Influence of the construction stages analysis on the distribution of displacement and forces in columns of reinforced columns tall buildings

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Abstract. The increasing construction of tall buildings in the world, as well as in Bulgaria, defines the desire for a more precise study of this type of structures. To satisfying this necessity, the possibility of carrying out nonlinear analysis of structures is included in many software packages. The question of the proper definition of material characteristics and the application of computational software in the design of structures with consideration of the stages of construction remains open. In addition to purely research, the problem has also a practical application related to the increasing number of tall buildings at different stages of design and construction. The issue of more accurate modeling of the behavior of tall buildings is discussed, with a focus on the distribution of forces and displacements in columns. A computational model of a tall building is considered. The distribution of forces and displacements in a computational model that accounts for the stages of construction is compared to one in which such consideration is not included. A comparison of the forces and displacements in representative sections of the columns in the two modeling options is presented as a result. Finally, general conclusions and recommendations for the research and design of tall buildings with reinforced concrete structure are given.

1. Introduction
The number of tall buildings in the world is constantly growing. They are the subject of increasing research mainly due to the fact that the effects of vertical and horizontal loads on the structure are much greater than in buildings with the usual number of storeys. The analysis and design are also hampered by the fact that the applicable technical standards are not specifically designed for tall buildings. Defining the main steps and issues in the design of tall buildings taking into account the specific experience of the authors is carried out in [1], [2]. One of the essential features in the design of tall buildings is the necessity to reflect the stages of construction and their influence on the distribution of forces and displacements in the structural elements. Each construction is carried out in separate stages. At each stage of the construction, the structure is deformed under its own weight. The loads from the next phases of the construction are applied on a part of the structure, in which certain displacements, internal forces and stresses have already taken place. Taking the nonlinear behavior of the studied structures into account leads to different in size and sometimes type of deformations. This affects the magnitude and distribution of stresses in the structural elements [4,6].
The nonlinear behavior of a structure is influenced by the technology and speed of execution, the type and geometry of the structure and structural elements, including the location and number of columns and walls in plan, the ratio in the cross-sections between columns and walls, the stiffness of the storey structures, number of storeys, accounting of shrinkage and creep, the properties of the materials and the affect of the environment [3,6].

For tall buildings, the longitudinal deformations and the distribution of normal forces in the vertical structural elements due to gravitational loads have the main affect. As a consequence of the longitudinal deformations a difference in the length of vertical elements is obtained, which leads to redistribution of internal forces in the load-bearing structural elements and the appearance of cracks and deformations.

Traditional for the construction of tall building structures with cores and columns, which are located along the contour of the slabs is considered below. The analysis shows the sensitivity of this type of structures when the construction sequence is taken into account.

2. Description of the structure and the loading
A 42-storey residential building with a total height of 144 meters above lv. 0.000 is presented.

2.1. Description of the structure
The structure consists of reinforced concrete cores and walls, a system of columns and beams along the contour of the floor slabs. The architectural solution requires a change in the contour of each floor slab, which leads to a change in the geometry of part of the walls and columns. The soil conditions are not taken into account and the structures supports are considered as fixed. The walls are 70 cm thick, the dimensions of the columns are 100/100 cm, the beams are 60/70 cm and the slabs are 18 cm thick. The properties of concrete grade C35/45 and reinforcement steel B500 are used in the calculations (Fig.1). In order to clearly highlight the effects of redistribution of internal forces the dimensions of the cross-sections of the columns and walls are assumed to be constant throughout the height of the structure.

2.2. Defining load function
The load on the structure is modelled and is divided into two main groups: Fk – self weight of the structural elements; Fдоп - load from non-bearing structures and other long-term loads. Live loads are not included because the structure is studied at the time of its construction.

The load for the i-th floor would be:

\[ F_i = (F_k + F_{доп}) \times (n - i + 1) \]  

(1)
The influence of time or speed and sequence of execution can be presented by the rate of application of the loads or the average rate of change of $F_i$ [3].

$$C_i = \frac{F_i}{t_i},$$

where $C_i$ – speed of the construction process; $F_i$ – service loads (in this case without live load); $t_i$ – the total time required to complete the structure.

Under these initial conditions, the load can be defined as a time function:

$$F_i(t) = C_{k,i} \cdot t_{k,i} + C_{dop,i} \cdot t_{dop,i}$$

This function takes into account that different construction processes require different speeds and start at different times. I.e. $C_k \neq C_{dop}$ and $t_{0,k} \neq t_{0,dop}$.

The loads are as follows: $F_k$ – is automatically calculated by the software; $F_{dop} = 4.50 \text{ kN/m}^2$.

The accepted speed of the construction processes is $C_{k,i} = C_{dop,i} = 1$ floor per 20 days, as $t_{0,k} = 0$ day and $t_{0,dop} = 80$-th day.

Only static analysis of the frame is carried out. The coefficient $\psi = 1$ as the results are used only for comparison of the two different ways of loading. The construction stages are considered in the analysis correspond to a possible construction schedule.

3. Numerical model

The analysis software SAP2000 [7] is used for modelling and structural calculations. The beams and the columns are modelled with Frame elements. The slabs and the walls are modelled with Shell elements (Fig.2).

For the purposes of this research, four variants of calculation models have been created and analyzed, in which the number of storeys of the building varies - 10, 20, 30 and 42 floors.

To take into account the embedded reinforcement in the reinforced concrete structure, the modulus of elasticity of the concrete is increased by 5% [5].

Two different variants of defining the loading are considered and modelled numerically:
- The loads are defined and combined in a way that is usual in the engineering. The deformations due to the self-weight of the structural elements during construction are not taken into account and it is also not considered that the rest of the loads are applied to the structure after the elements are deformed due to their self-weight. The results are presented in the following tables under the name “C”;
- The second variant the loads $F_{dop}$ are applied to the already constructed structure that is deformed because of the self-weight. The results are presented in the following tables under the name “CS”.

Figure 2. Computational models – versions with different number of storeys
4. Analysis and comparison of the results

The main results of the calculations of the two variants of modelling are compared. The loads and the load cases are the same, but the number of storeys vary for every of the different models. The results present the vertical displacements and the normal forces at 3 of the columns (Fig.1) on specific floors – 1-st, 10-th, 20-th, 30-th and 41-st. A comparative analysis is given of whether and what influence the number of storeys have on the distribution and magnitude of displacements and internal forces for the same loads applied under the same law.

The two sets of results reveal differences in the vertical displacements and the normal forces. Comparison of the differences in % between the results of the two solutions is presented in the Figure 4.

![Figure 3. The differences in % between the results of the two solutions](image)

The main conclusions that follow from the presented results are:

- The vertical deformations in the columns are significantly smaller when the construction stages are taken into account;
- Normal forces are significantly greater when the construction stages are taken into account;
- In the case of building structures with up to 10-15 storeys, the consideration of the construction stages in the computational model does not have a significant impact on the distribution of forces in the columns.

In tall buildings, the increased number of floors changes the way how displacements and forces are being distributed compared to structures with fewer storeys.

In the nonlinear structural analysis considering the stages of construction, it is required to ensure the proper definition of the loads and the speed with which they are applied.

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