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Original Article

Effects of the Construction Sequence on the Distribution of Internal Forces in Reinforced Concrete Elements

Albert Jorddy Valenzuela Inga[1*], Nelfa Estrella Ayuque Almidon[1], Gianswen Kevin Meza Terbullino[2], Pamela Rodríguez Pérez[2], Giancarlo Fernando Meza Terbullino[3]

[1]*Escuela de Posgrado, Universidad Continental, Lima, Peru.*
[2]*Facultad de Ingeniería, Universidad Tecnológica del Perú, Huancayo, Peru.*
[3]*Department of Engineering, University of Miami, Miami, United States.*

[*]*Corresponding Author : 73449915@continental.edu.pe*

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Abstract *- To ensure reliable design in RC buildings, especially in high seismic hazard zones, it is important to represent the structural behavior during construction accurately. Typical analyses tend to assume the structure is being built and loaded from the beginning, and the load is applied in a continuous manner, rather than in phases. This may result in incorrect calculations of internal forces. Therefore, the primary objective of this work was to analyze and assess the impact of staged construction analysis on the redistribution of bending moment and axial forces of the reinforced concrete elements, and its effect on the overall seismic behavior. As a result, a representative building model was created and subsequently analysed using four methods: a conventional method without stages and three modified methods that included various sequential methods. As per the results shown, the proposed model resulted in 49% reduction in negative moments at supports and 48% increase in positive moments in spans, while the negative moments at lower-level columns increased beyond 79% compared with the conventional model. As far as the seismic analysis procedure is concerned, only the model with an integrated construction sequence was able to keep the magnitude of the base shear and overturning moment, while the other methods were only applicable to gravity loads. These results show that the staged analysis increases the accuracy of the design, while at the same time optimising material use, avoiding unexpected stress concentration, and even minimising uncertainty in the structural modelling. The study was performed based on a representative case, but the outcomes are transferable to buildings of similar characteristics, and the implementation of the study in future projects is recommended, as well as the validation of the study through parametric analysis and field monitoring.*

Keywords *- Sequential Modeling, Gravitational Loads, Axial Forces, Force Redistribution.*

1. Introduction

Today, with the computer age, the specialized structural analysis software has become an indispensable tool for the design and assessment of buildings. Platforms like ETABS, SAP2000, Robot Structural, and R-FEM enable more accurate modelling of more complex structures, saving time and complying with design codes. The increased rate of urbanization, especially in seismically active countries, has made the medium and high-rise construction increasingly complex and required more and more strict analysis procedures. However, the current practice is still in use that the structure is fully built and loaded from the initial stage of analysis, which is an oversimplification and not representative of the behavior of the structure in the construction process; similarly, there is no set of guidelines in the current regulations that should be considered during the preliminary design and/or during the construction process, taking account for phased construction of the structure. However, with recent research on complex structures, it has been found that it is important to consider how the structures are made up, how the structures are mounted, and how loads vary with time when analysing the structures. Specifically [1], they studied a long, continuous metal bridge. They analyzed it by a procedure known as "phased analysis. The method takes the features of "finite elements," "real-time monitoring," and "deformation control. Results of the study demonstrated that a structure can change its nature during construction as compared to its design. This emphasizes the need to employ more realistic and modern models in complex structures.

Sequentiality, by its nature, is a characteristic of the construction process in reinforced concrete buildings, since it involves the sequential assembly of structural elements, the sequential development of loads applied, and the sequential development of deformations due to time. Therefore, omitting this sequence may result in substantial errors in understanding the bending moments, axial forces, and deformations -- particularly in columns and beams at lower levels -- affecting the accuracy of the design and structural safety in construction and operation [2, 3].

Numerous previous studies have demonstrated that the sequential process can be omitted, which would lead to overestimation of stiffness and underestimation of cumulative displacements and thus to less reliability of the design, especially for tall buildings [4]. According to the early research done in Vietnam and Brazil, the results of the research showed that a lower level has a greater effect under the condition of without staged construction analysis [5-7]. Moreover, P-Delta effects, creep, and concrete shrinkage create significant axial demands in columns in irregular buildings on slopes [8].

Comparative works performed in India have shown that staged construction analysis represents structural behavior in a more realistic manner, avoiding significant underestimations of moments in key elements [9]. In the United States, this approach has been used as a preventive tool to identify critical construction phases and mitigate failure risks [10]. Other studies, both in mid-rise structures and in buildings with floating columns in severe seismic zones, highlight that the combination of incremental loading and construction sequence is decisive in preventing non-conservative designs [11-13].

The effect of temporary live loads during construction has also been documented, showing that they generate significant deflections and stress redistributions in beams and slabs, and that their omission can compromise the safety and durability of structural elements [14-17]. In the case of South Korea, practical methods for compensating differential column shortening have been proposed; these methods consider the construction planning as a design variable [18]. Furthermore, another study evaluating phased construction in tall post-tensioned slab structures found that bending moments and total stresses vary significantly with height [19].

In the case of Latin America, a study executed in Peru compared MIDAS GEN and ETABS for staged modeling, finding discrepancies in displacements and internal forces that underscore how significant the critical selection of the tool of analysis is [20].

Additionally, research on tall mixed-use buildings with floating columns has unveiled significant increments of the stresses in transfer zones when applying staged analysis [21]. Furthermore, sensitivity assessments performed in Turkey have revealed that the stiffness properties and loads applied during the early construction phases exert a decisive influence on stress accumulation [22].

On the other hand, there are methods [23] that can be used to verify the minimum requirements specified in structural design codes of different standards in the Building Information Modeling (BIM) environment, including the real-world application of a prestressed concrete bridge, where the workflows were proposed for verification of limit states and rules in structural design, and the possibility was allowed to customize any data source environment in structural engineering, including the modelling of construction structures in phases.

The results of these precedents investigations show that there is a long-standing lack of adequate modeling capabilities within the realm of available modeling tools, and that simple models are still used in professional practice, either for their efficiency or technical merits. This is a big challenge. Studies, performed in recent years, with a 3D building model have demonstrated that the 3D representation of the building and the inclusion of time-dependent effects such as concrete creep and shrinkage can result in significant changes as compared to a conventional linear elastic analysis of the building. In particular, [24], A 3D model of a 15-story building was analyzed. The model showed significant differences in how vertical loads moved. This suggests that simpler methods used by professionals may not be correct.

In response to this issue, the present study aims to evaluate the influence of the staged construction process on the redistribution of bending moments in reinforced concrete buildings. For the attainment of this purpose, a representative building model was developed and later analyzed using both a conventional and a sequential approach. This approach is similar to previous research that has shown that structural analysis based solely on the final state can lead to results that do not represent how things actually behave during construction. In particular, [25] By studying multi-story buildings in order, they showed that explicitly considering construction phases greatly changes the distribution of internal forces and bending moments compared to conventional analysis. By comparing the results, we can measure these differences and provide technical evidence to incorporate this approach into structural design and evaluation.

2. Materials and Methods

The research was conducted through numerical simulation in ETABS v21.1, considering the effect of the staged construction process on the evolution of internal forces in reinforced concrete buildings. The analysis incorporated the level-by-level construction sequence, allowing for the evaluation of the redistribution of bending moments, shear forces, and axial forces throughout the structural development. The study focused on horizontal and vertical elements, with particular attention to the lower levels, where the cumulative effects of construction progress are most significant.

2.1. Structural Model Configuration

The structural model corresponds to a reinforced concrete building with a lateral load–resisting system composed of structural walls in both principal directions. This configuration, widely used in medium- and high-rise buildings in urban areas of Peru [26], provides high lateral stiffness and efficiency against seismic loads, in accordance with the provisions of Standard E.030 [27].

The building model consists of 20 above-grade stories and 2 basement levels, with a rectangular floor plan with the dimensions of 14.60 m × 25.78 m. The most common story height is 2.80 m for the upper floors and 3.50 m for the underground levels. With regards to the structural walls and columns, they were modeled with concrete strengths of 28 MPa and 21 MPa, which were distributed by levels to maintain uniform sections, while the slabs and beams were modeled with 21 MPa concrete, as shown in Figure 1.

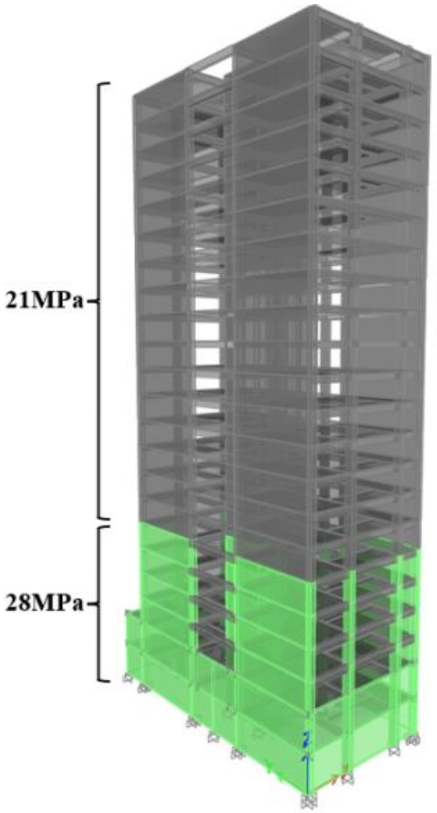


Fig. 1 Schematic view of the building with material assignment by level and symmetrical distribution of structural elements

The structural layout in plan can be observed in Figures 2 and 3, corresponding to the basement levels and typical floors, respectively. These views show the location of the walls and columns, as well as the slab direction and the beam layout. All columns were modeled with a constant section of 50 cm × 80 cm. The walls have thicknesses of 25 cm in the basement levels and 20 cm in the upper floors, represented schematically in plan.

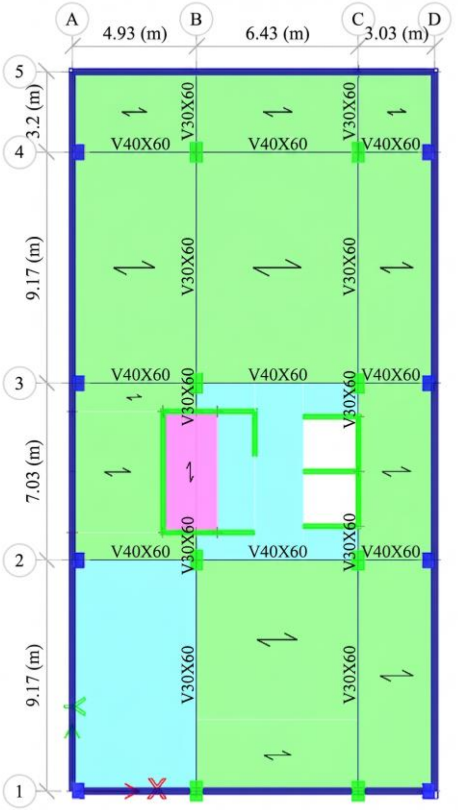


Fig. 2 Plan view of the structural configuration of the basement levels

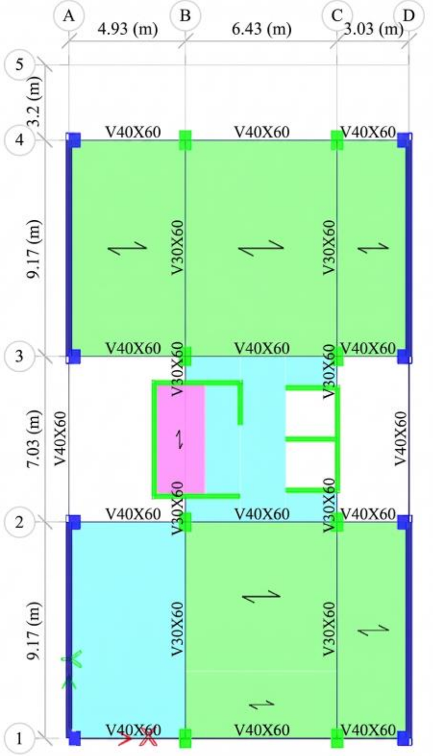


Fig. 3 Plan view of the structural configuration of the typical floors

2.2. Gravitational Loads Assigned in the Structural Model

The structural model considers the gravitational loads corresponding to the self-weight of the elements, slabs, finishes, and live loads, in accordance with the guidelines established in Standard E.020 [28]. The values adopted for each structural and non-structural component are detailed in Table 1.

Table 1. Gravitational loads assigned in the structural model

Componente	Tipo	Valor	Unidad
Reinforced concrete	Self-weight	24.00	kN/m³
Concrete slab	Self-weight	5.25	kN/m²
Floor finish	Dead load	1.00	kN/m²
Partition walls	Dead load	1.50	kN/m²
Live load	Live load	2.00	kN/m²

2.3. Estructural Modeling Procedure

The structural modeling assumed fully fixed conditions at the base to conservatively represent the soil–structure interaction. The floor slabs were assigned as rigid diaphragms and modeled using membrane-type elements, allowing for the transfer of in-plane forces without permitting out-of-plane bending deformations.

The structural walls were represented using shell-type elements, preserving their integrity as complete elements without subdivision into smaller panels, which is consistent with the required level of accuracy and the regular geometry of the building. The columns and beams were modeled with frame-type elements, using constant sections throughout their height.

These considerations are based on methodological guidelines similar to those used in previous studies conducted in the Peruvian context [29]. Table 2 below presents a comparison of the conventional structural model with Gonzales's research [30].

Table 2. Results of the MEF and González model [31]

	Period (seg)		Shear force at base (kN)	
Model	MEF (ETABS v21.1)	[30]	MEF (ETABS v21.1)	[30]
R0	2.50 s	1.93 s	455.70 Ton	372. 07 Ton

The shear force at the base depends on the ductility and energy dissipation capacity, which, in this case, for both studies considered the typology of structural walls, the input parameters for the concrete (modulus of elasticity, poisson's ratio) did not present any variation; however, the geometric area in plan of the building is 18.43% higher than the case study [30].

2.4. Seismic Analysis

For the seismic analysis, the parameters established by the Peruvian Technical Standard E.030 [27] were used. Seismic zone 3 was considered, with a zoning factor Z equal to 0.35, corresponding to use category C with an importance factor U of 1.00, and soil type S1 with a soil factor S of 1.00. The adopted characteristic periods were Tp equal to 0.40 seconds and Tl equal to 2.50 seconds. The analysis was performed using a dynamic modal response spectrum approach, considering a total of sixty vibration modes, which allowed achieving a cumulative modal participation greater than ninety percent in both principal directions. Modal results were combined using the SRSS rule and included the effects of accidental torsion through the application of the regulatory eccentricity of 0.05 in plan. The seismic mass was calculated automatically by the software, considering one hundred percent of the dead load plus twenty-five percent of the live load, in accordance with E.030. A seismic response reduction factor R equal to 6 was adopted. The response spectra used, applied in both principal directions of the model, were employed for both structural design and drift verification, and are shown in Figures 4 and 5.

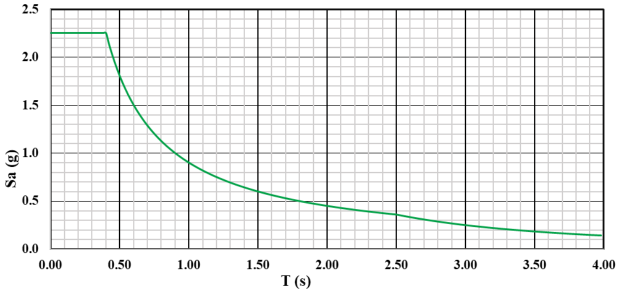


Fig. 4 Seismic design spectrum ZUCS/R g

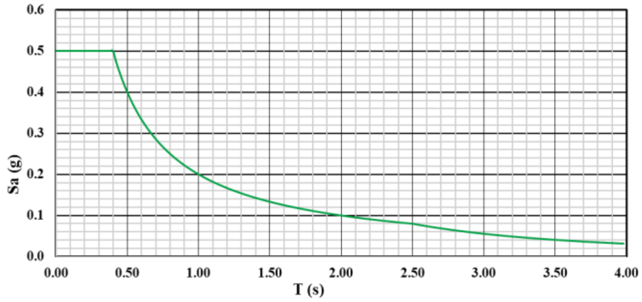


Fig. 5 Spectrum for drift verification 0.75ZUCS g

2.5. Influence of the Construction Process on the Distribution of Bending Moments in Beams

The distribution of bending moments in beams is considerably affected when the actual construction sequence of the building is incorporated into the structural analysis. While conventional models apply loads to the fully constructed structure, generating an artificial accumulation of deformations from the lower levels, in practice, the executed elements gain stiffness before receiving additional loads, which partially restricts their deformation and modifies the structural response.

As a consequence, it could be observed that the negative moments at supports tend to decrease, while the positive moments in mid-spans show a slight increase. This noticed behavior has been illustrated through simplified examples of continuous beams, allowing the identification of key differences in the distribution of forces when the staged construction process is considered. The incorporation of this approach is essential in high-rise buildings, due to the fact that the progressive accumulation of loads can generate significant differences in the final design of structural elements.

With the objective of illustrating the impact of the construction process on the distribution of bending moments, a simplified analytical model of a multi-span continuous beam with specific support conditions was developed. The analysis was carried out through numerical simulation because it enabled the performance of the comparison of the structural behavior under different conditions, like conventional simultaneous loading, sequential loading representing construction stages, and cases with differential settlements.

In Figure 6, the bending moment distribution of a continuous beam influenced solely by the arrangement of fixed and movable supports is displayed, but the staged construction process was not considered. In addition, the concentration of negative moments at supports reflects the expected response under loads applied simultaneously to the entire structure. This observed behavior serves as a baseline reference for the identification, in subsequent comparisons, of the loss of moments that occurs when the actual construction sequence is incorporated into the structural analysis.

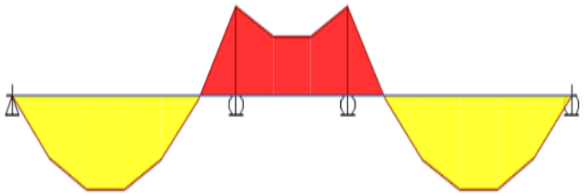


Fig. 6 Bending moment diagram of a continuous beam with fixed and movable supports under static loads

Figure 7 shows the bending moment distribution in a continuous beam with movable intermediate supports and fixed-end restraints. A greater magnitude of negative moments is observed at the ends, generated by the stiffness of the fixed supports, along with a more balanced distribution in the mid-spans. This configuration serves as a reference for evaluating, in subsequent analyses, how incorporating the construction sequence can reduce these end moments and modify the overall distribution of internal forces.

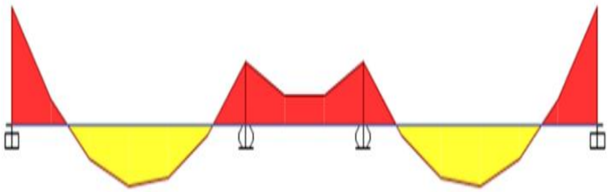


Fig. 7 Bending moment distribution in a continuous beam with fixed ends and movable intermediate supports

Figure 8 shows the model with a differential settlement at the third support, simulating the progressive accumulation of deformations associated with the construction process.

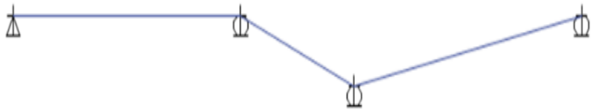


Fig. 8 Analytical model with differential settlement at the third support

As a result, the bending moment diagram shown in Figure 9 reveals an inversion of the usual negative moment, generating a positive peak at the settlement point. This behavior indicates that the beam adopts a curvature opposite to that induced by conventionally distributed gravitational loads.

The redistribution of internal forces caused by the settlement reflects the emergence of additional moments not accounted for in ideal static models, which must be considered in the structural analysis to avoid underestimating the internal demand on critical elements.

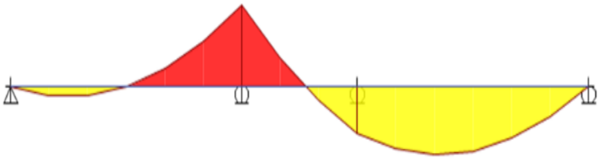


Fig. 9 Variation of bending moments due to differential settlement at the third support

Figure 10 shows the analytical model with a differential settlement applied at the fourth support, considering the right end fixed. This configuration allows for analyzing how a localized deformation affects the structural response when there is significant restraint at the beam's end.

Fig. 10 Analytical model with differential settlement at the fourth support

Figure 11 depicts that the curvature imposed by the settlement significantly modifies the distribution of positive moments; this circumstance generates a notable increase in the spans that are adjacent to the affected support. At the same time, the negative moments at the intermediate supports tend to decrease. This observed phenomenon highlights the structural sensitivity of these elements to non-ideal support conditions; it also demonstrates how the construction process or local settlements can actually redistribute the internal forces in a non-intuitive manner.

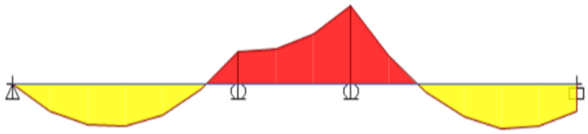


Fig. 11 Redistribution of bending moments due to differential settlement at the fourth support

Figure 12 shows the model with settlements at consecutive supports. This condition represents a critical situation where two deformations simultaneously alter the curvature of the beam.

Fig. 12 Analytical model with differential settlements at consecutive supports

The structural outcomes shown in Figure 13 reveal a concentration of positive moment in the intermediate span, which is accompanied by a reduction of negative moments at the supports. It is this observed response that shows how the distribution of internal forces can be greatly altered, even for beams with symmetrically distributed supports.

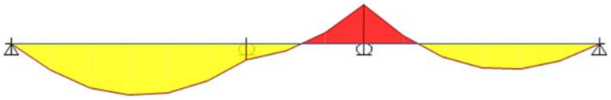


Fig. 13 Concentration of positive moments induced by differential settlements at consecutive supports

Based on the illustrated cases, it is evident that the incorporation of differential settlements or the actual construction sequence can substantially modify the distribution of bending moments in beams. These changes not only affect the design of horizontal elements but also have direct repercussions on other internal forces, such as shear force and axial load transferred to vertical elements. In the scenarios where the magnitude of negative moments is reduced, columns may lose part of their expected axial load; this situation alters the path of gravitational and seismic loads. This loss of compression in critical columns can compromise the overall stability of the structural system, affecting both the strength and ductility of the system. Therefore, the omission of the construction process in analytical modeling can lead to situations of significant underestimations or overestimations of structural demand, which are particularly meaningful in high-rise buildings because the accumulation of deformations in this type of building notably influences the final distribution of internal forces.

2.6. Methodologies for the Adjustment of Internal Forces

To mitigate the undesired effects on the distribution of internal forces caused by the omission of the construction process or the presence of differential settlements, three complementary analysis methodologies have been proposed. These strategies aim to evaluate the impact of different numerical treatments on the reduction of axial deformations and the redistribution of bending moments and shear forces in key elements of the structural system. The procedure for the analysis considering the step-by-step construction is shown in Figure 14.

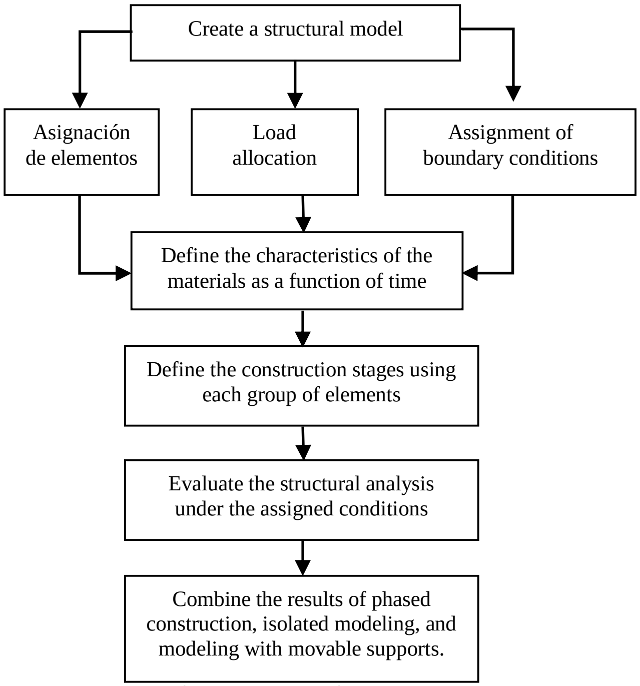


Fig. 14 Flowchart for the analysis of phased construction modeling

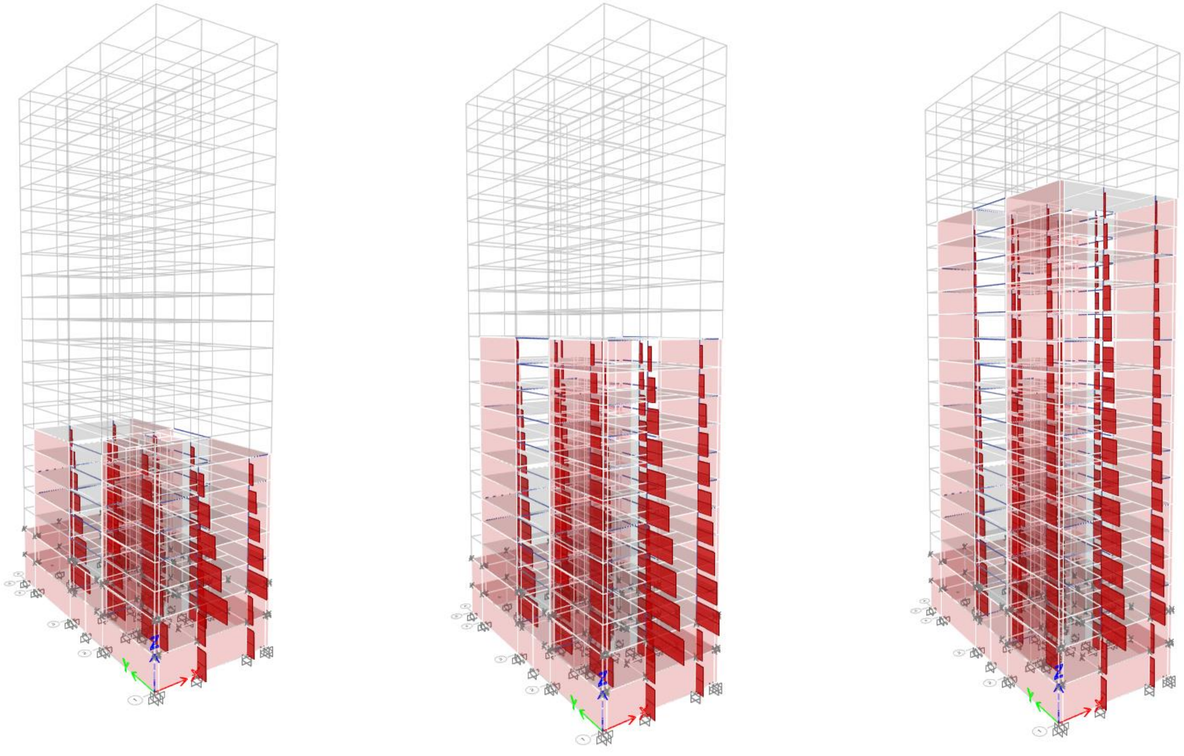
2.6.1. Staged Construction Analysis in ETABS

This methodology involves the simulation of progressive incorporation of structural elements in the sequence by which they are performed in the actual construction with the Construction Sequence tool present in the ETABS software [32]. This function allows for the programming of the activation of floors, columns, and beams in a sequence, taking into account the weight of each. Thus, the progressive deterioration in the stiffness of the elements is simulated before new loads are applied to the structure.

The implementation of this staged analysis allows for more accurate capturing of the time-dependent effects of deformation and the accumulation of internal forces, mainly in elements subjected to axial load, such as columns, and in continuous beams where the magnitudes and signs of bending moments are affected.

Likewise, it reduces the distortions generated by conventional analysis, which considers the complete structure from the beginning and tends to overestimate negative moments at supports and internal forces in the lower levels. This chosen methodology is considered to be the most representative approach to analyze the actual behavior on site. Also, it is recommended by several recent studies for medium- and high-rise buildings.

As exhibited in Figure 15, the structural model is progressively activated, and it goes from the lower levels up to the completion of the building. This reflects the application of dead and live loads as construction progresses in a sequential manner. It is important to mention that this procedure enables the execution of a more accurate evaluation of the redistribution of internal forces and deformations throughout the construction process.



(a) Level 5 completed

(b) Level 10 completed

(c) Level 15 completed

Fig. 15 Configuration of staged construction analysis in the ETABS modeling environment

2.6.2. Isolated Modeling by Structural Levels

This procedure involves modelling each floor of the building as a separate structural unit, and only the associated gravitational loads and restraints from the immediately lower level are considered. Such an approach will enable a more precise evaluation of the accumulating deformations and the redistribution of internal forces that takes place in sequence during the execution of the floors.

The methodology was previously used in some studies to analyze the construction process in reinforced concrete buildings, and will serve as a conceptual basis for the use in the present study [33]. The scheme of the structural model isolated by levels is presented, which enables the independent analysis of each floor while adhering to the steps of the actual construction sequence, as shown in Figure 16.

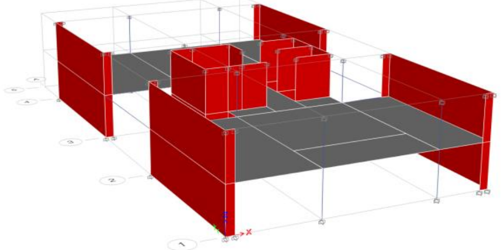


Fig. 16 Structural model with isolated levels

2.6.3. Use of Movable Supports in Vertical Elements

The method involves placing movable supports at the foundation of vertical components of each floor level while developing the model, to prevent the transfer of axial forces between the two adjacent floors. Free vertical movement at the bottom of the columns and walls eliminates accumulated compression deformations as if the floors were laid in a structure without direct axial contact with the floor below. This approach aims to simulate the actual behavior when the building is being constructed, when the lower elements have not yet acquired the same stiffness as the upper ones, and when the latter are applying load to them.

After using movable supports on the vertical elements, only the schematic representation of the resulting structural model is shown in Figure 17. This representation can be used to visualize the modified geometry of the system and enable analysis of the floor-level deformation without artificially adding up axial forces. This method is an idealization of the actual response, and thus, the results should be taken with technical judgment as a minimum estimation of the expected axial stiffness.

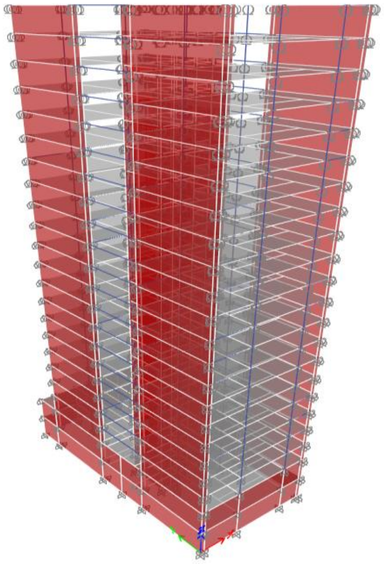


Fig. 17 Structural model with movable supports in vertical elements to simulate axial decoupling by levels

2.7. Limitations of the Study

In this study, idealized models are used, in which inelastic effects, soil–structure interaction, and time-dependent deformations are not taken into account. They simplify the analysis to reveal the effect of the construction sequence and differential settlements on the redistribution of internal forces, but do not provide a complete representation of the response of structures under complex conditions. Similarly, the methods used to minimise or eliminate axial deformations have been devised for analytical use, and may need to be adapted for use in practice. Despite these limitations, the results obtained provide useful evidence for understanding relevant structural trends and improving conventional analysis approaches.

3. Results

3.1. Comparison of Bending Moments in a Beam

The results show that model R0 exhibits the highest negative moment value. An exemplification of it is that at the 6.18-meter location, the value in the R0 model reaches 6.32 tons per meter, while in the models R1, R2, and R3, these measurements are reduced to 3.59, 3.18, and 3.27, respectively. This observed trend is coherent with other relevant points, like in the mid-spans, where positive moments in R0 exceed 2.67 tons per meter, compared to the values obtained in the case of the corrected models, which range between 1.71 and 1.39.

In the case of the R0 model, a loss of negative moment is observed at one end of the beam, while an increase in the other end of the beam is noticed. This circumstance reduces the positive moment in the span, but increases the negative moment in support. In contrast to the previous case, the models R1, R2, and R3 present similar negative values at both ends; this result is consistent with the structural symmetry and the expected behavior under gravitational loads. This observed consistency indicates that any of the three proposed methodologies can be applied with reliable results. Nonetheless, it is important to take into consideration that the choice that is made will directly influence the flexural design of beams and, consequently, the prevention of undesired failures. In Figure 18, this variation observed through the comparative bending moment diagram for the four models analyzed is illustrated.

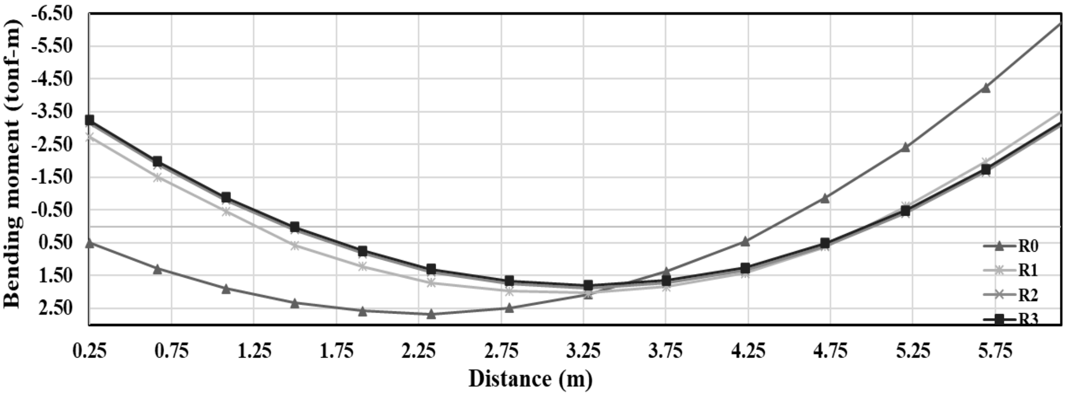


Fig. 18 Comparison of bending moment diagrams in the beam on axis 3 between B and C at level 19 for models R0, R1, R2, and R

It should be noted that, for the case of live loads, the observed behavior follows a trend similar to that described for dead loads. However, under seismic actions, only the model with criterion R1 preserves the transfer of forces, while in models R2 and R3, a loss of such demands occurs due to level isolation or the introduction of movable supports, making them applicable solely for the evaluation of gravitational effects.

3.2. Comparison of Axial Forces in a Column

For this case, criterion R2 was not considered because level isolation interrupts the transfer of gravitational loads, preventing direct results of axial forces from being obtained.

However, model R3 exhibits behavior analogous to R2 if the reactions obtained at the movable supports are summed, allowing for the estimation of axial loads per level.

The evaluated column corresponds to the one located on axis 4 between B and the end of the structure. The results obtained from the evaluation exhibit that model R0 records the lowest values of accumulated axial load, reaching 256.06 tons at the first level. In contrast, models R1 and R3 present notable increases, with values of 317.75 and 460.00 tons, respectively. This difference is constant throughout the building's height, with gaps that progressively increase from the roof to the base.

In the upper levels, the initial discrepancies are smaller; for example, at level 20, values of 11.17, 21.79, and 21.70 tons are recorded for R0, R1, and R3, respectively, but these differences expand as load accumulation increases toward the lower levels. Figure 19 presents the comparative diagram of axial forces, showing the direct influence of the modeling method on the magnitude of vertical forces transmitted to the foundation.

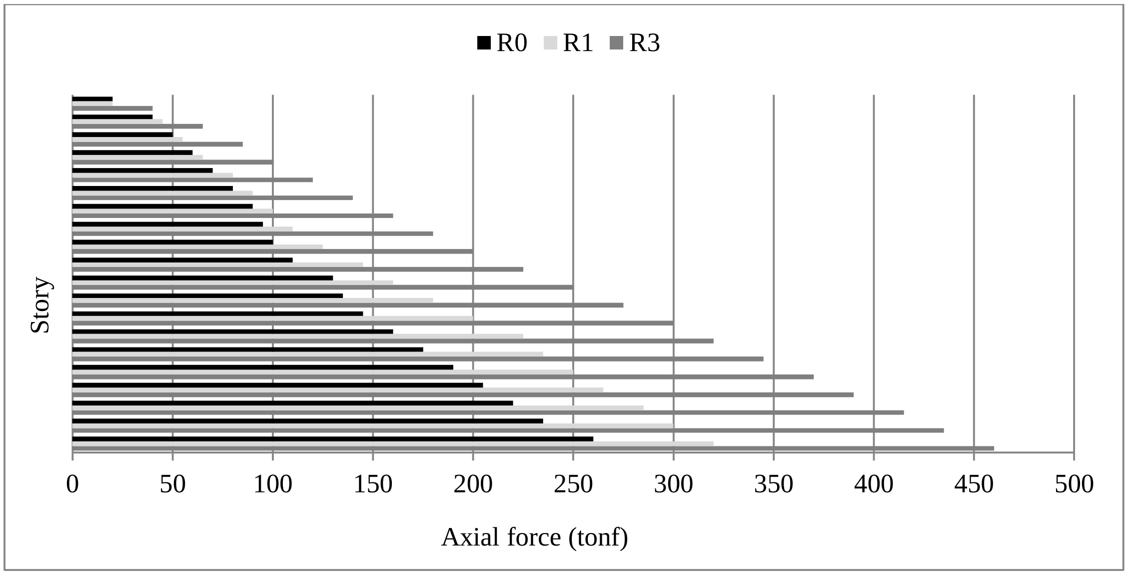


Fig. 19 Comparison of axial force diagrams in the column on axis 4 between B and the end of the structure for models R0, R1, and R3

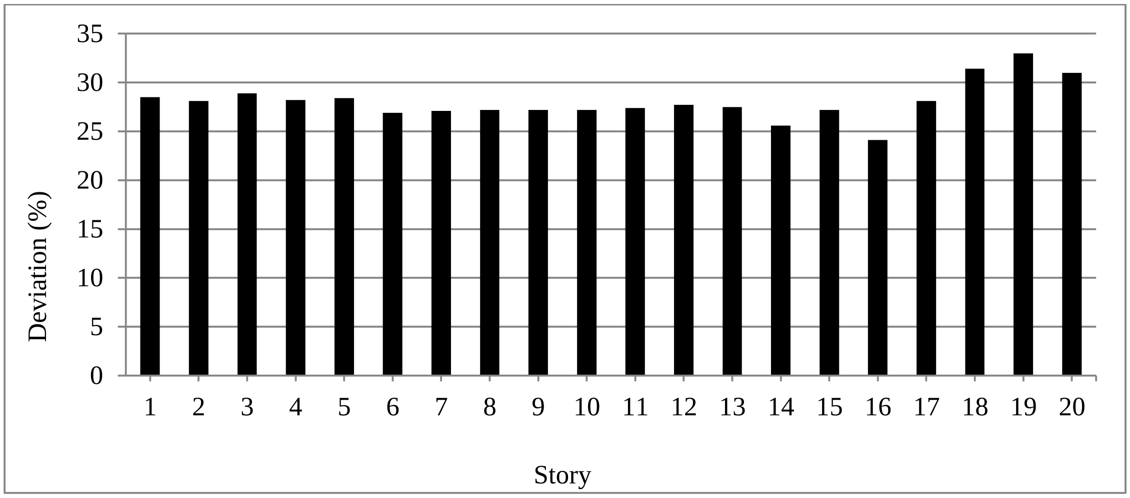


Fig. 20 Sensitivity of axial forces in the pillars for models R0, R1, and R3

Sensitivity analysis was performed for models R0, R1, and R3 for a particular case corresponding to the pillars described in Figure 18. A high rate of variability of axial forces was found in the upper floors, reaching up to a value of 33.25% and a minimum value of 24.12%, as shown in Figure 20.

3.3. Global Evaluation of Seismic Loads in Corrected Models

The global response of models R0, R1, R2, and R3 to seismic actions was evaluated, using model R0—corresponding to the conventional scheme without construction process corrections—as the reference. The results show that model R1, which incorporates the construction sequence through the integrated ETABS tool, fully preserves the magnitude of the global seismic forces, maintaining base shear and overturning moment values practically equivalent to those of the reference model.

In contrast, models R2 and R3 lose the transmission of seismic forces due to level isolation and the implementation of movable supports, which prevents their use for seismic considerations. Consequently, it is recommended that, if these models are employed solely for gravitational load analysis, combinations that include seismic actions should be performed externally, using the results obtained from model R1 as the basis.

4. Discussion

The decision to incorporate the staged construction process in the analyzed models unveiled that the R1, R2, and R3 models produce a more balanced redistribution of the bending moments in beams compared to the conventional R0 model, correcting asymmetries and avoiding overestimations at supports and spans. This observed behavior is consistent with reported findings in previous studies conducted in a variety of countries, like Turkey, Brazil, and Vietnam, where sequential modeling yielded diagrams that represented real behavior more accurately and improved the structural consistency, [2, 5, 6].

The progressive increase of axial forces in columns at lower levels, observed in R1 and R3, confirms that omitting construction progress leads to underestimation of gravitational load accumulation, as documented in research on high-rise structures that evaluated the influence of accumulated loads during execution - [5, 6]. These findings can be explained by the fact that staged execution modifies the effective stiffness of elements and alters the load transfer sequence, directly affecting the magnitude of internal demands.

With regards to the seismic analysis, only the R1 model preserved the base shear and overturning moment magnitudes of the conventional scheme; these outcomes are consistent with observations from studies that applied staged construction analysis using structural modeling tools that are capable of maintaining the transfer of lateral forces [2].

In contrast, R2 and R3 models interrupted the structural continuity due to isolation levels or movable supports, reducing the transmission of seismic loads; this is an effect also identified in research on configurations with vertical discontinuities that affect global dynamic response [3].

This behavior limits the application of R2 and R3 in seismic-resistant design, although they are useful for analyses focused on gravitational loads. Overall, the results reinforce evidence that integrating staged construction analysis improves the accuracy of demand estimation and optimizes structural evaluation, in line with what has been reported in recent studies, [2, 5, 6].

On the other hand, the progressive increase in axial forces in the columns of the upper floors brings with it the phenomenon of "vertical shortening," which is established to be directly proportional to the height of the building and inversely proportional to the concrete's strength. Therefore, staged and time-dependent studies are usually the most realistic approaches for analyzing vertical shortening [34]. In these tall buildings, if we replace the conventional slab structure with post-tensioned solid slabs to reduce weight, a redistribution of internal stresses also occurs, altering not only the service bending moments but also slab pre-compression, service tension, and the punching shear effect [19].

The Peruvian technical standard E030 employs technical parameters to safeguard against nonlinearity based on the structural typology, preserving the distribution of stresses throughout the system that provides rigidity, in this case, as could be identified in the local elements of the structure, which are the beams and columns (Figures 17 and 18). Thus, in the study [2] where 8 typologies in buildings (reinforced concrete, rigid system, structural wall) were analyzed in the nonlinear range, they showed the evolution of the internal stresses that produce the shortening phenomenon in vertical elements (columns) and horizontal elements (beams).

The increased internal effort resulting from this phased analysis translates into a higher cost of construction materials, specifically in the reinforced concrete component (concrete pouring, formwork and stripping, curing, and placement of reinforcing steel). However, this only applies to the construction phase, as the cost of a structural monitoring plan and its implementation must be considered during the preliminary design phase.

Furthermore, in the short term, the increased use of construction materials will have a greater environmental impact. However, in the long term, preventing unacceptable cracking or fissures in the structure through this phased construction analysis avoids future concrete anomalies such as internal corrosion and carbonation, thus ensuring the structure's lifespan and preventing demolitions or structural reinforcements that have greater environmental impacts [35].

5. Conclusion

The study demonstrated that incorporating the staged construction process into structural analysis produces a more balanced redistribution of bending moments in beams and a coherent increase of axial forces in columns at lower levels compared to the conventional model. These results confirm that sequential modeling more accurately represents the progressive accumulation of gravitational loads and corrects asymmetries in the structural response, contributing to more precise sizing of primary elements.

It was verified that model R1 maintains the magnitude of global seismic actions obtained with the conventional approach, making it a versatile alternative for jointly evaluating gravitational and seismic loads. In contrast, the R2 and R3 models interrupted the transfer of lateral forces; this interruption limits their use in seismic-resistant design, although they proved to be effective for the analysis of gravitational load redistribution.

This methodological distinction highlights the importance of selecting the most adequate modeling approach according to the specific objectives of the project.

The application of this approach in future buildings guarantees the improvement of the accuracy of structural design, the optimization of material use, the prevention of unforeseen stress concentrations, and the contribution to meeting code requirements.

Furthermore, it reduces modeling uncertainty and facilitates the identification of critical conditions during construction. It is recommended to extend the analysis to different structural typologies and validate the findings through parametric studies and field monitoring, thereby strengthening the applicability and generalization of the conclusions reached.

Unfortunately, current regulations do not require this analysis, but in real practice, evaluating construction in stages is necessarily important; however, multiple external factors (creep and shrinkage) may occur, therefore, it is important to develop a structural monitoring plan before the execution of the project.

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