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Reduction of Material and Labor Costs in Construction Production: Optimization of Reinforcement Solutions for Monolithic Slabs

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Abstract

The objective of this research project is to optimize the reinforcement of monolithic reinforced concrete slabs to reduce material consumption and labor costs, which is a pressing issue in modern construction. To address this issue, advanced numerical modeling methods were applied using the LIRA-SAPR software suite. These methods include nonlinear finite element analysis (FEA), force redistribution principles, and the concept of variable reinforcement. A methodology for implementing variable reinforcement was developed, based on a detailed analysis of the slab's stress-strain state. The results of numerical experiments demonstrated that the proposed optimization methods, particularly variable reinforcement, can reduce the consumption of reinforcing steel by 12-15% without significantly increasing labor intensity. The significance of this project lies in the development of practical recommendations for construction companies seeking to improve economic efficiency and resource conservation in monolithic construction. This contributes to reducing construction costs and promoting more rational resource utilization.

Keywords: finite element analysis; LIRA-SAPR; material efficiency; monolithic slabs; nonlinear analysis; optimization; reinforced concrete; variable reinforcement.

1. Introduction

In contemporary construction, characterized by expanding building volumes and heightened demands for economic efficiency and resource conservation, optimizing the reinforcement of monolithic reinforced concrete slabs has become paramount [16]. Monolithic slabs, integral to framed structural systems, constitute a significant proportion of material consumption and labor costs in overall construction operations [17].

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Amidst fluctuating material prices, particularly for reinforcing steel, and a growing scarcity of skilled labor, the pursuit and implementation of effective reinforcement optimization methods are not merely economically prudent but strategically imperative for maintaining the construction industry's competitiveness. The current trend in monolithic reinforced concrete design and construction increasingly favors advanced computational technologies and numerical modeling techniques [1]. This shift is driven by the need for more precise consideration of material properties, structural behavior, and environmental factors. Simultaneously, sustainable development principles and life-cycle thinking emphasize minimizing environmental impact throughout a building's lifespan, from material production to waste disposal [7; 5]. Within this context, optimizing slab reinforcement is recognized as central to enhancing both the ecological and economic sustainability of construction projects [14].

Specialized software suites, offering sophisticated tools for detailed modeling, static and dynamic analysis, and automated reinforced concrete design, are therefore gaining importance. LIRA-SAPR, a recognized and reliable software, enables engineers to conduct in-depth analyses of monolithic slab stress-strain states, account for nonlinear material behavior, and implement various reinforcement optimization strategies based on modern code requirements and advanced engineering practices [6]. While digital concrete production has progressed [3; 10; 15; 16], research into structural optimization and efficient reinforcement for digital reinforced concrete elements remains limited. Existing studies [2; 4; 11] primarily focus on forming methods and mixes, overlooking material optimization, especially steel consumption in digital production. Furthermore, within the sustainability framework [8; 14], strategies for optimizing slab reinforcement to minimize material intensity and carbon footprint are underdeveloped. Existing research [9; 13] tends to be general, lacking quantitative assessments of reinforcement optimization methods' environmental impact, particularly the potential of nonlinear analysis and variable reinforcement to reduce steel usage in monolithic slabs.

This paper addresses this gap by aiming to present a comprehensive analysis and systematization of advanced reinforcement optimization methods for monolithic reinforced concrete slabs, specifically within the LIRA-SAPR software environment. To achieve this aim, the research investigates the application of detailed finite element modeling, linear and nonlinear numerical analysis, and modern optimization techniques, including nonlinear analysis, force redistribution, and variable reinforcement. The effectiveness of these methods in reducing material consumption and labor costs is quantitatively evaluated to develop practical recommendations for construction organizations. This research offers a systematic development and quantitative evaluation of a methodology for optimizing reinforcement in monolithic reinforced concrete slabs using nonlinear static analysis and variable reinforcement in LIRA-SAPR, emphasizing material and resource conservation. Unlike traditional approaches, the proposed methodology focuses on detailed consideration of nonlinear material behavior and adapting reinforcement to the localized distribution of internal forces, demonstrably reducing reinforcing steel consumption and enhancing the environmental sustainability of reinforced concrete structures.

2. Materials and Methods

Within this research, the LIRA-SAPR software suite, version 2023, a certified software widely used in engineering practice for the analysis and design of building structures, served as the primary tool for modeling and analyzing structural solutions. For numerical experiments, a parametric finite element model of a monolithic reinforced concrete slab, measuring 24x24 meters (79x79 feet) in plan and representing a typical 200 mm (8 inches) thick slab common in multi-story residential buildings with a column grid of 6 meters (20 feet), was developed. The model materials consisted of B25 class concrete with a design compressive strength of 14.5 MPa (2100 psi) and A500C class reinforcing steel with a yield strength of 500 MPa (72,500 psi). The load on the slab included a permanent load from its self-weight and flooring (4 kN/m² (84 psf)) and a temporary standard live load (2 kN/m² (42 psf)).

The model incorporated a detailed description of the slab geometry, the physical and mechanical properties of concrete and reinforcing steel, as well as the appropriate assignment of hinged-movable supports along the perimeter, simulating the slab's support on the building frame columns. The stress-strain state analysis of the slab was performed using the finite element method (FEM) based on four-node plate elements of type 41, in both linear and nonlinear formulations. Material nonlinearity was accounted for by implementing a bilinear stress-strain diagram for steel and a Prandtl diagram for concrete in the "Nonlinear Static Analysis" module of the software suite.

To investigate various reinforcement optimization strategies for monolithic slabs, the following methods were implemented and analyzed within the developed finite element model: utilizing nonlinear analysis to refine the distribution of forces and moments in the slab, considering concrete cracking and stress redistribution, specifically with iterative refinement of element stiffness; applying the principles of bending moment redistribution in support zones up to 15% of the maximum value, to reduce peak values and, consequently, reduce reinforcement intensity in these areas; implementing the concept of variable reinforcement, which involves changing the spacing of reinforcing bars from 150 to 300 mm (6 to 12 inches) and using rebar diameters from 10 to 16 mm (approximately #3 to #5 rebar) of class A500C depending on the local values of bending moments and shear forces obtained from the numerical analysis.

Each of the aforementioned methods was implemented in the LIRA-SAPR environment using specialized modules "RCU" (Reinforced Concrete Section Analysis and Design) and "Reinforcement," allowing for flexible configuration of calculation and design parameters of reinforcement elements, as well as exporting results in the form of drawings and specifications. The effectiveness assessment of the proposed reinforcement optimization methods was conducted based on a comprehensive analysis of several indicators characterizing material consumption, labor costs, and economic feasibility of design solutions.

The main evaluation criteria considered were: reinforcing steel consumption per unit volume of concrete, expressed in kg/m ³ (lbs/cu ft), determined as the total length of reinforcing bars of various diameters required to ensure the slab's load-bearing capacity and related to the slab volume of 115.2 m³ (4070 cu ft); estimated labor intensity of reinforcement work, evaluated in person-hours per 1 m³ of concrete (per cu ft) based on consolidated time standards and considering the complexity of implementing various reinforcement schemes, ranging from 1.5 to 2.5 person-hours/m³ (per cu ft); total cost of reinforcing materials, calculated based on average market prices for rebar in the research region at the time of calculations, in the range of $535 - 594, and the volume of reinforcing steel obtained for different optimization options.

The obtained results of numerical experiments were subjected to comparative analysis to identify the most effective methods for optimizing the reinforcement of monolithic slabs, providing an optimal balance between the economic and technical characteristics of structural solutions, with a target indicator of reducing steel consumption by 10-15% compared to traditional approaches.

3. Results

3.1. Conceptual framework for monolithic construction of reinforced concrete slabs

Monolithic reinforced concrete slabs, serving as load-bearing horizontal elements in building structures, are constructed through a sequence of technological operations: installation of formwork systems, placement of the reinforcing cage, and pouring of the concrete mix [12; 17]. This technology facilitates the formation of a spatially continuous diaphragm with rigidity, where the composite action of concrete and reinforcing steel achieves the required load-bearing capacity and deformability parameters [12]. Constructive monolithicity ensures enhanced spatial rigidity and stability of the slab in the horizontal plane, and also promotes efficient distribution of internal forces within the slab [12]. In structural engineering, monolithic slabs are integrated into the load-bearing frame of a building, forming a horizontal diaphragm and resisting vertical static and dynamic loads from upper floors and standard live loads [17]. The effectiveness of monolithic technologies largely depends on the rationality of design solutions, including reinforcement optimization and precise adherence to the technological regulations of construction and installation work [16; 17].

The construction cycle of monolithic reinforced concrete slabs begins with the installation of formwork systems. Formwork establishes the design geometry and supports the concrete mix until it reaches the necessary strength [12]. The range of formwork solutions, encompassing prefabricated modular, framed, beam-and-girder, and slip-form systems, is determined by architectural and planning decisions, concrete volumes, and techno-economic justification. Formwork structures are subject to stringent regulatory requirements concerning strength, stiffness, geometric accuracy, and joint watertightness. Upon completion of the formwork operations, slab reinforcement procedures are carried out. These operations include cutting and bending reinforcing steel, forming rebar meshes and cages, and their precise positioning within the formwork, ensuring the specified concrete cover [17]. Reinforcement of monolithic slabs is a complex process requiring skilled professionals and strict adherence to design documentation as well as building codes and regulations. To expedite the process and reduce labor intensity, optimization of reinforcement work logistics, including prefabrication of reinforcement assemblies and the use of small-scale mechanization, is of significant importance.

Concreting of monolithic slabs is a critically important technological operation determining the operational characteristics and durability of the structure [16]. Transporting the concrete mix to the placement location can be accomplished through various methods, including truck mixers, stationary and truck-mounted concrete pumps, as well as lifting mechanisms with buckets. It is crucial to ensure a placement rate that prevents initial setting of the concrete mix before its consolidation. The process of concrete mix vibration consolidation, involving internal and surface vibration, is aimed at removing entrapped air and achieving maximum density and homogeneity of the concrete mass. Adherence to regulated parameters of the concrete mix, such as workability (slump, stiffness), water-cement ratio, and aggregate gradation, which ensure the design strength characteristics and rheological properties, is a key factor. After concreting is complete, it is necessary to organize a set of measures for curing the freshly placed concrete during the cement hydration period. This set of measures includes moistening exposed surfaces, thermal insulation during cold weather, and protection from atmospheric effects, which are necessary to minimize the risk of cracking and ensure that the concrete achieves its specified strength.

At all stages of monolithic reinforced concrete slab construction, a multi-stage quality control system (input, operational, acceptance) is implemented, aimed at verifying the conformity of the completed work to the design and estimate documentation, current building codes and regulations, and technical specifications. The quality control system includes input control of construction materials (cement, aggregates, chemical admixtures, reinforcing steel, formwork elements), operational control of technological processes (formwork installation, reinforcement, concrete mix placement and consolidation, concrete curing), and acceptance control of finished structures for compliance with geometric parameters, concrete surface quality, and strength characteristics. Acceptance control includes visual inspection, instrumental geodetic surveying, and non-destructive testing methods for concrete strength (ultrasonic testing, impact-pulse method). Quality control results are documented in work logs and certificates of acceptance for concealed works, which are an integral part of the as-built documentation for a capital construction project. An effective quality control system guarantees the reliability and safe operation of the constructed monolithic reinforced concrete slabs.

In the modern construction industry, optimization of production processes and resource conservation are strategic vectors for the development of monolithic construction [16]. The optimization vector is directed towards integrating advanced formwork technologies, comprehensive mechanization of reinforcement and concrete works, implementing innovative concrete placement and hardening acceleration technologies, as well as rational use of material resources [17]. In the context of monolithic slab reinforcement, optimization is focused on reducing the unit consumption of reinforcing steel while ensuring the required level of load-bearing capacity and operational reliability. The use of high-strength concrete and reinforcing steel grades, as well as optimization of reinforcement schemes based on finite element analysis results, contributes to reducing material intensity and construction costs. The integration of Building Information Modeling (BIM) technologies and automated design and construction management systems enhances the efficiency of construction process management and ensures precise implementation of design solutions [1].

3.2. Modern Optimization Methods Applied in the LIRA-SAPR Software Suite

The LIRA-SAPR software suite is an effective tool for implementing modern methods of optimizing the reinforcement of monolithic reinforced concrete slabs, based on the principles of detailed numerical analysis and consideration of nonlinear material behavior. In contrast to traditional approaches based on simplified design schemes, LIRA-SAPR provides the ability to model the stress-strain state of slabs, which allows for identifying reserves in load-bearing capacity and reducing over-reinforcement. At the heart of optimization strategies lies the concept of adaptive reinforcement, which involves the differentiated assignment of rebar depending on the local values of internal forces obtained from detailed analysis. The application of LIRA-SAPR facilitates the transition from unified solutions to customized designs, maximally adapted to specific operating conditions and ensuring material resource savings without compromising structural safety and durability.

The main tool for reinforcement optimization in LIRA-SAPR is the nonlinear static analysis module, which allows for considering the physical nonlinearity of concrete and reinforcing steel. The implementation of nonlinear material models, such as the Prandtl diagram for steel and diagrams that account for concrete cracking and nonlinear deformation behavior, provides a more adequate reflection of the actual behavior of reinforced concrete elements under load. Nonlinear analysis enables the identification of force redistribution in the structure due to cracking and plastic deformations, which leads to a refinement of bending moment and shear force diagrams compared to linear-elastic analysis. Considering the nonlinear properties of materials allows for more accurately determining stress concentration zones and zones with reduced reinforcement requirements, which serves as the basis for developing economically efficient reinforcement schemes with variable bar spacing and diameter. Iterative refinement of element stiffness during nonlinear analysis allows for achieving solution convergence and obtaining reliable results suitable for practical application in design.

Within LIRA-SAPR, the possibility of applying the principles of bending moment redistribution in the support zones of monolithic slabs is implemented, which significantly adds to the effectiveness of overall reinforcement optimization. Regulatory documents permit partial redistribution of negative support moments in favor of positive span moments, within established limits, provided that the overall load-bearing capacity and crack resistance of the structure are ensured. The "RCU" (Reinforced Concrete Section Analysis and Design) module in LIRA-SAPR automatically performs moment redistribution in accordance with specified coefficients and regulatory guidelines, which leads to a reduction in peak values of support moments and, consequently, a decrease in reinforcement intensity in support zones. Moment redistribution allows for more uniformly loading the reinforcement across the slab area and reducing the overall consumption of reinforcing steel, especially in multi-span and continuous slabs, where support moments can reach significant magnitudes.

The implementation of the variable reinforcement concept in LIRA-SAPR is ensured by integrating the results of numerical analysis with tools for designing and detailing reinforcement elements. Based on the bending moment and shear force diagrams obtained from linear or nonlinear analysis, the "Reinforcement" module automatically selects the required reinforcement area for each element of the finite element mesh. Furthermore, the design engineer has the ability to flexibly configure reinforcement parameters, setting ranges for rebar diameters, spacing, and concrete cover. The functionality of LIRA-SAPR allows for creating variable reinforcement schemes that involve changing the spacing of bars or rebar diameter depending on the local values of forces, which ensures optimal use of reinforcing steel and reduces the material intensity of the structure. Automated generation of drawings and specifications for reinforcement products based on the results of reinforcement optimization contributes to increasing the efficiency of the design process and reducing the probability of errors in detailing.

3.3. Construction of a Detailed Finite Element Model of a Monolithic Slab in the LIRA-SAPR Software Suite

Further research focused on constructing a detailed finite element model of a monolithic slab within the LIRA-

SAPR software suite, for subsequent reinforcement optimization.

The initial stage of modeling involved the geometric representation of the slab. A plate model was created in the LIRA-SAPR environment, replicating the contour and thickness of the slab under investigation. Geometric parameters, namely plan dimensions of 24x24 meters (79x79 feet) and a thickness of 200 mm (8 inches), were entered using the plate creation tool, with precise specification of the corner point coordinates in the global coordinate system. To ensure high accuracy of the model geometry, node coordinates were entered with increased precision. Alternatively, for more complex slab configurations, the possibility of importing a contour from a CAD system in DXF format was considered, which would allow for reproducing curvilinear boundaries and more complex architectural forms. The choice of a rectangular slab shape was driven by the desire to create a typical model characteristic of multi-story residential buildings, which ensured the representativeness of the research results and the possibility of their extrapolation to a wide class of objects.

A crucial aspect of modeling was the correct definition of the physical and mechanical properties of the materials constituting the structure. In accordance with the adopted conditions, B25 class concrete was assigned for the slab, and A500C class rebar for reinforcement. The built-in material library of LIRA-SAPR provided the option to select the corresponding grades of concrete and steel. For B25 class concrete, the design characteristics regulated by normative documents, including the design compressive strength R = 14.5 MPa (2100 psi), modulus of elasticity E, Poisson's ratio, and other parameters necessary for linear and nonlinear analysis, were automatically assigned. Similarly, for A500C class reinforcing steel, the yield strength R = 500 MPa (72,500 psi), modulus of elasticity E, and other characteristics were defined. The selection of concrete and rebar classes B25 and A500C is due to their widespread use in modern residential construction and the economic feasibility of their application in typical multi-story building structures. If necessary, to account for the nonlinear properties of materials in further stages of the research, it was planned to use nonlinear deformation models for concrete and steel implemented in the "Nonlinear Static Analysis" module of LIRA-SAPR.

For discretizing the solid slab into a finite element mesh, the automatic triangulation method using four-node plate elements of type 41 was applied. This element type is adequate for modeling flexural plates and provides sufficient accuracy of results with moderate computational costs. To ensure solution convergence and evaluate the influence of the finite element size on the analysis results, it was intended to conduct a series of analyses with a sequential reduction in element size and comparison of the obtained stress and strain values. In stress concentration zones, in particular, near column support nodes, local mesh refinement of finite elements was planned for more accurate modeling of the stress state in these critical areas.

The boundary conditions of the model, simulating the interaction of the slab with the load-bearing columns of the building frame, were implemented by assigning hinged-movable supports along the slab perimeter. The choice of hinged-movable supports is due to the adopted design scheme, assuming the slab is supported on columns without considering the rigidity of the connection joints. In LIRA-SAPR, hinged-movable supports were assigned by selecting nodes located on the slab contour and assigning them constraints that restrict displacements in the vertical direction (Z-axis), but allow free movement in the horizontal plane (X and Y axes). This support scheme adequately reflects the operating conditions of a monolithic slab in typical framed buildings, where the slab receives vertical loads and transfers them to the columns, while horizontal movements in the plane of the slab are limited by the overall rigidity of the building frame. Accurate assignment of boundary conditions is critical for correct modeling of the distribution of forces and deformations in the slab.

The final stage of constructing the finite element model was the application of loads and setting up the calculation scheme parameters. In accordance with the assignment, a permanent load, including the self-weight of the slab and the floor load (4 kN/m² (84 psf)), and a temporary standard live load (2 kN/m² (42 psf)), were applied to the model. The self-weight of the slab was accounted for automatically by specifying the density of concrete in the material properties. The floor load and live load were applied as a uniformly distributed load on the slab surface, using the "Distributed Load on Plate" tool. To conduct the stress-strain state analysis, load cases corresponding to permanent and temporary loads were created.

In particular, for a detailed assessment of the stress-strain state of the slab based on the numerical modeling results, diagrams of shear forces Qy and bending moments My were constructed for each considered load case. Analysis of the shear force diagrams Qy reveals a закономерную (systematic) concentration of shear stresses in the support regions of the slab, which is a characteristic feature of the behavior of bending plates. Thus, for the live load, the Qy values reach maximum positive values up to 0.548 tons-force/m (369 lbs-force/ft) and negative values up to -0.494 tons-force/m (-333 lbs-force/ft) in the corner zones of the slab, which is due to the superposition of shear stresses from biaxial bending and the concentration of support reactions in these areas. A similar trend is observed for self-weight, where the maximum Qy values reach 0.685 tons-force/m (462 lbs-force/ft) and -0.617 tons-force/m (-416 lbs-force/ft) in the same corner zones. In the span zone of the slab, the shear force Qy values show a significant decrease, approaching zero values in the range of ±0.1 tons-force/m (±67 lbs-force/ft), which corresponds to theoretical representations of the distribution of shear forces in bending elements.

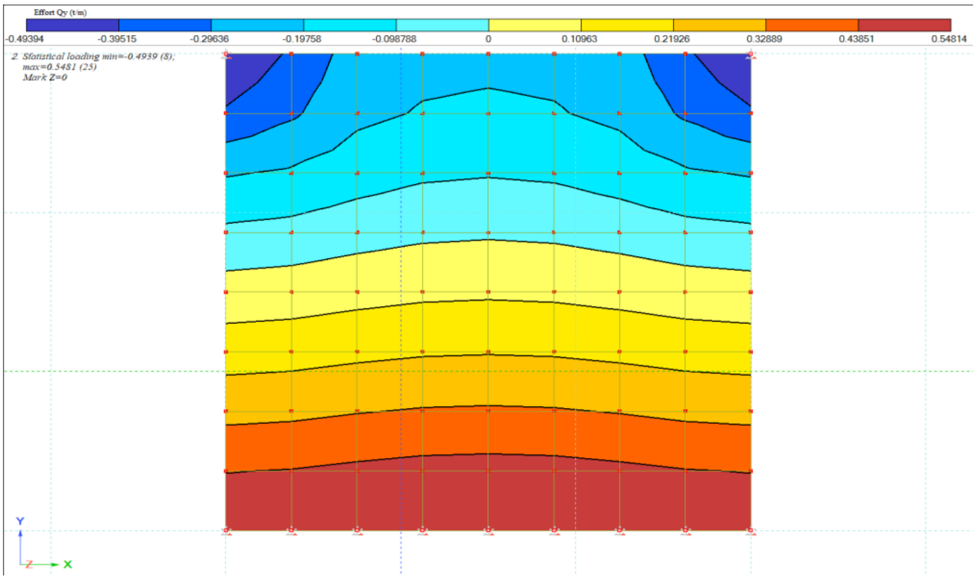

Figure 1: shear force distribution diagram Qy ((tons-force/m (lbs-force/ft)) in the floor slab from live load, obtained by the finite element method

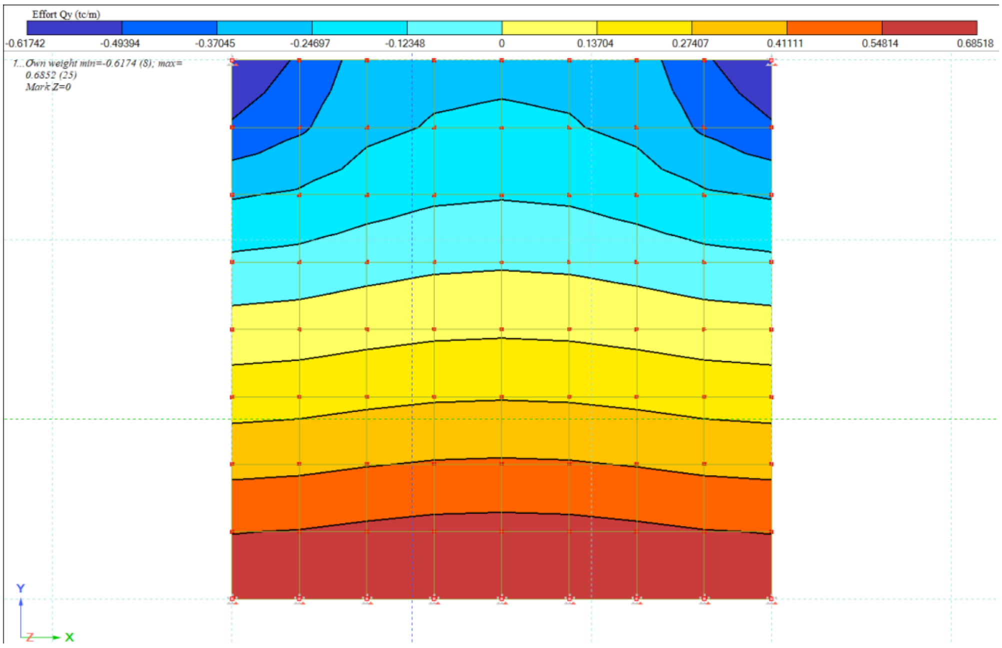

Figure 2: shear force distribution diagram Qy ((tons-force/m (lbs-force/ft)) in the floor slab from self-weight, obtained by the finite element method

The bending moment diagrams My provide comprehensive information regarding the distribution of moments that govern the slab's bending in the X-axis direction. Visualization of the My diagrams clearly demonstrates the dominance of positive bending moments in the central portion of the slab, where, for the live load, the My values reach 0.479 tons-forcem/m (1064 lbs-force-ft/ft), and for self-weight, 0.594 tons-forcem/m (1319 lbs-force-ft/ft). Moving towards the slab perimeter, a systematic decrease in My values is observed, reaching minimum values of approximately 0.092 tons-force (204 lbs-force). A notable feature is also the formation of pronounced "bands" of elevated bending moments, elongated along the short sides of the slab. This phenomenon is a direct consequence of the slab's biaxial bending behavior, dictated by its geometry and support conditions, and indicates the necessity of considering bending in both directions when designing the reinforcement cage.

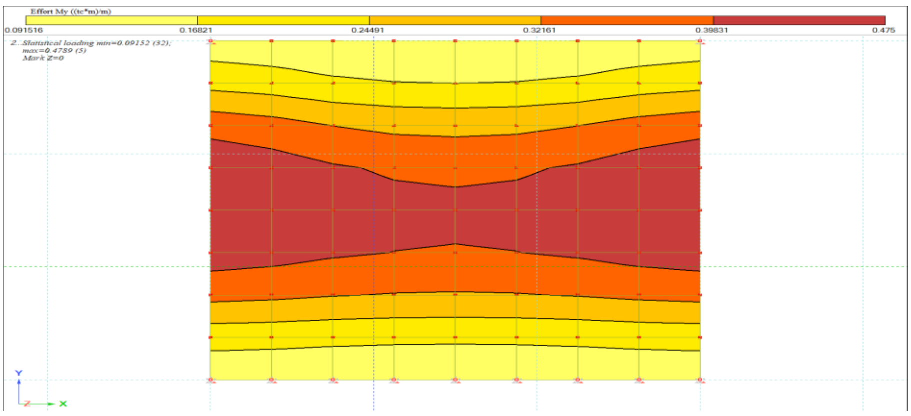

Figure 3: bending moment distribution diagram My (tons-force*m/m (lbs-force-ft/ft)) in the floor slab from live load, obtained by the finite element method

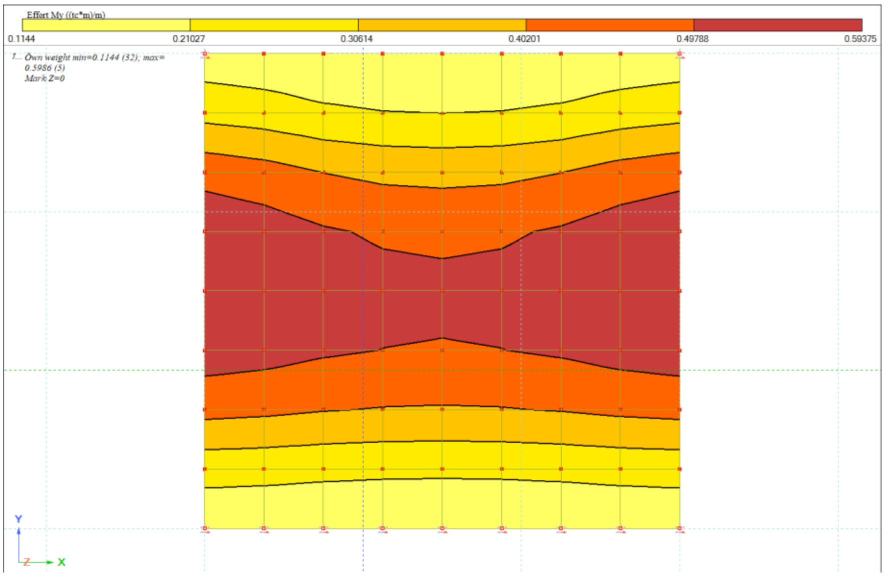

Figure 4: bending moment distribution diagram My (tons-force*m/m (lbs-force-ft/ft)) in the floor slab from self-weight, obtained by the finite element method

In the next stage of the research, it was planned to create load combinations (LCs) in accordance with regulatory requirements, as well as to perform both linear elastic and nonlinear static analyses using the "Nonlinear Static Analysis" module of LIRA-SAPR. This was done to account for the physical nonlinearity of concrete and reinforcing steel and to more accurately determine the internal forces in the floor slab. After completing the model construction process, it was ready for numerical analysis and subsequent reinforcement optimization.

3.4. Numerical Analysis of Stresses and Strains in the Structure

Upon completion of the creation and verification stage of the monolithic slab's finite element model, the next step was to conduct a numerical analysis of the stress-strain state of the structure. To illustrate traditional approaches to reinforcement, which serve as a starting point for optimization, let's consider the reinforcement schemes shown in Figures 5 and 6.

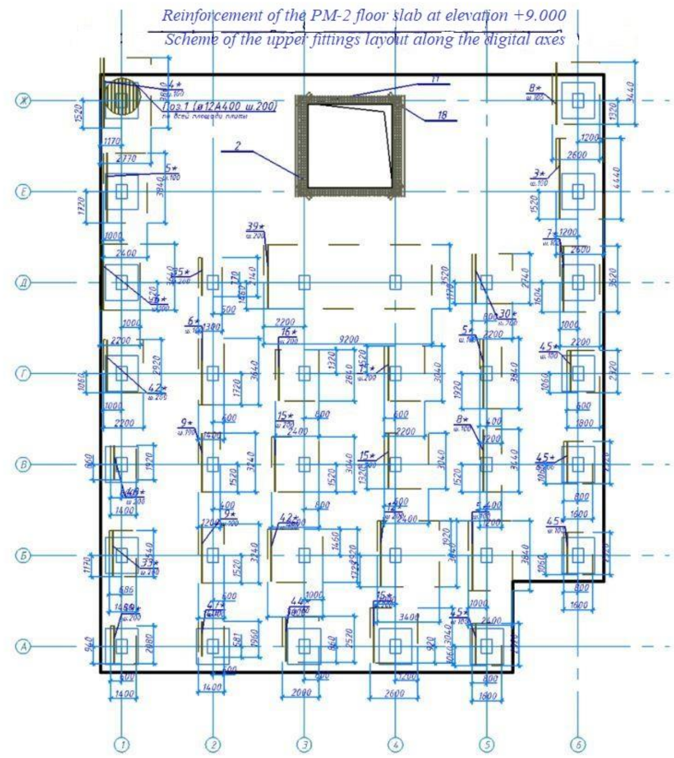

Figure 5: slab reinforcement PM-2 at elevation +9.000. Layout diagram of bottom reinforcement along numerical axes

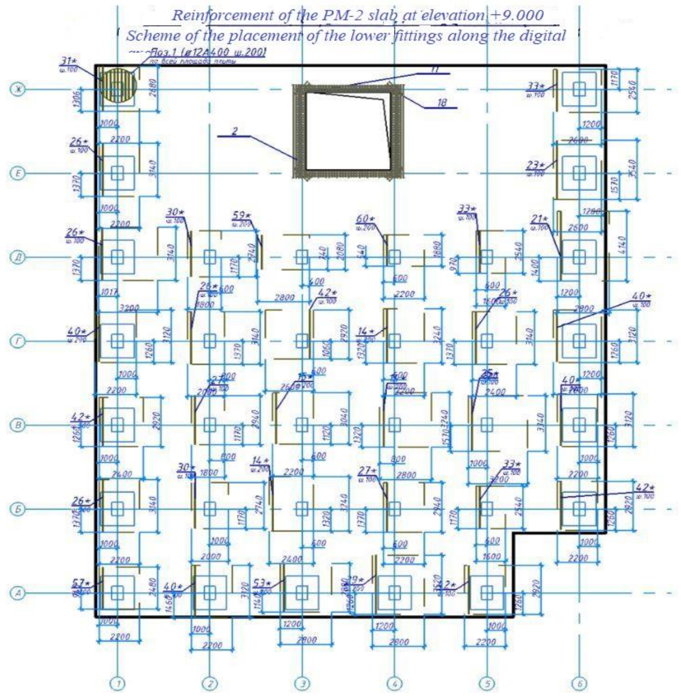

Figure 6: slab reinforcement PM-2 at elevation +9.000. Layout diagram of top reinforcement along numerical axes

For a comprehensive investigation of the slab's behavior under load and to evaluate the effectiveness of various reinforcement optimization approaches, two types of static analysis were performed: linear elastic and nonlinear static analysis, considering the physical nonlinearity of materials. Each type of analysis served distinct purposes and provided valuable information for subsequent design and reinforcement optimization.

Initially, a linear elastic static analysis was conducted. The purpose of this analysis was to obtain a baseline distribution of internal forces (bending moments and shear forces) in the floor slab under the assumption of linear-elastic behavior of concrete and reinforcing steel. Within the linear analysis framework, two main load cases were created: "Permanent Load" and "Live Load," corresponding to the loads previously defined for the model. After defining the load cases, the "Linear Static Analysis" module of the LIRA-SAPR software suite was executed. The results of the linear analysis were diagrams of bending moments and shear forces in the floor slab. Analysis of the diagrams showed that the maximum bending moments in the slab span, for example, in the center of the span in the X-axis direction, reached a value of 45 kNm/m of width (33,190 lbs-ft/ft). Negative bending moments over supports, for example, over the support along the Y-axis, were significantly higher and reached -70 kNm/m of width (-51,630 lbs-ft/ft). These moment values, obtained from the linear analysis, served as a starting point for assessing the reinforcement intensity in the traditional approach and for comparison with the results of the nonlinear analysis.

The second stage of numerical analysis was a nonlinear static analysis, performed using the "Nonlinear Static Analysis" module of LIRA-SAPR. The main objective of the nonlinear analysis was to more accurately determine the stress-strain state of the floor slab, considering the physical nonlinearity of concrete and reinforcing steel, including concrete cracking and plastic deformations in the reinforcement. To account for the nonlinear properties of materials, a bilinear stress-strain diagram for reinforcing steel and a Prandtl diagram for concrete, implemented in the nonlinear analysis module, were used. The nonlinear analysis was performed using an iterative method with refinement of element stiffness at each iteration, which allowed for considering the change in structural stiffness during loading, caused by cracking and nonlinear deformations. For the nonlinear analysis, the same "Permanent Load" and "Live Load" load cases were used. The results of the nonlinear analysis were refined diagrams of bending moments and shear forces, as well as the distribution of deformations and cracks in the floor slab. It is important to note that the maximum negative moments over the supports in the nonlinear analysis significantly decreased; for example, over the same support along the Y-axis, they decreased to -60 kNm/m of width (-44,220 lbs-ft/ft). At the same time, the moments in the span, for example, in the center of the span in the X-axis direction, remained practically unchanged and amounted to approximately 46 kNm/m of width (33,927 lbs-ft/ft).

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For the purposes of reinforcement design and accounting for various load combinations, Load Combinations (LCs) were created. LCs were created in accordance with the requirements of current building codes and regulations, using load factors for permanent load (e.g., a factor of 1.2) and live load (e.g., a factor of 1.4). The creation of LCs made it possible to account for the most unfavorable load combinations that may arise during the operation of the building and to ensure the necessary load-bearing capacity and structural safety. LCs were applied to both the results of linear and nonlinear analyses, which made it possible to evaluate the effect of nonlinearity on the magnitude of design forces and, ultimately, on the required amount of reinforcement.

Analysis of the numerical analysis results, both linear and nonlinear, provided comprehensive information about the stress-strain state of the monolithic slab. Comparison of the internal force diagrams obtained in linear and nonlinear analyses revealed the effect of moment redistribution due to cracking and nonlinear deformations. In particular, a decrease in the peak values of support moments in the nonlinear analysis of approximately 14% (from -70 kNm/m (-51,630 lbs-ft/ft) to -60 kNm/m (-44,220 lbs-ft/ft)) was observed compared to the linear analysis, which indicated a potential opportunity to reduce the reinforcement intensity in the support zones. The moments in the span, in this case, remained practically unchanged, indicating that the redistribution of forces occurs mainly due to a decrease in support moments.

3.5. Investigation of the Methodology for Implementing Variable Reinforcement Based on Numerical Analysis Results and Evaluation of its Effectiveness

The methodology for implementing variable reinforcement is based on a detailed analysis of the bending moment and shear force diagrams obtained from the numerical analysis of the monolithic slab, whether linear or nonlinear analysis. The first step is to zone the floor slab into areas with approximately the same intensity of internal forces. To do this, the moment diagrams are visualized and analyzed for zones with close moment values. Zoning can be performed both along the directions of principal moments and along the coordinate axes, depending on the adopted reinforcement scheme. For example, zones of maximum span moments can be identified in the center of the slab, zones of increased support moments near the columns, and zones with minimum moments in the corners of the slab or on the periphery of the spans. The number of zones and the boundaries between them are determined based on the gradient of moment changes and the desired degree of detail in variable reinforcement. For each identified zone, based on the maximum design moments in this zone (obtained from LCs), the required reinforcement area is determined in accordance with regulatory requirements for the strength and crack resistance of reinforced concrete elements. In zones with smaller moments, the required reinforcement area will be correspondingly smaller.

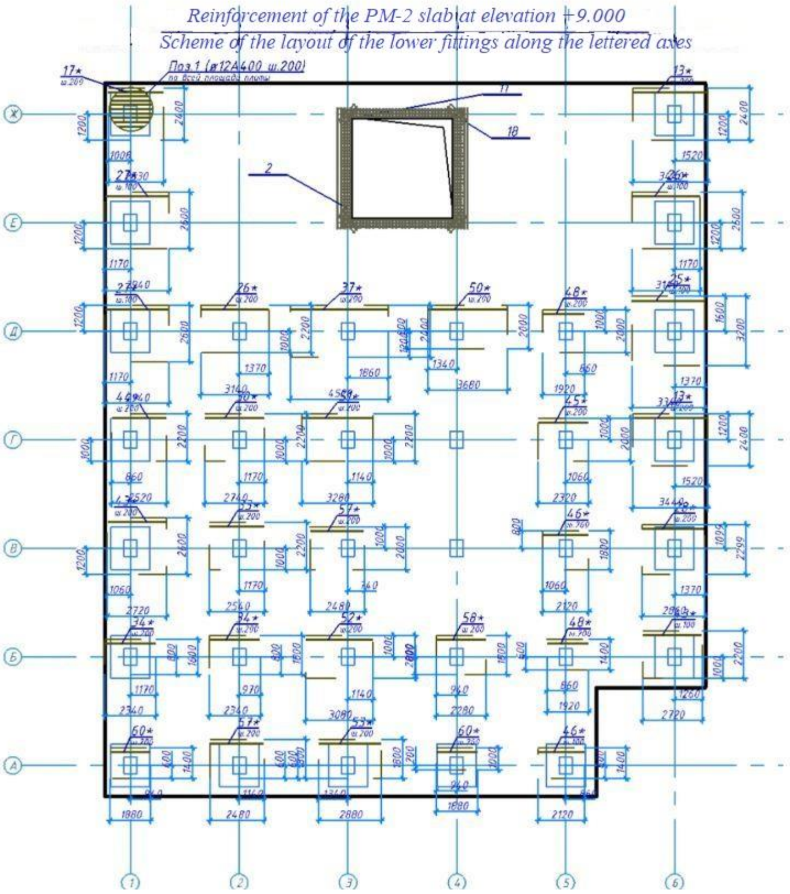

Figure 7: slab reinforcement PM-2 at elevation +9.000. Layout diagram of bottom reinforcement along alphabetical axes

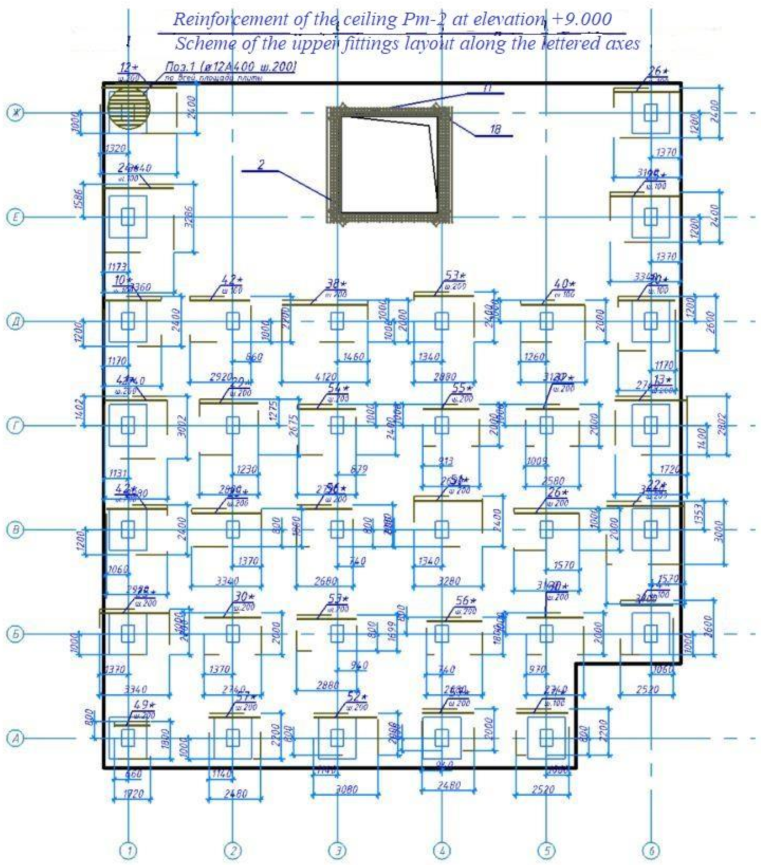

Figure 8: slab reinforcement PM-2 at elevation +9.000. Layout diagram of top reinforcement along alphabetical axes

To implement variable reinforcement in practice, the optimal rebar assortment is selected for each identified zone by varying the diameter and spacing of the reinforcing bars. In zones with a high reinforcement demand, larger diameter rebar and/or smaller spacing may be used, for example, 16 mm diameter (approximately #5 rebar) with 150 mm spacing (6 inches). Conversely, in zones with lower demand, smaller diameter rebar and/or larger spacing is used, for example, 12 mm diameter (approximately #4 rebar) with 250 mm (10 inches) or 300 mm spacing (12 inches). This approach allows for adapting the reinforcement to the actual force distribution in the slab, concentrating rebar where it is needed and reducing its quantity in less stressed areas. When designing variable reinforcement, it is necessary to consider the available rebar assortment and technological limitations on the minimum and maximum bar spacing, as well as the minimum concrete cover. The result of implementing this methodology is a reinforcement scheme with variable spacing and/or rebar diameter, adapted to the distribution of internal forces in the floor slab.

The effectiveness of variable reinforcement was evaluated by comparing the consumption of reinforcing steel and labor costs for reinforcement work for two options: variable reinforcement and traditional uniform reinforcement. For uniform reinforcement, a scheme with uniform distribution of rebar over the entire slab area, selected based on the maximum bending moments obtained from linear analysis, was adopted. The calculation of reinforcing steel consumption for both options was carried out by counting the total length of reinforcing bars of various diameters required for slab reinforcement, considering overlaps and bends. The comparison showed that the use of variable reinforcement allowed for reducing the total consumption of reinforcing steel by up to 12-15% compared to uniform reinforcement. Savings were achieved by reducing the amount of rebar in less stressed zones. The assessment of labor costs for reinforcement work was more indicative in nature and was based on expert estimates and consolidated time standards. Although variable reinforcement introduces some complexity into the reinforcement work process due to the need to lay rebar with variable spacing and diameter, the overall labor intensity of reinforcement work, according to estimates, does not significantly increase, and in some cases may even decrease due to a reduction in the total weight of reinforcement and facilitation of operations for lifting and placing lighter reinforcement elements in less stressed zones. Thus, variable reinforcement is an effective optimization method that allows for achieving significant savings in reinforcing steel without a significant increase in labor costs, which contributes to improving the economic efficiency of monolithic construction.

4. Conclusion

The conducted research has confirmed the high relevance of optimizing the reinforcement of monolithic reinforced concrete slabs in modern construction. The application of the LIRA-SAPR software suite in combination with nonlinear finite element analysis methods and the concept of variable reinforcement has demonstrated significant potential for reducing material consumption and labor costs in construction production. In particular, the use of nonlinear analysis made it possible to refine the distribution of forces in the slab, reveal the effect of moment redistribution, and, as a result, reduce the reinforcement intensity in support zones. The implementation of a variable reinforcement methodology, adapted to the local values of internal forces, ensured a reduction in reinforcing steel consumption of up to 12-15% compared to traditional unified solutions, without a significant increase in the labor intensity of reinforcement work.

The results of this research have direct practical significance for construction organizations striving to improve economic efficiency and resource conservation in monolithic construction. The proposed methodological approaches and recommendations can be directly implemented into the design and construction practice of monolithic reinforced concrete slabs, providing significant savings in material resources and reducing the cost of construction projects. Further research in this area may be directed towards expanding the range of optimization methods, including the optimization of concrete and reinforcing steel grades, the development of automated design systems for variable reinforcement, and the evaluation of the economic efficiency of optimized solutions in real construction projects of various scales and purposes.

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