“OVIDIUS” UNIVERSITY OF CONSTANȚA
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FIELD: CIVIL ENGINEERING AND INSTALLATIONS

SUMMARY OF THE DOCTORAL THESIS

CONTRIBUTIONS TO INCREASING THE STRUCTURAL SAFETY OF MULTI-STOREY BUILDINGS

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Chapter 1 – Introduction

The present research project holds significant importance due to its primary objective of highlighting, through comprehensive studies and investigations, both the long-term performance of buildings and the response of multi-storey structures to exceptional actions. The research aims to identify and develop methods and procedures for structural optimisation, applicable to both newly designed buildings and existing structures requiring structural and functional intervention.

The research activity conducted within this framework has sought to examine the evolution of the multi-storey building concept, with a particular emphasis on developments at the national level, while also considering international trends.

The analysis has revealed that Romania, like other European Union countries, possesses a substantial stock of collective housing buildings, many of which date back to the 19th century. In recent years, the issue of progressive collapse has become a growing concern at the international level. Globally, the degradation of buildings is driven not only by meteorological phenomena but also by the rapid evolution of construction technologies, technical standards, regulations, and by exposure to chemical, physical, and mechanical agents. Human factors, such as insufficient or delayed maintenance, poor construction quality, and interior modifications to residential units, further contribute to structural vulnerability.

In order to correctly understand the performance of the existing building stock in Romania and to optimise the structural design of new multi-storey buildings, it is essential to analyse the evolution of design codes following the two major earthquakes that occurred in 1940 and 1977. This aspect is particularly relevant for tall buildings, especially in Bucharest, where seismic events have historically had the most significant impact.

The doctoral research project is of particular relevance as it aims to identify, through applied studies and investigations, optimisation strategies for the structural behaviour of multi-storey buildings under both ordinary and exceptional loads. These strategies are applicable to both newly constructed buildings and existing ones requiring intervention.

As outlined in the research objectives, the study focused on the following key directions:

1. Analysis and investigation of various structural systems in multi-storey buildings to identify critical points in the implementation of construction projects and the underlying contributing factors;
2. Development of a database to support inspection processes and to quantify levels of risk and vulnerability;
3. Identification of the most practical, rapid, and efficient intervention measures in emergency and critical situations;
4. Reduction of operational costs, improvement of construction quality, and enhancement of efficiency and productivity in the execution phase;
5. Identification of digitalisation strategies applicable within this field;
6. Definition of structural design and intervention procedures for existing buildings that require safety upgrades, contributing to the refinement of technical codes and regulations;
7. Identification of factors involved in adopting appropriate crisis management strategies.

The applied research methods aimed to support a scientific and economic assessment of multi-storey buildings, based on a structured investigation programme. This allowed for the analysis of destructive factors contributing to building degradation, as well as the evaluation of the potential impact arising from the rehabilitation or enhancement of structural and architectural components.

Chapter 2 – Brief Historical Overview of Multi-Storey Buildings: Structural Solutions, Materials, and Technologies

This chapter presents a concise historical overview of multi-storey buildings, focusing on the structural solutions, materials, and technologies used from the late 19th century to the present day.

In Romania, the earliest multi-storey buildings were constructed using structural masonry walls. These residential condominium-type buildings typically included commercial units on the ground floor and had two or three upper storeys. Such constructions were founded on brick or stone masonry foundations, with vaulted brick floors and, in many cases, timber and metal profile floor systems on the uppermost levels, anchored using the systems available at that time. These buildings, generally ranging from two to five storeys, were primarily found in urban settings. The use of unreinforced masonry in seismic areas posed significant challenges during earthquakes. However, buildings that incorporated metal profiles within floor systems or vertical steel ties embedded in the masonry walls performed satisfactorily.

After 1915, multi-storey buildings began to be designed and constructed using reinforced concrete slabs and staircases, although confined masonry was not yet implemented in the early 20th century.

The emergence of multi-storey buildings became a prevalent solution after World War I, driven by a severe housing shortage and the need to maximise land use efficiency through vertical expansion. Although Bucharest already had buildings with three to four storeys, and occasionally five, prior to 1916, the widespread development of multi-storey buildings only gained significant momentum after 1918. One notable issue was the distribution of ownership within these buildings, given the existence of shared spaces and shared utility systems. While the concept of multi-storey living with distributed ownership is often associated with the 20th century, such constructions already existed as early as the 18th century in France, England, Corsica, Sardinia, and the Scandinavian countries—thus, the model had long been available for adaptation.

The foundations of urban planning theory in Romania emerged in the first decade of the 20th century, with the concept of planned urban development taking shape. The issue of mass housing began to concern municipal authorities in the final decades of the 19th century, and during the interwar period, housing became a central theme in both urban planning theory and legislation.

Subsequently, multi-storey buildings in Romania were constructed with reinforced concrete frame structures—referred to at the time as column-and-beam systems—with non-structural masonry infill walls.

After 1950, confined masonry systems with vertical cores (referred to as "sâmburi") were introduced, initially with sparse distribution, which became denser over time. Influenced by post–World War II trends in Eastern European countries, the number of multi-storey buildings increased, using both flexible and rigid reinforcement systems.

Starting in 1956, major urban streets saw the construction of taller buildings, typically with 4 to 10 storeys (ground floor + 4 to 10 floors), featuring confined brick masonry structures and monolithic reinforced concrete slabs. Buildings taller than three storeys were often designed with longitudinal and gable-end reinforced concrete shear walls (diaphragms) to enhance lateral resistance.

In 1956, the first residential building made of large precast panels (Basement + Ground Floor + 4 Storeys) was constructed. By 1959, significant improvements had been made in the jointing systems for these large-panel structures.

The introduction of Normative P13/1963 marked a major milestone in the design of multi-storey buildings, bringing advancements in both structural calculation methods and prescriptive construction requirements that designers and builders were required to follow.

A review of the structural solutions implemented after 1963 reveals the presence of symmetric, well-ordered buildings, where the centre of rigidity was intentionally aligned with the centre of mass to avoid torsional effects during seismic events.

In 1963–1964, the first prefabricated systems were applied to floor slabs and, shortly thereafter, to the load-bearing structure itself. Full prefabrication brought significant benefits in terms of construction productivity and the urgent need to provide housing during the country's industrialisation process, which led to a strong migration of the workforce toward urban centres.

After 1970, the concept of large-panel block construction was increasingly promoted. Initially, honeycomb-type monolithic reinforced concrete buildings were constructed, later replaced by buildings entirely made of prefabricated components.

Analysis of the seismic performance of these buildings has generally shown good overall behaviour, with no structural damage reported that could compromise their stability or load-bearing capacity. This satisfactory performance is largely attributed to the relatively high rigidity of buildings constructed with large panels, due to diaphragms distributed in both directions. The only commonly observed damage involved cracking in the joint areas and, in rare cases, spalling of concrete at the joints. Another noted vulnerability was the appearance of diagonal cracks in the lintel zones.

Toward the end of the 20th century, apartment buildings were widely constructed using reinforced concrete frame structures with shear walls, also known as dual structural systems.

Chapter 3 – A Brief History of the Evolution of Design Technical Codes

This chapter presents research and comparative analysis of all design codes that have served as the foundation for seismic design in Romania. The evolution of technical design regulations is of particular significance, especially considering the seismicity of Romania, a country situated in a region prone to major seismic activity.

The chapter outlines the main seismic design codes used in Romania from the post–World War I period to the present day.

The seismic zoning of Romanian territory has undergone numerous substantive changes over time, focusing primarily on the following aspects:

- The delimitation and number of seismic zones in which seismic intensity was considered constant. This number evolved from two zones (as per the *Instructions for Preventing Damage to Buildings Caused by Earthquakes*, Regulation No. 120 of May 30, 1945), to three zones (as defined in *STAS 2923/1952*), then to four zones (as found in the seismic maps of *STAS 2923-1963* and *STAS 11100/1*), later to six zones (*P100-1992*), and eventually to **seven zones**, as presented in the maps included in *P100/1-2006* and *P100/1-2013*.

- The expression of seismic intensity, which initially was given in degrees using the macroseismic MSK scale (adopted in Romania via *STAS 3684/1971*). In codes prior to 1992, intensity was primarily qualitative; however, starting with *P100-1992*, the intensity began to be expressed in terms of peak ground acceleration (ag), associated with the control period (TC) of the elastic response spectrum in acceleration.
- The mean return period (MRP) associated with the peak ground acceleration (ag), which began to play a central role in defining seismic hazard levels.
- The parameters and shape of the horizontal elastic acceleration response spectrum, which have become increasingly refined in recent design codes, in alignment with Eurocode methodologies and probabilistic seismic hazard assessments.

In addition to seismic regulations, the design codes for wind loads and live loads have also experienced continuous evolution, both in terms of loading magnitudes and methodological approaches.

The calculation methods themselves have undergone significant transformation over the past century. The progression has moved from the allowable stress design (ASD) method to the more comprehensive limit state design (LSD) method. The latter offers a more realistic and analytical framework for assessing stress-strain behaviour, ultimate capacity, and serviceability limits of structures—both in design and in actual exploitation.

The evolution of structural codes in Romania reflects a broader trend toward probabilistic design principles, improved safety margins, and better alignment with international standards, ensuring increased resilience of structures to seismic and environmental actions.

Table 1 – Examples of Locations, Seismic Coefficients (ks), Corner Periods (TC), and Seismic Intensity Grades

Example Locations	P13-63 (70)	P100-78 (81)	P100-90 (92)		P100/1-2006		P100/1-2013 (2019)	
	Seismic Intensity Grade	Seismic Intensity Grade	T_C	k_s	T_C	a_g	T_C	a_g
Bucharest	VII	VIII	1,5	0,20	1,6	0,24	1,6	0,30
Constanța	VII	VII	0,7	0,12	0,7	0,16	0,7	0,20
Ploiești	VIII	VIII	1,5	0,25	1	0,28	1,6	0,35
Bacău	VII	VIII	1,0	0,20	0,7	0,28	0,7	0,35

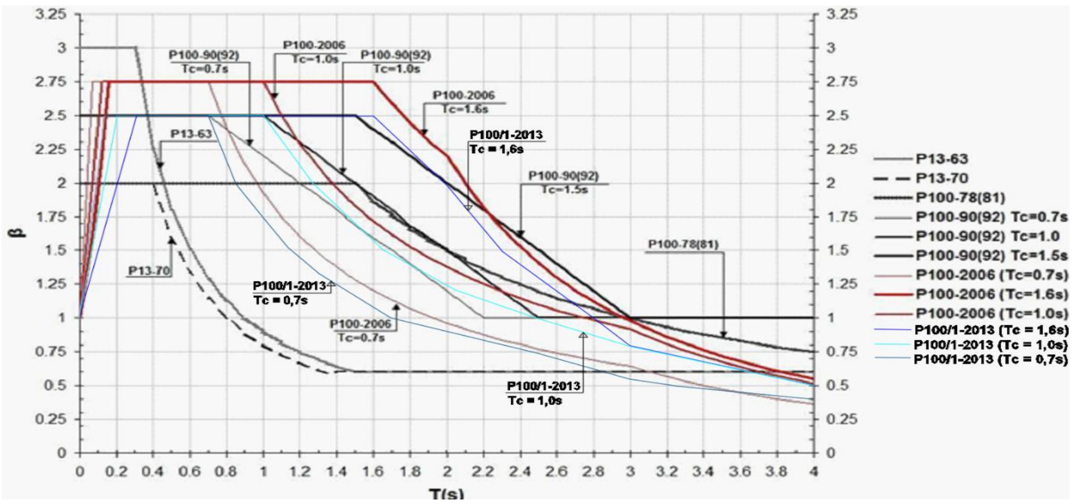

Figure 1 – Evolution of the β Factor from 1963 to Present

Table 2 – Examples for Reinforced Concrete Frame Buildings – Values of Coefficients Ψ_1 and Ψ_2					
P13-63	Reinforced concrete skeleton structures and buildings with roof articulated on reinforced concrete columns				Ψ_1
					1,2
P13-70	Frame structures				Ψ_1
					1,0
P100-78(81)	Multi-storey frame buildings with regularity in plan and elevation:				Ψ_2
	a) With a single bay				0,25
	b) With multiple bays				0,2
P100-90(92)	Multi-storey frame buildings:				Ψ_2
	a) Infill walls treated as structural elements, ensuring composite action with concrete elements				0,25
	b) Infill walls not treated as structural elements				0,2
P100-1-2006 Și P100/1-2013 (2019)	Ductility Class H $q = 5{,}0\ \alpha_u/\alpha_1$	Reinforced concrete frames or dual systems with predominant frames:	α_u/α_1	q	$\Psi_2 = 1/q$
		a) Buildings with one level	1,15	5.75	0,1739
		b) Buildings with multiple levels and a single bay	1,25	6,25	0,160
		c) Buildings with multiple levels and multiple bays	1,35	6,75	0,1481
	Ductility Class M $q = 3{,}5\ \alpha_u/\alpha_1$	a) Buildings with one level	1,15	4,025	0,2484
		b) Buildings with multiple levels and a single bay	1,25	4,375	0,2285
		c) Buildings with multiple levels and multiple bays	1,35	4,725	0,2116
P100/1-2013 (2019)	Ductility Class L $q = 2{,}0$	Frames, dual systems, or slender coupled walls, dual structures	1,00	2,00	0,500

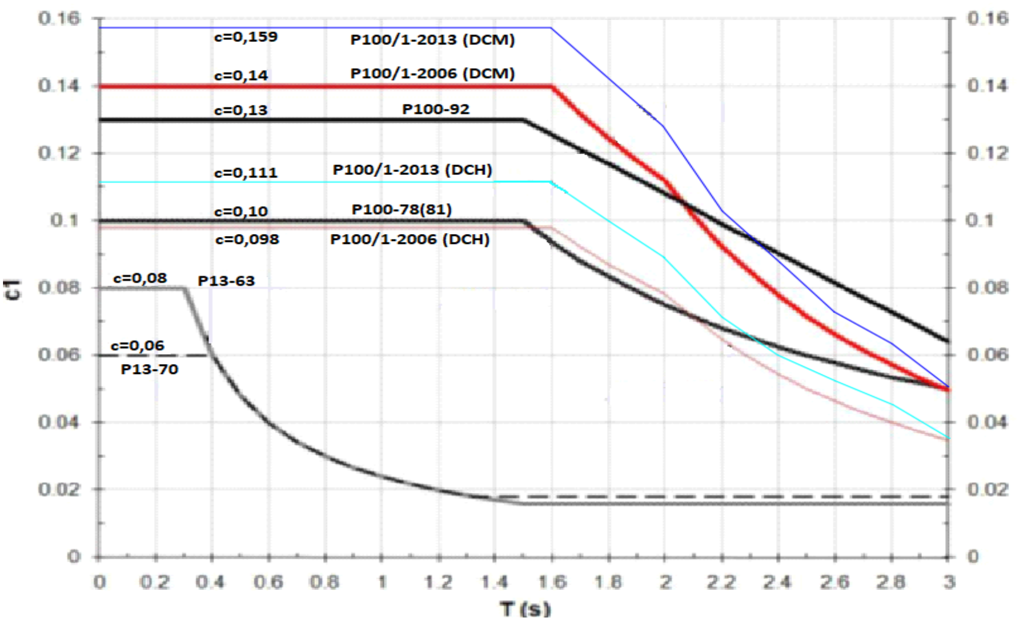

Figure 2 – Evolution of the global seismic coefficient *Cs* for a reinforced concrete frame structure building located in Bucharest, classified as Importance Class III (with a correction factor λ=1 for the P100/1-2006 and P100/1-2013 standards).

Chapter 4 – Durability and Influencing Factors

This chapter presents a synthesis of research on the multiple causes that lead to the degradation of various types of structures and their behavior over time.

One primary cause is defects arising from the use of inappropriate materials: materials with reduced strength that do not meet quality requirements and standards. Such situations are typically encountered in older buildings, where concrete was of inferior quality or bricks lacked adequate strength.

Another contributing factor is the execution technology: segregation in concrete, deviations from horizontality and verticality, which lead to additional loading of slabs with screeds or increased loading of wall plasters.

Design deficiencies also play a critical role. For example, the collapse of the Carlton Block in Bucharest during the 1940 earthquake involved a ten-story building sharing a common column with a cinema, which also supported the cinema's roof.

The most important factors influencing the increased risk of long-term behavior of various types of multi-story structures can be summarized as follows:

- Design errors;
- Construction errors;
- Meteorological phenomena;
- Biological and chemical attacks, repeated vibration effects;
- Unauthorized interventions on the buildings;
- Lack or poor quality of maintenance work or delayed execution thereof;
- Improper use of the building;
- Functional deterioration and the influence of human factors;
- Functional modifications potentially affecting the load-bearing structure;
- Seismic action;
- Fire action (fires);
- Differential settlements;
- Lack of appropriate legislation governing condominium functioning;
- Lack of education in construction for all personnel involved in ensuring building quality throughout the building’s life;
- Evolution of technical prescriptions and normative acts contributing to the quantification of varying risk levels in structural analysis — and the lack of involvement in ensuring an adequate structural response of the existing built environment (wind action, snow loads, seismic action, etc.).

Design and construction deficiencies are often more dangerous than the use of improper materials, potentially causing greater destruction. Regarding materials, reinforcement corrosion causes more problems than the concrete deterioration itself.

The concept of durability is also presented, defined as the period during which a structure can maintain all its characteristics to function within normal parameters. Durability is influenced by various factors, often acting simultaneously.

Generally, these factors can be classified into four major categories:

- The first category includes internal material degradation, namely the alkali reactions of cement in contact with aggregates and the conversion of high-alumina cement;

- The second category involves the penetration of chlorides, carbonation, sulfate attack — generally components of fluids and ions from the surrounding environment that penetrate the concrete structure and attack either the concrete and/or the reinforcement;
- The third category concerns the direct impact and wear of the material: erosion, cavitation;
- The fourth category involves mechanical destruction due to excessive deformations caused by temperature effects, bending-induced cracks, freezing-thawing cycles, wetting and drying of the material.

Adverse factors affecting durability can be classified as follows:

a) External factors

- Ambient environment (freeze-thaw cycles lead to exfoliation and strength loss; humidity and temperature variations cause cracks leading to durability loss);
- Chemical action (inorganic salts causing reinforcement corrosion, carbonation causing reinforcement corrosion, acids eroding surfaces);
- Mechanical action (vibrations, water and wind erosion);

b) Internal causes

- Salts and chlorides causing reinforcement corrosion;
- Volume changes producing cracks leading to durability loss;
- Alkali-aggregate reactions causing strength and durability loss;

c) Structural causes

- Joints' reserves producing cracks leading to durability loss;
- Structural overloading also producing cracks;

d) Accidental factors

- Including explosions, fires, landslides, etc.

Chapter 5 – Requirements and Demands for Multi-Story Buildings

This chapter presents the principles of ductile design, the occurrence of plastic deformations, potential plastic hinge zones, and the requirements for ductility, strength, and stiffness.

The research conducted within this program highlighted a series of complex issues faced by multi-story buildings, both new and existing.

The problematics relate not only to the structural concept and operating conditions but also to the quality of the executed works and the materials used. The specialized literature presents numerous examples of failure in multi-story buildings, from which, based on technical expertise reports, a series of causes have been identified, statistically quantified, and which offer a broad range of case studies and interpretations.

Of course, in the case of such events, a combination of causes is encountered that can be interpreted as contraventional aspects, but there is always a dominant cause.

In this context, the conducted research targeted different types of multi-story structures, aiming to highlight the manner in which their durability is affected, to collect conclusions regarding the causes of failure, to gather intervention measures, as well as to create a database concerning the optimization of structural design for multi-story buildings.

Within the research program, a scientific and economic evaluation of these multi-story buildings was pursued, starting from an investigation program that enabled the analysis of the structural concept, the analysis of dominant degradation factors, the analysis of intervention measures, and the development of an optimized structural intervention concept that allows the execution of works concurrently with the building's operation.

The research continued with an analysis of the load-bearing structures of multi-story buildings, emphasizing some very important aspects in establishing strengthening solutions.

The structural analysis of existing buildings showed that seismic design principles, the realization of a well-conceived structure both in plan and elevation, and the proper distribution of masses can lead to very good performance, with important roles played by adherence to technical quality prescriptions, materials quality, and construction technologies.

For the structures analyzed within the research project, a category of intervention measures was identified based on structural type, constituent material, and type of degradation.

The main properties to be examined in designing a structural system for seismic actions are stiffness, load-bearing capacity, and ductility.

Each of the three structural systems—frames, structural walls, and dual systems—has its specific properties. The choice among them should be made based not only on architectural or building use considerations but also on the expected intensity of seismic actions.

Chapter 6 – Behavior of Multi-Story Buildings Under Seismic Actions

Residential buildings, as well as certain social-cultural buildings such as hospitals, are typically occupied near their maximum capacity due to their specific functionality. This fact gives paramount importance to the behavior of these buildings during earthquakes. Most casualties resulting from severe earthquakes come from the collapse of residential buildings.

The diversity of responses of constructions to the 1977 earthquake was particularly evident in the case of residential buildings. Representing the largest share of buildings in the areas and centers severely affected by the earthquake, these buildings suffered the most and exhibited a wide variety in terms of form, height, use, structural system, seismic resistance level, construction quality, building age, and influences from their service period.

When presenting the seismic behavior of residential buildings, it is necessary to distinguish between their construction periods (old buildings versus new buildings). It is also important to highlight some specific aspects regarding the behavior of buildings in Bucharest, due to their concentration in a central zone severely affected by the earthquake and their particular height characteristics (up to 13 stories for old buildings and up to 20 stories for new ones). These characteristics increased the risk of seismic exposure.

This chapter presents in detail the behavior of the following building types:

1. Residential buildings constructed before 1950

These buildings were classified as very old buildings; buildings with load-bearing masonry structures; buildings with combined structures; buildings with reinforced concrete frames having a height regime of P+6 to 12 stories.

None of these building types were designed for seismic loads, and many did not comply with design and execution rules even for normal conditions. Their static schemes were irregular, with eccentric masses and intermediate supports for structural elements. These buildings suffered damage during the 1940 earthquake, which was not properly repaired, worsening their inadequate seismic behavior and the damages sustained in 1977. Of approximately 300 old apartment blocks with more than eight levels, 25 completely collapsed during the 1977 earthquake, and another three were later demolished due to severe damage.

Approximately 100 buildings exhibited serious damage, requiring emergency strengthening.

The 1940 earthquake exhausted much of the bearing capacity of Bucharest's old residential blocks without adequate compensatory strengthening, thus influencing their behavior during the more recent earthquake and the resulting known effects. Consequently, some of the above-mentioned buildings cited in the literature, as well as others that were only partially and often insufficiently strengthened, totally or partially collapsed during the March 4, 1977 earthquake, unable to resist the second strong shock.

Additionally, most of the old tall apartment blocks in Bucharest suffered severe damage to both the structural system and non-structural elements.

2. Residential buildings constructed after 1950

Residential buildings built after 1950 up to the present show considerable variety in functional schemes and constructive solutions, determined by the efforts of various design institutes to integrate multiple requirements. These include accommodating a growing number of dwellings corresponding to the continuous rise in the population's economic and ecological living standards.

These solutions were mainly implemented in large-scale typical projects starting after 1960, when over 90% of the total new residential buildings in the country were constructed under the socialist planned economy. The standardized solutions for large-scale residential buildings used during this period, including in seismic regions, can be grouped into the following main constructive systems:

a) For low-rise buildings:

- Load-bearing masonry (often reinforced with reinforced concrete cores) for ground floor + 1-4 floors, with monolithic slabs and especially prefabricated ones;
- Large panels for ground floor and 4 floors;
- Monolithic reinforced concrete diaphragms for ground floor and 4 floors, honeycomb or cellular systems, built using various technologies (sliding formwork, flat formwork, spatial tunnel formwork, etc.), with monolithic or prefabricated slabs;
- Reinforced concrete frames for ground floor and 4 floors, with monolithic columns, monolithic or prefabricated beams, and usually prefabricated panels or prestressed slabs, more rarely monolithic reinforced concrete slabs;
- Spatial elements for ground floor and 4 floors.

b) For high-rise buildings:

- Large panels for ground floor and 7-8 floors;

- Monolithic reinforced concrete diaphragms for ground floor and 10 floors, honeycomb or cellular system similar to the low-rise system;
- Reinforced concrete frames for ground floor and 6-14 floors, with monolithic columns and similar elements as the low-rise system;
- Central core and monolithic concrete columns for ground floor and 10 floors, with monolithic or prefabricated beams and slabs.

A particular case is represented by residential buildings constructed in Bucharest after 1950 and before the March 4, 1977 earthquake, which comprise nearly 400,000 apartments, most (about 80%) being in collective buildings built using state funds or state loans. The collective residential buildings in the capital were mostly constructed as multi-story (about two-thirds of the total), with the main share consisting of buildings with monolithic cast-in-place reinforced concrete diaphragms (60%), followed by large panel buildings (23%), load-bearing masonry (13%), and reinforced concrete frames (4%).

Within the various structural system types, numerous technologies were used (prefabricated, industrialized formworks for monolithic concrete casting, etc.) and variants regarding the plan shape of buildings (including number and position of diaphragms), assembly methods of building segments, and materials for exterior and interior walls. A general characteristic of the seismic behavior of new series-built residential buildings is that they performed significantly better compared to old buildings. Collapse cases were isolated, and serious damage cases were much fewer. This difference is attributed to the design of these buildings to withstand seismic loads and the fact that these buildings have not been subjected to a second earthquake during their service life.

In Bucharest, the seismic behavior of new residential buildings was overall better than that of the old ones, with only two collapse cases. Damaged buildings represent only 2% (with major damage) and 11% (with minor damage), according to statistics from the Bucharest Design Institute.

The good seismic performance of new residential buildings reflects the competence of Romanian engineers who quickly adopted design and construction techniques for new earthquake-resistant structural systems.

3. Social-cultural and administrative buildings

Old buildings in this category generally exhibited effects similar to those of old residential buildings with comparable structures. Collapses, except for some major cases in Bucharest, mostly occurred in very old and small buildings. Damage, similar to that of old residential buildings, affected almost all categories of social-cultural and administrative buildings made of load-bearing masonry or reinforced concrete structures in Bucharest and the provinces, such as hotels, hospitals, schools, cultural and administrative buildings, etc. No collapses were reported in buildings housing large auditoriums, with severe damage occurring only in particular cases of very old, less significant halls.

Chapter 7 – Structural Analysis Aspects with Reference to the Building's Degradation State

This chapter studies how the elements of the load-bearing structure present visible degradations, failures caused by subsequent interventions that impact the bearing capacity, deficiencies in installations, lack of timely repair works that affect the structural elements, or cases where the structure experiences settlements due to excessive moisture, with implications on the structural system.

An important factor in this analysis is the age of the structure, to consider the design principles that formed the basis of the design and construction of multi-story buildings, whether the structure has undergone any previous residual deformations, if it has suffered fire, explosions, or if functional modifications or re-functionalizations of the usable space have been carried out.

The research conducted within the investigation reports highlighted the behavior of different structural systems, aspects that must be considered in the structural analysis through behavior factors. Buildings constructed after 1950, as shown in the previous chapter, were built with weakly confined masonry structures with reinforced concrete diaphragms on the gables and monolithic reinforced concrete slabs.

Another situation examined within the program refers to execution deficiencies that can influence resistance and stability, and whose non-conformities must be resolved during construction by means of repair measures aimed at increasing the bearing capacity. The evaluation of the implications of these non-conformities considers their impact on the requirements for resistance and stability identified on the construction site.

All these aspects can define a degree of seismic risk assessment based on qualitative evaluation relying on the building's composition and the degree of structural damage. A particularly important role is played by analytical evaluation through calculation, which is based on the modeling of the structure, the characteristic strengths of the component materials (or laboratory testing when unknown), and the quantified behavior degree expressed through the behavior factor.

In the analytical method, the level of knowledge (KL) is significant; this level can be advanced when technical documentation of the building exists or can be estimated according to regulations. The result of the analytical calculation is recorded in a synthesis report that provides concrete elements and grounds the intervention measures proposed by the expert.
Consequently, the strengthening methods for multi-story structures rely on a complex criteria-based analysis carried out by a certified specialist according to Order 817/2021 of the Ministry of Regional Development and Public Administration (MLPDA).

The next chapter will present some intervention methods for multi-story building structures. It is noteworthy that the legislator allows for local interventions on structures when there is a specific case where a local part of a construction has been affected, applicable to buildings constructed after 1981, according to P100/1981.

This normative, C254/2022, serves as a guideline for particular technical expertise cases regarding buildings' fundamental requirement of mechanical resistance and stability, in accordance with legal provisions. These particular cases refer to:

- Placement adjacent to a new construction near an existing building;
- Functional reconfiguration;
- Local degradation.

Chapter 8 – Criteria for Assessing the Vulnerability Level of Multi-Storey Buildings

Based on the research conducted and synthesized in Research Report No. 1, a very important concept regarding vulnerability is retained. Vulnerability is defined as the way a multi-storey building responds to the entirety of conditions generated by physical, socio-economic, and environmental factors that add to natural hazards. In this context, it is observed that ensuring mechanical resistance and stability is closely linked to the evaluation of the vulnerability of different categories of multi-storey buildings.

Considering seismic characteristics, seismic vulnerability is the one that decisively impacts the existing built environment in Romania. According to the criteria set forth in technical prescriptions and normative acts, vulnerability can be classified as either observed vulnerability, estimated through visual investigations, or calculated vulnerability. Moreover, vulnerability can be static or evolving. Seismic vulnerability is considered an evolving vulnerability due to the fact that after each seismic event, no effective measures are generally taken to restore the load-bearing capacity; rather, interventions usually involve works concerning the visual aspect, such as finishes. In this context, a building has an unfavorable historical evolution in terms of seismic behavior.

It should be noted that in Romania, the 1940 earthquake left its mark on multi-storey buildings that existed at that time, and the 1977 earthquake further worsened their degradation state, destroying about 28 high-rise reinforced concrete skeleton buildings constructed between the two World Wars. Considering these aspects, the doctoral research aimed to study the failure modes of multi-storey structures on a sample of buildings of the same structural type, expressed through vulnerability functions or vulnerability matrices.

The studied sample considered the following structural types:

- Multi-storey buildings with load-bearing brick walls and reinforced concrete slabs;
- Multi-storey buildings with weakly confined masonry structures and reinforced concrete slabs;
- Multi-storey building structures with beams and columns built between the two World Wars (thin frames);
- Reinforced concrete frame structures with diaphragms;
- Large-panel structures.

In selecting these samples, it was considered that the first category was not based on seismic calculation codes, the second was designed according to standard P13/63, and the following ones according to P13/1970 and P100/1981. In fact, current technical prescriptions impose the mandatory calculation of the seismic risk level for buildings constructed up to 1971, according to the old standards.

The vulnerability analyzed after the 1977 earthquake highlighted that the primary factors leading to poor behavior of multi-storey buildings consist of:

1. Erroneous design concepts, manifested through:

- Lack of structural calculation

- Selection of an inadequate geometric shape
- Defective composition of the structural system presenting deficiencies in load transfer
- Inadequate preliminary sizing of structural elements
- Lack of proper execution details necessary for construction

2. Major execution defects:

- Concrete with inadequate strength
- Pouring deficiencies
- Unauthorized modifications in execution type

3. Operational deficiencies:

- Lack of timely and quality maintenance works
- Unauthorized modifications of functional spaces
- Re-functionalization of ground floor spaces involving major modifications

All these aspects resulted in a series of damages following the seismic action, manifested through:

- Cracking of masonry walls
- Detachment of lintels
- Cracks appearing in reinforced concrete frame structures at beam ends
- Diagonal cracking of median diaphragms at upper floors
- Formation of plastic hinges on columns, failure of some segments
- Expulsion of concrete from monolithic joints in large-panel buildings

It can be appreciated that buildings with honeycomb-type functional spaces made of reinforced concrete did not show degradations, behaving like a rigid box.

Chapter 9 – Criteria for Choosing Intervention Solutions

This chapter presents the various criteria on which the selection of techniques and intervention solutions for a building is based.

The choice of intervention plan depends on a thorough understanding of the deficiencies of structural and non-structural elements, as well as the overall deficiencies related to the strength, redundancy, structural regularity, and deformability.

Intervention measures must be correlated with the level of degradation of materials and the structure, aiming to reduce or eliminate deficiencies in order to achieve the safety condition: the seismic demand should be less than or equal to the building's capacity. The intervention strategy may include reducing seismic demands, improving mechanical properties, or combined measures.

Generally, a technical expertise analyzes at least two intervention alternatives, evaluating the reduction of vulnerability to seismic hazard sources and selecting the most effective solution.

The conclusions of the seismic evaluation report form the basis of the intervention design (where structural and/or non-structural deficiencies are identified) and where the seismic risk class is established.

Seismic performance has two main objectives: limiting damage and ensuring life safety. The decision to repair and strengthen buildings damaged by earthquakes involves considering multiple essential factors to justify the chosen solution from a technical, economic, and other conditions perspective.

Based on the calculation analysis performed during the technical expertise or further developed during the design phase (including dynamic behavior in the post-elastic stage, for more important buildings), the necessary repair and strengthening works are determined and designed, with the primary objective of restoring the load-bearing structure to its initial state. It is important that the repair and strengthening project includes as precise an assessment as possible of the actual seismic resistance capacity of the structure, and that any resistance reserves considered are certain.

Furthermore, careful monitoring of the time-dependent behavior of these buildings is required, carrying out analyses and interventions when anomalies or initial defects are detected. In establishing the repair and strengthening solutions for earthquake-damaged buildings, a set of fundamental principles applicable to multiple building types must be respected. Additionally, the objectives to be achieved must be specified, taking into account how the building reacts to seismic actions.

Repair and strengthening works have distinct characteristics from ordinary new construction works. Although they mostly use common materials and procedures, specific adaptations are necessary for each type of building, depending on the actual damage situation and available resources.

Repair and strengthening solutions and methods vary according to the nature of materials and type of structure (load-bearing masonry, reinforced concrete frames, reinforced concrete diaphragms, metal structures, etc.), the degree of damage, execution technology level, and economic conditions.

It is important to distinguish between the overall structural strengthening, to ensure spatial rigidity against lateral forces, and the strengthening of individual elements, to provide the required load-bearing capacity for each.

Also crucial is that overall strengthening solutions and methods do not hinder the strengthening of individual structural elements or their connections.

Within the thesis, methods for repairing massive concrete elements, reinforced concrete buildings, load-bearing masonry buildings, metal constructions, and plain concrete elements are presented, along with examples of repair and strengthening solutions applied after the March 4, 1977 earthquake to different building categories.

Chapter 10 – Case Study

In Chapter 10 of the doctoral thesis, two case studies are presented for multi-storey buildings, built during the period 1962-1972, located in Bucharest.

1. Case study – Multi-storey collective housing building D+P+9F

The inspected building is located on Str. Gării de Nord, no. 6-8, block A, staircase 1, sector 1, Bucharest. Importance class III and seismic exposure category "C" – normal importance. An evaluation was carried out to determine the state of stresses and deformations, using the structural calculation software Scia Engineering. A three-dimensional model of the structure was created, which was analyzed in the elastic domain by the modal calculation method with response spectra for the considered site, according to P100-1/2013. Since it is a structure with a flexible ground floor, the vertical elements of the ground floor were checked.

The relative inter-story displacements verified the admissible value for the Ultimate Limit State but not for the Serviceability Limit State. The natural period given by translation on the short side is 0.74 s and does not imply a quasi-resonance phenomenon relative to the corner period TC = 1.6 s. The maximum displacements resulting from the maximum envelope load class on the two directions are Ux – displacement on the short global side 87.0 mm and Uy – displacement on the long global side 57.8 mm, and Utotal – 103.3 mm.

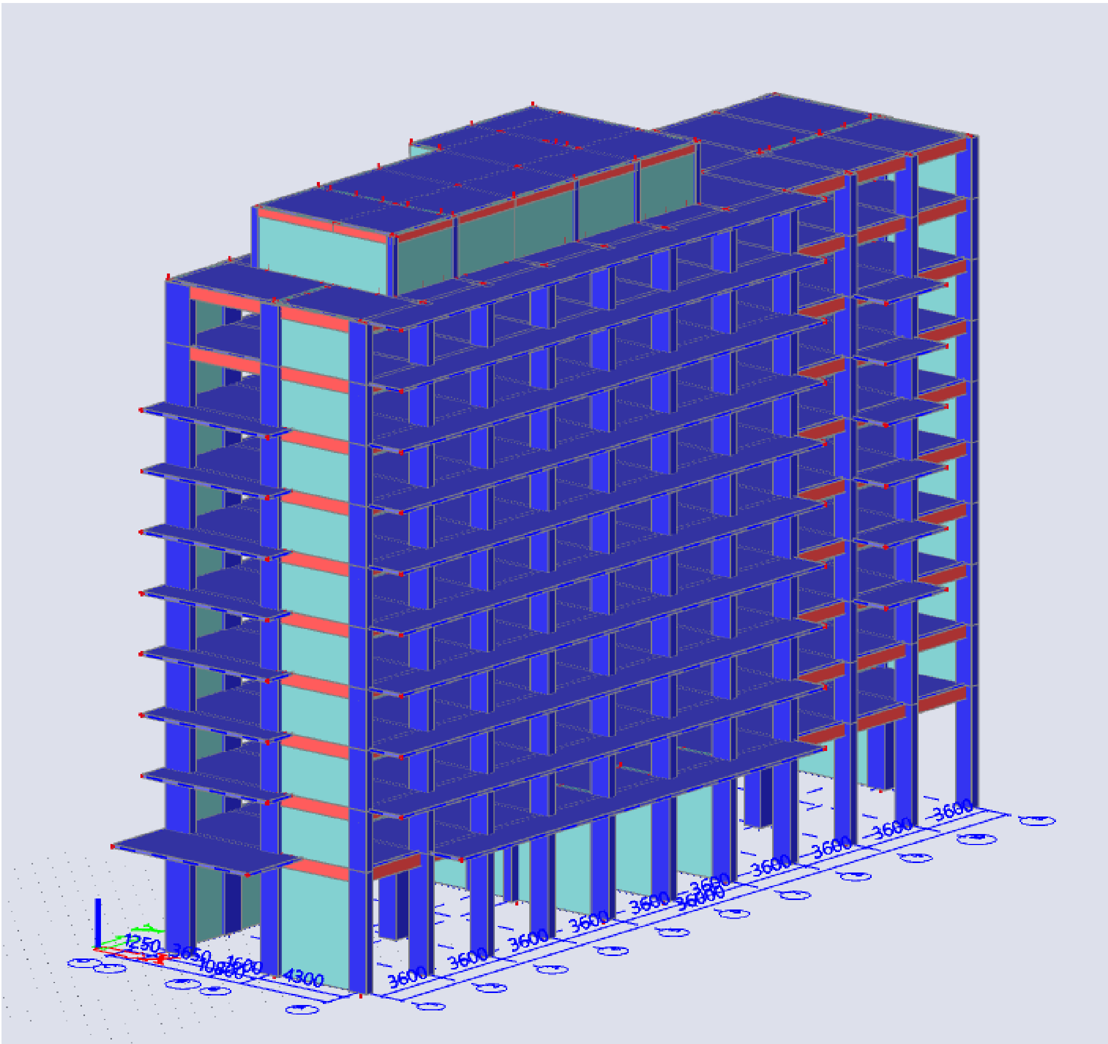

Figure 3 – 3D Model of the building

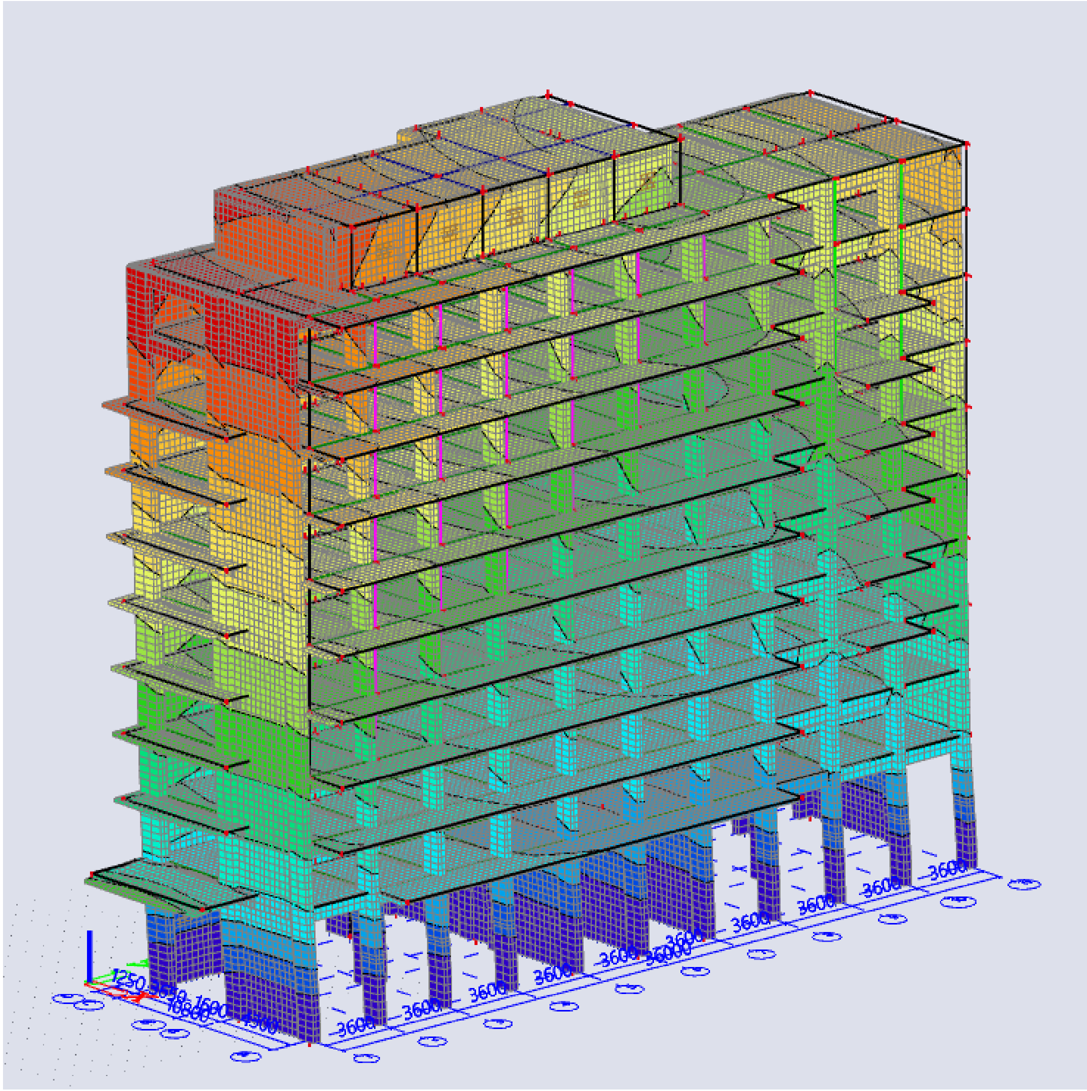

Figure 4 – Deformed 3D model of the building – Utotal – total displacement

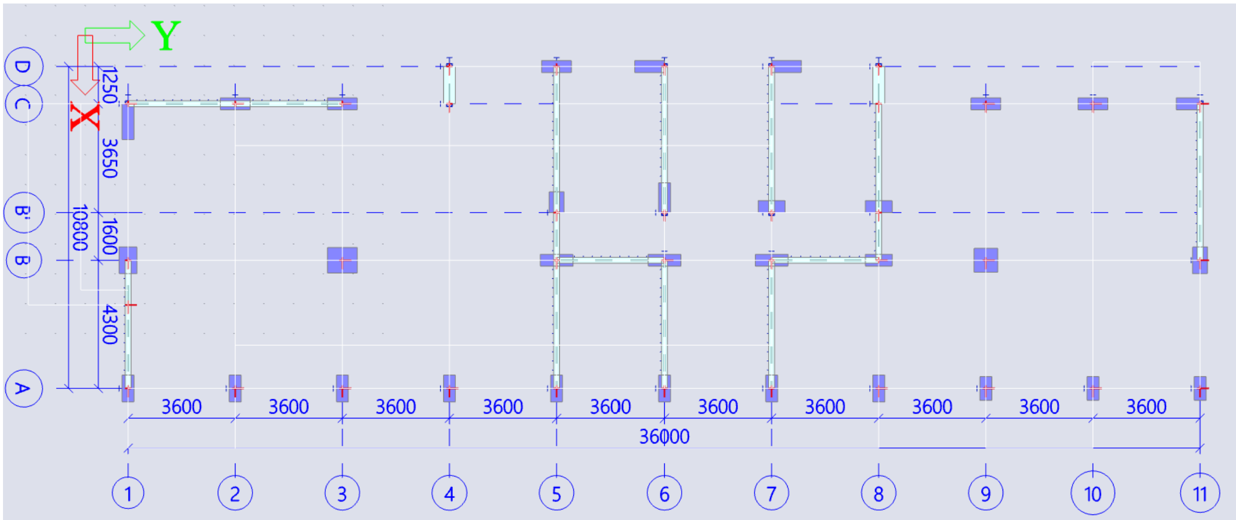

Figure 5 – Ground floor plan with vertical load-bearing elements

The fulfillment ratio of bending moments R_3^M is 0.68 and of shear forces R_3^V is 0.32 for seismic action in the longitudinal direction.

The fulfillment ratio of bending moments R_3^M is 0.50 and of shear forces R_3^V is 0.41 for seismic action in the transverse direction.

This indicates the need for structural reinforcement.

2. Case Study – Multi-story Administrative Building D+P+2E

The building is located in Bucharest Municipality, designated for office use, classified in Importance Class I for earthquake exposure, and falls under Importance Category "B."

The structural system resisting horizontal and vertical loads consists of spatial reinforced concrete frames. The slabs are also reinforced concrete, approximately 12 cm thick (according to extracted cores). The foundation system consists of isolated reinforced concrete footings.

The seismic risk class classification was performed in accordance with the provisions of code P100-3:2019, based on the analysis of indicators R1 and R3.

The R1 indicator value = 54 corresponds to the building being classified in seismic risk class RsII. This means that, overall, the conformity defects present in the building are serious.

The R3 value = 27 corresponds to classifying the building in RsI.

In the scenario where the contribution of masonry walls is not considered (the scenario used in the R3 calculation), it is observed that the R3 indicator is at the borderline for classification of the building in seismic risk class RsII. It can be estimated that the actual risk of total collapse of the building is lower (compared to that of a building decisively classified as RsI), so this building would rather be classified in seismic risk class RsII. Consequently, the classification of the building in seismic risk class RsII is considered relevant.

The structural resistance analysis of the building and the determination of the load-bearing capacity of the proposed components were carried out based on a three-dimensional numerical model, using a linear elastic analysis with the "modal response spectrum method."

The seismic evaluation was performed using scaled design spectra corresponding to the proposed situation (70% assurance level, seismic risk class RsIII).

The proposed strengthening method is presented, which also took into account the optimal use of the basement: 12 longitudinally oriented walls and 10 transversally oriented walls, each 20 cm thick, and the casing of the 5 columns.

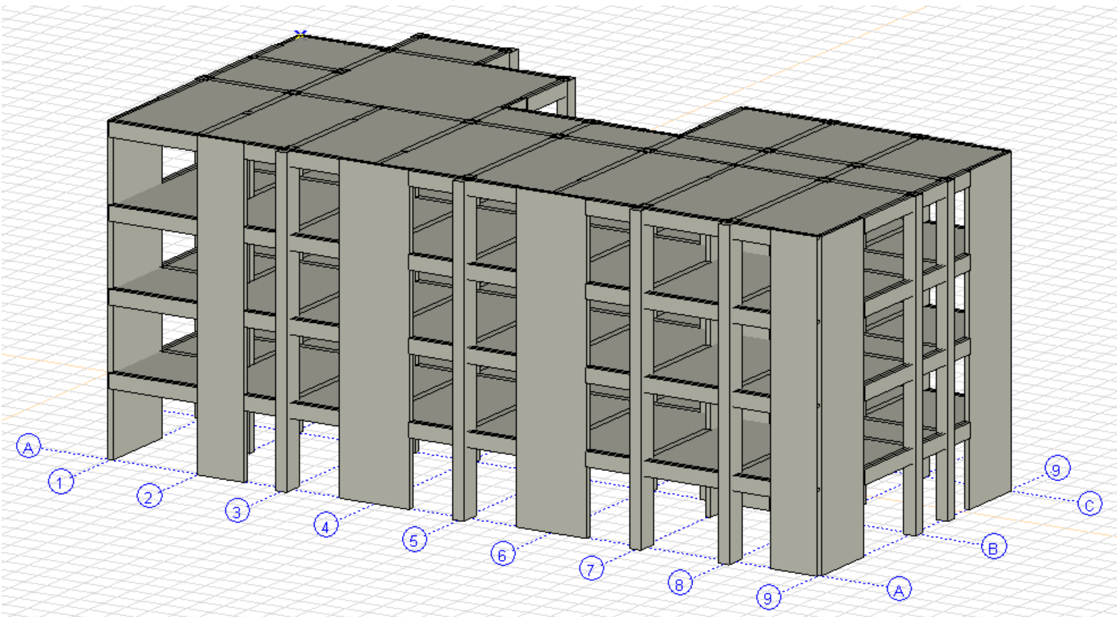

Figure 6 – Extruded 3D view of the structural calculation model

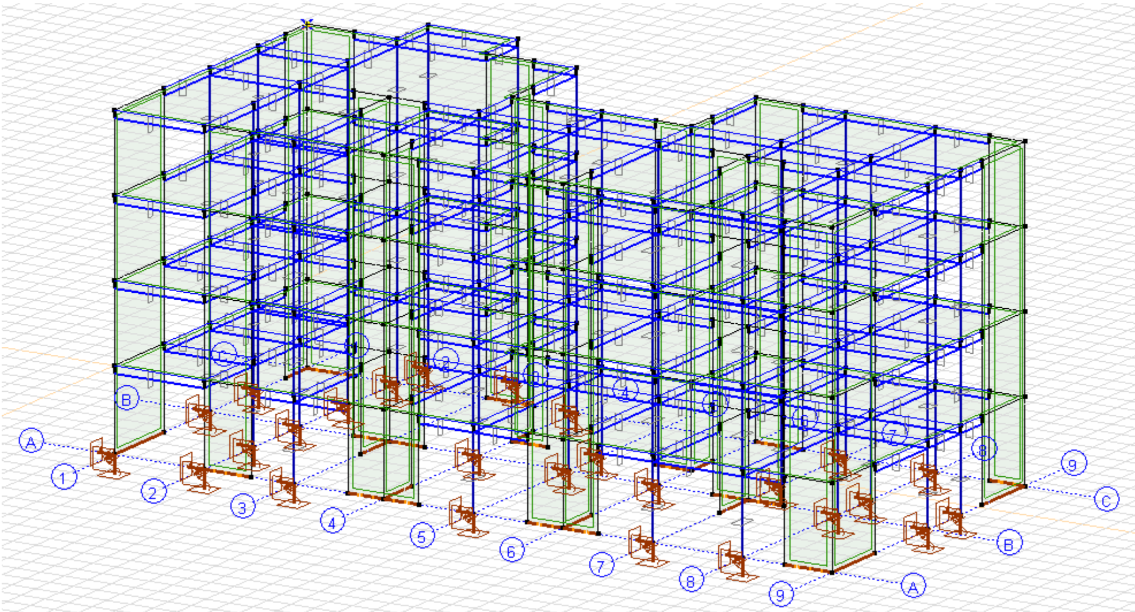

Figure 7 – 3D view of the structural calculation model

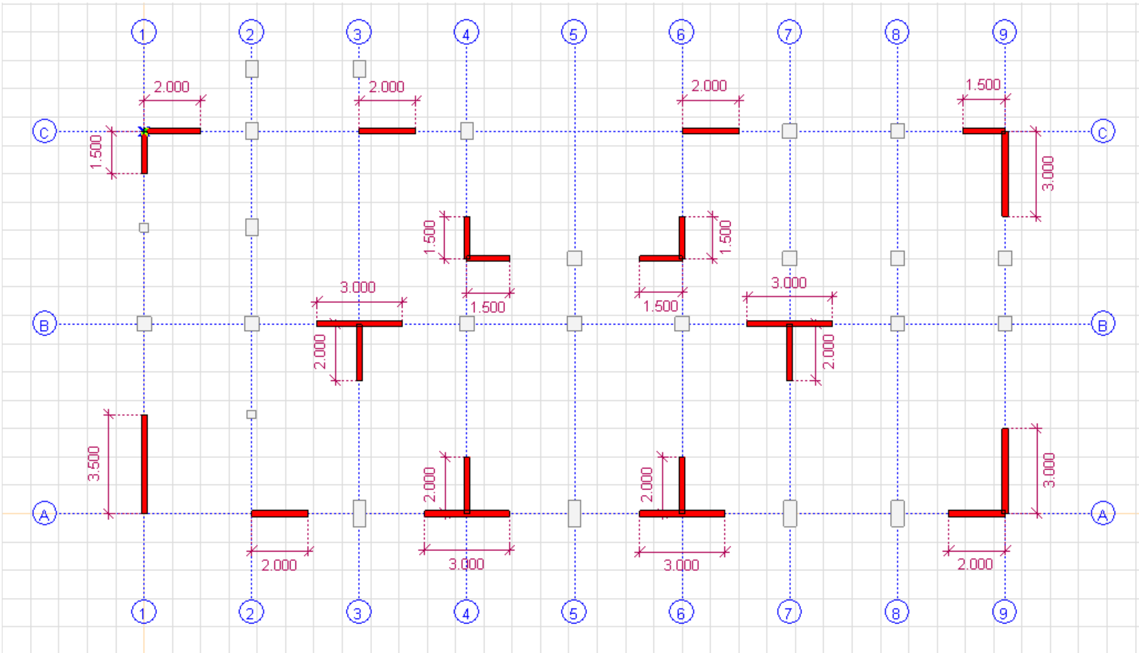

Figure 8 – General plan for the arrangement of the new structural walls

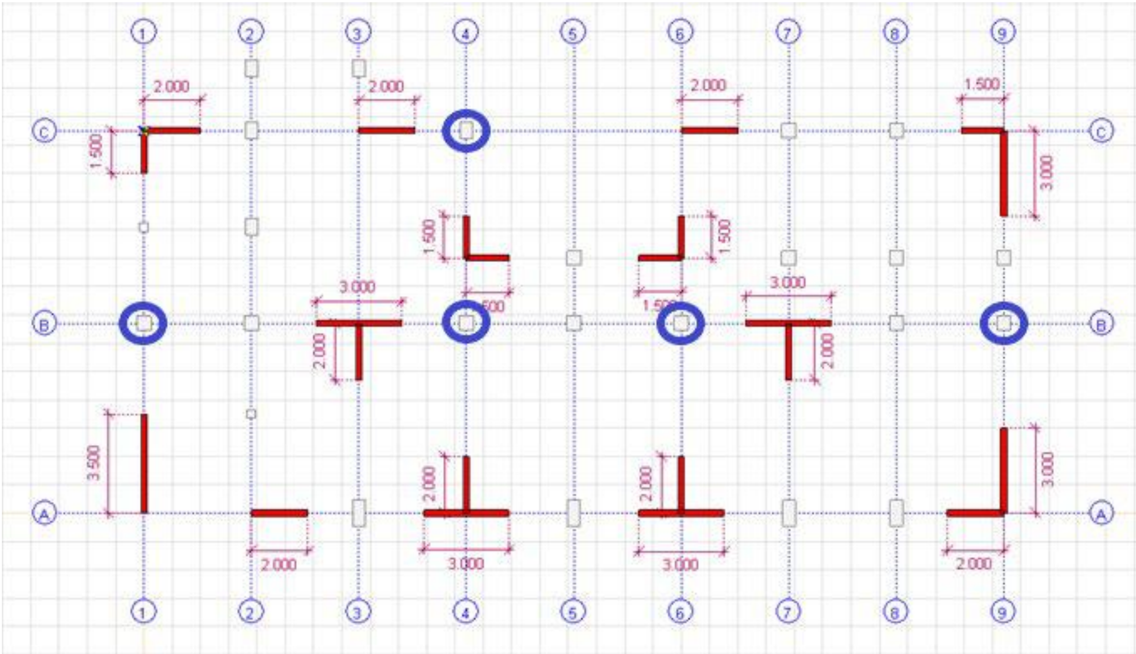

Figure 9 – Proposal for column jacketing

The verification of inter-storey drift is satisfied for both ultimate limit states.

The verification of the structural capacity of the elements was carried out by comparing the required amount of reinforcement needed to ensure sufficient capacity of the elements under the loads resulting from the linear static analysis with the actual amounts of reinforcement proposed. For the evaluation of each individual element, the most unfavorable stress/load conditions identified in all load combinations were considered.

The possibility of reinforcing the new beams (20x60cm) that will connect the proposed walls was also verified.

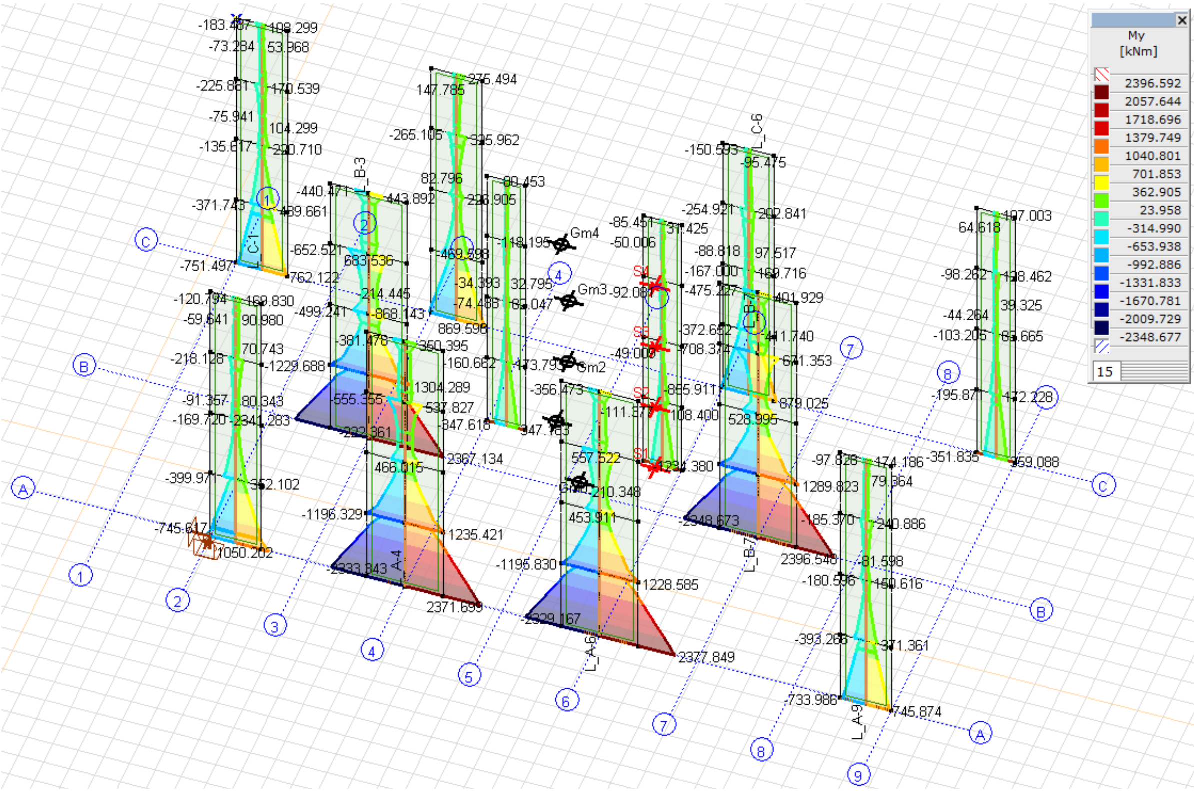

Figure 10 – Bending Moment Envelope for Longitudinal Walls

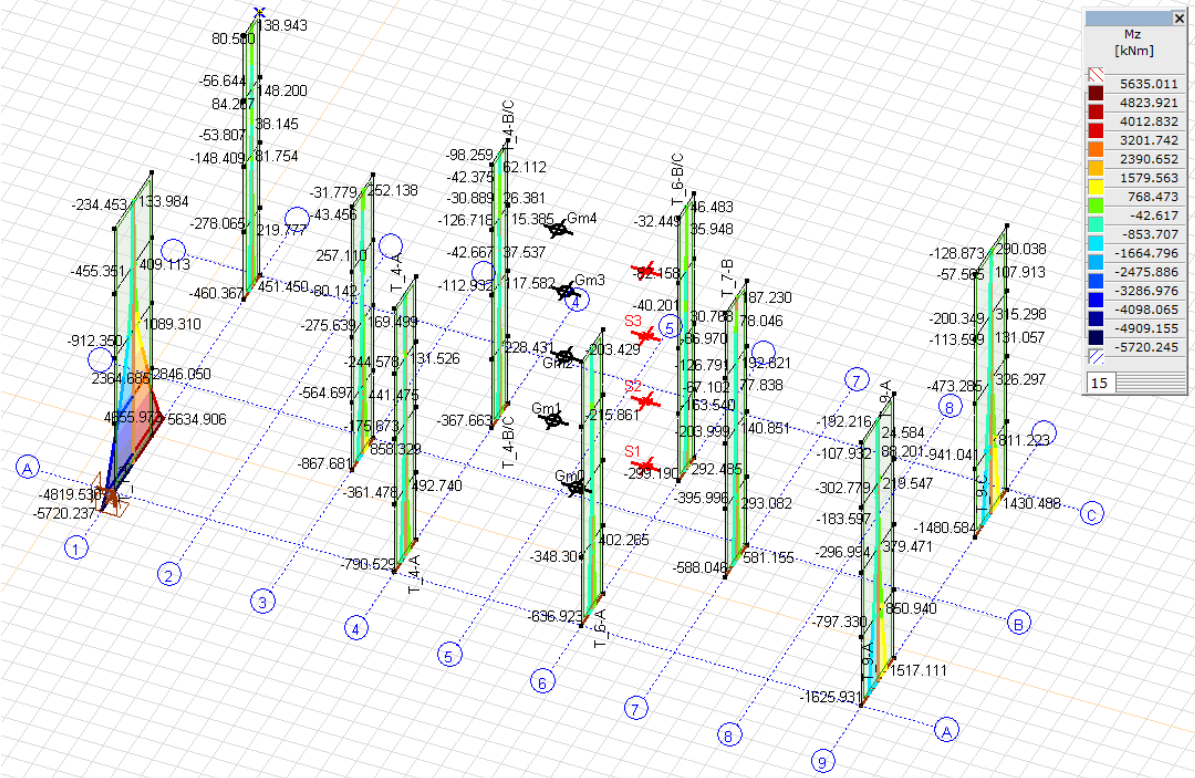

Figure 11 – Bending Moment Envelope for Transverse Walls

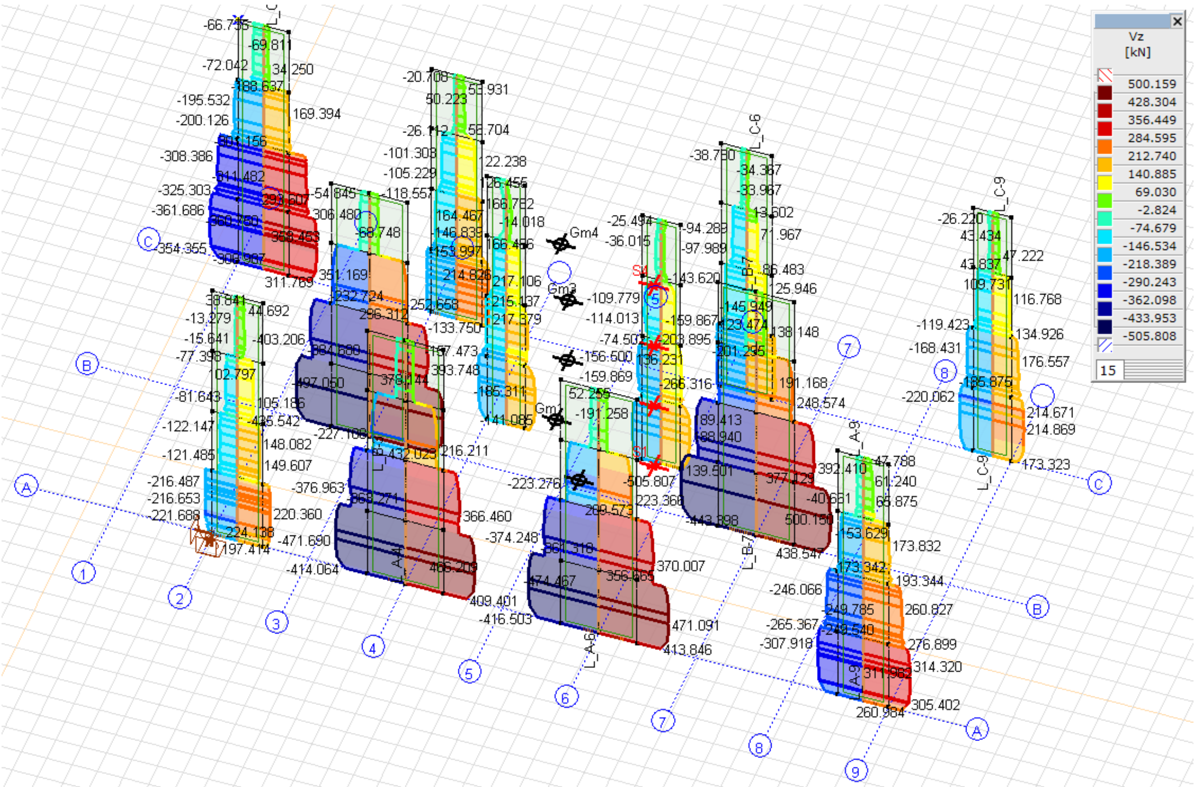

Figure 12 – Shear Force Envelope for Longitudinal Walls

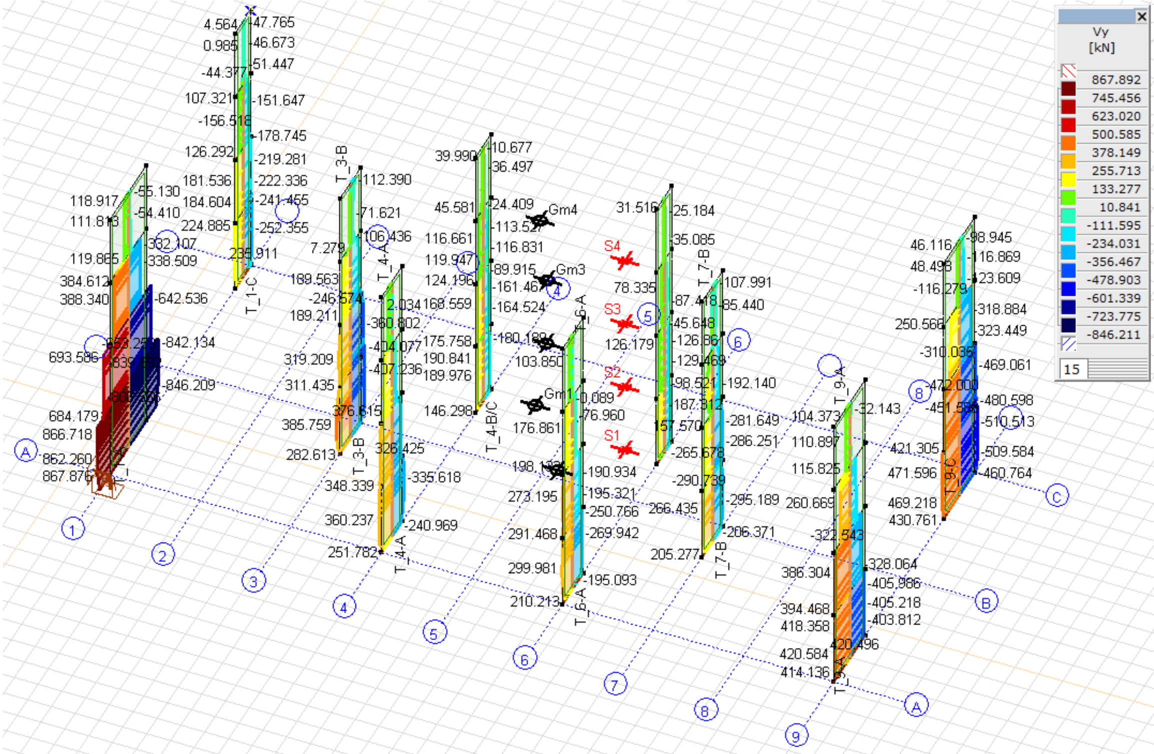

Figure 13 – Shear Force Envelope for Transverse Walls

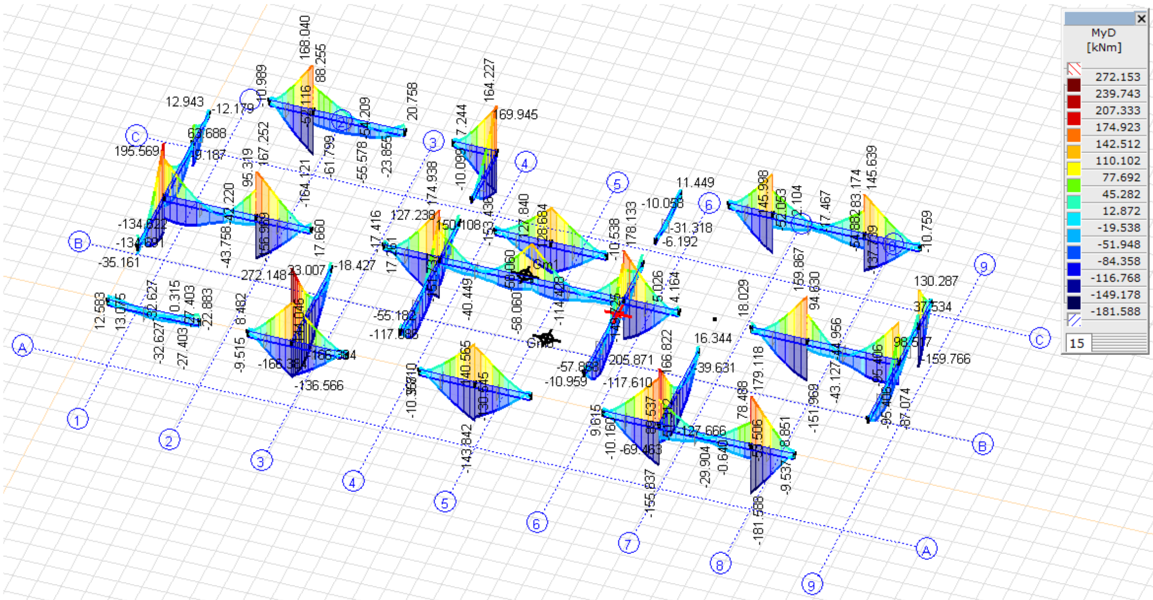

Figure 14 – Bending Moment Envelope for Proposed Ground Floor Beams – 20x60cm (M_{max} = 272 kNm; M_{min} = 182 kNm)

The application of the previously presented solutions leads to the classification of the building in seismic risk class RsIII. To achieve classification in seismic risk class RsIV, the presented solution is maintained and the cross-sections of the vertical elements are increased by 5 cm.

Research in the field of methods and techniques for strengthening multi-storey buildings is essential for ensuring structural integrity and public safety. In a world constantly exposed to seismic risks, climate change, and other extreme natural phenomena, multi-storey buildings must be capable of withstanding significant demands without compromising structural stability.

Chapter 11 – Final Conclusions

The research project highlighted the importance of thoroughly understanding multi-storey buildings from all perspectives, starting with the structural configuration, the period of construction, the technical regulations in force at the time of design, the quality of execution, the behavior of the building over time (with identification of all factors contributing to its degradation), as well as whether or not the building was rehabilitated after each earthquake. The research also revealed that, following major earthquakes, multi-storey buildings were not subjected to a consolidation program, but in most cases, they were rehabilitated only through finishing works. This justifies the conclusion that the vulnerability of multi-storey buildings can be considered **evolutionary**.

Through the research program, a number of **7 objectives** were established, aiming at the study of the history of blocks in Romania, design prescriptions with identification of factors influencing durability, the materials and technical solutions used—data absolutely necessary for adopting intervention solutions.

A correct evaluation of the seismic risk level, based on the aspects mentioned above and correlated with the building's behavior over time, contributes to increasing the level of understanding and to the possibility of applying new technologies.

The research project, through its objectives and obtained results, aligns with sustainability and resilience programs promoted by the government, as well as those initiated at the European level.

- Under **Objective 1**, analyses and studies were carried out on different types of multi-storey structures, identifying the constituent material, construction technology, and the structural concept designed according to the technical prescriptions valid at the time of construction. These aspects were correlated with the evolution of technical prescriptions, allowing the identification of critical points to be considered in future investments, as well as the factors that generated them.
- Under **Objective 2**, based on research conducted on different structural types—from those built at the end of the 19th century, through the interwar period, and up to those built after 1950—taking into account the entire scientific evolution of design codes, the research results allowed the creation of a highly useful **database** for quantifying the degree of risk and vulnerability.
- Under **Objective 3**, the most permissible intervention measures were identified, and selection criteria were established depending on the observed deficiencies, nonconformities, as well as shortcomings of the technical prescriptions and regulations used during the various construction stages. Additionally, the doctoral thesis identified modeling and calculation procedures for existing buildings, which made it possible to highlight vulnerable zones and critical elements, facilitating the adoption of an appropriate **crisis management** approach.

In this way, the research project achieved all of its proposed objectives.

An important aspect in achieving the objectives was the use of a **research method that combines theoretical analysis with experimental testing**, based on studies and research conducted in accredited laboratories.

This experimental testing was carried out both destructively, by extracting core samples from various elements, and non-destructively, using **ultrasound, radiography, vibrations, or thermography** to detect cracks or degradation without affecting the structure.

To achieve **Objective 6**, the thesis presents an analysis of a multi-storey building constructed in 1962 (D+GF+9F) and another structure built between 1966–1972 (D+GF+2F), using finite element modeling under various loading scenarios. The simulations were performed using structural calculation programs to quantify **structural performance** under different conditions.

The long-term behavior was interpreted through **structural monitoring**, which quantified the building's response in real time.

Importantly, the doctoral thesis also presented several possibilities for the application of **BIM** (Building Information Modeling), both for a **synthetic and realistic quantification** of behavior and for identifying vulnerable areas, as well as for **predicting future high-risk zones** to adopt effective measures.

The objectives were met, and the **research results provided highly valuable information** necessary for applying to multi-storey buildings, making it possible to **quantify both real risk and intervention coordination** in exceptional scenarios.

Throughout the research project, a significant volume of publications was studied, and the research findings were synthesized in the **doctoral thesis of 243 pages**, containing **112 images and graphics**.

It is evident that a chronological record of construction solutions, materials used, main behavior deficiencies, and identified vulnerabilities can provide a necessary **database for working hypotheses** in monitoring activities.

The thesis includes a **synthetic analysis of intervention works**, considering the possibility of performing strengthening work **without affecting residential units**. This represents an original concept, as strengthening and rehabilitation works raise significant challenges due to the intervention approach, both in **Romania and across the EU**.

The originality of the research lies in:

- Demonstrating that **Building Information Modeling (BIM)** is no longer limited to design use, but also valuable for:
    - **Simulating structural behavior** (as shown in the case study);
    - **Real-time risk management** (identified in the case study);
    - **Coordinating interventions** in the event of a new earthquake.

The results of the research are expected to be used in the next stage, especially for buildings owned or administered by public institutions, providing a valuable support for real-time intervention management.

The research results have been disseminated through the preparation of **two research reports**, presented at scientific events organized by "Ovidius" University of Constanța, and through the publication of five articles, including:

- One article under review in an ISI journal (MDPI);
- Two articles published in BDI-indexed journals;
- Two articles in Category C journals, indexed in Index Copernicus International, CEEOL, ROAD, and IBN.

The researcher also participated in seven national and international conferences and gave lectures at scientific events.

Through the project's objectives, significant personal contributions were made to advancing knowledge and supporting the digitization of construction processes.

The conducted research will contribute to reducing structural risks, modernizing the existing building stock, and thus implementing Romania's safety policy for buildings through an integrated approach to regulatory and governmental policies.

Finally, the results of the research open new directions regarding sustainability and resilience of buildings, particularly in their response to natural disasters, energy efficiency, and climate change.