Study of the influence of construction stages on the analysis of tall reinforced concrete buildings

Mateus M. Marinho[1], Leandro L. da Silva[1]

[1]*Dept. of Structural Engineering, Federal University of Minas Gerais*
Presidente Antônio Carlos Avenue 6627, 31270-901, Minas Gerais, Brazil
mateusmmarinho@hotmail.com, leandro@dees.ufmg.br

Abstract. This study proposes to investigate the influence of considering construction stages in tall reinforced concrete buildings by evaluating conventional strategies, which do not take the construction stages into account, and strategies that consider them in an approximate way, including a model interpreted as a reference, known as construction effect. Since the structure is subjected to internal forces as it is built, it is desirable for structural engineers to consider the loading being applied progressively and the evolution of the mechanical properties of materials with time. The main distinction between analysis strategies lies in how displacements along the height of the building are treated. In the conventional model, since the loads are applied in a single step, displacements occur simultaneously and cumulatively. On the other hand, in incremental analysis, the loads acting on a given floor do not cause displacements, or consequent internal forces, on an upper floor not yet built. Analysis without consideration of the construction stages may result in an inconsistent distribution of internal forces and may not represent the real behavior of the structure, wich may even result in inadequate design and consequent pathological manifestations and/or collapse of the structure.

Keywords: Construction Stages; Conventional Method; Approximate Method; Construction Effect

1 Introduction

Structural analysis is the design stage responsible for predicting structural behavior, aiming at dimensioning. Naturally, the selection of an appropriate structural model is a necessary condition for the quality of this prediction. In multi-story buildings, this choice requires a careful evaluation, including the point in time at which the loads act on the structure. According to Coelho [1], simplifying the analysis using conventional methods related to construction stages can lead to an inadequate structural model.

Since the structure is built in stages, the loading actions occur as construction progresses. Defining the loading on the floors during construction establishes the loading history of structural elements from the beginning to the end of the construction process (Prado [2]).

The structural design of tall reinforced concrete buildings, when carried out through conventional analysis, considers the simultaneous application of all loadings on the completed structure, corresponding to the occupancy phase of the building. Additionally, it takes into account the young's modulus of concrete at 28 days. Regarding the mechanical behavior of concrete, it is known that, during the usual construction process, the structure is subjected to loading already in the construction phase, when the concrete has not yet reached its final properties of strength and deformability as specified in the structural design (Freitas [3]).

Through a system of formwork and shoring, the already constructed floors temporarily support the weight of the upper floors under construction. According to NBR15696:2009 [4], shoring system is defined as temporary structures capable of resisting and transmitting to the support bases all actions resulting from the concrete pouring process until the concrete becomes self-supporting. In other words, displacements on a given floor will only occur once its shoring is removed. Additionally, naturally, the upper floors that have not yet been constructed do not experience any displacements or influence from the actions of the lower floors (Kripka [5]).

According to Kripka [5], in the conventional analysis process, displacements along the height of the structure accumulate simultaneously. As illustrated in Figure 1, the differential axial displacement between adjacent columns (supports in the figure), when reaching significant values, alters the distribution of the internal forces in the beams supported by these columns. In other words, an inconsistent prediction of column displacements results in an inconsistent prediction of internal forces distribution in the beams.

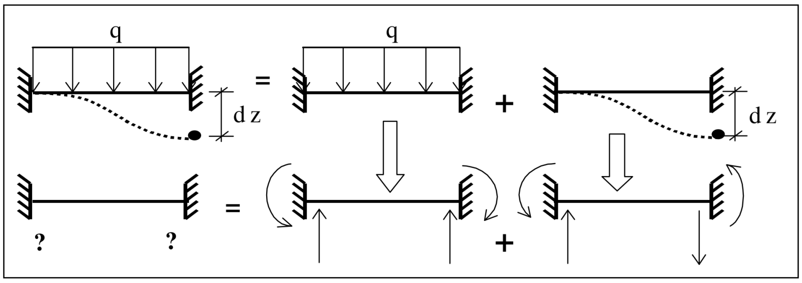


Figure 1. Forces at the beam ends due to differential support displacement (Gorza [6]).

In a conventional analysis process, on the upper floors of a given building, the inconsistency in predicting internal forces and displacements in the beams becomes even more prominent. It is because, in reality, a significant portion of the floor displacements, and consequently the supports of these beams, are smaller than indicated by this analysis strategy. These displacements are primarily due to the construction of the respective floor and those above it, rather than the building as a whole. In the analysis that considers the construction sequence, this inconsistency is circumvented since the loads are applied incrementally to the structure. This allows for determining the interaction of the response of one floor with the other floors of the building. For instance, it permits disregarding the influence of deformation due to the self-weight of a floor on the upper floors that are not yet constructed.

Therefore, it can be observed that, depending on the scenario, the conventional analysis of buildings should be replaced by an analysis that considers the successive stages of construction and loading, known as the **construction effect**, to ensure safety and durability throughout the useful life of the structure.

Structural design software plays an important role in the analysis of buildings. Computational resources enable the analysis and design process through increasingly sophisticated models. During the design stage, using construction effect analysis, the chronological stages of construction and, consequently, the application of loads at each stage of the construction are considered. For this purpose, it is necessary to know the construction schedule, as the refinement of the analysis directly depends on the execution time of each stage of the building.

As mentioned, the main distinction between the conventional and construction effect approaches lies in how displacements are treated. In construction effect analysis, the loads acting on a given floor do not influence the distribution of internal forces and displacements on an upper floor that has not yet been constructed. Consequently, when the displacements of the lower floor have already occurred due to the corresponding load, in the subsequent analysis with the upper floor, all previously applied loads are considered irrelevant. The result of the analysis is achieved through the superposition of effects, each corresponding to the number of floors constructed at the time of the respective analysis.

When a structure is analyzed using the conventional method, the application of loads occurs in a single stage, assuming the structure is complete. Thus, the displacements occur simultaneously and cumulatively, as shown in Figure 2.

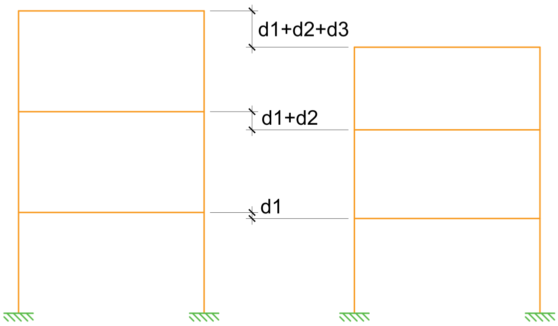


Figure 2. Building displacements through the conventional analysis process.

In an analysis considering the successive stages of construction and loading, displacements do not occur all at once in the structure. Thus, when a given floor is constructed and new loads are introduced, the lower floor already presents an initial displaced configuration. In reality, the actual impact on the upper floors to be constructed is in the deformation of the columns and their implications, rather than in the displacement, assuming that the floors will be built on this initial displaced configuration. In other words, it is as the floor were constructed with an initial displaced configuration that does not impose deformation on it. From a construction practice point of view, it makes sense to refer to displacement, as it is common to respect the absolute level of a floor rather than the relative level between floors. In other words, there is a compensation for the displaced configuration of the lower floors during the construction of the current floor, as illustrated in the Figure 3 by the regularizations r1 and r2.

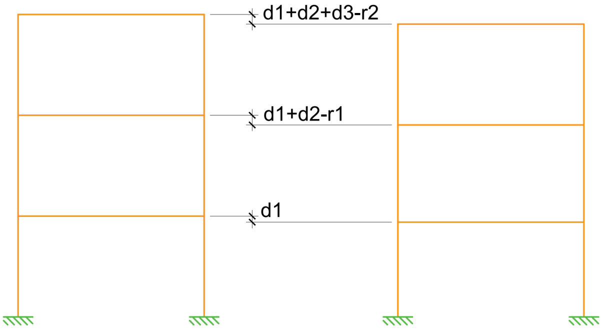


Figure 3. Building displacements through the construction effect analysis process.

2 State of the art

Reinehr [7] performed numerical simulations on 5, 12, and 20-story buildings using the TQS software, comparing conventional and incremental models. The building modeling, considering the construction stages, was carried out using the software's incremental effect module, which enables the description of loading stages and concrete properties over time. Both models analyzed have the same final load, differing only in the stage at which the structure is subjected to the load.

It was observed that, in the conventional model, the loads acting on the first floor influence the forces on the upper floors, even those that have not yet been constructed. This does not occur in the incremental model, as it considers the natural construction sequence. By accounting for the loading history, the incremental model determines the portion of the load acting at each phase, as well as which parts of the structure are impacted by that portion.

In his analysis, Reinehr [7] observed no significant variation in the vertical support reactions at the foundations obtained from both analysis models. Regarding the differential axial displacements between columns, it was noted that, in the conventional model, the differential displacements continuously increased until reaching their maximum value on the top floor. In the incremental model, the differential displacements increased up to half the height of the building, where they reached their maximum. From that point, the differential displacements between columns decreased. It is worth noting that the largest differences in differential displacements occurred on the upper floors, which significantly affects the distribution of forces in that region of the structure.

Rachinhas [8] proposed a numerical model for a five-story building using the ANSYS software, aiming to compare global and phased analyses, corresponding to the conventional and incremental approaches, respectively.

It was observed that, in the evaluation of forces in the end columns, the normal forces were smaller in the analysis that considered the construction stages compared to the conventional approach. On the other hand, regarding the forces in the internal columns, the incremental analysis presented higher values compared to the conventional process. Furthermore, a significant difference in the forces of the first-floor columns was noted, attributed to a redistribution of forces in the conventional process.

In the evaluation of bending moments in the columns, significant differences were found between the analyzed models. In the end columns, the bending moment values in the incremental model were lower than those obtained through the conventional method, with a notable inversion of moment signs on the first floor. Conversely, for the internal columns, the incremental analysis showed higher values compared to the conventional model.

On the other hand, regarding the bending moments in the beams, the values obtained at the junction with the internal columns were higher in the incremental analysis. These differences can be attributed to the smaller differential displacements between the columns, resulting in less force redistribution.

Regarding the displacement of the analyzed frames, the incremental model showed higher values compared to the conventional analysis, due to the consideration of concrete shrinkage and creep phenomena in this strategy.

Thus, Rachinhas [8] emphasizes the importance of incorporating construction stages into structural analysis, not only through the gradual application of loads but also by considering the rheological effects of concrete, such as shrinkage and creep. The analyses performed using both incremental and conventional methods revealed significant differences in some cases, which could affect the design and, consequently, the performance and integrity of the structural elements.

The conventional analysis of buildings assumes that all acting loads are applied simultaneously to the completed structure. As a result, the quantification of structural displacements occurs in an accumulative and unrealistic manner, meaning that the deformation corrections of the columns inherent to the construction process are not considered. This can lead to an inconsistent distribution of internal forces within the structure. Consequently, the internal forces in structural elements may be underestimated due to the actual gradual application of loads as the structure is built in practice.

The MULAXI - AXIal MULtiplier - is used to approximately simulate the construction effects in structural design. This tool artificially increases the axial stiffness of columns when considering gravitational loads, aiming to reduce displacements, particularly differential displacements. The stiffness enhancement is achieved by multiplying the cross-sectional area of the columns by a factor greater than 1. By increasing axial stiffness and reducing displacements, the MULAXI also alters the internal forces applied to columns and beams. It is important to note that this is an approximate analysis, as it does not account for the successive stages of loading and construction (TQSDocs [9]).

An extension of the MULAXI, the floor-by-floor increment increases the axial stiffness of columns to reduce their deformability. However, in this strategy, the stiffness increment is applied individually for each floor, rather than using a single value for the entire analysis as considered in MULAXI. It is recommended to apply higher values for the lower floors and smaller values for the upper floors (QiSuporte [10]).

The incremental effect mitigates the approximations related to construction stages by incorporating the construction schedule directly into the structural analysis data. In this method, the building is analyzed using different structural models at each construction phase, providing a more realistic representation of the structure's internal forces and displacements. The analysis is conducted from the bottom up, following the assembly and loading sequence of the building. The results obtained from each model are progressively accumulated until the project is completed (TQSDocs [9]).

3 Case study

The building to be analyzed consists of 40 floors designated for commercial use, modeled using TQS software. The structural plan is presented in Figure 4.

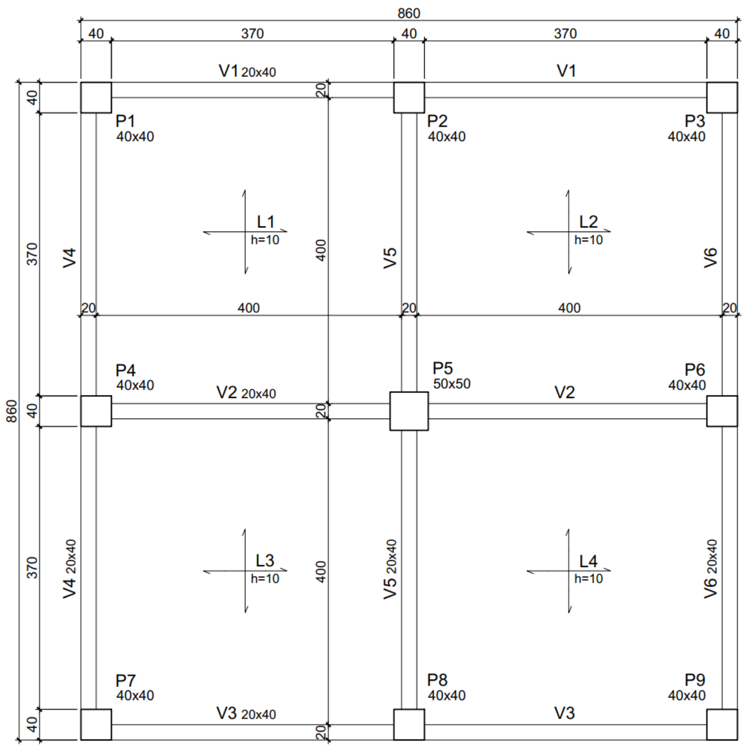


Figure 4. Structural plan of the building (measurements in cm).

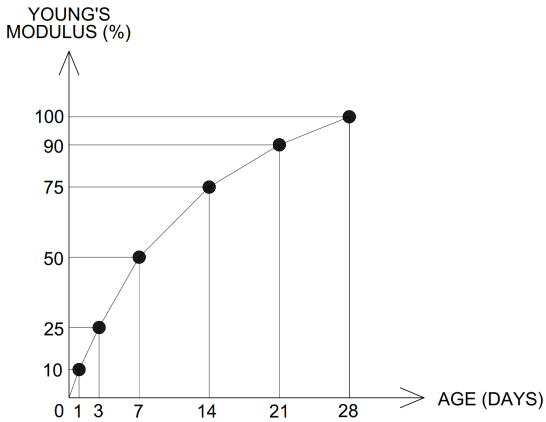
Parameters adopted in the project:

- Structural concrete with a compressive strength f_{ck} = 30 MPa;
- Ceiling height = 3 meters;
- Uniformly distributed load on the slabs: live load = 2.00 kN/m² and dead load = 1.50 kN/m²;

- Linear load on the beams resulting from the weight of masonry = 6.00 kN/m.

To minimize differential displacements between columns, an approximate strategy will also be investigated using the AXIal stiffness MULtiplier for columns - MULAXI with a value of 3.

For construction effect analysis, a 14-day concreting cycle between floors was adopted, and the young's modulus of concrete was varied over time, as shown in Figure 5(a). This approach aims to represent the natural sequence of building construction and loading. For the structural analysis, multiple models are created in which loads are applied progressively. When a given floor is concreted, its self-weight is considered, and the permanent loads, such as masonry, are applied with a delay of two concreting cycles, as illustrated in Figure 5(b) below.



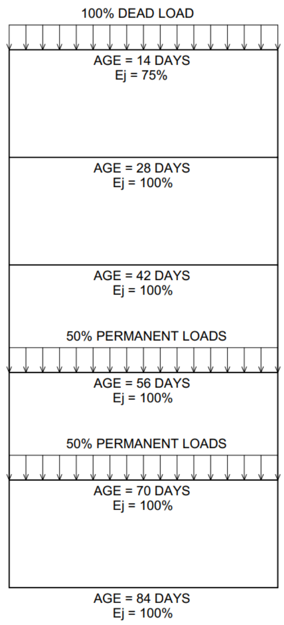


Figure 5. (a) Variation of the young's modulus of concrete over time (b) Application of loads according to concreting cycles

Considering the different analysis strategies, Figure 6 below presents the vertical displacement in column P5 across the floors of the building.

It is observed that, in conventional analysis, since all loads are applied simultaneously when the structure is completed, the vertical displacement of each floor is influenced by the construction of the floors below it. Consequently, the maximum vertical displacement occurs at the top of the column.

On the other hand, in construction effect analysis, the vertical displacement of the column increases with the construction of the floors above it and is not influenced by the floors below it. Therefore, the maximum vertical displacement does not occur at the top of the column, as it does in conventional analysis.

The simulation of construction stages using the approximate MULAXI method reduces displacements, primarily to avoid differential displacement between columns. However, it is observed that the displacement of the analyzed column does not converge to the results obtained by the construction effect method.

As a consequence of differential displacements between columns, the bending moments in beams are impacted by the disregard for construction stages in the structural design. In light of the analysis strategies, Figure 7 presents the bending moment diagram of V5 beam on the first floor for both methods.

Subsequently, Figures 8 to 10 present the bending moment diagrams of this same beam on the top floor obtained with the different analysis strategies.

It is observed that, using the conventional method, since loads are applied in a single stage, displacements are obtained cumulatively. Additionally, the inconsistent vertical differential displacement between adjacent columns influences the distribution of internal forces. On the top floor, the bending moment at the central column P5 is significantly smaller than that observed on the first floor. On the other hand, the final segments of the edge columns on the top floor experience greater internal forces, which does not occur when considering the construction effect method.

In considering successive loading stages, the construction effect method provides a bending moment diagram that closely approximates the actual behavior of the building. Differential displacements between adjacent columns are minimized, reducing the redistribution of internal forces within the structure.

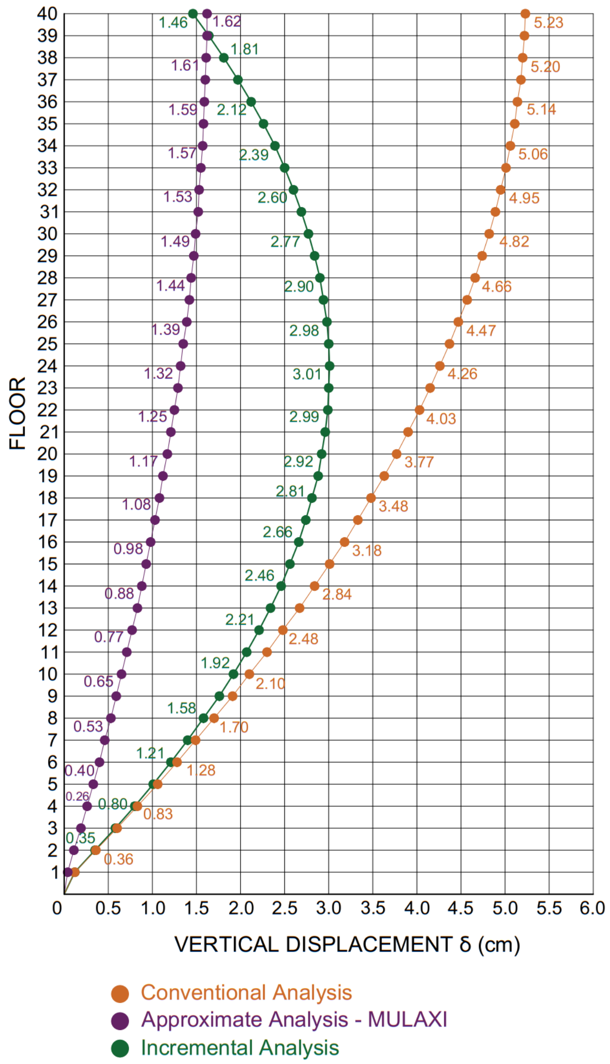


Figure 6. Vertical displacement in column P5.

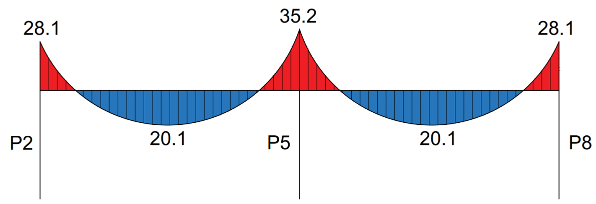


Figure 7. Bending moment diagram of V5 beam on the first floor (values in kN.m).

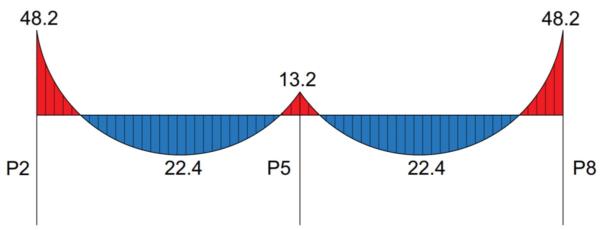


Figure 8. Bending moment diagram of V5 beam on the top floor using the conventional method (values in kN.m).

4 Conclusions

The inconsistent prediction of load effects in a multi-story building can significantly impact the sizing of structural elements. During the construction of the building and the successive application of loads over time,

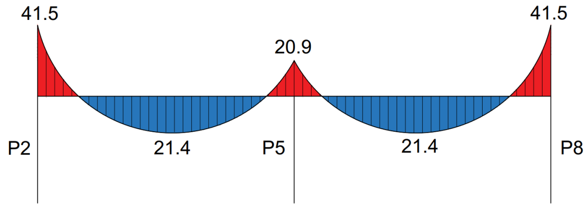


Figure 9. Bending moment diagram of V5 beam on the top floor using the MULAXI approximate method (values in kN.m).

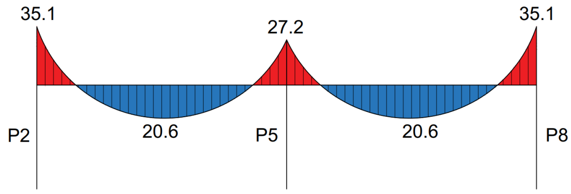


Figure 10. Bending moment diagram of V5 beam on the top floor using the construction effect method (values in kN.m).

the arrangement of reinforcements in the structure may not correspond to the conditions analyzed in the design phase. It is important for structural engineers to have knowledge of different structural analysis strategies and an understanding of their limitations and fields of application. The design of high-rise reinforced concrete buildings is challenging, and understanding the application of each strategy to simulate construction effects is necessary to ensure the safety of the project.

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