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Original Article

Enhancing the Seismic Resistance through Strengthening the Structure with RC Jacket Layer, High Strength Mortar and Adding New RC Walls. Case Study National Gallery of Arts Building in Tirana

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Abstract - *The National Gallery of Arts in Tirana remained undamaged during the powerful earthquakes of 2019. Nevertheless, the building has undergone a strengthening process to bolster its seismic resistance. This enhancement primarily involved the application of concrete jacketing to the existing foundations and columns, further supported by the addition of vertical and horizontal reinforcement rebars. To further increase the dissipative capacity of the structure, five new reinforced concrete walls are being constructed at various points within the structure. The slabs and beams, already reinforced and dimensioned optimally, will be covered with high-strength structural mortar. This approach effectively negates the necessity for additional concrete jacket layers and further reinforcement. Adhering to Eurocode's standards, the strengthening technique has been meticulously applied. To demonstrate the efficacy of these enhancements, we have conducted a comparative analysis between the un-strengthened and strengthened structures using finite element software for structural analysis. The results revealed that strengthening the structure with a reinforced concrete jacket significantly enhanced its seismic performance. Specifically compared to the un-strengthened structure, the vibration period of the strengthened structure decreased by over 50%, while the storey drifts diminished significantly, showing a reduction of up to 80% in the Y direction and up to 78% in the X direction. Strengthening methods serve a dual purpose: they not only enhance the structural integrity of existing buildings but also resonate with worldwide objectives for sustainable development. This approach symbolizes a seamless integration of preserving the architectural heritage while fostering a future that is both safer and more efficient in terms of resource utilization. Modeling existing reinforced concrete structures with FEM software requires a lot of assumptions and simplifications that may not represent the realistic behavior of the structure. To surmount this challenge, it's imperative to employ sophisticated modeling techniques capable of accounting for the nonlinearities and complexities inherent in the structure. These advanced methods provide a more accurate and comprehensive understanding of structural behavior*.

Keywords - *Structural Strengthening, Seismic Resistance, Reinforced Concrete Jacket Layer*.

1. Introduction

This paper's publication is essential for highlighting the importance of strengthening reinforced concrete structures using a reinforced concrete jacket layer. This method has been overlooked and is often considered outdated. However, despite its long application history, the reinforced concrete jacket layer remains the most effective technique for reinforcing concrete structures. Research highlights the RC jacket layer's superiority in enhancing the structural capacity and durability of concrete structures. Studies demonstrate that this method significantly improves load-bearing capacity and structural integrity compared to modern materials [1].

In recent years, new reinforcement techniques have been developed, such as carbon fiber fabrics, glass fiber fabrics, and metal profiles. These methods may be more aesthetically pleasing to architects, but they do not match the effectiveness of the reinforced concrete jacket layer.

RC jackets contribute to sustainable development by utilizing fully recyclable materials like concrete and steel, offering both ecological and safety benefits [2]. The durability of the RC layers can be enhanced using novel cementitious materials, improving the corrosion resistance and overall lifespan of the strengthened elements [3].

Furthermore, this paper emphasizes the use of structural plaster. Structural plaster can significantly enhance resistance and prevent concrete degradation without needing an additional concrete layer, particularly for elements meeting Eurocode standards [4].

Built in the 1970s, the National Gallery of Arts (NGA) in Tirana was designed in adherence to the Albanian Technical Design Codes prevalent during that era. The current structure consists of three above-ground floors with a total height of 13.5 meters and one underground level, as shown in Figure 1. It is primarily constructed from reinforced concrete, supplemented by non-structural masonry walls. The building's original design, dating back to 1974, was based on the Technical Design Conditions (KTP), the authoritative design codes of that time. To conduct an exhaustive analysis of a structure, it's imperative to gather comprehensive data. This includes detailed information about the structure's history, specifically any historical or existing structural damage and repairs undertaken. Knowledge of the construction and design practices prevalent during its construction is also vital. Understanding the building's typology and conducting preliminary evaluations are key steps. Additionally, accurate identification of the structure's geometric data and specific details is crucial. This encompasses the types and typologies of structural elements, precise dimensions of various structural components such as foundations, RC walls, slabs, beams, and columns, as well as details of their reinforcement, including both longitudinal and transverse reinforcement.

Fig. 1 Assessment of current structural conditions before intervention

The primary objectives of performing a structural intervention on existing buildings encompass several key aspects. These include assessing the need for architectural and functional interventions, determining the projected lifespan of the building, and evaluating current seismic hazard assessments. Additionally, it's important to consider the evolution of design codes from the time of construction to the present day. This evaluation is also crucial for buildings that may have experienced various forms of damage over the years due to minor earthquakes. Such assessments help ensure the ongoing safety and functionality of the building in light of contemporary standards and environmental conditions.

Significant advancements have been made in the realms of civil and earthquake engineering since the era in which this type of building was conceptualized and erected. In Albania, the prevailing Technical Design Conditions (KTP-78 and KTP-N.2-89) were instituted in 1978 and 1989, respectively, marking them as 46 and 35 years old today. While the KTP-78 (KTP-N.2-89) design codes were compliant with the standards of their time, they do not align with contemporary seismic design criteria.

The provisions in KTP-N.2-89 represent a more stringent set of regulations than its predecessors. Nonetheless, the transition to Eurocodes is already underway in Albania, setting forth even more rigorous criteria for building design. This indicates that buildings crafted based on technical specifications that offer a lower degree of safety compared to modern benchmarks, such as the Eurocodes, necessitate a comprehensive structural re-evaluation.

The dynamic structural analysis conducted on the existing building of the National Gallery of Arts revealed a need for structural strengthening. This retrofit is crucial to guarantee that the structure can effectively endure both serviceability loads and seismic forces, ensuring its resilience and safety.

This study is dedicated to the preservation of the National Gallery of Arts building in Tirana, targeting the reinforcement of all structural elements that do not meet Eurocode standards. The objective is to accomplish this with minimal structural interventions that maintain the building's architectural integrity while simultaneously enhancing its seismic resistance.

This article is meticulously organized into distinct sections, offering an in-depth analysis of structural strengthening for existing buildings. It commences with the literature and theoretical framework, laying out the foundational concepts and ecosystem approach that underpin the study. Following this, the Methodology section delves into the specifics of the research design, detailing the structural analysis methods and analytical techniques utilized throughout the research. The Results section presents the findings of the study, where they are interpreted in detail and their implications thoroughly explored. Finally, the Conclusion synthesizes the key insights gleaned from the study and underscores its contributions to the field of structural strengthening of existing buildings in Albania.

2. Literature Review

There are various strengthening techniques, each with its own set of advantages, depending on the structural requirements and conditions. These include increasing cross-section reinforcement, replacing concrete reinforcement, bonding steel reinforcement, pasting steel reinforcement, and using fiber-reinforced plastic reinforcement [5].

Identifying structural deficiencies such as low-quality concrete, inadequate splice lengths, and improper hooks of the stirrups is crucial for seismic strengthening. Methods include system-based strengthening and member-based strengthening, targeting improvement in ductility or stiffness and strength characteristics of the load-bearing system [6].

Strengthening techniques can significantly increase the load-bearing capacity of structures, making them more robust against applied loads. For instance, some methods have been shown to increase the ultimate load by over 200% compared to non-reinforced beams, simultaneously reducing sagging and enhancing rigidity [7].

Jacketing under service load level shows significant strengthening effects. Understanding the performance of structures strengthened under service loads is crucial, as it affects further work of jacketed RC columns [8].

Some strengthening techniques offer the advantage of being fast and economical, providing significant structural benefits without requiring extensive disruption or high costs. This makes structural strengthening an attractive option compared to more extensive reconstruction efforts [9]. Structural strengthening not only improves the load-bearing capacity but also extends the service life of the structures, contributing to their sustainability. The use of composite materials, due to their interesting mechanical properties and lightweight, has been recognized as one of the most promising technologies in structural materials engineering [7].

The use of FRP composites for retrofitting can lead to changes in the structural behavior under seismic actions. The application of FRP can improve the load-carrying capacity and alter the structural period, especially in structures located in seismic zones [10].

Steel jacketing as a retrofitting method can enhance the performance of buildings under seismic excitations. The responses of retrofitted buildings, such as displacement, base shear, and structural periods, can significantly differ from those of non-retrofitted structures [11].

The study investigated the behavior of RC columns jacketed with reinforced concrete under axial loads using finite element-based numerical simulation in ABAQUS software. The results showed that RC jacketing significantly enhances the load-bearing capacity of the columns [12].

Drawing from established methods and research on strengthening reinforced concrete structures, we will discuss how seismic resilience can be significantly improved for the National Gallery of Arts Building in Tirana. This will be achieved through the application of a Reinforced Concrete (RC) jacket layer, the use of high-strength mortar, and the construction of additional RC walls.

3. Methodology

3.1. Structural Analysis

To evaluate the structure, we will perform a structural linear analysis with response spectrum and behavior factor according to Eurocode 8 [13].

The fundamental period is calculated based on (EN 1998-1 Eqn. 4.6). The value of H is determined by the software concerning the floor heights in the inputs.

$T = C_t \cdot H^{3/4}$ (EN 1998-1 Eqn. 4.6)

Where C_t is defined as (EN 1998-1 section 4.3.3.2.2(3)):
$C_t = 0.075$ when the moment is resisted by concrete frames
The height H is measured from the minimum of the first floor defined to the maximum of the last floor defined in meters.

Regarding the permissible inter-storey drifts, by Eurocode 8 (EN 1998-1), the following limits must be adhered to [13]:

For buildings having ductile non-structural elements: $d_v \upsilon \leq 0.0075 h$
d_v is the design inter-storey drift as defined in 4.4.2.2(2);
h is the storey height
υ is the reduction factor which takes into account the lower return period of the seismic action associated with the damage limitation requirement.

Linear analysis with response spectrum and behavior factor is a method used in structural engineering to assess the seismic performance of buildings. It provides guidelines for the design and assessment of structures, including seismic design.

In seismic design, both periods are important. The fundamental period is used for initial design and linear analysis, while understanding the effective period is crucial for evaluating the structure’s performance during large, potentially damaging earthquakes. While the fundamental period is a basic characteristic of a structure under elastic conditions, the effective period represents the dynamic behavior of the structure under actual seismic loading, accounting for non-linear effects and potential damage. Next, the key steps involved in conducting a linear analysis with response spectrum and behavior factor according to EC8 will be presented.

3.2. Seismic Characteristics of the Site

Gather information about the site, including seismic hazard data from the "Seismic Report of the Construction Site of National Gallery of Arts building in Tirana", and determine the appropriate response spectrum for the seismic zone. According to Eurocode 8, the elastic reaction spectra are: *For a probability of 10% / 10 years for category "C" of the land according to EC-8, the following parameters result in Maximum spectral acceleration a0=0.199 g; Se (T) = 0.497 g, S= 1.15, TB = 0.2 sec, TC = 0.6 sec, and TD = 2.0 sec, and *For a probability of 10% / 50 years for category C of the plot according to EC-8, the following parameters result: maximum spectral acceleration a0=0.404 g; Se (T) = 1.01 g, S= 1.15, TB = 0.2 sec, TC = 0.6 sec, and TD = 2.0 sec. The appropriate site factors are applied.

3.3. Determine the Structural Factors

The performance of RC frame buildings designed according to Eurocodes is significantly affected by various design factors. A detailed evaluation of individual factors on global structural performance is essential [14]. The structure factors are determined based on the structural system and detailing according to EC8, as shown in Table 3 in the annexes, taking into account the type of the structure. The Importance Factor adjusts the loads based on the importance of the structure. In contrast, for critical structures like hospitals, service buildings, and crowded buildings, a higher importance factor is used, reflecting the need for enhanced safety and performance under loads. The behavior factor (q) approach (see 2.2.1(4)P), the design spectrum for linear analysis is obtained from EN 1998-1: 2004, 3.2.2.5. A value of q = 1.5 and 2.0 for reinforced concrete and steel structures, respectively, may be adopted regardless of the structural type. Higher values of 'q' may be adopted if suitably justified concerning the local and global available ductility, evaluated by the relevant provisions of EN 1998-1: 2004. Referring to Eurocodes, for the behavior factor q, we have q=2.0. Eurocode 8's ductility classes have implications for the design of RC frame structures. The study provides a full analysis of the impact of the ductility class on design, showing that the medium ductility class (DCM) has high performance close to the high ductility class (DCH) even in high-hazard seismic zones [15].

3.4. Load Combination

Loads and their combinations are applied according to Eurocodes.

Dead (Permanent) loads include the Self-weight of all supporting elements of the masonry and reinforced concrete structure (foundations, beams, columns, walls, self-weight of slabs, floor layers, self-supporting partition walls with bricks, and parapets of balconies, stairs, etc.).

Live loads represent the loads that are not constant and are associated with the intended use of the structure. Live loads include the weight of people, furniture, vehicles, equipment, and other movable objects that may be present on or within a structure. The rated load combinations taken into consideration are according to EC8.

If necessary, iterate the analysis and design process to achieve a satisfactory seismic performance.

It's important to note that this is a general overview, and the specific details may vary based on the complexity of the structure and the seismic zone. Always refer to the latest versions of Eurocode 8 (EN 1998) for the most up-to-date information and requirements.

A numerical method that subdivides a complex structure into smaller, simpler parts called finite elements. The linear behavior of these elements is then analyzed, and the results are synthesized to understand the behavior of the entire structure.

3.5. Assessment of the Structural Condition of the Existing Building

The primary reasons for undertaking structural strengthening of existing buildings that earthquakes have not damaged are [16].

- The designed lifespan of the buildings (their age).
- Current assessments of seismic risk.
- Degradation of concrete and steel rebars.
- Various damages (not earthquakes) that buildings have sustained over the years.
- Changes in design codes from the time of construction to the present.
- Planned architectural interventions.

The general methodology for assessing the structural condition of an existing structure is a detailed process that involves the following steps [16]:

- *Collection of Existing Data on the Structure*

This phase involves gathering information about the building's history, construction, and design methods used during its construction, typology, and classification, as well as a preliminary assessment of the structure.

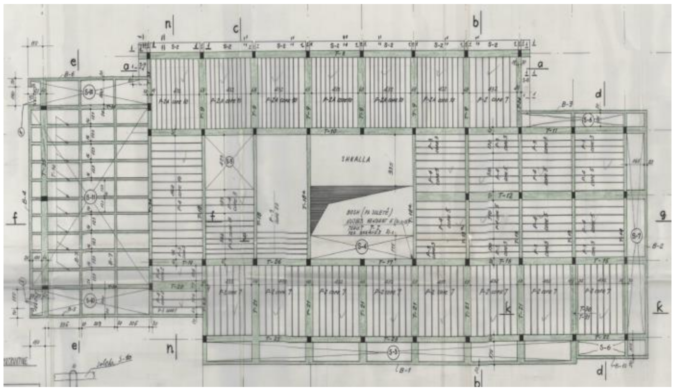


Fig. 2 Structure plans of the first floor

- *Identification of Characteristic Geometric Data*

This includes detailed data of the structure, covering the type and typology of structural elements, dimensions and characteristics of foundations, columns, slabs, beams, and details of their reinforcement. These data are gained from the old designs of the 1970s.

The building has a structure where all its elements are made of reinforced concrete. The columns are mainly rectangular in section, measuring 30x50 cm, as shown in Figure 2. The slabs (ribbed) consist of a series of small reinforced concrete T-beams, spaced at regular intervals of 50cm, with a thickness of up to 45cm. Meanwhile, the beams have a depth of up to 175 cm, as shown in Figure 3. The spaces of the NGA are divided by hollow brick masonry.

- *Identification of Material Characteristics*

This step involves analyzing the materials through the existing design and detailed studies to determine their strength and level of degradation. According to the existing designs, the concrete characteristics of the existing building are R_{ck} = 17 MPa, and the rebar's characteristics are ST-5, with f_{yk} = 2500 kg/cm^2.

- *Reassessment of Applied Loads*

This stage involves revisiting the loads on the building, especially if some parts are used for purposes different from those originally intended, taking into account the building's importance class.

- *Collection of Data on Structural Damages (if any)*

This includes identifying current or past damages to the structure, as well as any repairs that have been made. The building's history and current condition are also considered. The building does not have structural damage, but the protective layer of some beams and slabs is damaged and degraded due to the long-term effects of atmospheric agents.

This methodology provides a comprehensive approach to assess and then enhance the seismic resilience of the existing structure of the National Gallery of Arts in Tirana.

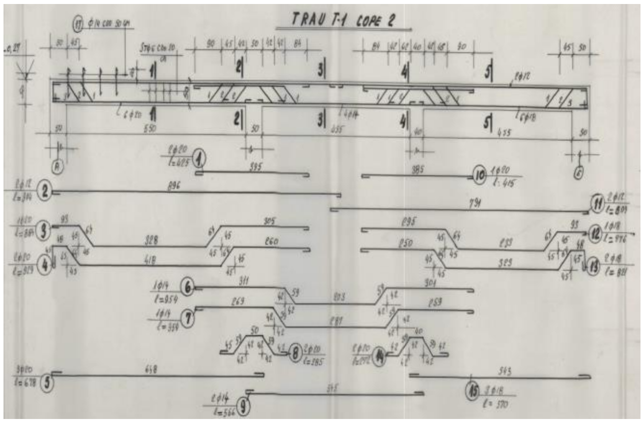


Fig. 3 Section and reinforcement detail of beam T-1 placed on axis 1 of the ground floor

3.6. Structural Modeling

A detailed 3D model of the structure with finite element software ETABS 19, using "Frame" elements (for beams and columns), "Shell" elements (for slabs and stairs b/a), and "Wall" (for walls) will be created. For the foundations, the Winkler coefficient was used as support. Also, in the software are assigned material properties, member sizes, and support conditions based on the Designs of the "Construction of The National Gallery of Arts in Tirana", Author: "Urban Planning and Design Bureau (1974)".

- *Modeling the Structural Framework of the Existing Structure of the National Gallery of Art*

The existing structure has been modeled using the finite element software ETABS 19.1, as shown in Figure 4. The material characteristics and the dimensions of the structural element's sections have been set according to the existing designs, which have been obtained from the Albanian Construction Archive. Also, even the concrete façade elements are modeled. Additionally, the concrete façade elements are also modeled.

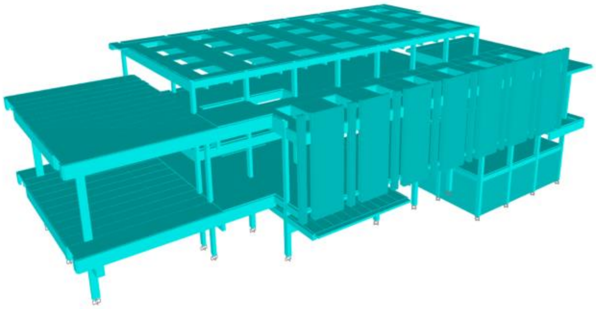
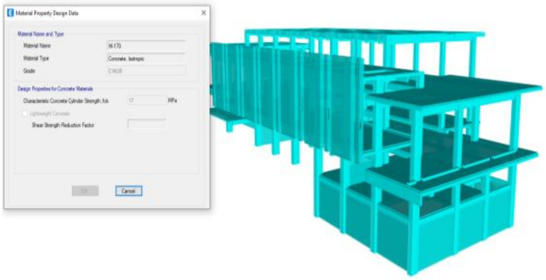


Fig. 4 Existing structure finite element model

The loads are applied according to the tables shown in the annexes. Below is shown the application in the FEM software of the materials, live, dead, and seismic loads, shown in Figures 5, 6, 7, and 8. Reinforced concrete jacketing has been proposed as a simple and reliable method to repair and strengthen structural elements and improve the seismic resistance of existing structures.



Material Name: M-170
Material Type: Concrete, Isotropic
Grade: C16/20
Characteristic Concrete Cylinder Strength, fck: 17 MPa
Shear Strength Reduction Factor

Fig. 5 Existing structure materials characteristics input

The figures below illustrate the procedure followed for creating the structural model of the existing, unreinforced structure.

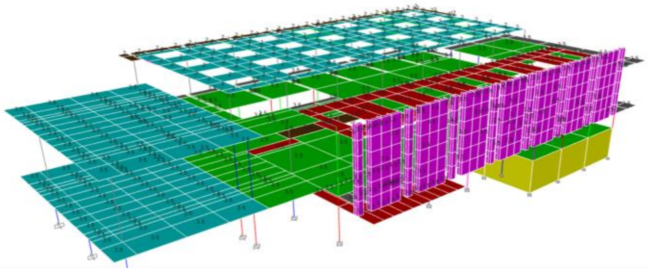


Fig. 6 Dead Load application

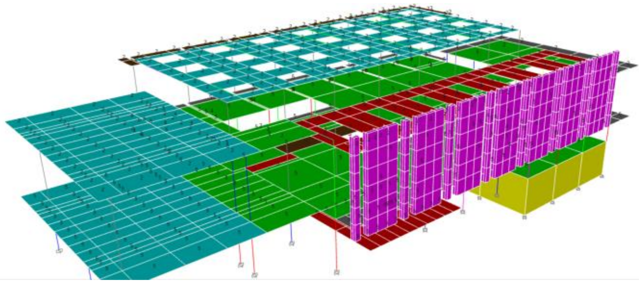


Fig. 7 Live load application

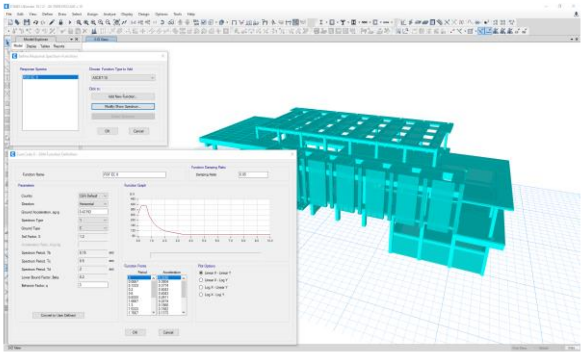


Fig. 8 Seismic load application according to seismic design

All columns, beams, and slabs have been modeled in the finite element program according to the drawings of the existing design, as shown in Figure 9 [2015]. Also, the quantity of reinforcement has been set in the software according to the existing designs, as shown in Figure 10.

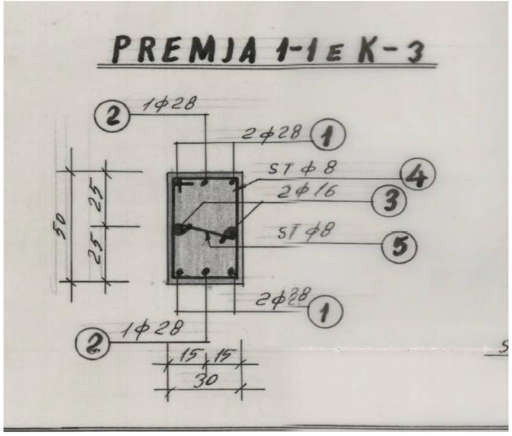
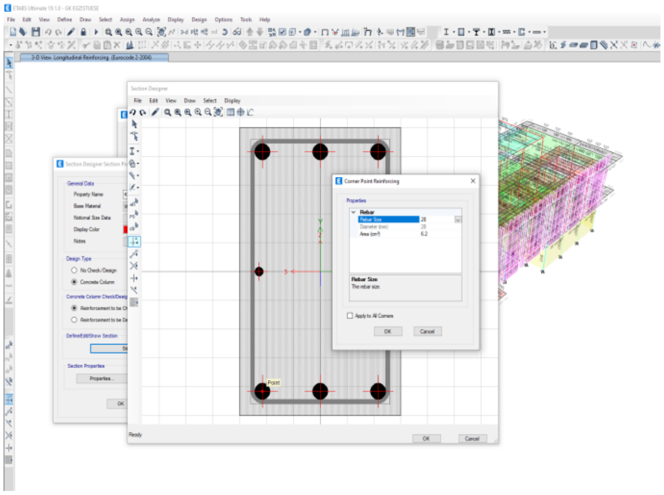


Fig. 9 The section of the existing column taken from the Archive's design

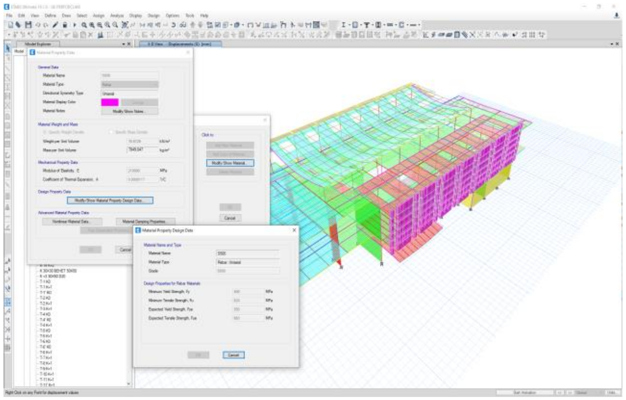


Rebar Size: 28
Diameter (mm): 28
Area (cm²): 6.2
☐ Apply to All Corners

Fig. 10 Modeling the existing column and rebars in FEM software

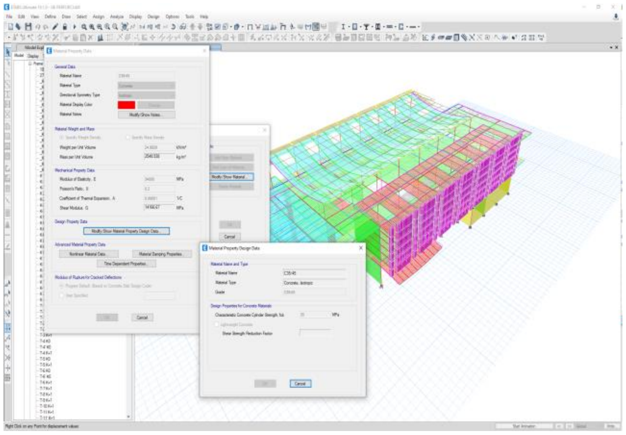
- *Modeling the Strengthened Structure of the NGA of Tirana*

Based on preliminary calculations, the characteristic cylindrical and cubic resistance of concrete has been chosen as $f_{ck} = 35$ *MPa* and Rck = 45 *MPa* (C35/45). In contrast, the characteristic yield strength of steel has been selected as $f_{yk} = 550$ *MPa*, and the calculated resistance of steel is $f_{yd} = f_{yk} / \gamma s = 215$ *MPa*, as shown in Figures 11 and 12.



Material Name: S500
Material Type: Rebar - Uniaxial

Fig. 11 Strengthen structure materials characteristics input



Material Name: C35/45
Material Type: Concrete, Isotropic

Fig. 12 Concrete jacket layer characteristics input

Beyond the application of a concrete jacket layer and the addition of reinforcing bars to the existing columns and foundation, five new reinforced concrete walls were meticulously integrated at strategic locations across different floors, as shown in Figures 13 and 14.

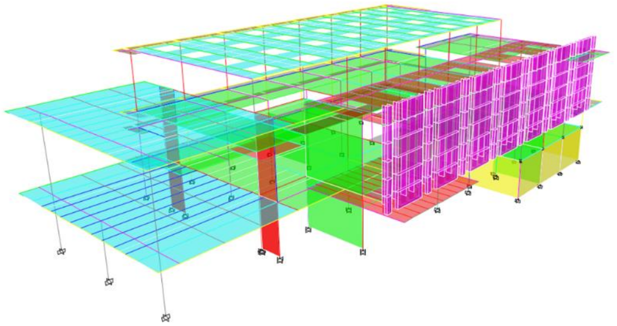


Fig. 13 FEM model of the structure with 5 new reinforced concrete walls

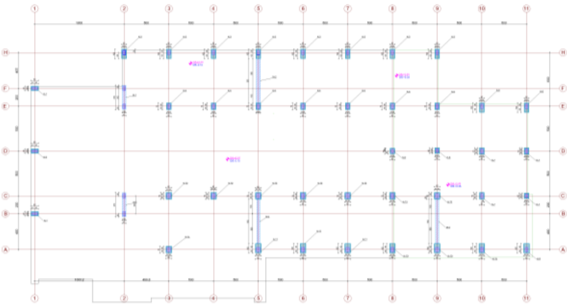


Fig. 14 The plan for the reinforced columns and five new RC concrete walls

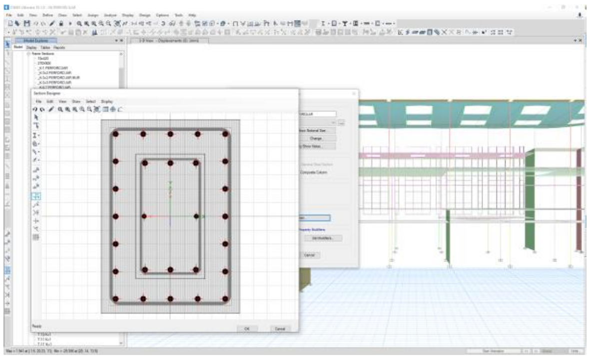


Fig. 15 Modeling of the reinforced concrete jacketing layer and rebars of the columns

The column's longitudinal reinforcement is designed with Φ22 and Φ20 rebars at a maximum distance of 100cm from each, while the column transverse reinforcement (stirrups) is designed with Φ 10/10cm and Φ 12/ 10 cm, as shown in Figure 15. The reinforcing steel used is of Class S500 grade, characterized by high strength and durability. The new reinforced concrete walls are designed with C35/45 concrete like the columns, and the longitudinal reinforcement is designed with Φ16 rebars, while the transverse reinforcement (stirrups) is designed with Φ12/10 cm.

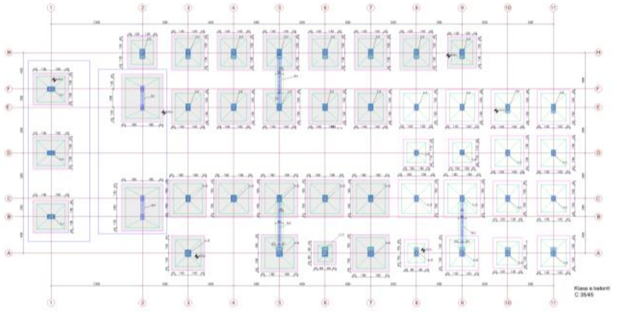


Fig. 16 The plan of the strengthened foundations

The foundations were strengthened by adding a concrete jacket layer of up to 50cm on the top and sides, and additional reinforcement was placed, as shown in Figure 16. Some rebars were also embedded into the body of the existing foundation to create a stronger bond between the new reinforcement and the existing reinforcement. The strength resistance of the new concrete layer is designed to be C30/37, while the reinforcement is designed to be with Φ16, Φ10, and Φ8 rebars.

4. Results and Discussion

Static and dynamic analysis to determine the response of the structure to various types of structural loading has been performed using the ETABS ULTIMATE® software. The modeling of the entire structure and each element is based on the Finite Element Method (FEM) methodology, which is a widely used and practical approach, especially in today's competitive conditions, where the use of computer programs is prevalent.

4.1. Existing Building (Unstrengthen Structure) Results

The following section presents the results obtained for the existing structure of the National Gallery of Arts using finite element software. It includes detailed data on the periods and frequencies of the un-strengthened structure, as well as drifts, which are comprehensively documented in the annexed tables. The data in these tables indicate that the structure surpasses the permissible limits. As evidenced by the data in the tables, the structure surpasses the permissible limits regarding column strength (Shown in Figure 17), the period, and the drift displacement of the building.

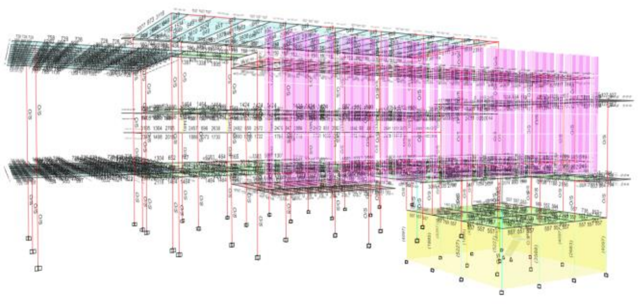


Fig. 17 Overstressed columns (shown in red color) of the un-strengthen structure due to vertical and horizontal loads

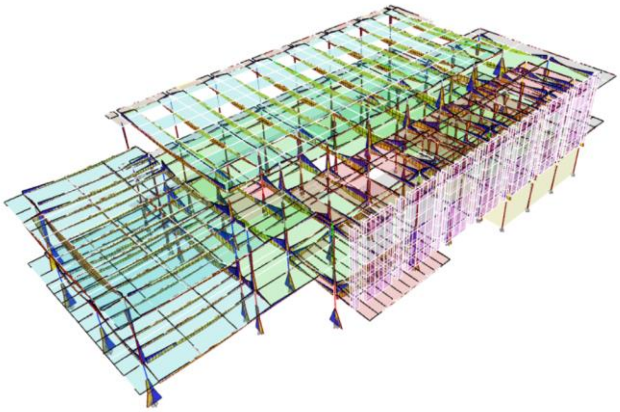


Fig. 18 Maximum moments in columns of the un-strengthen structure

The ETABS program automatically identifies modes with lower circular frequencies (corresponding to longer periods), shown in Table 1, as the primary contributors to the absorption of seismic loads by the structure. The maximum number of modes required by the program is determined by the expertise group itself, typically set at n=12 modes. Additionally, the masses of the floors in this analysis are considered to have three degrees of freedom, comprising two rotational and one translational degree of freedom along the plane of the base plate. Cyclic frequency (f, cycles/sec), angular frequency (ω, rad/sec), and period (T, sec) are interconnected through the following relationships: $T=1/f$ and $f=\omega/2\pi$. The analysis yields displacement values, internal forces (M, Q, N), and stress levels (σ) for each element within the structure.

The software calculation of the structure period with the $T=C_t \cdot H^{3/4}$ formula is an approximation to find out the period of the structure without taking into account the structural properties. The software calculates the period of mode T modes to have the largest participation factor in the direction that loads are being calculated (X or Y) and takes into account structural properties and deformation characteristics. According to Eurocodes, periods T_{modes} calculated from the software should not be greater than fundamental period T.

The results obtained from the analysis of the existing structure using a finite element program gathered data regarding its oscillation period, *as* shown in Table 4 in the annexes. Twelve vibration modes of the structure were analyzed, where the periods of the first three modes exceeded their fundamental period.

Table 1 shows the control of the unstrengthened structure's periods.

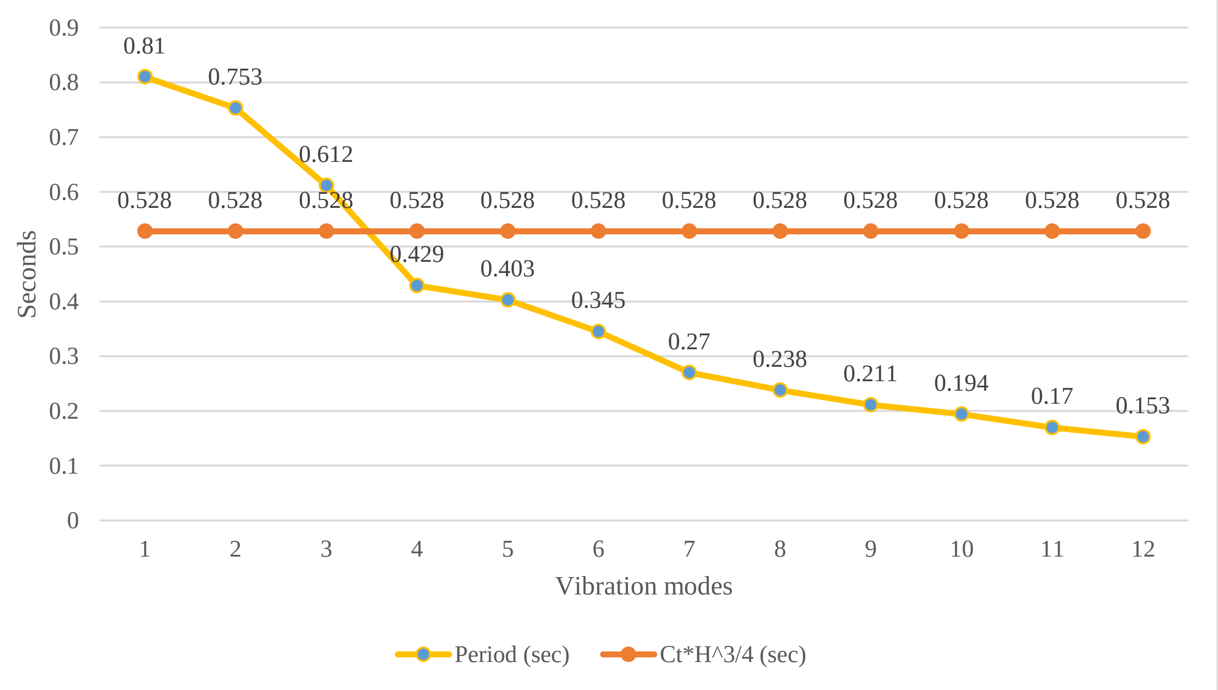


Fig. 19 Comparison between the un-strengthen structure period and fundamental period

Figure 19 presents the comparison between the un-strengthen structure period and the fundamental period. The orange line in the chart shows the period of the structure (T_{mode}) for each vibration mode. It starts at a higher value for the first mode and decreases as the mode number increases. For the first three modes, the periods are 0.81, 0.753, and 0.612 seconds, respectively, which are higher than the fundamental period.

Table 1. Unstrengthen structure period control

MODE	Period	H	Ct	Ct*H^3/4	Result
	sec	m			
1	0.81	13.5	0.075	0.528	Not allowed
2	0.753	13.5	0.075	0.528	Not allowed
3	0.612	13.5	0.075	0.528	Not allowed
4	0.429	13.5	0.075	0.528	Allowed
5	0.403	13.5	0.075	0.528	Allowed
6	0.345	13.5	0.075	0.528	Allowed
7	0.27	13.5	0.075	0.528	Allowed
8	0.238	13.5	0.075	0.528	Allowed
9	0.211	13.5	0.075	0.528	Allowed
10	0.194	13.5	0.075	0.528	Allowed
11	0.17	13.5	0.075	0.528	Allowed
12	0.153	13.5	0.075	0.528	Allowed

The red line ($Ct·H^{3/4}$ - sec) is flat and represents the constant fundamental period as calculated by Eurocode recommendations, which is T = 0.528 seconds. The fundamental period is meant to be a benchmark for evaluating the performance of the structure under seismic activity. Suppose the period of the structure in any vibration mode is significantly higher than the fundamental period. In that case, it implies that the structure is not as stiff as recommended (referring to the recommendations of the Eurocodes), which can lead to higher seismic vulnerability.

The chart indicates that the structure's period exceeds the fundamental period for the first three modes, suggesting reduced stiffness and potential non-compliance with seismic safety as per Eurocode standards in these specific modes. Starting from mode 4 and onward, the periods of the structure are less than the fundamental period, which could suggest that these modes are stiffer than required. However, the overall seismic safety cannot be determined from this information alone since the first three modes are crucial and have already been found lacking.

Figure 20 presents the comparative chart between the drifts of the un-strengthened structure in the X and Y directions (Table 6 in the annexes) and the allowable inter-storey drifts limit according to Eurocode 8.

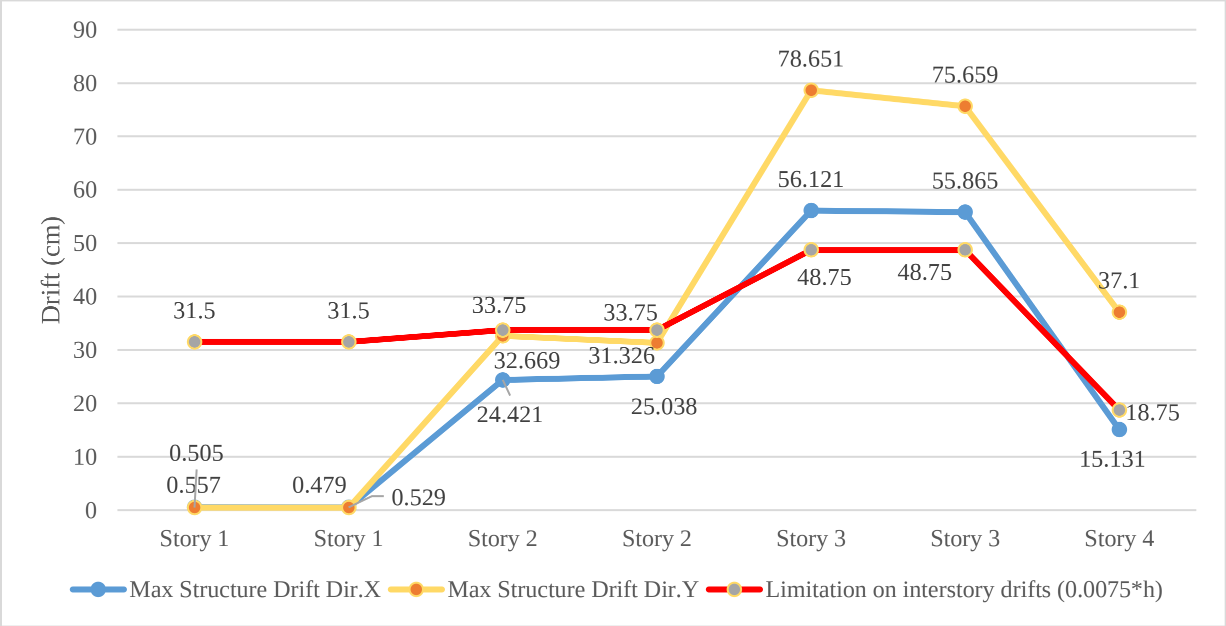


Fig. 20 Comparison between un-strengthened structure maximum drifts in X and Y direction and drift limitation (0.0086*h) according to Eurocode 8

The blue line represents the maximum un-strengthen structure drifts measured in the X direction for each storey. The values at each storey level indicate the drift in millimeters. The Yellow Line represents the maximum un-strengthen structure drifts in the Y direction.

The red line limitation on inter-storey drifts (0.0075*h) represents the allowable structure drift limit as per Eurocode standards, calculated as 0.0075 times the storey height (h).

The values labeled on the graph above each storey indicate the actually measured drifts. For example, in storey 1, the unstrengthening structure drift in the X direction is very small (0.505 mm and 0.557 mm), while in the Y direction, it is slightly larger (0.479 mm and 0.529 mm).

As the stories increase, the drifts become larger, which is expected due to the cumulative effect of lower storey movements. The largest drifts are observed in Storey 3, reaching up to 78.651 mm in the X direction and 75.659 mm in the Y direction.

The red line is crucial because it represents the limit beyond which the structural drift may be considered unsafe according to the Eurocodes. Wherever the blue and yellow lines are below the red line, the building's drift is within acceptable limits. However, if these lines exceed the red line, it would suggest that the building's drift at that storey exceeds what the Eurocodes deem acceptable, indicating a potential safety issue. In the graph, the red line is consistently below the blue and yellow lines, which suggests that the drifts in both directions exceed the limitations set by the Eurocodes for all stories. This could mean its lateral displacement under certain conditions (like wind or seismic activity) is greater than what is considered safe by Eurocode standards, thus necessitating further investigation or additional strengthening measures.

4.2. Strengthened Structure Results

The moments in each column and wall and the stresses in the slab are graphically presented below, as shown in Figures 21, 22, and 23.

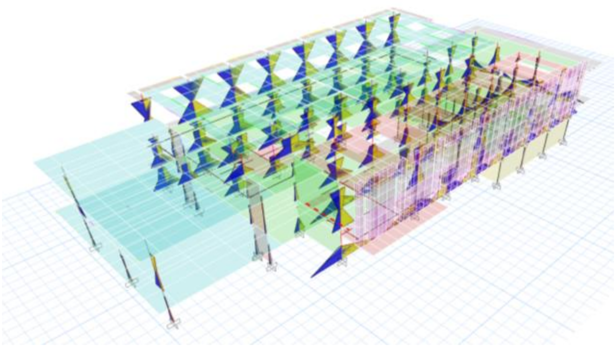


Fig. 21 Moments 2-2 in the columns and walls (Envelope)

The results obtained from the finite element program, such as the periods and frequencies of the strengthened structure, drifts, and displacements, are presented in the tables of the annexes.

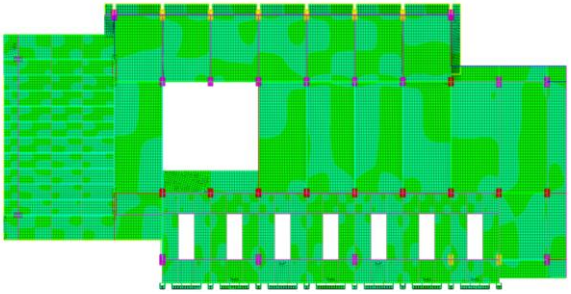


Fig. 22 Stresses of the second-floor slab

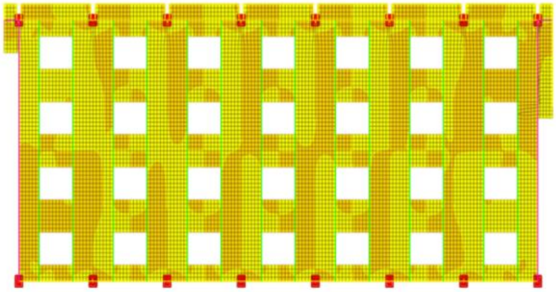


Fig. 23 Stresses in the terrace slab

From the analysis of the strengthened structure using finite element software, data on its oscillation period were obtained (*refer to Table 5 in the annexes*). Twelve vibration modes of the structure were examined, and it was observed that none of the structure's periods exceeded its fundamental period. Table 2 shows the control of the strengthened structure's periods. Also, all the columns reinforced with reinforced concrete jackets are checked, as shown in Figure 24.

Table 2. Strengthened structure period control

MODE	Period	H	Ct	Ct*H$^{3/4}$	Result
	sec	m			
1	0.385	13.5	0.075	0.528216046	Allowed
2	0.307	13.5	0.075	0.528216046	Allowed
3	0.191	13.5	0.075	0.528216046	Allowed
4	0.189	13.5	0.075	0.528216046	Allowed
5	0.142	13.5	0.075	0.528216046	Allowed
6	0.118	13.5	0.075	0.528216046	Allowed
7	0.103	13.5	0.075	0.528216046	Allowed
8	0.093	13.5	0.075	0.528216046	Allowed
9	0.075	13.5	0.075	0.528216046	Allowed
10	0.069	13.5	0.075	0.528216046	Allowed
11	0.055	13.5	0.075	0.528216046	Allowed
12	0.05	13.5	0.075	0.528216046	Allowed

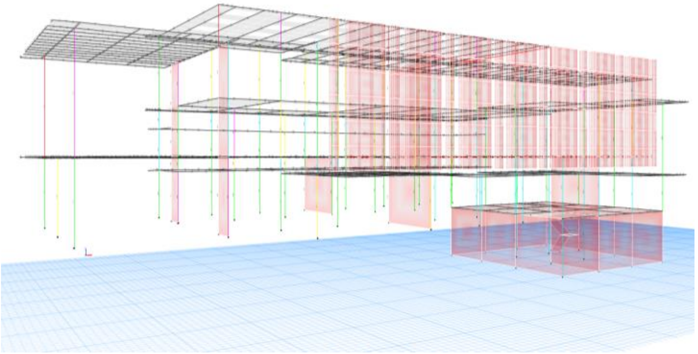


Fig. 24 Column relaxed condition of the strengthened structure due to vertical and horizontal loads

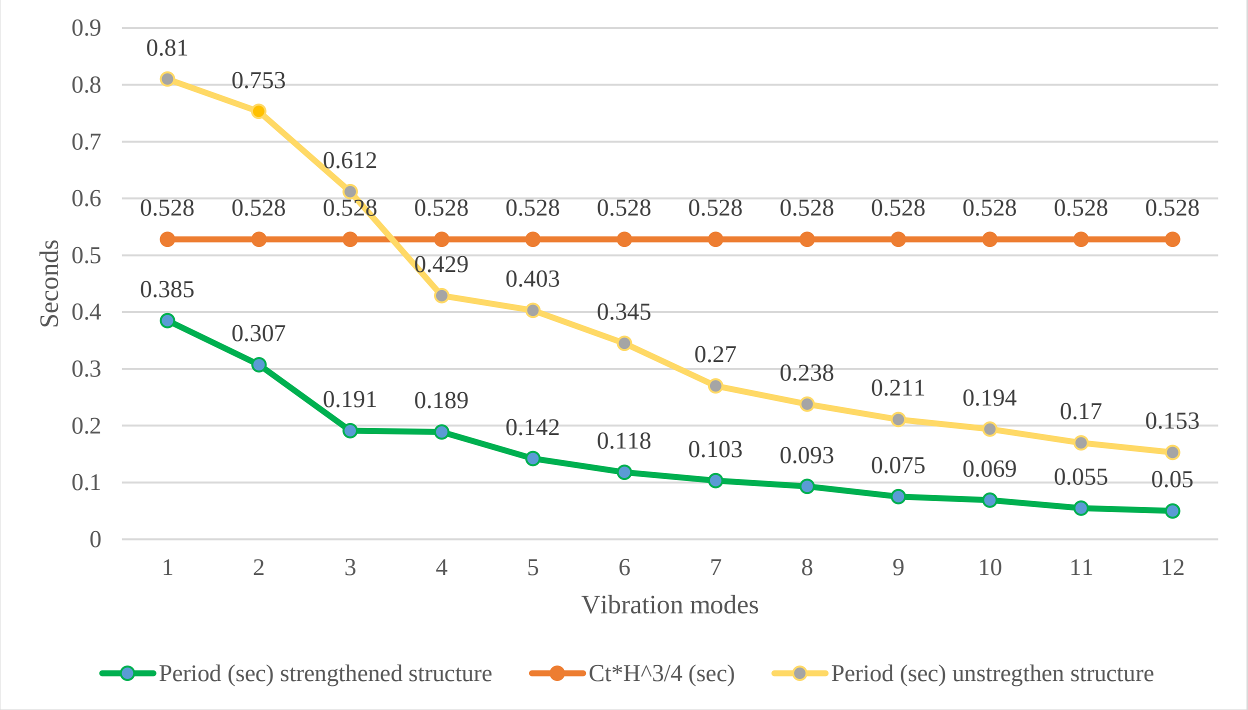


Fig. 25 Comparison between the strengthened and un-strengthened structure period

Figure 25 presents a graphical comparison between the periods of the reinforced structure and the existing structure.

The period of the un-strengthened structure (yellow line) starts higher than the strengthened structure (green line) for the first mode. It remains higher across all modes, indicating that the original structure is less stiff and has a longer natural period of vibration.

The strengthened structure has a much lower period across all modes, which indicates an increase in stiffness and seismic performance, as a shorter period generally corresponds to a more rigid structure.

Particularly for the first three modes, the period of the un-strengthened structure is well above the reference line. In contrast, the strengthened structure's period is closer to the reference line, indicating a better performance in these crucial initial modes after strengthening.

Overall, the effectiveness of the strengthening by applying a concrete jacket layer and reinforcement to the existing columns and building 5 new reinforced concrete walls reduced the structure's periods of vibration, which is typically a desirable outcome for seismic design, as it suggests a stiffer and more robust structural system.

Figure 26 presents the comparative chart between the drifts of the strengthened structure in the X and Y directions (*Table 7 in the annexes*) and the allowable inter-storey drifts limit according to Eurocode 8.

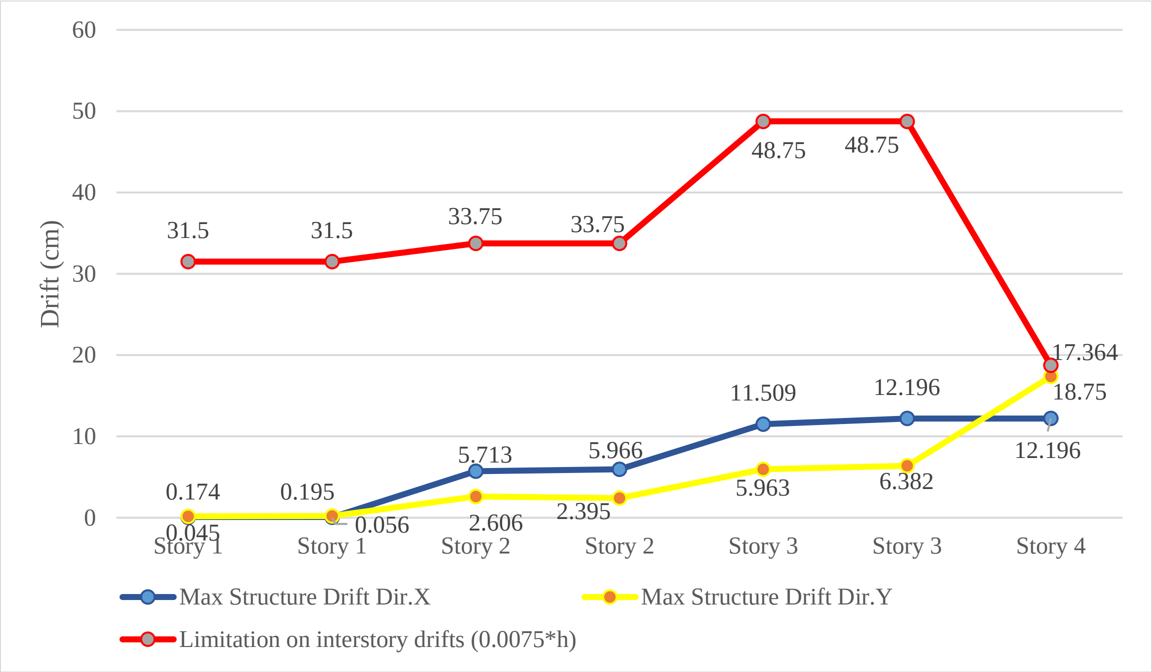


Fig. 26 Comparison between strengthened structure maximum drifts in X and Y direction and drift limitation (0.0086*h) according to Eurocode 8

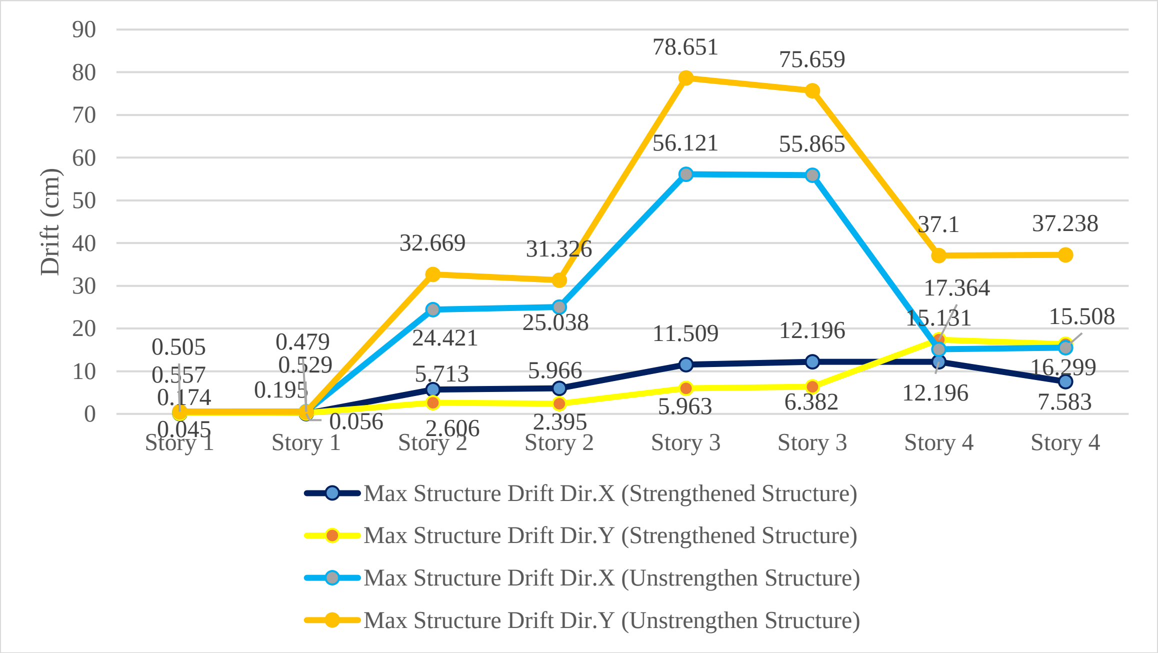


Fig. 27 Comparison between strengthened structure maximum drifts and un-strengthened structure maximum drifts in X and Y direction

The blue line represents the maximum structure drifts in the X direction for each storey.

The yellow line represents the maximum structure drifts in the Y direction for each storey.

The red line indicates the limitation on inter-storey drifts, calculated as 0.0075 times the height of the storey (h). This is a standard set by Eurocodes, which specifies the maximum allowable drift for buildings to ensure structural safety under lateral loads, such as those generated from seismic events.

The chart's values above each storey indicate the drift measured or calculated in that particular direction. For instance, in storey 1, the drifts are minimal in both directions, well below the red limitation line. As we move up the building to higher stories, the drifts increase, which is typical due to the leverage effect in taller structures.

In the X direction, the drift increases significantly in storey 3 and then decreases in storey 4 but remains higher than the drift in the Y direction for all stories.

In the Y direction, the drift shows a gradual increase with each storey and is consistently below the drifts in the X direction. The drift limitation line (red) is consistently above the strengthened structure drifts for the X and Y.

The comparison of allowable drift and strengthened structure drifts is critical for structural engineers to assess whether the building, after being strengthened, meets the safety standards for lateral displacements. Suppose the actual drift dot exceeds the drift inter-storey limitation line. In that case, it may indicate that the structure does not need further strengthening or design modification to ensure the building's safety in the event of lateral loads.

Figure 27 presents a comparison chart between the lateral displacements (drifts) of the strengthened structure and the un-strengthened structure, where the difference between them is evident.

The results and graphical representations clearly show that the strengthened structure experiences a significant reduction in both periods and drifts. The comprehensive analysis of the data and the accompanying graphical displays reveal marked improvements in the structural performance post-strengthened.

5. Conclusion

The strengthening through the addition of a concrete jacket layer and rebars in the foundations and columns, as outlined in the above paragraphs of this paper, substantially augmented the seismic resistance of the existing reinforced concrete structure of the National Gallery of Arts in Tirana. Numerous simulations conducted using the finite element software concluded that the implementation of the concrete jacket and reinforcement layers in the foundations and columns and the addition of 5 anti-seismic reinforced concrete walls were sufficient to reduce the structure's vibration period by more than 2 times. The structure storey drifts by up to 5 times in the Y direction and up to 4.5 times in the X direction, as shown in the above charts. The addition of a concrete layer and rebars to retrofit the beams and slabs will not yield any further benefits. The finite element simulation showed that the structural layout, the existing sections, and the rebars of the beams and slabs were adequate to handle the vertical (dead and live loads) and horizontal (seismic and wind load) forces that could be applied during the lifetime of the structure.

Regarding the beams and slabs of the NGA building, it was recommended that they be coated with high-strength structural mortar since the protective layer of concrete on some beams and slabs was damaged and degraded. The reinforcements and interventions in structural elements brought the structure within the building design standards according to the Eurocodes. Strengthening existing structures with a concrete jacket layer, undamaged by earthquakes, not only increases the seismic resistance of the structure as a whole but also prevents the corrosion and further degradation of structure materials and sections. This method has been overlooked and is often seen as outdated. However, despite its long-standing application, the reinforced concrete jacket layer remains the most effective technique for reinforcing concrete structures. This method offers enhanced safety, durability, and ecological benefits, as both concrete and steel are entirely recyclable materials.

Strengthening methods not only address the need for structural improvement of the existing buildings but also align with global goals for sustainable development. It represents a harmonious blend of preserving the past while building for a future that is more secure and resource-efficient. Reinforcing with an RC jacket layer is especially important for sustainable development.

When using Finite Element Method (FEM) software to model existing reinforced concrete structures, numerous assumptions and simplifications are often made, which may not adequately reflect the structure's true behavior. To address this issue, it is crucial to utilize refined modeling approaches that are designed to encompass the nonlinearities and intricacies of the structure. By adopting these sophisticated techniques, a more precise and thorough comprehension of the structural dynamics can be achieved, enhancing the accuracy of the model. These advanced methods provide a more accurate and comprehensive understanding of structural behavior.

Acknowledgement

We are very grateful to my colleagues for their appropriate and constructive suggestions to improve this template.

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Appendix

Table 3. Structure factors

Importance factor:	kr (ɤ) = 1.2	Accidental alienation:	5%
Structure recognition factor:	CF = 1.2	Critical Damping Factor:	ζ=5%
Behavior factor:	2	Spectral Amplification Factor:	η=1
Type of structure:	DCM	Foundation’s factor:	β=2.5

Table 4. Period of the existing structure (un-strengthened)

Case	Mode	Period	Frequency	CircFreq	Eigenvalue
		sec	cyc/sec	rad/sec	rad^2/sec^2
Modal	1	0.81	1.235	7.7617	60.2442
Modal	2	0.753	1.329	8.3481	69.6914
Modal	3	0.612	1.634	10.265	105.3698
Modal	4	0.429	2.331	14.6469	214.5311
Modal	5	0.403	2.481	15.5901	243.0499
Modal	6	0.345	2.899	18.2164	331.8367
Modal	7	0.27	3.71	23.3103	543.3705
Modal	8	0.238	4.193	26.3479	694.2099
Modal	9	0.211	4.737	29.7611	885.721
Modal	10	0.194	5.161	32.4294	1051.6663
Modal	11	0.17	5.887	36.9909	1368.325
Modal	12	0.153	6.533	41.0484	1684.9714

Table 5. Period and frequency of the strengthened structure

Case	Mode	Period	Frequency	Circ.Freq	Eigenvalue
		sec	cyc/sec	rad/sec	rad²/sec²
Modal	1	0.385	2.599	16.3276	266.5897
Modal	2	0.307	3.259	20.4784	419.3663
Modal	3	0.191	5.245	32.9525	1085.87
Modal	4	0.189	5.297	33.2836	1107.8
Modal	5	0.142	7.035	44.2052	1954.098
Modal	6	0.118	8.485	53.3099	2841.943
Modal	7	0.103	9.746	61.2343	3749.638
Modal	8	0.093	10.778	67.7231	4586.418
Modal	9	0.075	13.383	84.0903	7071.173
Modal	10	0.069	14.577	91.5901	8388.742
Modal	11	0.055	18.084	113.6225	12910.07
Modal	12	0.05	20.179	126.7883	16075.26

Table 6. Drift control of the un-strengthened structure

Storey	Output Case	Case Type	Step Type	Direction	Max Drift	Avg Drift	Ratio	H	v	dr*v	Drift lim. **0.0075*h**	Check
					mm	mm						
Storey4	ENVELOPE	Combination	Max	X	15.508	13.471	1.15	2500	1	7.75	18.75	Allowed
Storey4	ENVELOPE	Combination	Max	Y	37.238	25.125	1.48	2500	1	18.6	18.75	Not allowed
Storey4	ENVELOPE	Combination	Min	X	15.131	13.496	1.12	2500	1	7.57	18.75	allowed
Storey4	ENVELOPE	Combination	Min	Y	37.1	22.613	1.64	2500	1	18.6	18.75	Not allowed
Storey3	ENVELOPE	Combination	Max	X	55.865	34.543	1.62	6500	1	27.9	48.75	Not allowed
Storey3	ENVELOPE	Combination	Max	Y	75.659	54.093	1.4	6500	1	37.8	48.75	Not allowed
Storey3	ENVELOPE	Combination	Min	X	56.121	34.28	1.64	6500	1	28.1	48.75	Not allowed
Storey3	ENVELOPE	Combination	Min	Y	78.651	56.794	1.39	6500	1	39.3	48.75	Not allowed
Storey2	ENVELOPE	Combination	Max	X	25.038	21.542	1.16	4500	1	12.5	33.75	allowed
Storey2	ENVELOPE	Combination	Max	Y	31.326	25.547	1.23	4500	1	15.7	33.75	allowed
Storey2	ENVELOPE	Combination	Min	X	24.421	21.089	1.16	4500	1	12.2	33.75	allowed
Storey2	ENVELOPE	Combination	Min	Y	32.669	26.712	1.22	4500	1	16.3	33.75	allowed
Storey1	ENVELOPE	Combination	Max	X	0.529	0.344	1.54	4200	1	0.26	31.5	allowed
Storey1	ENVELOPE	Combination	Max	Y	0.479	0.333	1.44	4200	1	0.24	31.5	allowed
Storey1	ENVELOPE	Combination	Min	X	0.557	0.343	1.63	4200	1	0.28	31.5	allowed
Storey1	ENVELOPE	Combination	Min	Y	0.505	0.346	1.46	4200	1	0.25	31.5	allowed

Table 7. Drift control of the strengthened structure

Storey	Output Case	Case Type	Step Type	Direction	Max Drift	Avg Drift	Ratio	H	v	dr*v	Drift lim. 0.0075*h	Control
					mm	mm		mm				
Storey4	ENVELOPE	Combination	Max	X	7.873	5.529	1.424	2500	1	3.937	18.75	Allowed
Storey4	ENVELOPE	Combination	Max	Y	16.299	9.242	1.764	2500	1	8.15	18.75	Allowed
Storey4	ENVELOPE	Combination	Min	X	7.583	5.485	1.382	2500	1	3.792	18.75	Allowed
Storey4	ENVELOPE	Combination	Min	Y	17.364	9.76	1.779	2500	1	8.682	18.75	Allowed
Storey3	ENVELOPE	Combination	Max	X	12.196	9.981	1.222	6500	1	6.098	48.75	Allowed
Storey3	ENVELOPE	Combination	Max	Y	6.382	3.644	1.752	6500	1	3.191	48.75	Allowed
Storey3	ENVELOPE	Combination	Min	X	11.509	9.768	1.178	6500	1	5.755	48.75	Allowed
Storey3	ENVELOPE	Combination	Min	Y	5.963	3.593	1.659	6500	1	2.982	48.75	Allowed
Storey2	ENVELOPE	Combination	Max	X	5.966	5.43	1.099	4500	1	2.983	33.75	Allowed
Storey2	ENVELOPE	Combination	Max	Y	2.395	1.387	1.727	4500	1	1.198	33.75	Allowed
Storey2	ENVELOPE	Combination	Min	X	5.713	5.214	1.096	4500	1	2.857	33.75	Allowed
Storey2	ENVELOPE	Combination	Min	Y	2.606	1.542	1.69	4500	1	1.303	33.75	Allowed
Storey1	ENVELOPE	Combination	Max	X	0.056	0.028	2	4200	1	0.028	31.5	Allowed
Storey1	ENVELOPE	Combination	Max	Y	0.195	0.097	2	4200	1	0.098	31.5	Allowed
Storey1	ENVELOPE	Combination	Min	X	0.045	0.023	2	4200	1	0.023	31.5	Allowed
Storey1	ENVELOPE	Combination	Min	Y	0.174	0.087	2	4200	1	0.087	31.5	Allowed