

Comparative Analysis of Linear and Nonlinear Calculation of the Load-Bearing Capacity of Reinforced Concrete Frames in Multi-Storey Buildings

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Abstract. Reinforced concrete frame systems are widely used in multi-storey residential and public buildings due to their structural efficiency, durability, fire resistance, and architectural flexibility. However, increasing building height, longer spans, complex planning solutions, and stricter serviceability requirements make structural behavior increasingly sensitive to cracking, stiffness degradation and second-order effects, and a purely linear analysis may no longer adequately describe the real behavior of the system. This study presents a comparative analysis of linear and nonlinear calculations of an RC multi-storey frame. Three parametric models with heights of 36 m, 75 m, and 102 m (12, 25, and 34 storeys) with identical plan dimensions of 18×18 m were analyzed using LIRA-SAPR 2024 (Commercial License), Commercial License using five analysis variants: linear with initial stiffness, linear with code-recommended stiffness reduction, physically nonlinear, geometrically nonlinear and combined (physical + geometric) nonlinear. Structural response was evaluated in terms of internal forces, slab force redistribution, lateral displacements, and serviceability deflections. The results demonstrated that the influence of nonlinear effects increased with building height and structural flexibility. Physical nonlinearity associated with crack-induced stiffness degradation was identified as the dominant source of variation between linear and nonlinear analyses, while geometric nonlinearity became increasingly significant when combined with second-order ($P-\Delta$) effects. Combined nonlinear analysis produced substantial redistribution of internal forces, with support slab moments decreasing by 33–89% and significant changes observed in column forces and lateral displacements. The findings highlight the importance of accounting for both material and geometric nonlinearities in the analysis of medium- and high-rise RC frame-core buildings and provide practical recommendations regarding the selection of appropriate analysis methods for structural design.

Keywords: physical nonlinearity, geometric nonlinearity, second-order effects, stiffness degradation, force redistribution, finite element modeling, serviceability limit state, ultimate limit state, ($P-\Delta$) effects, frame-core system

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Сравнительный анализ линейного и нелинейного расчета железобетонного каркаса многоэтажного здания

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Аннотация. Железобетонные каркасные системы широко применяются в многоэтажных жилых и общественных зданиях благодаря своей конструктивной эффективности, долговечности, огнестойкости и архитектурной гибкости. Однако увеличение высоты зданий, пролетов, усложнение объемно-планировочных решений и повышение требований по эксплуатационной пригодности все в большей степени повышают восприимчивость конструкций к трещинообразованию, снижению жесткости и эффектам второго порядка, вследствие чего линейный расчет не всегда способен достаточно точно описать их реальную работу. Авторами выполнен сравнительный анализ линейных и нелинейных расчетов многоэтажного железобетонного каркаса. Рассмотрены три параметрические модели высотой 36, 75 и 102 м (12, 25 и 34 этажа соответственно) с одинаковыми размерами плана 18×18 м. Расчеты выполнены в программном комплексе LIRA-SAPR 2024 (Commercial License) с использованием пяти расчетных схем: линейный расчет с начальной жесткостью, линейный расчет с нормативным снижением жесткости, физически нелинейный расчет, геометрически нелинейный расчет и комбинированный нелинейный расчет, учитывающий одновременно физическую и геометрическую нелинейность. Оценка работы конструкций выполнялась по внутренним усилиям, перераспределению усилий в плитах перекрытий, горизонтальным перемещениям и прогибам по предельным состояниям второй группы. Результаты показали, что влияние нелинейных эффектов возрастает с увеличением высоты здания и его гибкости. Установлено, что физическая нелинейность, связанная с трещинообразованием и снижением жесткости, является основным источником различий между линейными и нелинейными расчетами, тогда как влияние геометрической нелинейности существенно возрастает при совместном учете эффектов второго порядка (P–Δ). Комбинированный нелинейный расчет приводит к значительному перераспределению внутренних усилий, при котором опорные моменты в плитах перекрытий уменьшаются на 33–89 %, а также наблюдаются существенные изменения усилий в колоннах и горизонтальных перемещений здания. Полученные результаты подтверждают необходимость учета как физической, так и геометрической нелинейности при анализе железобетонных каркасно-стеновых зданий

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средней и большой этажности и позволяют сформулировать практические рекомендации по выбору расчетных подходов при проектировании.

Ключевые слова: физическая нелинейность, геометрическая нелинейность, эффекты второго порядка, снижение жесткости, перераспределение усилий, конечно-элементное моделирование, предельное состояние по пригодности к эксплуатации, предельное состояние по несущей способности, эффекты (P–Δ), каркасно-стенная система

Вклад авторов. Рынкoвская М.И., Лей Б., Нин Л. — научное руководство исследованием; Беляк А.В. и Насибуллина Л.Р. — разработка численных моделей, выполнение расчетов и проведение анализа результатов; Дабн Г.М. — подготовка рукописи статьи и доработка по замечаниям рецензентов. Авторы ознакомлены с окончательной версией статьи и одобрили ее.

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1. Introduction

Reinforced concrete frame systems of multi-storey buildings are widely used in residential and public construction due to their manufacturability, cost-effectiveness, durability, fire resistance, and architectural flexibility [1; 2]. The continuous increase in building height, larger structural spans, more complex architectural layouts, and stricter serviceability requirements have significantly increased the sensitivity of structural systems to nonlinear effects. Under such conditions, the accuracy of structural analysis becomes one of the key factors influencing structural safety, reliability, material consumption, and economic efficiency [3]. Traditional linear structural analysis, based on the assumptions of small displacements, constant stiffness, and proportional stress–strain behavior, remains one of the primary tools in engineering design because of its simplicity, transparency, computational efficiency, and compatibility with standard design procedures. Linear analysis is still widely used for medium rise reinforced concrete buildings with sufficient spatial stiffness and regular structural configurations. However, the actual behavior of reinforced concrete structures is more complex than idealized linear models¹ [4]. Due to cracking, stiffness degradation, creep, shrinkage, plastic deformation, and complex interaction between concrete and reinforcement, reinforced concrete members exhibit pronounced nonlinear behavior even at relatively low stress levels due to the development of microcracks within the cement matrix as loading increases; crack propagation and stiffness degradation significantly influence the stress–strain state, redistribution of internal forces, displacement response, and overall load-bearing capacity of reinforced concrete structures [5; 6].

Karpenko, proposing generalized deformation models for reinforced concrete structures as shown in Figure 2, contributed to the development of nonlinear reinforced concrete theory [7]. Emphasizing the influence of crack formation and stiffness degradation on the stress–strain state and load-bearing capacity of reinforced concrete members, Bondarenko and Kolchunov further investigated the behavior of reinforced concrete structures during different loading stages.² Mentioning that physical nonlinearity is one of the most important characteristics of reinforced concrete structures, numerous studies have investigated constitutive models capable of describing nonlinear stress–strain relationships of concrete and reinforcement. Different analytical models have been proposed, including bilinear, trilinear, curvilinear, damage mechanics, and plasticity-based approaches. Modern nonlinear deformation models allow the simulation of cracking, crushing, stiffness degradation, and post-peak structural behavior with significantly higher accuracy than conventional linear methods [8; 9]. The bilinear and trilinear models are as shown in Figure 1.

¹ Guidelines for nonlinear structural analysis and design of buildings. part IIb — reinforced concrete moment frames. Gaithersburg MD: 2017

² Bondarenko VM, *Reinforced concrete and masonry structures*. Moscow: ASV Publ.; 2011. (In Russ.)

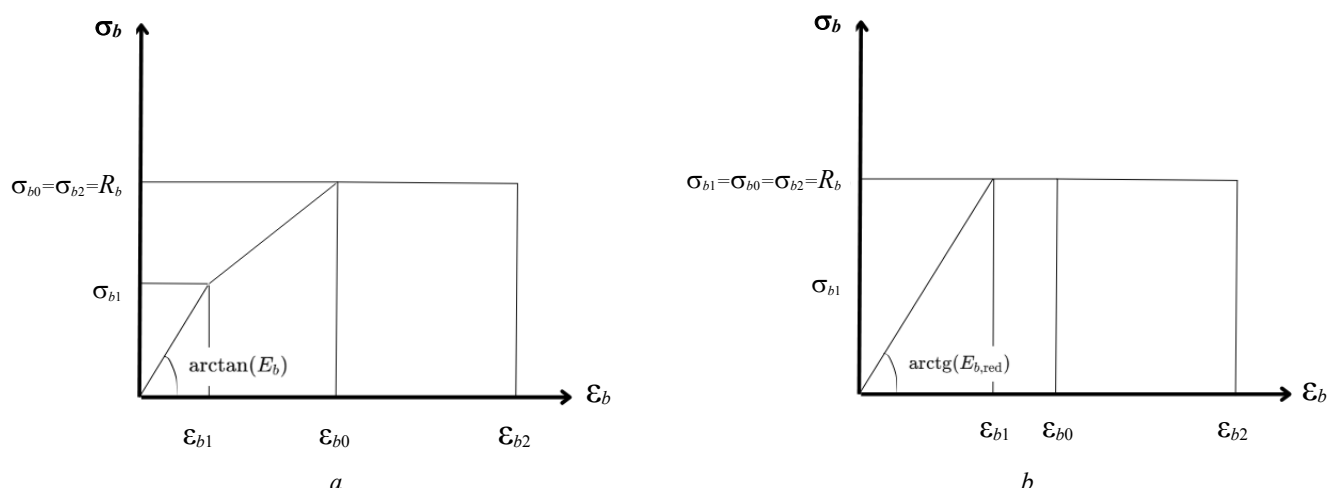


Figure 1. Strain diagrams of compressed concrete:

a — trilinear; *b* — bilinear

Source: made by A.V. Belyak.

The nonlinear deformation model shown in Figure 2, originally proposed by N.I. Karpenko and adopted in SP 63.13330.2018,³ is widely used for describing the nonlinear behavior of concrete and reinforced concrete structures because it realistically captures stiffness degradation and material response over a broad range of loading conditions.

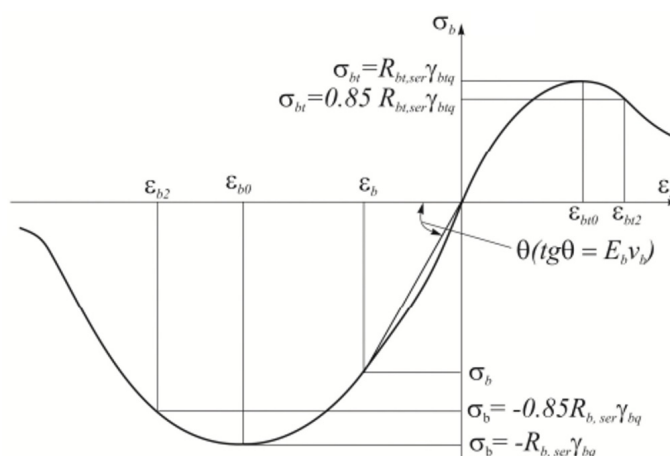


Figure 2. Nonlinear stress–strain diagram of concrete in compression and tension according to the deformation model proposed by N.I. Karpenko and adopted in SP 63.13330.2018

Source: made by A.V. Belyak.

On the other hand, in structures characterized by high slenderness ratios, reduced lateral stiffness, irregular structural layouts, significant wind or seismic loading and large height-to-width ratios, geometric nonlinearity plays an increasingly important role in high-rise and flexible reinforced concrete structures. The horizontal displacements caused by wind or seismic actions generate additional bending moments due to vertical gravity loads which are commonly referred to as second-order effects ($P-\Delta$) and ($P-\delta$) effects, illustrated in Figure 3, may substantially influence the stability and load-bearing capacity of multi-storey frame systems. Studies show that neglecting geometric nonlinearity may lead to underestimation of internal forces, inter-story drifts, and structural instability risks [10].

³ SP 63.13330.2018. Concrete and reinforced concrete structures. Moscow; 2019. (In Russ.)

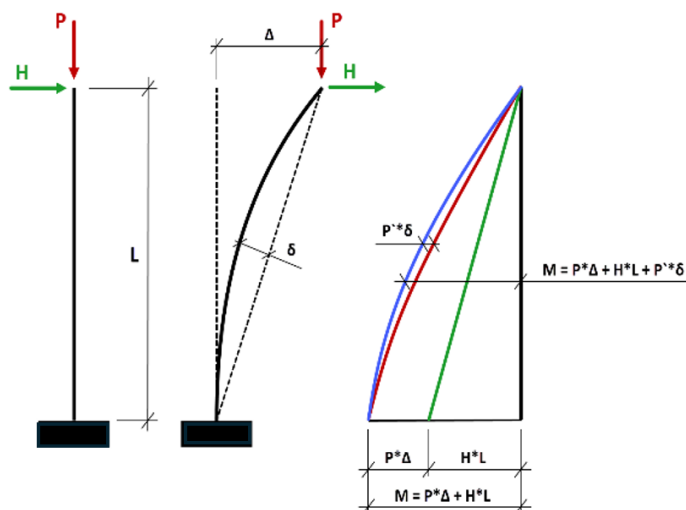


Figure 3. Illustration of the occurrence of second-order P–Δ and P–δ effects

Source: made by A.V. Belyak.

Different commercially available software are widely used to model nonlinear material behavior, crack development, stiffness degradation, plastic deformation, geometric instability, and progressive collapse mechanisms. Within a unified computational framework, studies increasingly focus on integrated nonlinear modeling approaches combining physical and geometric nonlinearities [11; 12].

Investigating nonlinear analysis of reinforced concrete buildings with different slab systems, Abd-Elhamed et al. concluded that nonlinear behavior may occur even under moderate loading conditions and becomes increasingly significant with increasing building height, resulting in greater displacement demands and changes in structural response [13]. Zavala et al. investigated the influence of stiffness irregularity and second-order (P–Δ) effects on reinforced concrete buildings and reported increases of up to 16.5, 11.0, and 14.0% in drifts, shear forces, and bending moments, respectively, together with stiffness degradation reaching 59.9% [14]. Their findings highlighted the importance of considering both stiffness degradation and geometric nonlinearity in structural analysis. The nonlinear dynamic and seismic analysis of reinforced concrete structures that consider only the linear spectral methods may fail to accurately capture plastic deformation, damage accumulation, hysteretic energy dissipation, and progressive collapse behavior during earthquakes. Therefore, nonlinear analysis emphasizing fracture energy regularization, damage mechanics, nonlinear stability analysis, probabilistic structural reliability, progressive collapse assessment and computational optimization has become an essential tool for performance-based seismic design and structural safety assessment [15–22].

Recent studies have emphasized that nonlinear analysis is essential for realistically capturing the behavior of reinforced concrete structures, including cracking, stiffness degradation, force redistribution, plastic deformation, and second-order effects. Consequently, nonlinear analysis has become an increasingly important tool for evaluating the safety, serviceability, and load-bearing performance of reinforced concrete buildings under various loading conditions [23]. Arruda et al. conducted a comprehensive review of reinforced concrete design guidelines incorporating nonlinear analysis and emphasized the increasing adoption of advanced nonlinear approaches for improving the accuracy of structural assessment and design [24]. Hariri-Ardebili and Sattar reviewed sensitivity analysis methods for reinforced concrete structures and demonstrated the significant influence of material properties, stiffness assumptions, geometric imperfections, and modeling parameters on structural response predictions [25]. These studies confirm the importance of accurately accounting for both material and geometric nonlinearities and emphasize the need for comparative investigations capable of quantifying their influence on structural behavior. The development of nonlinear analysis has also been accompanied by increasing attention to

structural reliability assessment. Holický et al. proposed a probabilistic framework combining nonlinear finite element analysis with the First-Order Reliability Method (FORM) for reinforced concrete structures and demonstrated the importance of accounting for uncertainties associated with material properties, structural modeling, and loading conditions in reliability evaluation [22]. Their work highlighted the potential of advanced nonlinear models not only for structural analysis but also for performance-based reliability assessment.

Despite significant advances in nonlinear structural analysis, the existing research on this area predominantly focuses on individual aspects of reinforced concrete behavior, including material, physical and geometrical nonlinearity, performance under seismic loadings, damage mechanics, or finite element modeling. Numerous studies have considered the factors such as cracking, stiffness degradation, plastic deformation, and second-order effects; however, these investigations are often performed separately and under specific structural conditions. So, a comprehensive comparative assessment of linear and nonlinear approaches for reinforced concrete multi-storey frame systems that considers the simultaneous influence of both physical and geometrical nonlinearities remains limited. Furthermore, although finite element software enables advanced nonlinear simulations, practical engineering design continues relying on linear analysis approaches due to their simplicity and computational efficiency. The comparison in applicability and the extent of the discrepancies that may arise when nonlinear effects are omitted have not been sufficiently quantified for typical reinforced concrete multi-storey frame buildings. Particularly, the combined effects of stiffness degradation, cracking, material nonlinearity, and second-order effects, internal force redistribution, and overall load-bearing performance have not been sufficiently investigated.

Hence, a research gap exists in the integrated comparative assessment of linear and nonlinear analysis methods that simultaneously consider physical and geometrical nonlinearities within a unified framework for reinforced concrete frame systems. Primarily, the present study is to address this gap which is essential for establishing rational criteria for selecting appropriate analysis methods and for improving the reliability and safety of structural design. The aim of the study is to evaluate the comparative investigation of linear and nonlinear approaches for reinforced concrete multi-storey frame systems and to quantify the influence of the combined effects of physical and geometrical nonlinearities on structural response, load-bearing capacity, and deformation behavior. To achieve this aim, the study addresses the following objectives:

- analysis of the theoretical foundations of linear and nonlinear structural analysis methods;
- investigation of the influence of physical nonlinearity, including cracking, stiffness degradation, and nonlinear material behavior;
- evaluation of the effects of geometric nonlinearity, including second order (P– Δ) effects, on structural stability and displacement responses;
- comparison of structural parameters obtained from linear and nonlinear analyses; and
- development of engineering recommendations regarding the applicability of different analysis approaches in practical design.

2. Methods

2.1. Structural Models and Geometric Characteristics

To investigate the influence of physical and geometric nonlinearities on the structural response of reinforced concrete frame systems, three parametric building models with heights of 36, 75, and 102 m, corresponding to 12, 25, and 34 stories, respectively, were developed. All models had identical square plan dimensions of 18×18 m and a constant story height of 3.0 m. The structural system consisted of a cast-in-situ reinforced concrete frame with a central core providing lateral stiffness. Perimeter columns were arranged on a regular 6×6 m grid. For clarity, the principal geometric characteristics of the investigated models are summarized in Table 1, while the overall structural configurations are presented in Figure 4. To ensure comparability of the results, the same material properties, loading conditions, support assumptions,

and finite element modeling approach were adopted for all three models. The primary variable parameter was the building height, which enabled the influence of structural slenderness and second-order effects to be evaluated independently of other factors.

Table 1. Geometric characteristics of the investigated building models

Parameter	Model 1	Model 2	Model 3
Building height, m	36	75	102
Number of stories	12	25	34
Plan dimensions, m×m	18×18	18×18	18×18
Storey height, m	3.0	3.0	3.0
Structural system	RC frame	RC frame	RC frame

Source: made by A.V. Belyak.

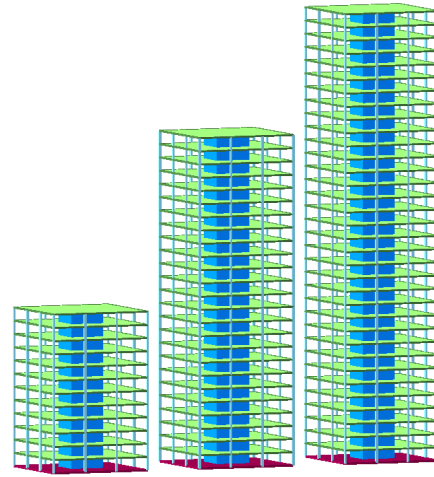


Figure 4. Generalized schemes of 36, 75 and 102 m building models

Source: made by A.V. Belyak.

2.2. Analysis Assumptions and Computational Procedure

In the linear analysis, small displacements, constant stiffness, and linear-elastic material behavior were assumed. The nonlinear analyses additionally considered concrete cracking, stiffness degradation, material nonlinearity, and geometric effects associated with the deformed configuration. The analysis methods were compared using lateral displacements, inter-story drifts, axial forces, bending moments, shear forces, and stability indicators, with particular emphasis on force redistribution and second-order ($P-\Delta$) effects.

All calculations were performed in LIRA-SAPR 2024 (Commercial License). Linear, physically nonlinear, geometrically nonlinear, and combined nonlinear analyses were conducted using the built-in step-by-step iterative procedure with automatic stiffness updating and convergence control. All analyses converged successfully at the prescribed load levels. The principal modeling assumptions adopted in the finite element analyses are summarized in Table 2.

Table 2. Modeling assumptions adopted in the finite element analysis

Item	Assumption
Material behavior (linear analysis)	Linear elastic
Material behavior (nonlinear analysis)	Physical nonlinearity according to LIRA-SAPR deformation laws
Geometric nonlinearity	Included through second-order analysis ($P-\Delta$) effects
Slab modeling	Shell finite elements
Columns and beams	Beam finite elements
Foundation slab	Fixed at the base
Mesh size	0.4×0.4 m
Cracking effects	Accounted for through stiffness reduction and nonlinear deformation laws
Reinforcement modeling	Equivalent reinforcement assigned according to design requirements
Load application	Incremental step-by-step loading
Load combinations	Generated automatically according to applicable design standards

Source: made by A.V. Belyak.

The structural system is a cast-in-situ RC frame with a central core for lateral stiffness; perimeter columns are placed on a 6 m grid. Cross sections are graded over the height of each model as tabulated in Table 3 to reflect realistic stiffness distributions.

Table 3. Geometrical characteristics of building elements

Parameter	Model 1, $H = 36$ m	Model 2, $H = 75$ m	Model 3, $H = 102$ m
Columns, mm	1–12 Stories: 400×400	1–2 Stories: 600×600 3–10 Stories: 500×500 11–25 Stories: 400×400	1–2 Stories: 700×700 3–6 Stories: 600×600 7–15 Stories: 500×500 16–34 Stories: 400×400
Core walls, mm	1–12 Stories: $t = 200$	1–8 Stories: $t = 250$ 9–25 Stories: $t = 200$	1–5 Stories: $t = 300$ 6–20 Stories: $t = 250$ 21–34 Stories: $t = 200$
Edge beams, mm	400×400	400×400	400×400
Floor slabs, mm	200	200	200
Foundation slab, mm	500	500	500

Source: made by A.V. Belyak.

2.3. Material Properties

The base models use concrete class B25 and reinforcement class A500. Design and characteristic properties are given in Table 4.

Table 4. Characteristics of materials

Property	B25 Concrete	A500 Reinforcement
Design resistance, MPa	14.5	435
Characteristic resistance, MPa	18.5	500
Modulus of elasticity, MPa	30 000	200 000
Density, kg/m ³	2500	7850

Source: made by A.V. Belyak.

2.4. Finite Element Modeling

2.4.1. Mesh Generation, Boundary Conditions, and Reinforcement Assignment

The finite element models were developed in LIRA-SAPR 2024 using bar elements for beams and columns and shell elements for slabs and walls. Two families of finite elements were employed in LIRA-SAPR 2024. Columns and beams were modeled using bar finite elements (FE 10, 210, 310, and 410), whereas slabs and core walls were modeled using shell finite elements (FE 41, 44, 230, 341, and 441). A regular mesh with an element size of 0.4×0.4 m was adopted, and the foundation slab was assumed to be fixed as shown in Figure 5. Reinforcement was assigned using the Specified Reinforcement module based on the governing load combinations as shown in Figure 6. The principal numerical modeling parameters are summarized in Table 5.

Table 5. Numerical modeling parameters

Parameter	Value
Software	LIRA-SAPR 2024 (Commercial License)
Structural system	RC frame with central core
Beam/column elements	FE 10, 210, 310, 410
Slab/wall elements	FE 41, 44, 230, 341, 441
Mesh size	0.4×0.4 m
Local refinement	Column–slab connection zones
Boundary condition	Fixed foundation slab
Concrete class	B25
Reinforcement class	A500
Reinforcement assignment	Specified Reinforcement module
Linear stiffness reduction	0.6E (vertical), 0.3E (horizontal)
Nonlinear analyses	Physical, geometric, combined

Source: made by A.V. Belyak.

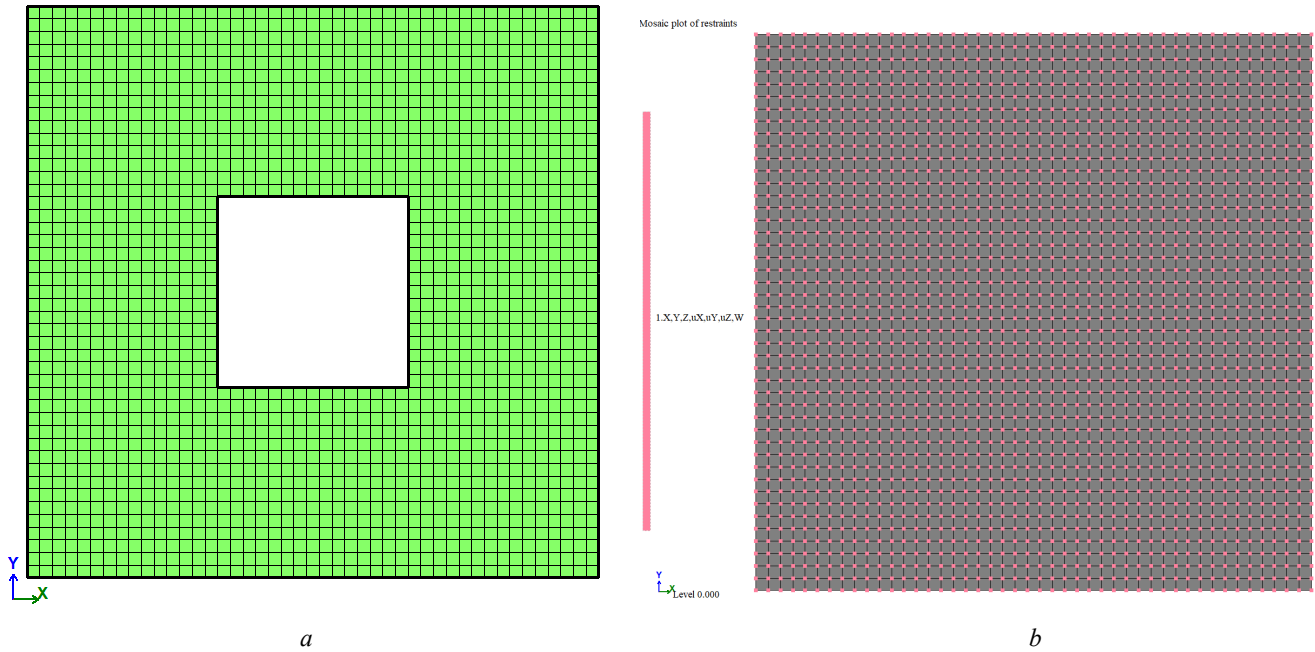


Figure 5. Finite element discretization and boundary conditions adopted in the numerical models:
 (a) typical slab mesh with an element size of 0.4×0.4 m; (b) implementation of fixed support conditions at the foundation slab
 Source: made by A.V. Belyak.

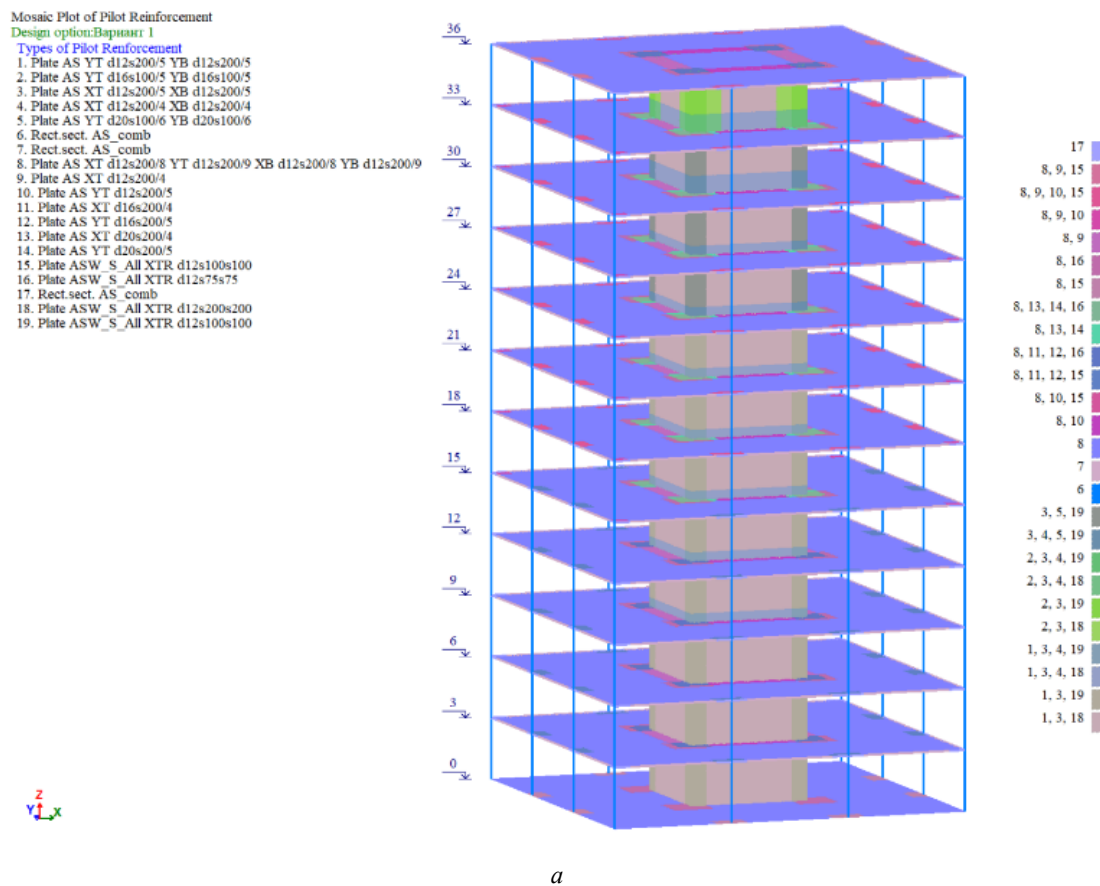


Figure 6. Reinforcement layouts of the investigated building models:
 (a) Model 1 (36m)

Source: made by A.V. Belyak.

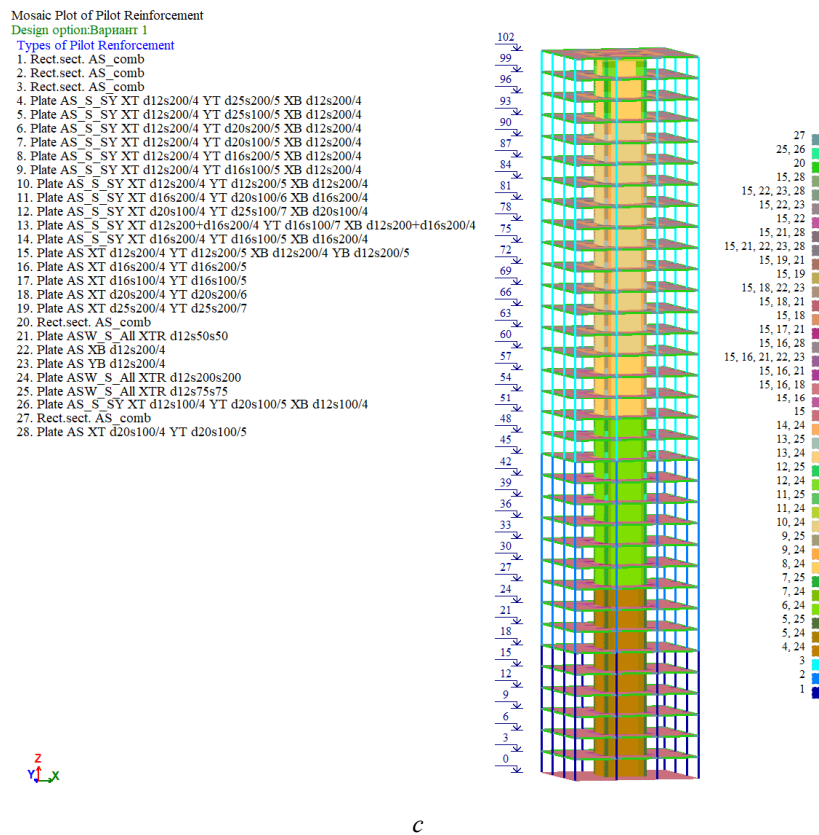
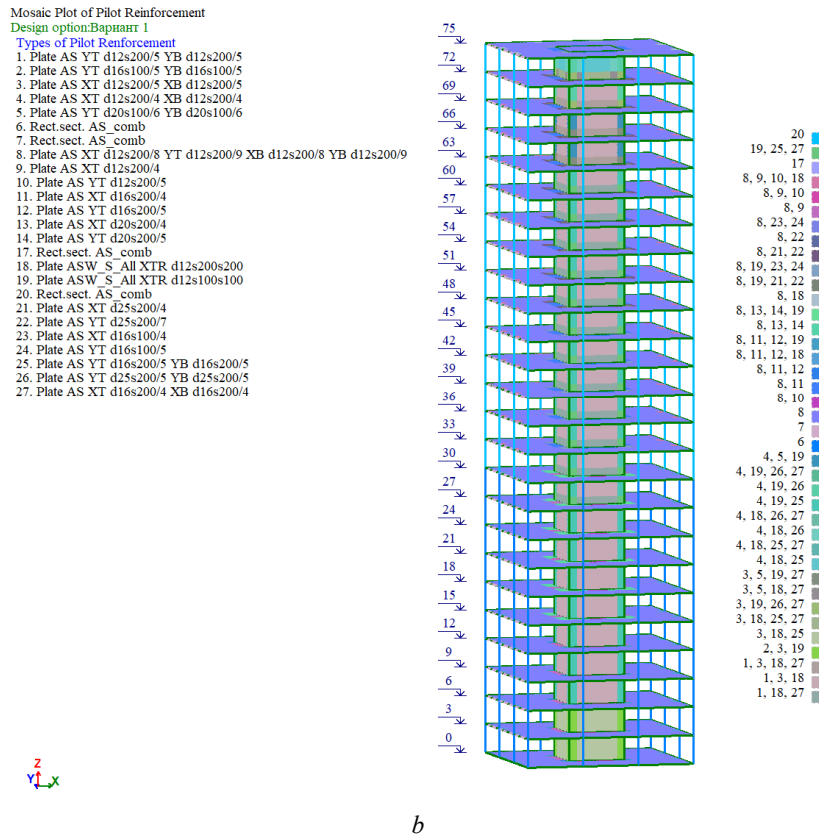


Figure 6 (Ending). Reinforcement layouts of the investigated building models:
(b) Model 2 (75 m), and (c) Model 3 (102 m)

Source: made by A.V. Belyak.

2.4.2. Mesh sensitivity

To assess the influence of mesh discretization on numerical results, a mesh sensitivity study was performed for the representative 75 m building model (Model 2). Four mesh sizes (0.6×0.6 m, 0.5×0.5 m, 0.4×0.4 m, and 0.3×0.3 m) were investigated. The comparison was based on the maximum lateral displacement obtained under the governing wind load combination. The results are summarized in Table 6.

Table 6. Mesh sensitivity study based on maximum lateral displacement of the representative 75 m building model (Model 2)

Mesh Size (m×m)	Linear Analysis (Initial Stiffness), mm	Linear Analysis (Reduced Stiffness), mm	Combined Nonlinear Analysis, mm
0.6×0.6	13.10	30.05	—
0.5×0.5	13.10	30.08	25.43
0.4×0.4	13.10	30.09	27.14
0.3×0.3	13.10	30.07	25.89

Source: made by A.V. Belyak.

As shown in Table 6, the maximum lateral displacement exhibited only minor variations with mesh refinement, indicating convergence of the numerical solution. Since the differences between the 0.5×0.5 m and 0.4×0.4 m meshes were negligible, the 0.4×0.4 m mesh was adopted for all subsequent analyses as a compromise between computational efficiency and numerical accuracy.

2.5. Load Cases and Load Combinations

In this numerical analysis, the structural models were subjected to permanent, variable, climatic, and accidental loading condition in compliance with the Russian design standards. The dead loads include self-weight ($\rho = 2500$ kg/m³), floor and roof finishes (0.3 t/m² floor; 0.45 t/m² roof) and facade load (0.5 t/m). Variable loads include 0.3 t/m² from partitions and 1.95 kPa live load for residential occupancy. Snow load (acting in both principal directions) is computed for Moscow, Russia (snow region III, $S_g = 1.5$ kPa, design value 210 kg/m²) and wind for wind region I ($w_0 = 0.23$ kPa, terrain category *B*), with wind-load diagrams shown in Figures 7 and 8.

7 Wind X+ [1. Main problem; C1. Main problem; D1. Main problem]
Mosaic plot q(lin) along axis X(G)
Units of measurement - t/m

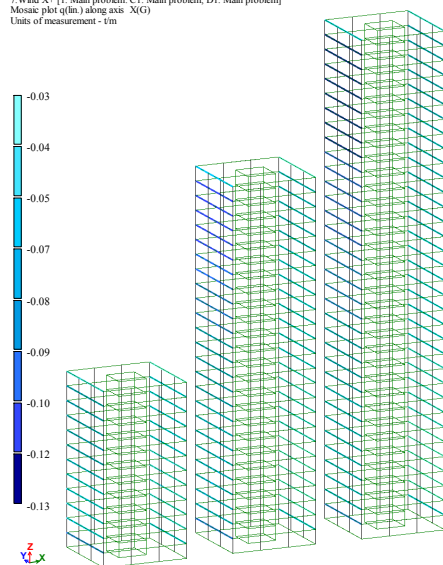


Figure 7. Wind Load Applied Along the X-Axis

Source: made by Belyak A.V.

7 Wind X+ [1. Main problem; C1. Main problem; D1. Main problem]
Mosaic plot q(lin) along axis Y(G)
Units of measurement - t/m

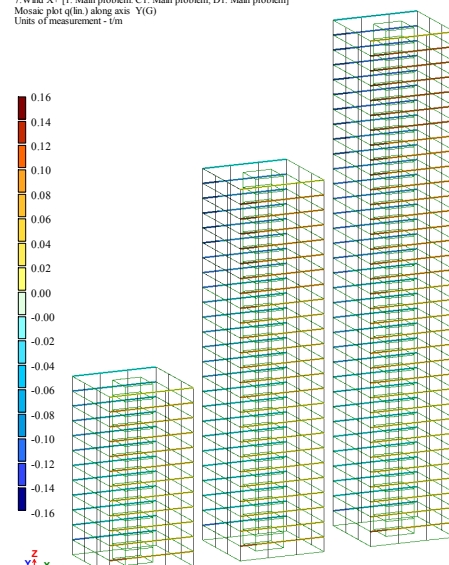


Figure 8. Wind Load Distribution (Zones A and B)

Source: made by Belyak A.V.

Dynamic wind components, and accidental eccentricity effects have been also considered. Two design groups of load combinations were defined in LIRA-SAPR 2024 for the nonlinear analyses:

- **First Limit State (ULS).** The combinations “Design Full” (all permanent and variable loads excluding wind) and “Design WX+” (all actions including wind in the positive X -direction) were used to evaluate internal forces in critical structural members, including axial force (N), bending moments (M_y , M_z), and shear forces (Q_y , Q_z).

- **Second Limit State (SLS).** The combinations “Characteristic Sustained” (long-term combination without wind) and “Characteristic WX+” (serviceability combination including wind) were used to evaluate vertical slab deflections and maximum horizontal displacements of the building, respectively.

The load cases, partial safety factors, and participation coefficients adopted in the ultimate and serviceability limit state combinations are summarized in Table 7.

Table 7. Load cases, partial safety factors, and participation coefficients used in the ULS and SLS load combinations

No.	Load Case	γ_f	ULS-X+	ULS-X-	ULS-Y+	ULS-Y-	SLS-X+	SLS-X-	SLS-Y+	SLS-Y-
1	Self-weight	1.1	1	1	1	1	0.909	0.909	0.909	0.909
2	Floor load	1.2	1	1	1	1	0.833	0.833	0.833	0.833
3	Partition load	1.2	1	1	1	1	0.833	0.833	0.833	0.833
4	Roof load 1	1.2	0.35	0.35	0.35	0.35	0.292	0.292	0.292	0.292
5	Roof load 2	1.3	0.35	0.35	0.35	0.35	0.269	0.269	0.269	0.269
6	Facade load	1.2	1	1	1	1	0.833	0.833	0.833	0.833
7	Snow load	1.4	0.5	0.5	0.5	0.5	0.357	0.357	0.357	0.357
8	Engineering equipment load	1.05	1	1	1	1	0.95	0.95	0.95	0.95
9	Soil load	1.15	1	1	1	1	0.87	0.87	0.87	0.87
10	Wind load (+X)	1.4	1	–	–	–	0.714	–	–	–
11	Wind load (–X)	1.4	–	1	–	–	–	0.714	–	–
12	Wind load (+Y)	1.4	–	–	1	–	–	–	0.714	–
13	Wind load (–Y)	1.4	–	–	–	1	–	–	–	0.714
14	Dynamic wind (+X)	1.4	1	–	–	–	0.714	–	–	–
15	Dynamic wind (–X)	1.4	–	1	–	–	–	0.714	–	–
16	Dynamic wind (+Y)	1.4	–	–	1	–	–	–	0.714	–
17	Dynamic wind (–Y)	1.4	–	–	–	1	–	–	–	0.714
18	Accidental eccentricity (+X)	1.1	1	–	–	–	0.909	–	–	–
19	Accidental eccentricity (–X)	1.1	–	1	–	–	–	0.909	–	–
20	Accidental eccentricity (+Y)	1.1	–	–	1	–	–	–	0.909	–
21	Accidental eccentricity (–Y)	1.1	–	–	–	1	–	–	–	0.909

Source: made by A.V. Belyak.

2.6. Linear and Nonlinear Analysis Procedures

Physical nonlinearity was modeled using the built-in nonlinear constitutive models available in LIRA-SAPR 2024. Concrete behavior was represented by the exponential stress–strain laws “35 — Exponential (Design Strength)” and “25 — Exponential (Characteristic Strength)”, which account for stiffness degradation and nonlinear compressive behavior. The model parameters were generated automatically by the software based on the specified properties of Concrete B25 in accordance with the LIRA-SAPR knowledge base. Reinforcement was modeled using Reinforcement Class A500 with an elastic modulus of 200 GPa and characteristic yield strength of 500 MPa. The nonlinear material models were applied consistently to all investigated building models. Five analysis variants were considered to separately evaluate the influence of stiffness reduction, material nonlinearity, geometric nonlinearity, and their combined effect on the structural response of reinforced concrete frame systems. The investigated calculation approaches are summarized in Table 8.

Table 8. Analysis of variants considered in the study

Analysis Variant	Description
Linear analysis (initial stiffness)	Linear elastic analysis using the uncracked elastic modulus of concrete specified in SP 63.13330.2018. Small displacements, constant stiffness, and the superposition principle were assumed
Linear analysis (reduced stiffness)	Linear elastic analysis considering stiffness reduction due to cracking. The elastic modulus was reduced to 0.6E for vertical members (columns and walls) and 0.3E for horizontal members (beams and slabs) for first limit state (ULS) calculations. For long-term second limit state (SLS) deflection checks, a reduction factor of 0.2E was adopted
Physically nonlinear analysis	Step-by-step nonlinear analysis considering material nonlinearity. Nonlinear finite elements of types 210, 230, 410, and 441 were employed. The analysis incorporated nonlinear deformation diagrams for concrete and reinforcement, allowing for cracking, stiffness degradation, and redistribution of internal forces
Geometrically nonlinear analysis	Step-by-step nonlinear analysis considering geometric nonlinearity and second-order effects. Equilibrium was evaluated in the deformed configuration while maintaining the initial stiffness characteristics. Nonlinear finite elements of types 310 and 341 were used
Combined nonlinear analysis	Step-by-step nonlinear analysis considering both physical and geometric nonlinearities simultaneously. Material nonlinearity, cracking, stiffness degradation, and second-order effects were accounted for within a unified computational framework using nonlinear finite elements of types 410 and 441

Source: made by A.V. Belyak.

The selected analysis variants were adopted to evaluate the influence of various levels of structural nonlinearity on reinforced concrete frame behavior. The linear analysis with initial stiffness served as the reference solution, while the reduced-stiffness analysis represented the simplified treatment of cracking commonly used in design practice. Physical and geometric nonlinear analyses were performed separately to isolate the effects of material nonlinearity and second-order ($P-\Delta$) effects, respectively. The combined nonlinear analysis considered both effects simultaneously and provided the most realistic representation of structural behavior. This approach enabled the individual and combined contributions of stiffness degradation and geometric nonlinearity to be quantified.

2.7. Model Verification and Validation

The adopted numerical modeling strategy was verified through consistency checks of the finite element formulation and validated by comparison with published studies on nonlinear analysis of reinforced concrete buildings. The validation focused on displacement amplification, force redistribution, stiffness degradation, and second-order ($P-\Delta$) effects. The reference studies used for validation are summarized in Table 9. A detailed comparison with the published results is presented in Section 3.6.

Table 9. Reference studies used for model validation

Reference	Validation Aspect
Abd-Elhamed et al. (2023) [13]	Nonlinear response, displacement amplification, building height effects
Zavala et al. (2022) [14]	($P-\Delta$) effects, stiffness degradation, force redistribution

Source: made by G.M. Dabi.

3. Results and Discussion

3.1. First Limit State

a. **Forces in the most loaded column.** The internal forces presented in Tables 10–12 were extracted from the most highly loaded ground-storey central column and top-storey slab under the governing ultimate limit state load combination. The same locations were used for all analysis variants. Axial force (N), bending moment (M_y), and shear force (Q_z) were adopted as the principal response parameters.

Table 10. Model 1 ($H = 36$ m)

Variant	N , t	ΔN , %	M_y , t·m	ΔM_y , %	Q_z , t	ΔQ_z , %
Linear (initial stiffness)	328.17	—	5.86	—	3.02	—
Linear (reduced stiffness)	337.22	+2.7	6.56	+10.7	3.38	+10.7
Physical nonlinearity	310.06	-5.8	6.13	+4.4	3.35	+9.9
Geometric nonlinearity	328.05	0.0	5.87	+0.2	3.01	-0.3
Combined nonlinearity	340.67	+3.7	7.93	+26.1	4.78	+36.8

Source: made by A.V. Belyak.

Table 11. Model 2 ($H = 75$ m)

Variant	N , t	ΔN , %	M_y , t·m	ΔM_y , %	Q_z , t	ΔQ_z , %
Linear (initial stiffness)	643.47	—	6.81	—	4.41	—
Linear (reduced stiffness)	678.25	+5.1	6.89	+14.9	4.59	+3.9
Physical nonlinearity	634.69	-1.4	12.60	+53.5	7.70	+42.7
Geometric nonlinearity	644.29	+0.1	6.39	+8.3	4.35	-1.4
Combined nonlinearity	667.31	+3.6	14.90	+60.7	8.65	+49.0

Source: made by A.V. Belyak.

Table 12. Model 3 ($H = 102$ m)

Variant	N , t	ΔN , %	M_y , t·m	ΔM_y , %	Q_z , t	ΔQ_z , %
Linear (initial stiffness)	883.52	—	10.80	—	5.70	—
Linear (reduced stiffness)	928.27	+4.8	11.65	+7.3	5.86	+2.7
Physical nonlinearity	825.65	-7.0	17.60	+38.6	9.08	+37.2
Geometric nonlinearity	869.09	-1.7	10.79	-0.1	5.56	-2.5
Combined nonlinearity	869.69	-1.6	11.81	+8.6	9.92	+42.5

Source: made by A.V. Belyak.

For the 36 m building model, geometric nonlinearity had a limited effect ($<0.3\%$), whereas the combined nonlinear analysis increased the bending moment and shear force by 26.1 and 36.8%, respectively, demonstrating the influence of stiffness degradation and second-order effects. For the 75 m building model, the influence of geometric nonlinearity became more pronounced. The combined nonlinear analysis increased the bending moment and shear force by 60.7 and 49.0%, respectively, relative to the linear analysis, primarily due to stiffness degradation and (P- Δ) effects. For the 102 m building model, the central core carried a larger share of the lateral load, reducing the axial force by 1.6% while increasing the shear force by 42.5% in the combined nonlinear analysis, indicating redistribution of internal forces between the frame and core wall system as nonlinear effects developed.

b. **Forces in the most loaded slab.** Table 13 summarizes the redistribution of internal forces in the most highly loaded floor slab resulting from nonlinear analysis. Support moments M_x decreased by 21–69%, while support moments M_y decreased by 33–89%. At the same time, span moments M_y increased by 45–56%, indicating redistribution of forces between the two principal slab directions. Significant reductions in Q_x and Q_y were also observed near the columns, confirming the influence of stiffness degradation and cracking on slab behavior.

Table 13. Summary of internal force redistribution in the most highly loaded floor slab under the “Design Full” load combination (combined nonlinear analysis relative to linear initial-stiffness analysis)

Building Model	ΔM_x	ΔM_x	ΔM_y	ΔM_y	ΔQ_x	ΔQ_x	ΔQ_y	ΔQ_y
	Span, %	Support, %	Span, %	Support, %	Span, %	Support, %	Span, %	Support, %
Model 1 ($H = 36$ m)	-21.7	-21.3	56	-33.7	-6.4	-24.6	-96.8	-29.6
Model 2 ($H = 75$ m)	-35.4	-68.8	46.2	-88.8	-76.1	-77.4	-6.1	-136.3
Model 3 ($H = 102$ m)	-16.6	-57.3	45.6	-54.8	-137.0	-55.7	51.5	-67.6

Source: made by A.V. Belyak.

3.2. Second Limit State — Lateral Displacements

Maximum lateral displacements were evaluated at the roof level of each building model under the governing wind load combination (Standard WX+). The displacement values correspond to the node exhibiting the maximum lateral translation in the direction of the applied wind load. The same evaluation criterion was adopted for all linear and nonlinear analyses to enable direct comparison of structural stiffness and second-order effects. The obtained displacement values are summarized in Table 14, while their variation with building height and analysis method is illustrated in Figure 9.

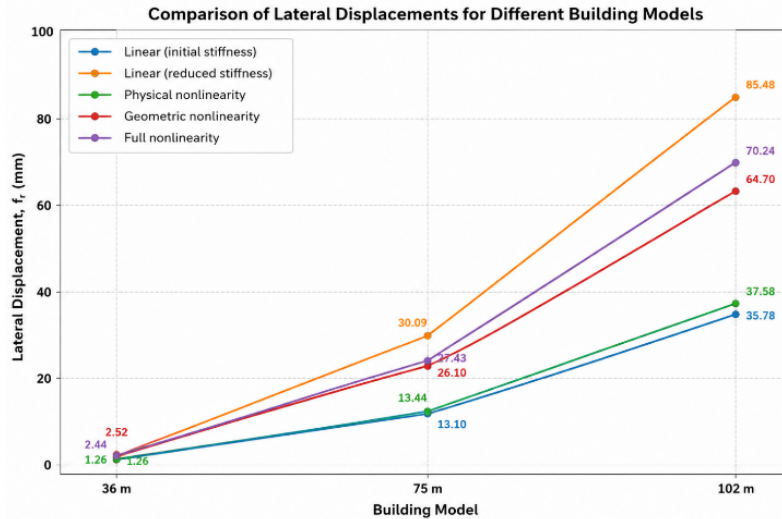


Figure 9. Comparison of horizontal displacements

Source: made by A.V. Belyak.

Table 14. Maximum lateral displacements at the top of the building, mm (load combination: Standard WX+)

Building Model	Linear (Initial Stiffness), mm	Linear (Reduced Stiffness), mm	Physical NL, mm	Geometric NL, mm	Combined NL, mm
Model 1	1.26	2.4	2.52	1.26	2.44
Model 2	13.1	30.09	26.1	13.44	27.43
Model 3	35.78	85.48	64.7	37.58	70.24

Source: made by A.V. Belyak.

Three main observations were identified. First, linear analysis with initial stiffness consistently underestimated lateral displacements because it neglected crack-induced stiffness degradation. Second, geometric nonlinearity alone had a limited influence, but its contribution increased when combined with physical nonlinearity due to second-order (P-Δ) effects. Third, the reduced-stiffness linear approach showed reasonable agreement with the combined nonlinear analysis for the 36 and 75 m models, whereas larger discrepancies were observed for the 102 m model. These observations are limited to the investigated building configurations.

3.3. Second Limit State — Vertical Slab Deflections

Vertical slab deflections were evaluated at the center of the slab panel exhibiting the maximum deformation under the long-term serviceability load combination. The reported values correspond to the maximum downward displacement obtained from the finite element results and were used to assess the influence of physical and geometric nonlinearities on serviceability performance. The obtained deflection values are summarized in Table 15.

Although the observed increases in internal forces and displacements are primarily attributed to stiffness degradation caused by cracking and the development of second-order (P– Δ) effects, other factors may also influence the structural response. These include the adopted support conditions, reinforcement distribution, member stiffness assumptions, and the interaction between the frame and the central core. Variations in these parameters may alter force redistribution patterns and deformation characteristics. Nevertheless, all building models were analyzed using identical modeling assumptions, material properties, boundary conditions, and loading procedures, allowing the influence of physical and geometric nonlinearities to be isolated and compared consistently.

Table 15. Maximum vertical deflections of floor slabs, mm (long-term serviceability load combination)

Building Model	Linear (Initial Stiffness), mm	Linear (Reduced Stiffness), mm	Physical NL, mm	Geometric NL, mm	Combined NL, mm
Model 1	6.58	24.88	18.36	6.54	17.93
Model 2	8.31	30.56	20.8	8.26	20.74
Model 3	11.58	34.33	17.58	9.19	17.36

Source: made by A.V. Belyak.

3.4. Interaction Between Physical and Geometric Nonlinearities

To quantify the interaction between physical and geometric nonlinearities, the interaction index defined by Eq. (1) was evaluated for the principal response parameters. The obtained values are summarized in Table 16.

A commonly used interaction index (I) can be defined as:

$$I = \frac{R_C - R_P - R_G + R_L}{R_L}, \quad (1)$$

where R_L , R_G , R_P , and R_C are the linear analysis, geometrically nonlinear, physically nonlinear, combined nonlinear results respectively.

Table 16. Interaction index between physical and geometric nonlinearities

Model	N	M_y	Q_z	Δ	δ
Model 1 (36 m)	0.094	0.305	0.477	–0.063	–0.059
Model 2 (75 m)	0.049	0.399	0.229	0.076	–0.001
Model 3 (102 m)	0.066	–0.535	0.172	0.105	0.187

Source: made by G.M. Dabi.

The interaction analysis showed that physical and geometric nonlinearities do not act independently and that their influence depends on the response parameter and building height. Axial forces exhibited weak interaction (0.049–0.094), whereas bending moments showed stronger interaction, reaching 0.399 in Model 2. The highest interaction was observed for shear force in Model 1 (0.477). For horizontal displacements, the interaction increased with building height, indicating stronger coupling effects in more slender structures. In Model 3, the negative interaction index for bending moments (–0.535) suggests redistribution of forces within the structural system. Overall, the results demonstrate that combined nonlinear analysis provides a more realistic representation of structural behavior than separate consideration of physical or geometric nonlinearity.

3.5. Sensitivity Analysis of Building Height

To address the robustness of the numerical results obtained based on the variation of the main response parameters obtained from the combined nonlinear analysis, since this approach simultaneously accounts for physical and geometric nonlinearities, an additional sensitivity analysis and COV have been performed with respect to building height. The results for sensitivity analysis are presented Table 17.

Table 17. Sensitivity of response parameters to building height under combined nonlinear analysis

Parameter	$H = 36$ m	$H = 75$ m	$H = 102$ m	Factor (75 / 36 m)	Factor (102 / 75 m)	Factor (102 / 36 m)
N , t	340.67	667.31	869.69	1.96×	1.30×	2.55×
M_y , t×m	7.93	14.9	11.81	1.88×	0.79×	1.49×
Q_z , t	4.78	8.65	9.92	1.81×	1.15×	2.08×
Δ , mm	2.44	27.43	70.24	11.24×	2.56×	28.79×
δ , mm	17.93	20.74	17.36	1.16×	0.84×	0.97×

Source: made by G.M. Dabi.

The result demonstrates that horizontal displacement is the most height-sensitive parameter. The change in Δ from 2.44 for the 36 m model to 70.24 mm for the 102 m model has been observed, corresponding to an increase by a factor of approximately 28.8. This confirms that the influence of nonlinear effects becomes significantly more pronounced with increasing building height and structural flexibility. In contrast, the maximum vertical slab deflection showed limited sensitivity to the overall building height. The δ parameter changed from 17.93 to 17.36 mm for 36 m and 102 models respectively, corresponding to a slight decrease of 3.18% which is an indicator of that vertical slab deflections are governed by local floor stiffness and long-term serviceability effects, whereas horizontal displacements are more strongly influenced by global structural height and lateral flexibility.

The variability analysis summarized in Table 18 reveals that coefficient of variation confirms the high sensitivity of horizontal displacement to building height, with a COV of 102.75%. Axial force, bending moment, and shear force also demonstrate moderate variability, while vertical slab deflection shows low variability with a COV of 9.69%.

Table 18. Variability indicators of response parameters for combined nonlinear analysis

Parameter	Mean	SD	COV, %	Minimum	Maximum
N , t	625.89	266.93	42.65	340.67	869.69
M_y , t×m	11.55	3.49	30.25	7.93	14.90
Q_z , t	7.78	2.68	34.40	4.78	9.92
Δ , mm	33.37	34.29	102.75	2.44	70.24
δ , mm	18.68	1.81	9.69	17.36	20.74

Source: made by G.M. Dabi.

Therefore, the reported trends are not isolated results of a single computational case but reflect systematic changes in structural response associated with increasing building height.

Overall, the sensitivity analysis confirms that the significance of nonlinear effects increases with building height, particularly for lateral displacement and internal force redistribution. This supports the conclusion that nonlinear analysis becomes increasingly important for taller and more flexible reinforced concrete frame systems.

3.6. Discussion in Relation to Previous Research

To evaluate the reliability and practical significance of the obtained results, the present findings were compared with recent studies on nonlinear analysis of reinforced concrete buildings. Particular attention

was given to displacement amplification, force redistribution, stiffness degradation, and the influence of second-order ($P-\Delta$) effects. Table 19 summarizes the comparison between the present study and selected publications.

Table 19. Comparison of present results with previous studies

Reference	Structural System	Reported Findings	Agreement with Present Study
Abd-Elhamed et al. (2023) [13]	5-, 10-, and 15-storey RC buildings	Nonlinear effects increase displacement demands and become more significant with building height	Similar increase in nonlinear effects with increasing building height
Zavala et al. (2022) [14]	RC buildings with stiffness irregularity and ($P-\Delta$) effects	Drift increase up to 16.5%; shear force increase up to 11.0%; bending moment increase up to 14.0%; stiffness degradation up to 59.9%	Similar influence of stiffness de-gradation and ($P-\Delta$) effects on displacement amplification and force redistribution
Present study	12-, 25-, and 34-storey RC frame-core buildings	Horizontal displacement: +93.7–109.4%; M_y : +8.6–60.7%; Q_z : +36.8–49.0%	Consistent with trends reported in recent studies

Source: made by G.M. Dabi.

As shown in Table 19, the present results are consistent with the trends reported in previous investigations. Zavala et al. [14] observed that stiffness degradation and $P-\Delta$ effects lead to increases in drifts, shear forces, and bending moments, while Abd-Elhamed et al. [13] demonstrated that nonlinear effects become increasingly significant with building height. Similar behavior was observed in the present study, where combined physical and geometric nonlinearities increased horizontal displacements by 93.7–109.4%, bending moments by 8.6–60.7%, and shear forces by 36.8–49.0% relative to the linear analysis. Although the magnitude of the response differs among the studies due to differences in structural configuration, modeling assumptions, and building height, all investigations confirm the importance of accounting for stiffness degradation and second-order effects in reinforced concrete structures.

Although the observed differences between linear and nonlinear analyses are primarily attributed to stiffness degradation caused by cracking and the development of second-order ($P-\Delta$) effects, other modeling assumptions may also influence the structural response. These factors include the adopted stiffness-reduction coefficients, reinforcement distribution, boundary conditions, finite element discretization, and the interaction between the frame and the central core. Variations in these parameters may affect force redistribution, displacement demands, and local stress concentrations. Nevertheless, identical modeling assumptions were maintained for all investigated building models and analysis variants, allowing the relative influence of physical and geometric nonlinearities to be evaluated consistently.

4. Conclusion

This study presented a comparative investigation of linear and nonlinear analyses of reinforced concrete frame-core buildings with heights of 36, 75, and 102 m.

1. Nonlinear effects significantly influenced the structural response of the investigated building models, and the difference between linear and nonlinear results increased with building height and structural flexibility.

2. Physical nonlinearity associated with crack-induced stiffness degradation was identified as the dominant source of variation between linear and nonlinear analyses, while geometric nonlinearity became increasingly important when combined with physical nonlinearity through second-order ($P-\Delta$) effects.

3. For the investigated 18×18 m building configurations, the reduced-stiffness linear approach showed reasonable agreement with the combined nonlinear analysis for the 36 and 75 m models, whereas larger discrepancies were observed for the 102 m model, particularly in the prediction of displacements and slab deflections. Further studies are required before generalized height-based applicability limits can be established.

4. Combined nonlinear analysis resulted in significant redistribution of internal forces throughout the structural system. Support slab moments decreased by 33–89%, while transverse forces near columns were substantially reduced, demonstrating the influence of stiffness degradation and stress redistribution on structural behavior.

5. The interaction analysis confirmed that physical and geometric nonlinearities do not act independently. Their combined influence became more pronounced with increasing building height and provided a more realistic representation of structural response than separate consideration of either effect.

6. For the analyzed building models, the engineering nonlinearity method implemented in LIRA-SAPR 2024 (Commercial License) provided a practical compromise between simplified reduced-stiffness approaches and full nonlinear analysis while maintaining computational efficiency.

Overall, the results indicate that linear and nonlinear analyses should be regarded as complementary engineering tools. Linear analysis remains suitable for preliminary design and routine verification, whereas nonlinear analysis is required for reliable assessment of displacement response, force redistribution, and second-order effects in the investigated medium- and high-rise reinforced concrete frame-core buildings.

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