses can be easily observed. Also similar is the elements shortening tendency along the height of the building obtained with both analyses. The axial displacements increase to about two-thirds of the height of the building, after which it decreases. As could have been expected, much of the deformations take place in the first 10 years after construction. Maximum total shortening values on both assessments occur at about levels 30 and 35. According to the “Staged Construction” analysis, after 30 years, column P1 undertakes the highest shortening value at level 33, with 6.3 cm, while on the concrete shear wall the maximum displacement of 4.5 cm is obtained at level 38. Using the simplified method, those values are of 5.9 cm at level 32 and of 4.3 cm at level 36.

Furthermore, a linear elastic analysis was performed to compare its results with those of the more realistic methods, which consider the time-dependent effects and the construction sequence. As noted above, this method often overestimates the internal forces of structural elements as well as the displacements of complex structures such as those of tall buildings. The model used is the same of the “Staged Construction” analysis, but without the consideration of the construction sequence and with linear elastic constitutive laws for the materials. The long-term values of displacements were obtained by multiplication of the elastic results by 2.5, which corresponds to a value of φ equal to 1.5, considered adequate for the concrete adopted.

A comparison of the differential displacements between the column P1 and the shear wall obtained with the three applied analyses are presented in Fig. 5.

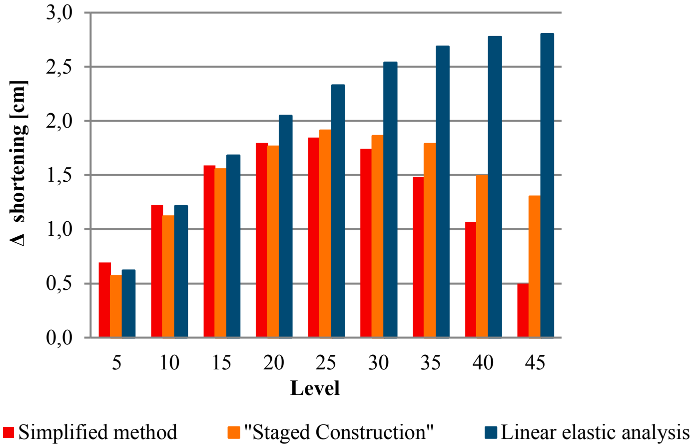

Fig. 5. Differential shortening values at 30 years after the construction of the building.

The maximum values of the differential shortening occur at approximately mid-height of the building, according to both the “Staged Construction” and the simplified method, whilst via the linear elastic analysis the maximum value is registered at the top of the building, at level 45. The results obtained with the latter analysis are continuously increasing from the bottom to the top of the structure. Once more, both time-dependent methods show similar values, but some inconsistency was obtained at the top levels, where it is noticeable a decrease at a higher rate when using the simplified method. Nevertheless, the maximum values obtained with both formulations are very similar. In contrast, the elastic analysis provided very unrealistic differential shortening values, assuming that the “Staged Construction” method delivers the most precise results.

The shear and bending moment values of the interior beams due to the long-term differential deformations are shown for every 10 levels in Table 1**Erro! A origem da referência não foi encontrada.**. The beams are identified with the letter “B” followed by the number of the floor level they belong to.

Table 1. Internal forces of beams due to the differential shortening of vertical elements.

	“Staged Construction” analysis		Simplified method		Elastic analysis	
	Shear [kN]	Moment [kN·m]	Shear [kN]	Moment [kN·m]	Shear [kN]	Moment [kN·m]
B10	23.1	-67.5 64.0	23.0	-70.0 67.5	28.2	-80.0 74.6
B20	35.5	-104.5 98.8	34.4	-105.3 101.1	47.5	-136.0 126.0
B30	38.4	-113.0 106.3	35.1	-106.4 102.0	59.2	-168.8 156.2
B40	31.5	-92.1 86.5	23.6	-72.4 69.6	64.7	-184.5 17.6

The values obtained with the “Staged Construction” method and with the simplified method are very similar. However, following the differences in the differential shortenings, the weaker correlation is found in the top floors of the building. Nonetheless, the final internal forces obtained with both methods correlate well, especially for the maximum values at approximately mid-height of the building. This indicates that the simplified method could be used to help structural designers make adequate choices at the early stages of a project.

The shear and bending moment values obtained using the linear elastic analysis are significantly different from the results of the other two methods, especially for the higher floors, following, as expected, the differences observed on the differential shortening values. Noteworthy are the high shear and bending moment values of B40 when using the linear elastic analysis, which are approximately twice the values obtained with the other two analyses.

5. Conclusions

Tall buildings are complex structures that need careful design in all aspects, one of which is the consideration of the constructive process. Also, the time-dependent response of concrete must be considered in the structural analysis.

A RC tall building with 45 floors and a structural system composed of a central core connected to a peripheral frame was considered. A simplified method for the assessment of the effects mentioned above on the response of tall concrete buildings was used. The results obtained were compared with the ones of a commercial software of structural analysis which incorporates a nonlinear “Staged Construction” analysis package. The total and differential shortening values obtained with both analysis are similar, with the largest difference occurring in the differential column/wall shortening values at top floors of the building. The shear and bending moment values due to the long-term differential shortenings computed with the nonlinear analyses are similar. Although smaller internal forces were determined for the interior beams of the top floors with the simplified method, the maximum values are identical and occur in the floors above the mid-height of the building, around level 30. These results were compared with those of a linear elastic analysis, which significantly overestimated the vertical displacements of the building as well as the resulting internal forces in the horizontal elements.

The comparison of the long-term results of the simplified method with those of the “Staged Construction” analysis indicates that the former may be useful in the early stages of the project of a tall building. It constitutes a simple method to estimate the long-term differential displacements of vertical elements as well as the resulting effects on the response of structures.

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