# REPAIR AND STRENGTHENING OF REINFORCED CONCRETE STRUCTURES

A THESIS SUBMITTED TO

THE FACULTY OF ARCHITECTURE AND ENGINEERING

OF

EPOKA UNIVERSITY

BY

ELGA SENKA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR

THE DEGREE OF MASTER OF SCIENCE

IN

CIVIL ENGINEERING

OCTOBER, 2020

**Approval sheet of the Thesis**

This is to certify that we have read this thesis entitled **"Repair and Strengthening of Reinforced Concrete Structures"** and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

______________________

Dr. Erion Luga
Head of Department
Date: October 06, 2020

Examining Committee Members:

Dr. Erion Luga (Civil Engineering) ________________

Dr. Enea Mustafaraj (Civil Engineering) ________________

Assist. Prof. Dr. Hüseyin Bilgin (Civil Engineering) ________________

**I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.**

Name Surname: Elga Senka

Signature: ______________

# ABSTRACT


REPAIR AND STRENGTHENING OF REINFORCED CONCRETE STRUCTURES



Senka, Elga

M.Sc., Department of Civil Engineering

Supervisor: Dr. Enea Mustafaraj



Concrete is the most common material used in civil engineering. It has been a key factor in improving human life and creating a safe environment for society to live. Although it is the best constructing material, it is of course prone to damage and failure. Different techniques have been created and discovered in order to maintain, repair or strengthen reinforced concrete structures. The most common method used is the Concrete Repair and Maintenance System created in the late 1990's and frequently improved by researchers and civil engineers. The system consists of seven basic steps which if implemented correctly, give results in determining and selecting the right repair method and material and repairing the concrete structure. There is a wide range of materials that can be used in the aforementioned processes of repairing which have also been studied in order to select the right material for the right process of repairing. The materials are of a wide range and variety, each having its advantages and disadvantages. Coherently with choosing the right materials, the most benefiting method or repairing is also determined. The strengthening of reinforced concrete structures is another process which has been studied and a few guidelines have been created to make a preexisting concrete structure better, stronger, more durable. Strengthening is done through various ways from jacketing to using a new methodology which has yet to be thoroughly studied. Strengthening is used to increase the longevity of concrete structures. A case study is undertaken, consisting of a 4-story building, in Linzë, Tiranë which showed signs of damage from the earthquake of 26$^{th}$ of November 2019. A structural and seismic analysis was done to determine the

capacity of the structure and further determine the right method for the repair and strengthening of the structure.

***Keywords:*** *Strengthening, repair, reinforced concrete, structures, failure, damage, techniques.*

# ABSTRAKT

RIPARIMI DHE PERFORCIMI I STRUKTURAVE BETONARME

Senka, Elga

Master Shkencor, Departamenti i Inxhinierisë së Ndërtimit

Udhëheqësi: Dr. Enea Mustafaraj

Betoni është materiali më i zakonshëm që përdoret në inxhinierinë e ndërtimit. Ka qenë një faktor kryesor në përmirësimin e jetës njerëzore dhe krijimin e një ambienti të sigurt për të jetuar shoqëria. Edhe pse është materiali më i mirë konstruktiv, natyrisht që është i prirur për dëmtime dhe dështime. Janë krijuar dhe zbuluar teknika të ndryshme në mënyrë që të mirëmbahen, riparohen ose forcohen strukturat e betonit të armuar. Metoda më e zakonshme e përdorur është Sistemi i Riparimit dhe Mirëmbajtjes së Betonit i krijuar në fund të viteve 1990 dhe i përmirësuar shpesh nga studiuesit dhe inxhinierët e ndërtimit. Sistemi përbëhet nga shtatë hapa themelorë të cilët nëse zbatohen si duhet, japin rezultate në përcaktimin dhe zgjedhjen e metodës dhe materialit të duhur të riparimit dhe riparimin e strukturës së betonit. Ekziston një gamë e gjerë e materialeve që mund të përdoren në proceset e sipërpërmendura të riparimit të cilat janë studiuar gjithashtu në mënyrë që të zgjidhni materialin e duhur për procesin e duhur të riparimit. Materialet janë të një game dhe varieteti të gjerë, secili ka përparësitë dhe problemet e veta. Në mënyrë koherente me zgjedhjen e materialeve të duhura, përcaktohet edhe metoda më e dobishme e riparimit. Forcimi i strukturave të betonit të armuar është një proces tjetër i cili është studiuar dhe janë krijuar disa udhëzime për ta bërë një strukturë betoni ekzistuese më të mirë, më të fortë, më të qëndrueshme. Forcimi bëhet përmes mënyrave të ndryshme nga xhaketa te përdorimi i një metodologjie të re e cila ende nuk është studiuar në tërësi. Forcimi përdoret për të rritur jetëgjatësinë e strukturave të betonit. Është ndërmarrë një studim rasti, i përbërë nga një ndërtesë 4-katëshe, në Linzë, Tiranë e cila tregoi shenja dëmtimi nga tërmeti i 26 Nëntorit 2019. Është bërë një analizë strukturore dhe sizmike për të përcaktuar kapacitetin e strukturës dhe për të përcaktuar më tej metodën e duhur për riparimin dhe forcimin e strukturës.

***Fjalët kyçe:*** *Përforcimi, riparimi, betoni i armuar, strukturat, dështimi, dëmtimi, teknikat.*

***Dedikuar mbesës sime, Mei, e cila erdhi ne jetë së fundmi dhe është dhurata më e bukur.***

***Dedikuar mamasë sime, Donikës, në mënyrë të veçantë, e cila është shtysa ime më e madhe, njeriu që e bëri të mundur këtë arritje dhe njeriu që shpresoj ta bëj krenar.***

***Dedikuar familjes sime, të cilët janë suporti im dhe arsyeja përse unë mund të bëhem versioni më i mirë i vetvetes.***

***Dedikuar motrës sime, Anxhelës, e cila ka qenë pjesë e rrugëtimit tim dhe një shpatull ku të mbështetesha në ditë me shi e në diell.***

# ACKNOWLEDGEMENTS

Special thanks to my thesis advisor, Dr. Enea Mustafaraj for his hard work and dedication and for pushing me to do better during my period as a student of Epoka University. Thanks to his persistence I was able to finish this task successfully.

I would also like to thank my friends Ola and Franc, my fellow colleagues Roberto and Enxhi for their help, my cousin Ani for being the best work partner there is and everyone who has been supportive.

Thank you to my classmates.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Ever since their creation, either manmade or created naturally, structures were subjected to destructive and disintegrative actions. Disintegration and destruction are common laws of nature. They act upon even the most modern structures where there is maximal optimization for structural performance and longevity. These modern structures, ranging from skyscrapers to lengthy bridges, have very expensive construction costs. Thus, it is of more interest and importance that durable structures are constructed, which have low maintenance costs. Maintenance pertains to the need of a certain structure to maintain a given level of technical performance. Whereas performance includes durability, load bearing capacity, serviceability and aesthetics.

There are many causes that incur concrete damage. Weather, structural overload, abrasion and erosion, chemical damages due to sulfate bearing waters or soil, acids, carbonation and corrosion of the reinforcing steel are some examples. With time, materials deteriorate. There is also the possibility of design and construction defects and foundation movements. Earthquakes are also very dangerous for concrete structures, especially for high structures such as skyscrapers. The higher the structure, the more seismic forces it is subjected to.

One very common mistake has been building without proper seismic codes, either Eurocodes or American Standard Building -*/Codes, especially in regions with high seismic activity. Lack of maintenance or improper maintenance operation, can accelerate the degrading process of the structure and results in lowering the structure's performance. If performance succumbs to lower levels than primarily designed, then there rises a need for repairing. To meet the ever-changing requirements, a structure needs to be improved or reinforced in order to increase its longevity and increase the level of technical performance.

Ever since the first concrete was poured in 1903, concrete repairs were needed. The ways to repair existing concrete have evolved in the 112 years of its use in engineering. The ways to repair concrete are multiple but one is proved to be the most effective and the most used among concrete repairers. It requires a 7-step procedure, called the Reclamation's Concrete Maintenance and Repair System that is designed to be specifically undertaken in sequential order. There also exists a guide called the Standard Specifications for Repair and Maintenance of Concrete, M-47 which contains an appendix with specifications regarding concrete workmanship using more up-to-date methods and materials.

The 7-step procedure is as follows, conducted in a logical sequence:

1. Determine the cause(s) of damage
2. Evaluate the extent of damage
3. Evaluate the need to repair
4. Select the repair method and material
5. Prepare the existing concrete for repair
6. Apply the repair method
7. Cure the repair properly

As previously mentioned, some of the causes for concrete damage are thawing and freezing weather, cavitation, structural overload, erosion-abrasion, sulfate bearing waters or soils, carbonation, alkali-aggregate reaction and corrosion of the reinforcing steel. Defects in the design or implementation phase also cause concrete damage. Poor materials, workmanship and foundation movements can cause this occurrence too. Human error or lack of professional information can cause damage to the concrete, which in turn depending on the role the element plays in the load bearing of the structure, can cause a collapse or a decrease in its load bearing capacity, as in the case of apartment buildings. It must be determined if the damage is a one-time event or a recurring event.

Inadequate design standards, low quality materials and inadequate workmanship reduce the durability of concrete and increased the probability of deterioration. Chemical effects, such as sulfate or alkali-silica deterioration cause cracks in the exterior surface of the concrete. These cracks may be from shallow to very deep cracks, the latter creating bigger problems such as corrosion of the reinforcing steel. Weather cycles can accelerate the deterioration of the surface cracks and make way for chemical reaction to affect the reinforcing steel. Structural problems are divided in three categories:

1. Concrete Problems - Flexure, Shear, Torsion, Tension Cracks;
2. Structural Members Problems - Splitting, Diagonal and Horizontal cracks in columns;
3. Steel Problems - Rusting, buckling, bending, twisting distress

To make a proper evaluation, samples are needed for testing to support decisions to make repairs.

## 1.2 Scope of works

In this thesis, there will be described some useful strengthening techniques such as concrete jacketing, steel bracing, replacement of damaged structural members or demolition the structure, as well as the materials used in these repairing and strengthening techniques and the methodology by which they are implemented.

The main objective is to investigate the structural behavior of a structure by taking into consideration the same structure when subjected to concrete jacketing and when constructed with conventional reinforced concrete.

## 1.3 Thesis Objective

The purpose of this topic is to study the techniques for repair and strengthening of reinforced concrete elements through classical and modern methods referring to Eurocodes. The first step in reinforced concrete repairment is determining the problem. The second step is to evaluate the extent of the damage. To choose the most adequate method for repair or strengthening, there need to be an evaluation of the damage structure in order to choose the right materials and method. Next, it is evaluated if the structure needs repairing or strengthening. Choosing the needed repair method and material is the next stop of the procedure. After these materials are selected, the repair method is applied and the concrete is cured according to orders and evaluations. The problems, as previously stated, are of different nature and calculation and the reinforcement strategy are accompanied by relevant details. Reinforcement methods are also commonly used in steel structures, wood, brick masonry and so on. The strengthening of said structures is done by the following methods:

1. Cast-in-place concrete – Replacing the defective concrete with new concrete.
2. Form and pour – Replacing damaged concrete by placing a repair mortar in a cavity.
3. Troweling – For shallow or limited areas of repair. Done by using Portland Cement Mortars, proprietary cementitious materials or polymer-modified grouts or polymer grouts and mortars.
4. Dry packing – Hand placement of a very dry Portland cement mortar which is tamped or rammed into place.
5. Preplaced aggregate – The aggregate is placed in the forms and the voids are filled by pumping cementitious or resinous grout.
6. Shotcrete – Pneumatically conveying concrete or mortar through a hose at a high velocity onto a surface.
7. Injection grouting – Filling cracks or open joints with cementitious or chemical materials.
8. External Reinforcing – This method uses steel elements, Fiber Reinforced Polymers (FRP), Post-tensioning cables or other materials placed on the surface of the structure to strengthen them.

These materials, referred to as FRP are materials with high tensile strength, which bind to the surface of a structural element, reinforcing it. The most common are FRP prepared with carbon fiber. We will dedicate one of the following chapters to concrete jacketing of a structure and its behavioral analysis.

## 1.4 Organization of the thesis

This thesis is divided in 5 chapters. The organization is done as follows:

In Chapter 1, the problem statement, thesis objective and scope of works is presented. Chapter 2, includes the literature review which consists on the repair and strengthening materials used in recent developments. Chapter 3, consists of methods used in strengthening and repair of RC structures and the strengthening of RC structures using FRP materials, steel plates, concrete jacketing, steel braces and adding reinforced concrete structural walls. In Chapter 4, a case study is taken in consideration to review what experimental results proved of these methods usage. In Chapter 5 conclusions and recommendations for further research are stated. References will show where this study is based and the guidance followed for the thesis. Appendices contain additional Figures and details regarding the case study.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

There are various categories of materials that are used in repairing and strengthening of RC Structures. These materials will be discussed thoroughly in the following subchapters, analyzing their properties, advantages and disadvantages.

## 2.2 Repairing and Reinforcing Materials

The main categories are cementitious materials, polymer materials and fiber reinforcement polymer materials and adhesives. The best materials are categorized using their ability to match the properties of the concrete that will be repaired or strengthened.

### 2.2.1 Cementitious Materials

Conventional concrete is made of Portland cement, water, aggregates and admixtures in case of accelerated results. Admixtures can improve workability, accelerate drying or retard hydration, increase strength and so on. Fly ash or silica fume are pozzolanic materials which can reduce early hydration and improve strength development. Conventional concrete is the most commonly used material in civil engineering and the most well understood, economical and easy to produce. It is a workable material, good in bending and has a great load bearing capacity.

Conventional mortar is a mixture of Portland cement, fine aggregate and water. Admixtures are added to minimize shrinkage. It is a highly workable material and it is great at small repairs and strengthening.

Dry Pack Mortar is one-part cement and ½ part sand or prepackaged proprietary materials and enough water to create mortar. It is a material with good durability, strength and water tightness. They are used to fill large or small cavities that allow for adequate compaction. It is also used for repairing dormant cracks but not recommended to repair or fill active cracks.

***Figure 1 Dry Pack Mortar***

Ferrocement is a form of reinforced concrete created by using hydraulic cement mortar with a relatively small diameter wire mesh made of steel or other ferrous materials. This material is of very high tensile strength and displays superior cracking behavior. It is suitable for curved surfaces.

Fiber-Reinforced Concrete is concrete strengthened with metallic polymer fibers. When adding fibers, the slump is reduced thus increasing workability. This material can be used by inexperienced workers. Structures that are subject to earthquakes can implement the usage of FRC. One downside to this type of concrete is that rust stains may occur due to the corrosion of the fibers on the surface. The presence of metallic fibers can influence corrosion activity on reinforcements. This type of material can be used in many different types of structures.

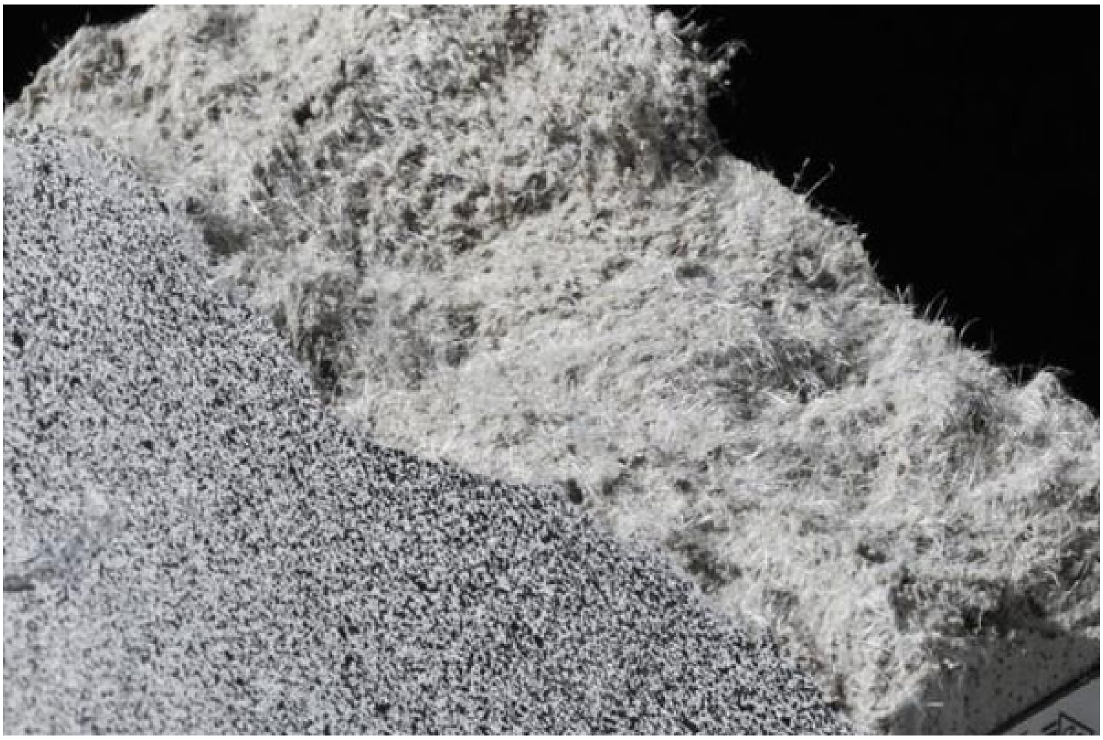


***Figure 2 Fiber Reinforced Concrete***

Grouts can be hydraulic, cement or chemical. Cement grouts are made of mixing hydraulic cement, aggregates, admixtures and water. This material is very trowel able, flowable and pumpable which means that it is very easy to apply. It is economical and easily mixed. Cement grouts are injected into the opening of the repair structures. Hydraulic cements are used in bonding old and new concrete. Chemical grouts consist of chemical solutions mixed with water to form a gel that is injected in cracks. A major pro of this material is that it can be applied in environments with high humidity, underwater or under moist environmental conditions. They have the ability to restore the full strength of the concrete members. Grouts are expensive and don't have high workability because of their viscous properties.

Low Slump Dense Concrete is a special type of concrete that gains strength rapidly and has high serviceability. It exhibits reduced chloride permeability thus can be used in environments with present of salt water. The low water to cement ratio means that this type of concrete needs longer continuous curing.

Shotcrete is a produced by mixing Portland cement, sand and water placed by compressed air. It is a very durable repair material that exhibits excellent bondage with existing concrete. However, it needs very good workmanship as it needs experienced workers.

Silica-Fume Concrete is a byproduct of silicon and ferrosilicon alloys which when added to a concrete mixture, scientifically improves compressive strength, decreases permeability and improves durability. It is an economical solution since they are a byproduct of alloys.

Bonding materials are categorized into epoxy resin materials which are not to be used in hot weather; Latex bonding agents shouldn't be used in high humidity areas; and cement-based systems.


***Figure 3 Epoxy Injection***

### 2.2.2 Polymer Materials

Polymer materials are commonly used in improving the qualities of hardened concrete. There are three types of polymers infused into concrete.

Polymer-Impregnated Concrete or PIC is hydrated Portland cement concrete infused with a monomer which is subsequently polymerized. The impregnation of polymers into the concrete improves resistance to penetration thus making it resistant to abrasion; penetration from water, acids, salt and other abrasive materials; increasing resistance to weathering effects like freezing and thawing. Polymer Impregnation can be done on pre-existing concrete with the proper procedures. All cracks must be filled prior to the impregnation in order to create a durable concrete and increase durability

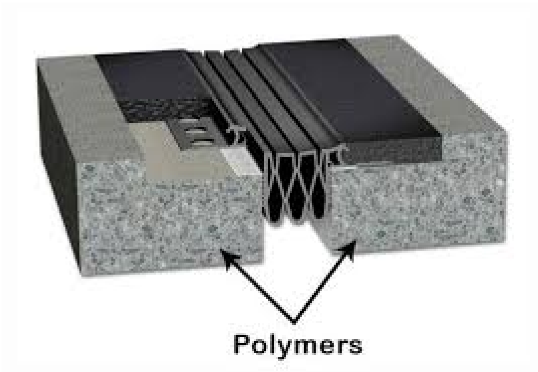



***Figure 4 Polymer Impregnated Concrete***

Polymer-Modified Concrete (PMC or LMC) sometimes called Latex-Modified Concrete is a mixture of Portland Cement and aggregates with organic polymers and dispersed in water. To improve concrete properties such as improved bond strength, increase flexibility and impact resistance; improve water and salt penetration resistance; improve resistance to freezing, polymers are added in the concrete. By using the method of overlaying of LMC, it has been observed that in the long-term, the performance of the concrete has greatly increased overlays continue to exhibit great results even after many years after installation. The installation of PMC is as easy as Portland Cement Concrete but curing is different. In differentiation form common concrete that needs continuous curing, PMC only requires a 1-2 days of curing. Another upside of PMC is its workability and ease of application. However, Polymer-Modified Concrete does not show good results when poured under hot weather conditions since it has a low water-cement ratio which makes it have a tendency for plastic shrinkage. This type of material is used in repairing and strengthening of bridges, decks and floors and patching of concrete surfaces.

Polymer Concrete has a different production method to the aforementioned materials. Although Portland Cement is present it is mainly used as a filler or aggregate. PC is a composite material made of a large group of different products instead of just a single product. The production of Polymer Concrete includes the use of epoxy, polyester, furan, styrene, et. Polyester resins are a low-cost material, Furan resins have good resistance to chemical attacks and also have low costs. Although Epoxy resins are more expensive than other resins, they have other advantages which greatly contribute to the final products properties. Depending on the amount used of different polymers, the properties of the final product vary. Rapid curing, high tensile, flexural and compressive strength, good adhesion to surfaces, good freezing and thawing durability, low permeability and good chemical resistance are some of the properties of PC. It is easily mixed and placed, just like conventional concrete. However, its working time depends on the atmospheric and weather conditions and it displays high shrinkage characteristics which need to be closely observed so unnecessary shrinkage is avoided. Epoxy resins can burn in fires and cause softening of the concrete. In such condition’s PC should be carefully considered in being used in structural members that can have fire presence. Polymer Concrete is mainly used in repair and strengthening of highways nut no limited to just that usage. It is a great repair material for high-strength structures and thin structures such as floors or bridge decks.

### 2.2.3 Fiber Reinforced Polymer Materials

Non-metallic fibers bundled in a resin matrix produce FRP materials. The type of fiber used refers to the type the FRP material, for example, AFRP is made of aramid fibers, CFRP is made of carbon fibers and GFRP is made of glass fibers. Generally, the volume of the fibers is about 50-70 % for strips and 25-35% for sheets thus making fibers the primary stress bearing material and the resins the stress transfer and protection of the FRP. The most common adhesive used is epoxy adhesive. Filler, solutions and toughening additives may also be used. There are two-time concepts when using epoxy adhesives. The pot life which represents the time to work with the adhesive after mixing the materials before hardening starts and the open time which is the time after the adhesive is applied to the adherents before they are joined together. Temperature level, called glass transition temperature, is also important since synthetic adhesives exhibit properties that very from temperature. Epoxy adhesives have many advantages, some being:

a) Good wetting properties
b) May have a long open time
c) Lack of curing agents minimizes shrinkage and makes way for bonding of large areas
d) Low shrinkage
e) Low creep and great strength under load
f) Can be applied on vertical surfaces

Polymeric matrix materials can wither be thermosetting or thermoplastic. The matrix provides protection for the fiber from abrasion and corrosion and binds the fibers to distribute load. Matrices also provide additional help to mechanical properties such as the transverse modulus and strength, shear strength and compression strength. Depending on the usage of the material, physical and chemical properties in example melting temperature viscosity have a say in the production process. Some thermosetting polymers are epoxy resins, polyester and used in high-performance reinforcing fibers. Polyester and vinyl ester are cheaper whereas resins display better mechanical properties and better durability.

Fibers are the best material that can be used in repairing and strengthening reinforced concrete structures. As previously mentioned, glass, aramid and carbon fibers are the types of fibers used in creating this FRP concrete.

Glass fibers are divided into E-glass, S-glass and AR-glass fibers (alkali resistant glass fibers). E-glass fibers have low alkali resistance and S-glass fibers have more strength and stiffness but are still on the lesser of alkali resistance. Glass fibers are of low cost which make them easily providable.

Aramid fibers have higher strength and modulus in the longitudinal direction. They respond good in tension as they are elastic, are tough and have damage tolerance but they are ductile under compression.

Carbon fibers are categorized in two; pitch fibers that are produced using refined petroleum or coal and Pan fibers that are made of polyacrylonitrile carbonized by burning. These fibers have extremely small diameters respectively 9-18 um for pitch fibers and 5-8 um for PAN fibers. Carbon fibers have a unique crystal structure that varies from the orientation of said crystals. Pitch carbon fibers, as do PAN fibers exhibit high strength and elasticity.

***Figure 5 Fiber Reinforced Concrete***

# CHAPTER 3

# METHODOLOGY

## 3.1 Techniques of repairing and strengthening reinforced concrete structures.

As previously discussed, there are many reasons for the degradation of reinforced concrete structures. Spalling, disintegration and cracking are some of the most common problems of concrete which can be caused from poor workmanship, poor materials, poor design or a combination of these human factors. Other reasons also include weather conditions, chemical conditions, cavitation, structural overloading, and so on. Crack repair is not usually associated with strengthening. When repairing spalling and disintegration, strengthening might be necessary since it is common for reinforcement corrosion and losses of section are present.

Cracks are categorized as dormant or active cracks and are determined by periodic observations. If the cracks show a significant displace after a period of time, usually 6 months or 1 year, then it is safe to say that the crack is dormant, otherwise the cracks are classified as dormant. Cracks are divided into solitary and pattern cracks. Solitary cracks are caused by concrete overstressing from extensive load or shrinkage. Pattern cracks are cracks that occur in the surface of concrete or on thin slabs. There are several techniques for crack repairs.

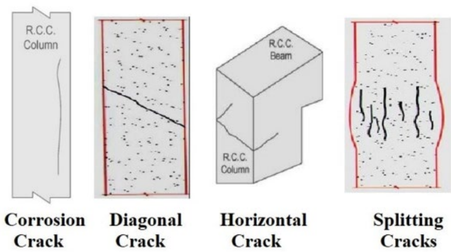



*Figure 6 Different Types of Cracks on Reinforced Concrete Structures*

## 3.2 Crack repair technique

### 3.2.1 Bonding with epoxies:

Cracks are drilled into and water or a different type of solvent is injected to flush he defect. The surface is then allowed to dry. Afterwards the surface between the injection points is sealed and epoxy is injected until it flows out of the adjacent crack. This technique is not effective unless the crack is dormant or turned into a dormant crack or if the cracks ae numerous.

### 3.2.2 Routing and sealing:

In this method the crack is enlarged along its exposed face and sealer of a suitable material is placed. Unfortunately, this method is not very esthetic as it leaves a damaged figure.

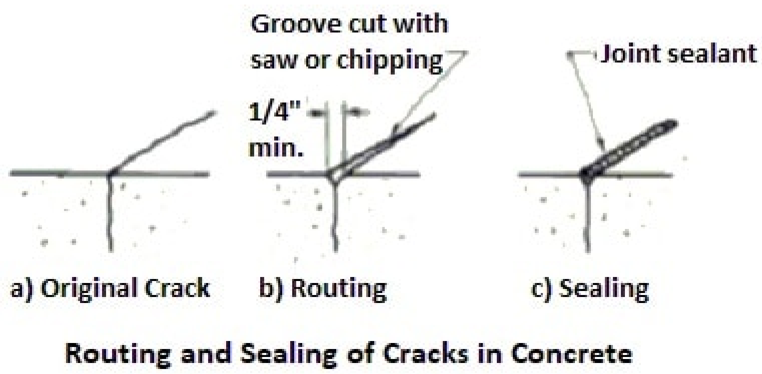
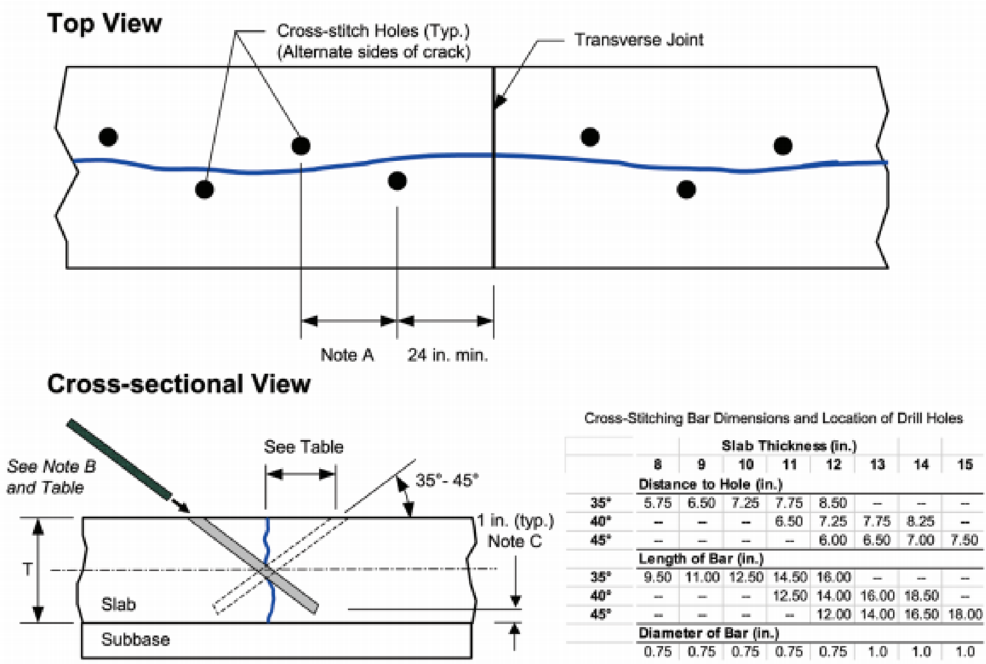



*Figure 7 Routing and Sealing of Cracks*

### 3.2.3 Stitching

Stitching is done by iron or steel dogs. Different lengths of rods are to be used, in the U-shape with 15 cm ends inserted into the body of the concrete. Holes are drilled on both sides of the concrete, starting on the side which is opening up first. Diagonal stitching helps with shear resistance along the crack. It is recommended that the lengths of the dogs are random so that no plane of weakness is formed.




Cross-Stitching Bar Dimensions and Location of Drill Holes

| | Slab Thickness (in.) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| | **Distance to Hole (in.)** | | | | | | | |
| **35°** | 5.75 | 6.50 | 7.25 | 7.75 | 8.50 | – | – | – |
| **40°** | – | – | – | 6.50 | 7.25 | 7.75 | 8.25 | – |
| **45°** | – | – | – | – | 6.00 | 6.50 | 7.00 | 7.50 |
| | **Length of Bar (in.)** | | | | | | | |
| **35°** | 9.50 | 11.00 | 12.50 | 14.50 | 16.00 | – | – | – |
| **40°** | – | – | – | 12.50 | 14.00 | 16.00 | 18.50 | – |
| **45°** | – | – | – | – | 12.00 | 14.00 | 16.50 | 18.00 |
| | **Diameter of Bar (in.)** | | | | | | | |
| | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 1.0 | 1.0 | 1.0 |

**Note A:** *Distance between holes is 24 in. for heavy traffic; 36 in. for light traffic.*
**Note B:** *Epoxy deformed bar into hole. Length shown in table provide 1 inch cover at surface and assume drilling per Note C.*
**Note C:** *Do not drill hole completely through slab. Stop drilling so epoxy/grout will not run out of the bottom while backfilling.*

***Figure 8 Stitching of Cracks***

### 3.2.4 External stressing

External stressing manages to close cracks by inducing a compressive force larger than the tension. A form of abutment is necessary to provide anchorage for the wires or rods.

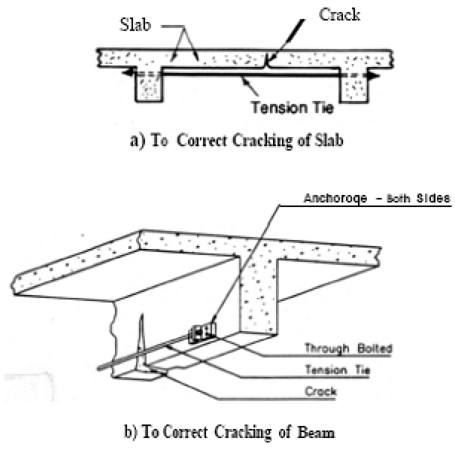



*Figure 9 External Stressing of RC Members*

### 3.2.5 Grouting

Grouting is very similar to injection. The surface along the crack is cleaned and built-up seats are installed at intervals along the crack. The crack is sealed between the seats and the crack is flushed in order to be cleaned and is finished by grouting the whole surface.

### 3.2.6 Blanketing

Blanketing is similar to routing and sealing and is used in both active and dormant cracks. A chase is cut in the form of a square and the bottom should be smooth in order to break the bond between the sealant and the concrete. Elastic sealants, mastic sealants or mortar-plugged joints are used depending on the amount of movement anticipated and the temperatures present on the surrounding environment.

### 3.2.7 Overlays

Active cracks are sealed using the method of overlaying. The overlay needs to be extensible and flexible. For repair on roofs, gravel is used. Concrete or bricks are also used in places where the fill is placed against the overlay. For asphalt repairs, an asphalt block is used in areas with heavy traffic.

***Figure 10 Overlaying Method***

## 3.3 Spalling and Disintegration repair

Spalling and disintegration, usually, are associated with substantial structure losses of section and reinforcement corrosion. Thus, when repairing spalling and disintegration, external reinforcement of the structural members is needed.

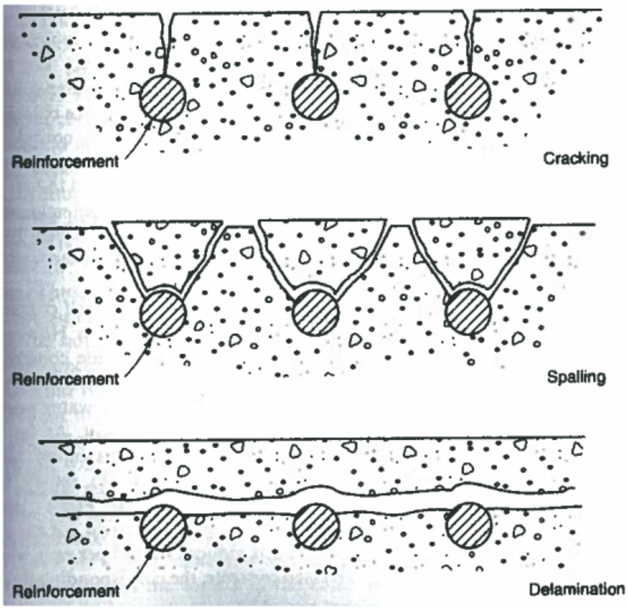



***Figure 11 Spalling and Disintegration***

### 3.3.1 Jacketing

Jacketing is applicable in the repair of columns, piers and piles. It is done by encasing a compression member which is deteriorated, through an encasement in new concrete. The encasement may be of different materials such as timber, gauge metal, iron or precast concrete. The forms are filed by pumping the grout, by using prepackaged concrete, dewatering the form if underwater works and placing the concrete to dry. Before placement, the forms should be filled more than the volume of the form, and after placement the grout should be allowed to settle. Finally, the forms should be vibrated went placed to settle.

### 3.3.2 Gunning

Gunning or shotcrete as previously mentioned, is used on vertical and overhead surfaces. It can also be used on horizontal surfaces that show spalling due to corrosion. As its name states, shotcrete is mixed and shot into place by compressed air. Cement and sand are mixed dry and transferred by air to a nozzle where water is injected through a spray at nozzle.

*Figure 12 Gunning*

### 3.3.3 Packed Concrete

Packed concrete is great when conducting underwater repairs. Forms with coarse aggregate and pumped with and-cement grout form prepacked concrete. When this method is applied the placing must be uninterrupted. It is used for surface repair of structures, jacketing, filling of cavities, on piers, abutments, retaining walls and footings.

### 3.3.4 Dry packing

Dry packing is used to produce intimate contact between new and old concrete. It is placed by hand, as the mortar is very dry and worked in place. It is a good mix for low shrinkage.

### 3.3.5 Concrete replacement

Concrete replacement is the act of replacing old damaged concrete with a fresh one in an area that is accessible and in water-tight constructions where the damage has completely destroyed the original concrete. It is also used to seal cracks, in overlays and in the restoration of spalled and disintegrated members. The materials used in this method of repair are mortar, bituminous compounds and epoxies.

## 3.4 Basic strategies for repairing and strengthening reinforced concrete structures

### 3.4.1 Introduction

Reinforced concrete elements repair is often done after a certain level of damage to the structure. Strengthening these elements is a good method to increase earthquake resistance, especially in regions with high seismic activity, as is Albania. These methods of repair improve ductility and increase the structure's strength. The first step prior to implementing these methods is acquiring information on the design of the structure, doing a structural load inspection and evaluating the structures load bearing capacity. After carefully considering all the above-mentioned inspections, interventions in the form of complete demolition, structural member replacement, strengthening with various methods of the existing damage elements or adding of new members can be done.

It is very important to establish the bond between old and new concrete, which is done by chipping away the cover of the original member and roughening the surface and laying epoxy prior to concreting. Additional welding or formations of steel dowels can also be necessary to complete the bond.

This chapter will explain what are some retrofitting techniques for damaged reinforced concrete structures, to increase their seismic performance, load bearing capacities and improve the structure's ductility.

### 3.4.2 Retrofitting

Retrofitting is the process of repairing a faulty structure which was affected by excessive load, earthquake motions or due to end of the structure's life service. It is also used in repairing old structures or strengthening its load bearing members. The selection of the retrofit type should be recognized by both the investor and the design team. This selection depends on the type of object to be studied; which goes in two directions: in the type of defects that the object may have from the point of view of its performance and the most efficient method that may be valid to perform this intervention. Thus, as the main techniques followed to perform a retrofit, for an existing object, we have: change of destination, total demolition of the object, temporary readjustment, partial readjustment, readjustment during the use of the object, readjustment when not in use, external and internal retrofit.

### 3.4.3 Addition of Reinforced Concrete Structural Walls

The addition of reinforced concrete walls, which intends to improve the repair, is one of the most commonly used methods. This method aims to reduce horizontal drifts and avoid the possibility of eventual damage to the structural elements of a given structure. Its final goal is increasing stiffness and load bearing capacities. The concrete walls can be prefabricated or be implemented in-situ. Particular attention should be paid to the method of calculation and the construction method by respecting design norms and codes. The addition of these walls increases the seismic performance. However, its main disadvantage is the integration of said walls into the existing structure. Another downside is the increase of the structure's load which increases the seismic loads. There is also the increase of vertical loads in the foundations of the new walls, which makes it necessary to intervene in the foundations of the structure. In total, the addition of reinforced concrete structural walls has high economic costs.

### 3.4.4 Steel Plates

Strengthening of reinforced concrete structures by adding reinforcement to their exterior is done using metal plates or carbon fibers (CFRP). Each of the materials used has its pros and cons. Steel plates are used when the reinforcement is insufficient but the concrete quality is good. This is called an external reinforcement done by using steel plates or hot rolled sections, mainly in the form of angle profiles. This method is successfully used because of its easy implementation, as they are easy to assemble and have great effectiveness in increasing the structure’s load bearing capacity.

The mechanical behavior and properties of these metal plates are also sufficiently studied in design. Their use is of great value increasing the bending of the structural members. Steel plates have good tensile properties and high tensile strength which improve not only the tensile resistance of the structure but also its tensile strength. These elements can also be used as external reinforcements in shear. However, the usage of steel plates has high economical costs. Steel plates can also be used as stirrups, by placing them in the perimeter of the structural elements, at certain areas (critical / non-critical) of the elements which need reinforcing. Their connection is done through bolting in the concrete or by using glues and epoxies.

***Figure 13 Steel Plate Strengthening of Beams***

### 3.4.5 Steel Braces

Steel braces are most commonly used to increase the lateral load resistance of steel structures. There exist two systems: internal bracing and external bracing. When using internal bracing system, steel frames are attached to the face of the building frame or as a whole external support. The members are inserted in the empty space between the beams and the columns. When bracing is attached to the frame, it can be direct or indirect.  In indirect internal bracing the transfer of the load of the steel bracing and the frame is exonerated indirectly through the steel frame. The usage of steel braces, in damaged building reduces bending moments and shear forces on columns. It transfers the lateral load to the foundation through axial action. Steel bracing is an economical, easy to implement method which provides flexibility to the structure. It has a tendency to improve lateral stiffness, strength capacity and displacement. Using steel elements in one of more floors is more efficient than using reinforced concrete walls, in terms of load bearing capacity, thus their use significantly increases the structure's load bearing capacity. The presence of the steel braces reduces to a relatively low extent the horizontal displacements. Having said that, earthquake damages of the structural members can be avoided. The fact that steel bracing does not allow for horizontal deformations, is also related to the denial of the predominance of the effect in the destruction of non-ductile points between the columns and beams or the destruction of the whole structure. Thus, steel braces are not effective in dual systems, in terms of stiffness.

The use of metal elements in the rigging of the structure constitutes a low cost in the intervention of the existing building. The special metallic elements that form the diagonals possess ductility from cyclic actions. From the above, it can be concluded that metal elements increase the flexibility of the structure and the load bearing capacity, so they increase the ductility of the structure. In this context, the structure is used in its plastic phase. The presence of steel braces, however, is not very desirable esthetically wise.

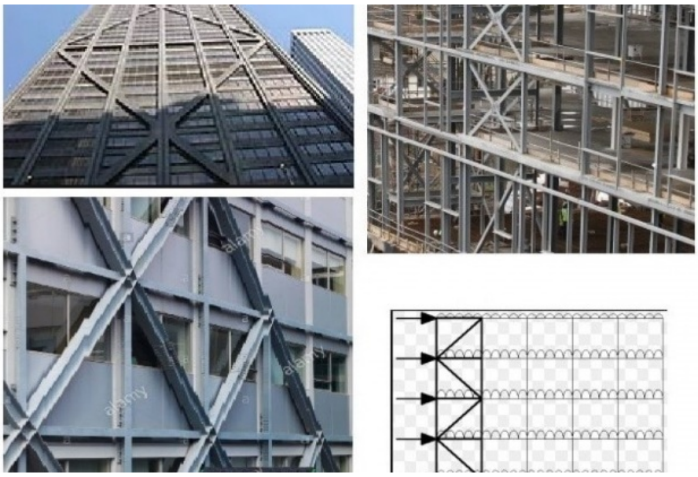


*Figure 14 Steel Bracing*

### 3.4.6 FRP Materials

FRP is the abbreviation of fiber reinforced polymers, which are non-metallic fibers mixed with a resin matrix. As previously stated, there are three types of fibers used specifically, AFRP or aramid fibers, CFRP or carbon fibers and GFRP or glass fibers. Carbon fibers are more economic when used in shear strengthening or flexural strengthening. The only matter that inflicts on the choice of the type of fiber used, that is laminate or sheet, is the economic aspect. When strengthening fluctuating live loads, carbon fibers should be used because of their better fatigue properties. Glass fibers should be chosen when confining concrete or at times for flexural strengthening. When layering curved surfaces, it is best to use aramid, glass or carbon fibers. On plane surfaces, only laminates can be applied. Carbon sheets are best used in narrow sections as carbon sheets are not easy to handle in thin strips.

In this section we will explain the advantages, disadvantages and usage of CFRP in repairing and strengthening damaged reinforced concrete structures. When compared to conventional construction materials, this method has many advantages, such as light weightiness and ease of application. FRP materials are not prone to corrosion since they are not made of metal. Its durability is directly linked to its matrix. Polymeric epoxy materials are more suitable in terms of durability. Epoxies do not absorb water but they can be destroyed by ultraviolet rays. However, by adding special additives to it, the risk of destruction by ultraviolet rays can be avoided. FRP materials must always be protected by fire. They are inflammable although more resistant to fire than steel plates. This is also due to the lower thermal conductivity of FRP. If the carbon fibers not in the matric come in contact with the reinforcement, there is a risk of corrosion. As long as the matrix is in contact with the fibers, this risk can be avoided. Electrical conductivity can be a risk for FRP destruction. To avoid this phenomenon, grounding is necessary. They are weightless, have high resistance to corrosion and are advantageous in repairing damaged structures.

***Figure 15 FRP Beams***

Three mechanisms can cause premature failure to the members which have been externally strengthened. Peeling failure is the occurrence of ripping of the over of the concrete. Debonding occurs far from the plate end. It is the removal of the layers due to the improper installation or the usage of an adhesive which is not strong enough. Debonding is associated with wide cracks, both flexural and shear. Finally, cover tension delamination, is the result of normal stresses which act upon the bonded laminate. When this phenomenon happens, the entire cover of the concrete is pulled away and the member is left with reinforcement on open air.

When wrapping a member in an FRP cover sheet there are three different types of covering methods: full cover, three-sided and two-sided. The full cover of the member is the safest and strongest way to ensure both structural strengthening and resistance increasing. When shear strengthening, the column should be completely wrapped by using cuts in the slab where the beam and the column are joined. The three-sided and two-sided wrap should be done with detailed structural member analysis and precautions taken into consideration.

There are no design codes regarding the usage of FRP materials in civil engineering, however there are guidelines that offer help in the design and implementation criteria. Eight national guidelines exist for the usage of FRP material which can be accepted as the best way to rightly use these materials in construction.

Although fiber reinforced polymers offer such great solutions regarding repairing and strengthening of reinforced concrete structures, it is not a cheap material. It is far more expensive than conventional concrete reinforced with steel. However, since FRP materials have shown great results in this area, the high demand will have a great lowering value to the cost of FRP's.

### 3.4.7 Concrete Jacketing

Concrete jacketing is primarily used for column strengthening. Steel rods are glued on the external surface of the members, by using epoxy resins. It is an easy to implement method of repair as it does not require demolition and does not increase the cross section of the member being repaired.  This technique consists of the intervention of specific elements of the structure. The main elements in a structure are the vertical elements (columns, walls). Column damage causes partial and / or global destruction of the entire structure. This is dictated by the sharp decrease of the resistance capability in the horizontal direction. Further, we have greater reduction of bearing capacity in shear compared to that in bending, so under the action of earthquake motions the structure becomes fragile. Thus, the most critical elements in the repairing of the structure are the vertical ones. A control of columns in shear, compression and bending should be primarily done because of columns being the most critical elements. To increase the bearing capacity of the column in shear, compressing and bending we can use reinforced concrete jacketing.

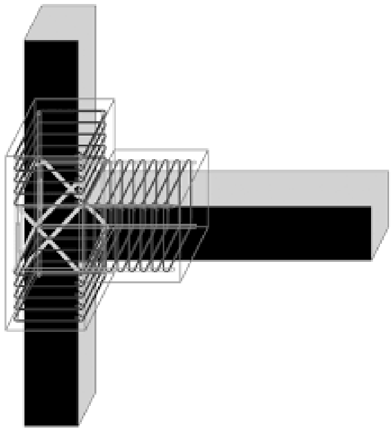


***Figure 16 Beam-Column Joint Jacketing***

Since the materials, physical and mechanical properties are well known, this makes for concrete jacketing to be a great way of repairing and strengthening of reinforced concrete structures. The fresh concrete replaces and increases the working surface of the structure and the new reinforcement is based on the existing one. Concrete jacketing makes possible for the continuity of the structural members, in example the joint cooperation between the columns and beams. It also increases the structural element's properties, thus increasing the whole structure's properties. Some of these properties are:

- Stiffness;
- Shear resistance;
- Horizontal deformations capacity;
- Anchoring of exposed reinforcement;
- Adjusting of load bearing capacity in the joints (creates relatively weak beams as opposed to columns.);
- Increases shear strengths in beam-column joints;
- Protects exposed reinforcement form corrosion and chemical attacks.

However, concrete jacketing increases the cross section of the members, thus decreasing the useable are of the structure. It is also relatively hard to implement because of the partial destruction of the structure which creates acoustic and environmental pollutions.

# CHAPTER 4

# CASE STUDY

## 4.1 Introduction

This chapter will contain information on the strengthening and repair of a damaged structure in Albania. The object is a 4-story villa in the "Chateau-Linze" residences, located in Tirana. The villa was built in 1995 and has been occupied ever since. The structure was damaged from the earthquake of 26th November 2019. The structure was strengthened using concrete jacketing and steel plates in load bearing members.

## 4.2 General Data of the Structure

The structure located in Njesia Administraive Nr.12, Tirane is located in 41°20'45.65"N; 19°52'3.39"E.

*Figure 17 Orthophoto of the Villa*

### 4.2.1 Structural Plans

The structure of the building is such that vertical and lateral loads are borne by a system with reinforced concrete supporting structure. The structural scheme of the building is a reinforced concrete spatial frame. The foundations are designed as separate foundations with RC piles with concrete of brand M-200 or C15/20 and steel, supported on a sole with resistance [σ] = 3 kg / cm2. The foundations are and grouped into 4 types, the dimensions of which are given in as follows:

*Table 1 Pile Cross Sections*

| Pile | Dimensions (axbxc) (cm) |
|---|---|
| Pile PL-1 | 180x180x110 |
| Pile PL-1* | 180x180x110 |
| Pile PL-2 | 180x180x110 |
| Pile PL-3 | 140x140x100 |
| Pile PL-4 | 110x110x80 |

The detailed foundation plan is as shown:

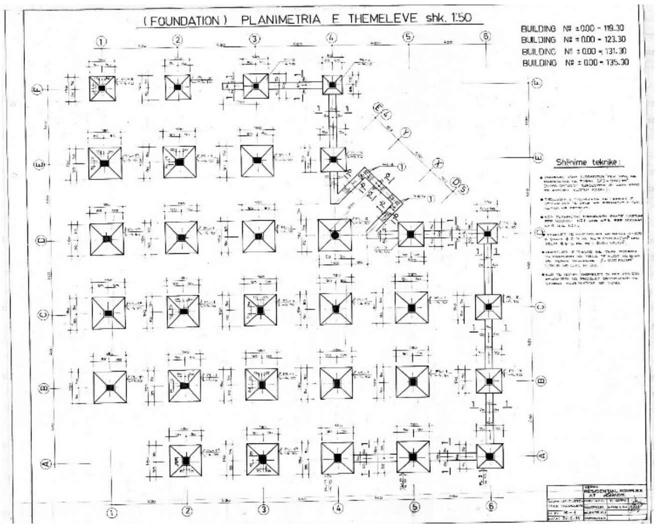



***Figure 18 Detailed Foundation Plan***

The structure's columns are grouped in 5 main types, as shown:

***Table 2 Column Cross Sections***

| Column | Dimensions (axbxc) (cm) |
|---|---|
| Column K-1 | 30x40(30x30) |
| Column K-2 | ϕ35 |
| Column K-3 | 30x30 |
| Column K-4 | 30x30 |
| Column K-5 | 20x25 |

The detailed column plans are as shown:

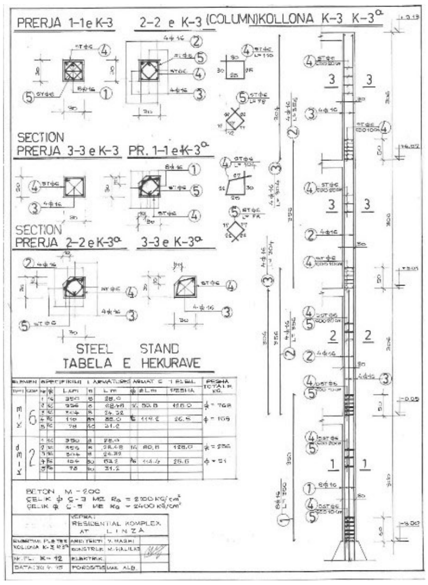



***Figure 19 Column Reinforcement Plan 1***

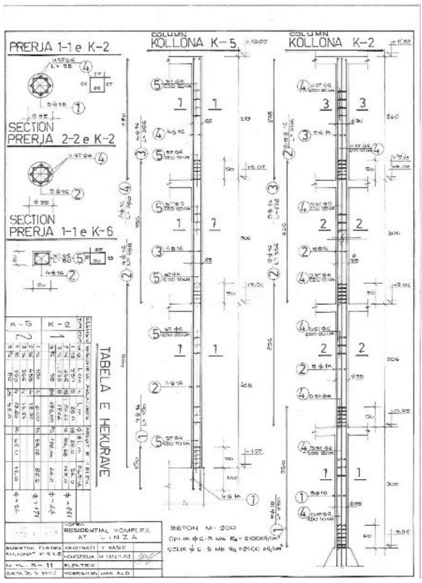



***Figure 20 Column Reinforcement 2***

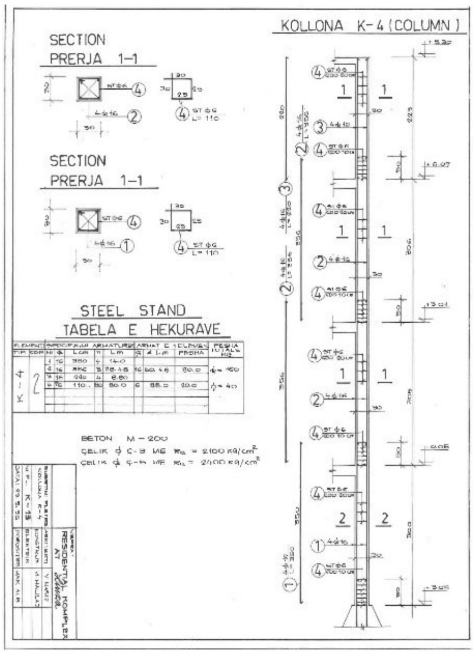



***Figure 21 Column Reinforcement 3***

The beams are designed as shallow beams with dimensions of 60 x18 cm. The reinforcement plan of the beams is as shown:

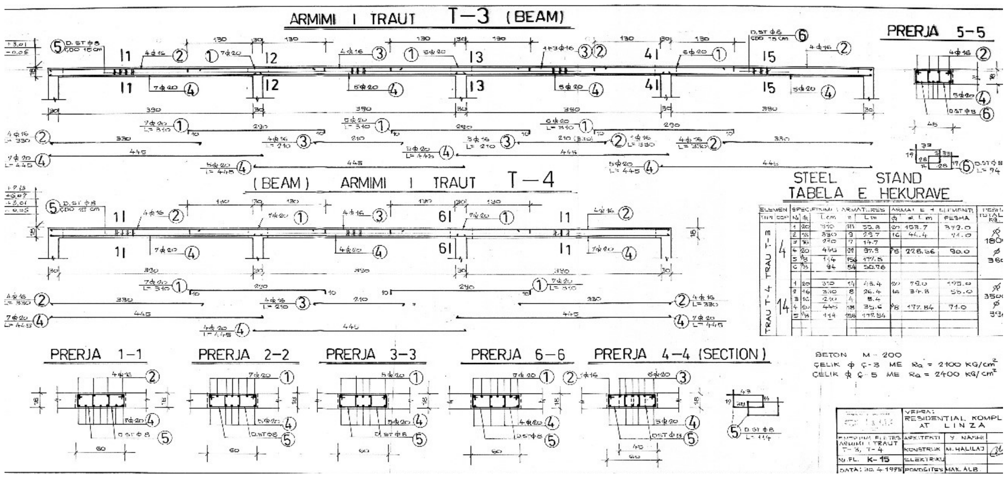



***Figure 22 Slab Reinforcement***

The slabs are designed as monolithic slabs with a thickness of 18 cm. The stairs are placed on the side and designed as monolithic slabs with a thickness of 10 cm.

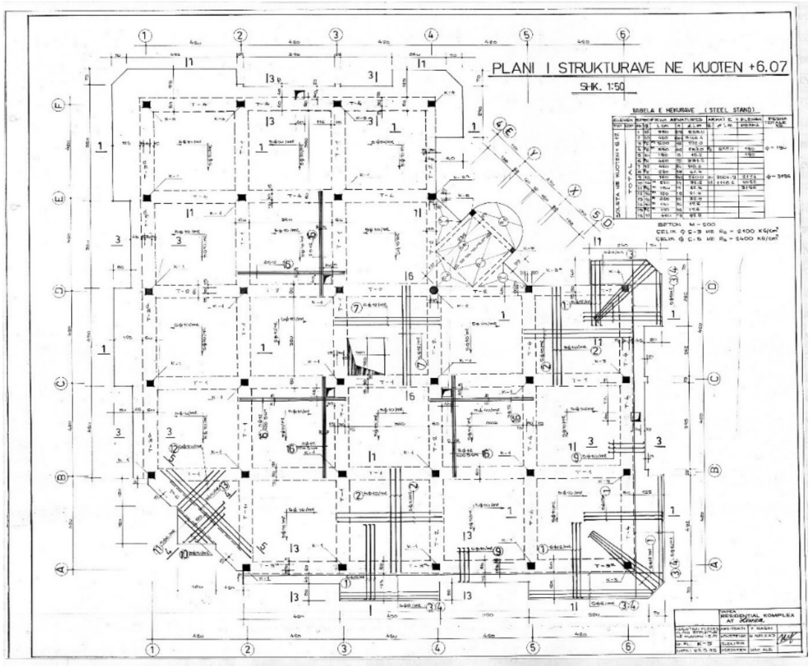



***Figure 23 Structural Plan***

Figures 18-23 show the structural plan before the repair.

The placement of the filling/partition walls, is mostly regular. On the ground floor, the distribution of brick filling/partition walls and unreinforced concrete walls in the contour of the building is irregular and has affected the behavior of the structure. The reinforcement of columns and beams is verified with the construction/constructive requirements of the technical condition of KTP-N2-89. Since the building is located in an area with intensity I = VII, only requirements for intensity less than VIII have been used to verify the reinforcement of columns and beams.

### 4.2.2 Materials

According to technical specifications and the technical tests done on the structure, the materials are as follows:

- Concrete used in the structure is M-200 or C20/25, with compressive resistance of $R_b$=200 kg/ cm$^2$ for columns, beams and slabs and M-200 or C20/ compressive resistance of $R_b$=200 kg/c cm$^2$ for pile foundations.

- According to the plans, the reinforcement steel is of class Ç-3 with resistance yield strength Rs = 2100 kg / cm$^2$ and grade Ç-5 with resistance yield strength Rs = 2400kg / cm$^2$. According to the in-situ tests the reinforcement steel results of class Fe400 with Rs = 4000kg / cm$^2$. For the engineering model we used steel of class Ç-5 with Rs = 2400kg / cm$^2$ in favor of safety.

Based on research the following damages were identified:

- Cracking and the creation of plastic hinges mainly because of shear forces in the upper joints of the column at -3.00.
- Cracking of fillings/partition walls.
- The structure used to have shear walls along its 4 stories' but the owners intervened on the structure and they were removed.

The following Figures 4.7-4.16 show the damages photographed in-site:

***Figure 24 Column Damage***

***Figure 25 Column Damage***

***Figure 26 Column Damage***

*Figure 27 Reinforcement Uncover*

*Figure 28 Reinforcement Uncover*

***Figure 29 Column Damage***

***Figure 30 Column Damage***

***Figure 31 Column Damage***

***Figure 32 Wall Damage***

*Figure 33 Column Damage*

## 4.3 Material Quality Tests

### 4.3.1 Walls

From the speed measurements of wave propagations in separate parts of the masonry, the masonry of the structural unit 1 turns out to be homogeneous and the connection between the mortar and the bricks is satisfactory, while in the structural unit 3 the connection between the mortar and the bricks is not good and the brick units are connected to the mortar almost only by friction and this connection is detached to a large extent. It should be noted that the measurements were carried out in an area that may have been damaged, in addition to seismic action also by damage to the masonry due to its opening.

### 4.3.2 Concrete

The compressive tests of the concrete, as shown in Table 4-4 were performed using the guidelines of EN 12390-1 and EN12504-1.

*Table 3 Concrete Compressive Test Results*

| Member | Cylindrical Resistance (MPa) |
|---|---|
| Slab (First Floor) | 23.1 |
| Slab (Second Floor) | 19.8 |
| Column D3 (First Floor) | 19.9 |
| Column B5 (Basement) | 45.7 |

### 4.3.3 Steel

A limited number of tests were performed on rods of different diameters and taken on different elements. To judge as accurately as possible on the physical-mechanical properties of steel, the results of steel tests in the surrounding buildings which are the same in the project and are applied at the same time as the building under consideration, are also taken into account.

*Table 4 Steel Tensile Test Results*

| Member | Yield Strength (Mpa) | Tensile Strength (Mpa) | Relative Extension (%) |
|---|---|---|---|
| Slab ( +0.00) | 284.9 | 436.8 | 31.71 |

## 4.4 Structural Analysis

### 4.4.1 Loads

Dead loads are calculated based on site verifications. The loads of the members are calculated according to KTP-N6-78. The layers on the slabs were taken according to the on-site verifications, which result in a thickness of about 7cm. The load of the wall's filling is taken as a uniformly distributed load with a value of 75kg/m$^2$. Based on the above data, the dead load on the slab is 600 kg/m$^2$ (including the load of the slab). The dead loads of inter-story slabs and the stair cage are calculated at 200 kg/m$^2$ and the dead loads of the terrace is estimated to be 75 kg/m$^2$. Intermediate measures are calculated taking into account the full permanent load and 30% of the temporary load. A factor of 0.3 (30%) was used to include in the analysis both the requirements of the technical condition in force and those of Eurocode (taking into account the degree of recognition). The weight of the structural supporting elements is multiplied by 1.2 to take into account the coating of the structural elements with plastering and other factors due to interventions during the time of use. After careful calculations the mass of the inter-story is estimated to be according to Table 4-6:

***Table 5 Calculated Floor Weight***

| Floor Number | Weight (kN) |
|---|---|
| 1 | 440 |
| 2 | 440 |
| 3 | 440 |
| 4 | 440 |

### 4.4.2 Seismic Loads

During the structural analysis of this unit, two seismic loads were taken into account: seismic loading according to Eurocode (from seismic study) and seismic loading according to September and November earthquakes (based on IGJEUM records obtained in spectral form). For the purposes of this report the earthquake spectra are represented by the type 2 spectrum according to the Eurocode, with ground acceleration $a_g = 0.15g$, and type B ground as shown in Figure 4.17.

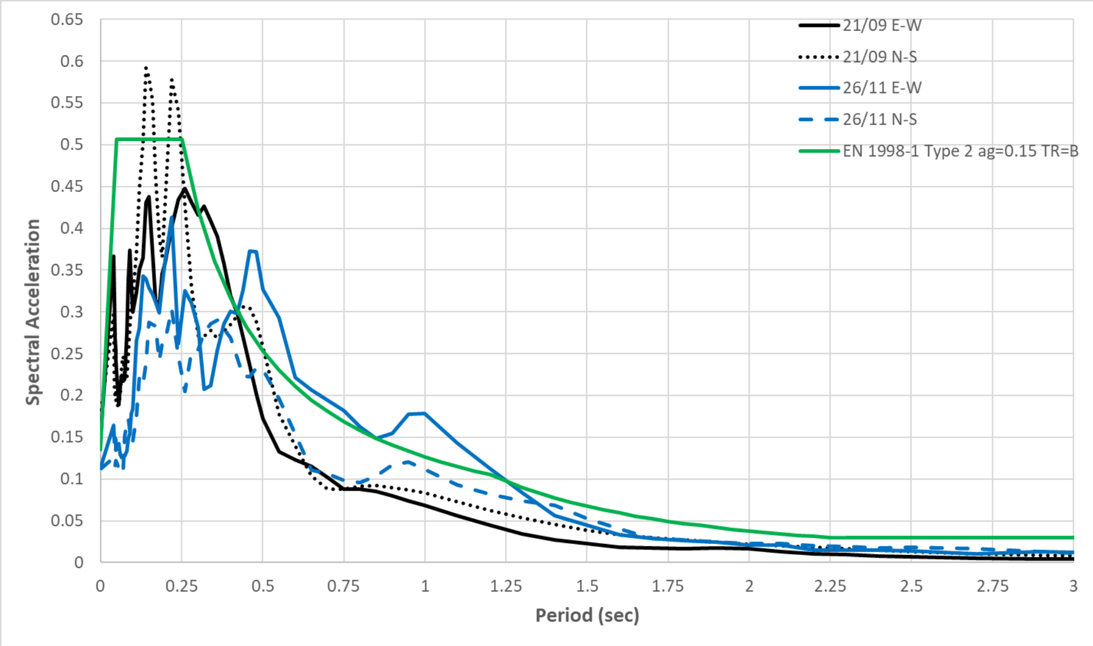



***Figure 34 Earthquake Response Spectrum***

The elastic spectrum shown in Figure 4.08 is used to verify and evaluate the existing condition of the building, while the spectrum shown in Fig. 30 which pertains to the boundary condition of significant damage according to SSH EN 1998-3, is used to estimate the seismic capacity for the design earthquake (6.1).

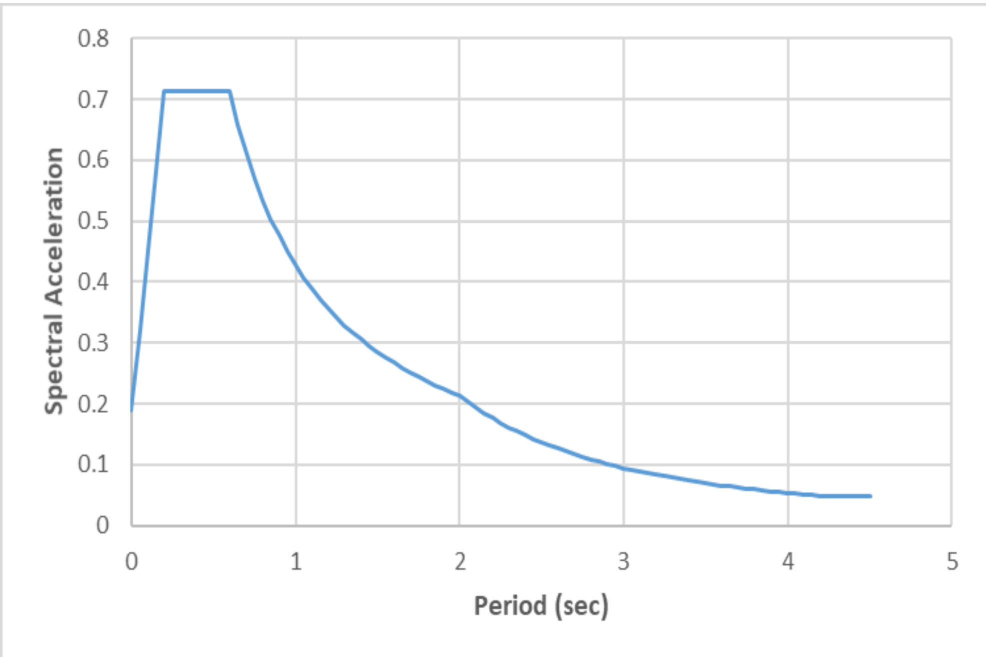



***Figure 35 Response Spectrum According to Eurocode***

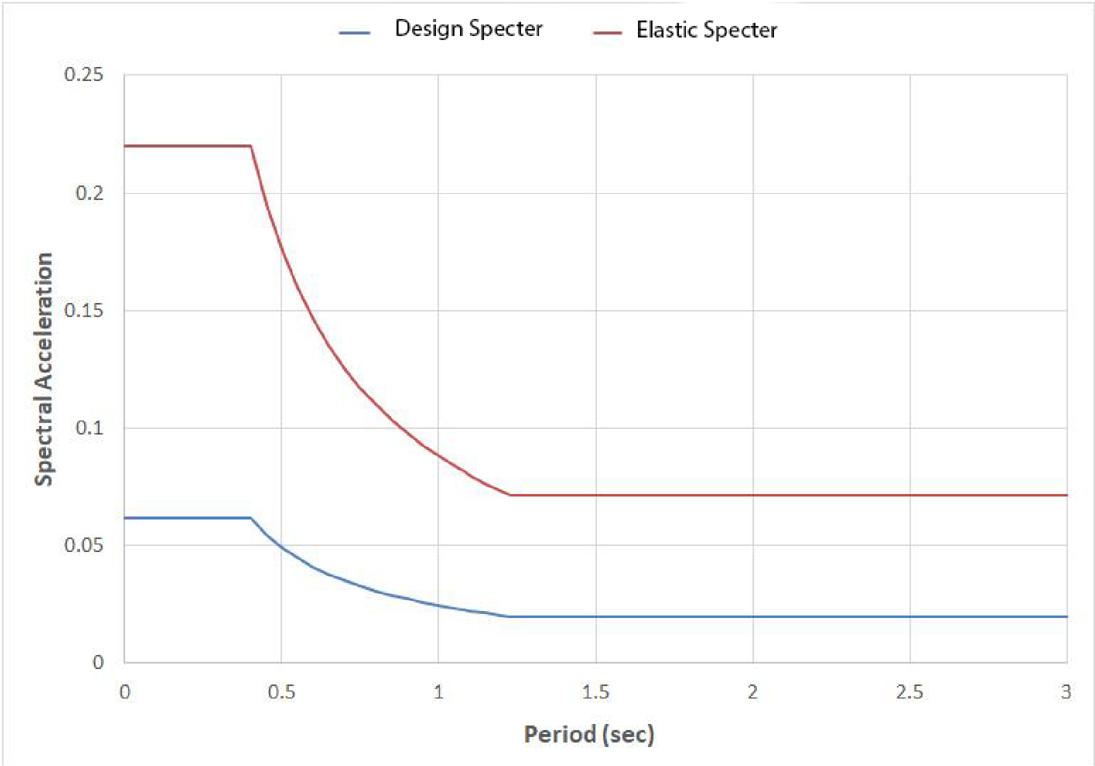



*Figure 36 Response Spectrum According to KTP-n2-89*

### 4.4.3 Modelling

Reinforced concrete members (columns and beams) are modeled as one-dimensional elements (frame), with dimensions of the cross section based on the survey carried out on site. The characteristics of the materials were obtained according to the results from the engineering tests carried out for the building. The following is a 3-dimensional view of the calculation model. Partition walls are not modeled but their impact as a load on the structure is taken into account. The following is a 3-dimensional view of the calculation model, Figure 4.20.

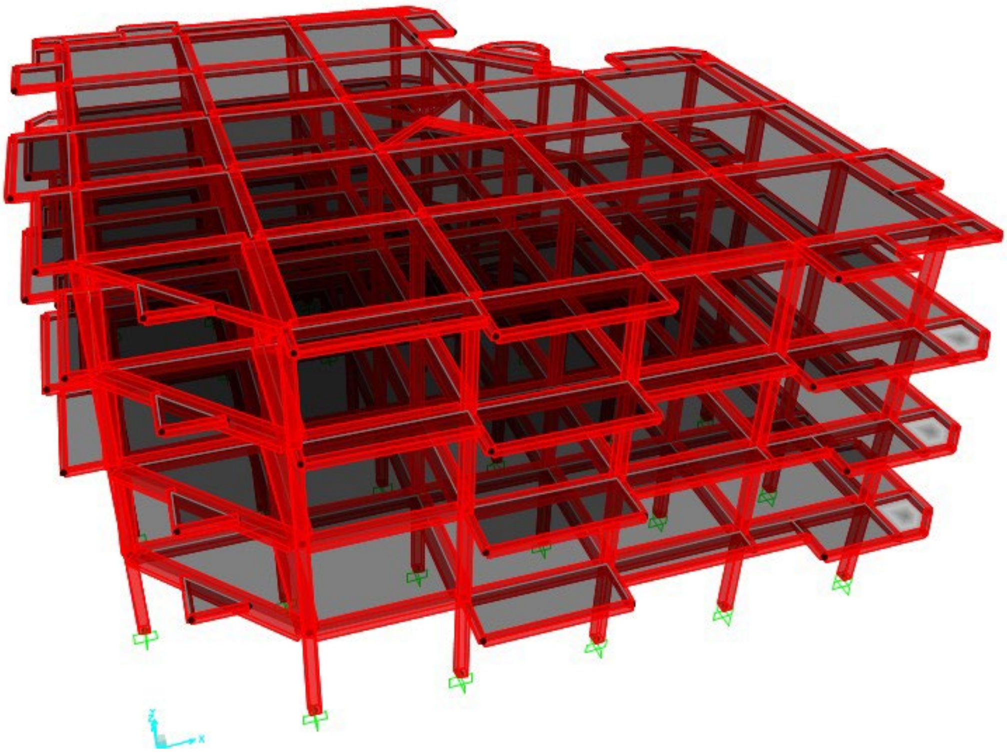


*Figure 37 3-Dimensional Model*

This section presents the results of the modal analysis for the structure. In order to have the highest possible mass participation, 12 modes were taken into account during the modal analysis. The following are tables of the sum of the effective modal measures taken into account in the calculation and of the mass participation for each mode.

The periods and frequencies of the mode are given in the following table:

*Table 6 Sum of Effective Modal Mass*

| Direction | Static Participation (%) | Dynamic Participation (%) |
|---|---|---|
| X | 99.966 | 97.889 |
| Y | 99.969 | 97.991 |
| Z | 6.570 | 0.963 |

*Table 7 Periods and Frequencies of Modes*

| Mode | Period | UX | UY | UZ | RX | RY | RZ |
|---|---|---|---|---|---|---|---|
| 1 | 0.524 | 41.30% | 40.70% | 0.00% | 2.10% | 2.20% | 0.00% |
| 2 | 0.488 | 40.70% | 41.00% | 0.00% | 2.20% | 2.20% | 0.70% |
| 3 | 0.452 | 0.20% | 0.55% | 0.00% | 0.00% | 0.00% | 81.90% |
| 4 | 0.410 | 5.60% | 5.60% | 0.00% | 7.20% | 7.30% | 0.00% |
| 5 | 0.402 | 5.50% | 5.40% | 0.00% | 7.30% | 7.50% | 0.30% |
| 6 | 0.385 | 0.10% | 0.20% | 80.00% | 0.30% | 0.10% | 10.60% |
| 7 | 0.223 | 0.40% | 0.00% | 0.00% | 0.60% | 0.20% | 0.00% |
| 8 | 0.220 | 2.60% | 1.70% | 0.00% | 0.40% | 1.70% | 0.00% |
| 9 | 0.218 | 1.30% | 2.70% | 0.00% | 1.80% | 1.00% | 0.20% |
| 10 | 0.211 | 0.00% | 0.10% | 0.00% | 0.10% | 0.00% | 4.30% |
| 11 | 0.198 | 0.20% | 0.00% | 0.00% | 0.00% | 0.20% | 0.00% |
| 12 | 0.197 | 0.00% | 0.00% | 1.00% | 0.70% | 1.10% | 0.00% |

*Table 8 Frequency and Period of Modes*

| Mode | Period | Frequency (Hz) | Radial Frequency (rad/s) |
|---|---|---|---|
| 1 | 0.524 | 1.908 | 11.988 |
| 2 | 0.488 | 2.049 | 12.874 |
| 3 | 0.452 | 2.212 | 13.898 |
| 4 | 0.411 | 2.435 | 15.300 |
| 5 | 0.403 | 2.482 | 15.594 |
| 6 | 0.385 | 2.595 | 16.307 |
| 7 | 0.223 | 4.479 | 28.144 |
| 8 | 0.220 | 4.541 | 28.53 |
| 9 | 0.218 | 4.577 | 28.757 |
| 10 | 0.212 | 4.727 | 29.701 |
| 11 | 0.199 | 5.031 | 31.612 |
| 12 | 0.198 | 5.062 | 31.803 |

The modal forms of the first three results are given below:

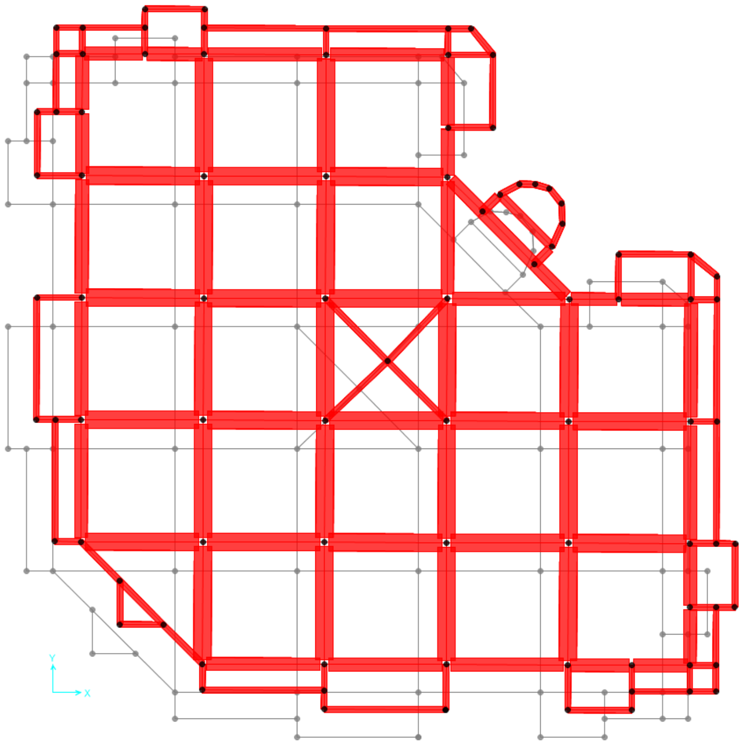



*Figure 38 First Modal Result*

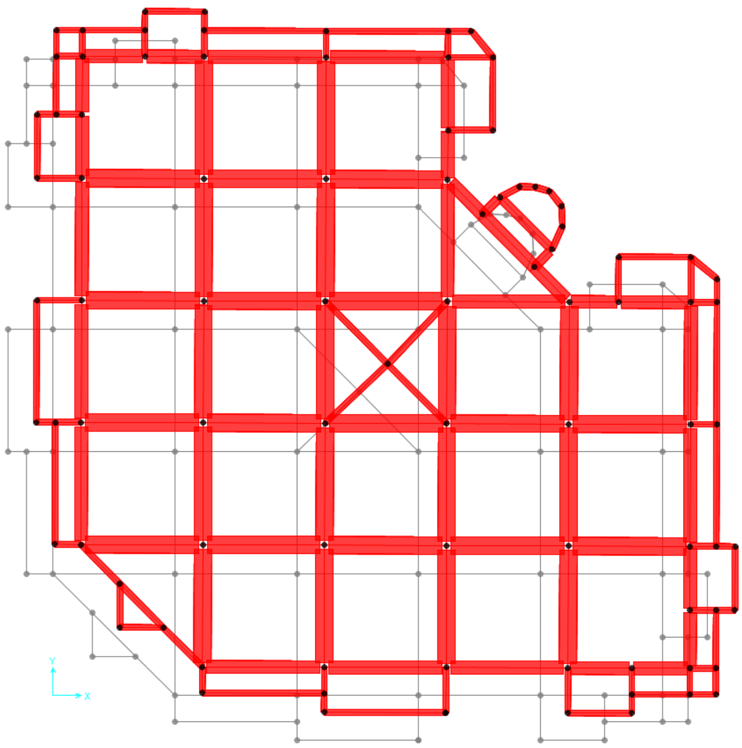



*Figure 39 Second Modal Result*

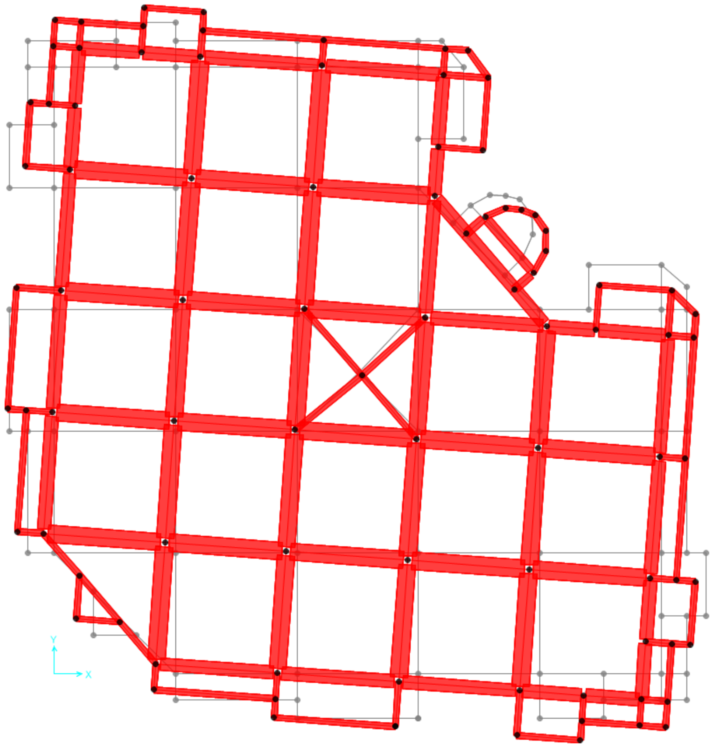



***Figure 40 Third Modal Result***

As can be observed from the above results, the second modal of the building is in rotation, which implies that the building either has relatively reduced torsional stiffness or the transverse stiffness of the structure is quite different from the longitudinal stiffness. The geometric shape of the structure is also a factor which affects stiffness. The fact that the second modal has rotational movements also indicates that the irregularity of the building, in terms of rigidity exists and consequently it should be handled with care during the repairing.

The calculations and graphs for the longitudinal displacements are as follows:

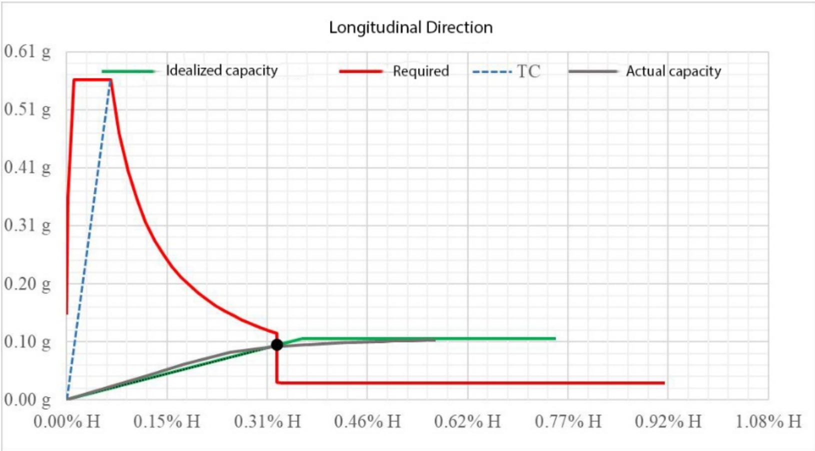



***Figure 41 Displacement According to Seismic Loading in the Longitudinal Direction***

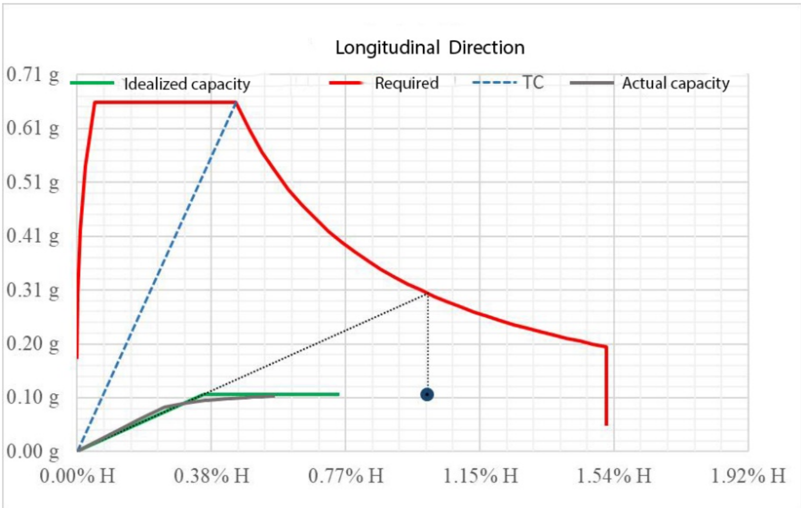



***Figure 42 Displacement According to Eurocode in the Longitudinal Direction***

The calculations and graphs according to transversal displacement are as follows:

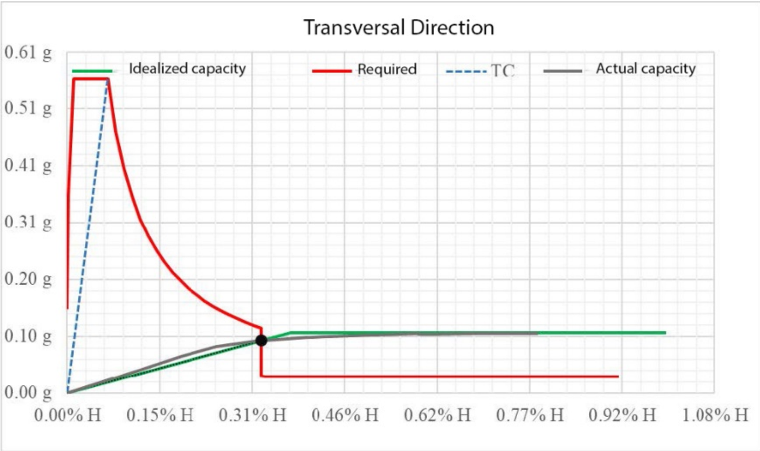



*Figure 43 Displacement According to Seismic Loading in the Transversal Direction*

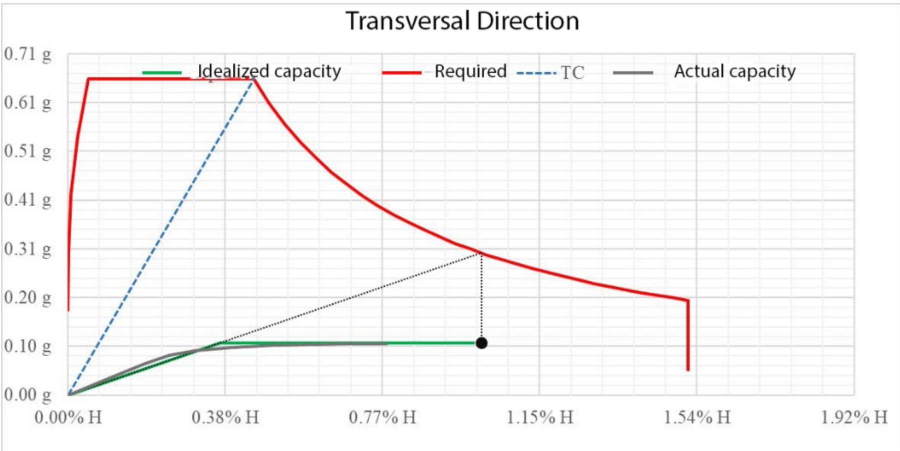



*Figure 44 Displacement According to Eurocode in the Transversal Direction*

| Damage | Damage distribution according to scales |
|---|---|
| Slight Damage | 0.0% |
| Damage Limitatio | 0.0% |
| Damage Significant | 20.00% |
| Near Collapse | 80.00% |

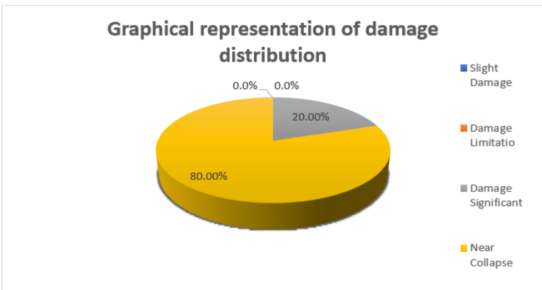



*Figure 45 Damage Distribution According to Eurocode 8.3 Standards*

*As seen from the above results, the building has a high probability of suffering a "collapse" if it is hit by a design earthquake referring to the seismic study and the requirements of Eurocode.*

## 4.5 Strengthening and Repairing

Structural rehabilitation requires that the intervention be carefully studied so that the reinforced elements withstand the bulk of the seismic force and the remaining elements withstand less force than what they are designed for. The improvement of structural regularity will play an important role, an improvement which indirectly reduces the seismic action in the building. According to this strategy, the structure intervenes in only a few areas in plan and height and the rest of the building can remain pristine. Moreover, the function and engineering networks will be little affected by this structural improvement intervention, and, consequently, the architectural elements together with the engineering networks will require little or no intervention. The impact cost of other building items (architecture and engineering networks) is low. The improvement will be done according to the following actions:

Removal of structural and non-structural elements that have deteriorated the structural regularity of the building and their reconstruction to enable them to perform their primary role (e.g. separation of premises or protection of slopes);

- Repair of structural damage to damaged elements;
- Selection and reinforcement of primary seismic frames and their design to withstand the main seismic force. the principle of "strong columns - weak beams" should also be taken into account;
- Control and reinforcement of foundations, if necessary in areas where elements with high strength and rigidity will be added;
- Control of other structural elements so that they are strained within their seismic capacity and special arguments for the transition to secondary elements of supporting elements that do not meet the requirements of the technical conditions;

- Control of secondary elements not to be strained beyond their ability by redistribution of seismic forces;
- Repair and completion of structural elements damaged by temporal and atmospheric factors;
- Other remedial repairs due to damage or as a result of remedial intervention;

The cost of this method will under the 70% of the rebuilding cost. The project and plans for the repair and strengthening of the structure is shown in Appendix B.

### 4.5.1 Methodology

The purpose of the rehabilitation is to modify the $E_d$ seismic demand, and / or the capacity of the structure, so that the structural elements of the rehabilitated structure meet the general verifications, $E_d \leq R_d$, for the boundary condition and the corresponding seismic action.

All reinforced concrete walls on the ground floor will be detached from the structure and the created spaces will be filled with lightweight material, to remove the impact of these walls on the structure and to avoid the creation of short columns. All existing columns will be connected to each other by adding a 20cm thick reinforced concrete slab. The columns of the frames that will be built will be jacketed 20cm on each side.

Frames will be constructed by jacketing the existing columns and beams of the building. The position of the frames and the details of their reinforcement are given in Figures. The intervention begins with the removal of the concrete cover of the columns and the removal of concrete throughout the crack depth in the area where the columns are cracked. Removal of the cover will be carried out carefully so as not to damage the structural elements. The created concrete surface should be 'pinned' to create a rough surface and before placing the reinforced concrete jacket it should be cleaned to enable the connection of the new concrete with the old concrete. The cover should be removed until the reinforcement appears in symmetrical shape from all sides of the column. It is advisable to remove the part of the concrete that surrounds the rusty rods. In cases of rust presence, the removal of concrete is easy as in these areas, there will be total detachment of the concrete material from the reinforcing steel.

Once the rods of the existing elements are fully visible the rods which show the presence of rust should be cleaned. Cleaning the existing column reinforcement from rust will be done with the sand blasting. After cleaning, the existing rods should be covered with "Mapefer 1k Mapei" (or equivalent) with two coats where the thickness of both coats should be at least 2mm. Concreting will be done after the material with which the rods will be painted has dried completely.

Prior to concreting, the concrete surface of the column must be rough and thoroughly cleaned of dust in advance to ensure the connection of the existing concrete with the new concrete. The concrete to be used will be of C30/37 with epoxy resin for gluing new concrete with old concrete and additive for plasticizing concrete.

The repair of plastic hinges on the ground floor will be done by using steel plates. The surfaces of the columns should be thoroughly cleaned from the existing layers (plaster). The corners of the columns should be the repair of plastic hinges on the ground floor will be done through their steel shirting. The reinforcement of the columns will be done according to the details given in the building rehabilitation project. Before lining the columns, their surfaces should be thoroughly cleaned from the existing layers (plaster). The corners of the columns should be corroded according to the detail on the project sheets. Before gluing the steel profiles, the surface should be cleaned of dust with an air compressor and cleaned with a nylon brush. Steel profiles will be mounted by gluing with epoxy resin. According to the detail on the project sheets. Before gluing the steel plates, the surface should be cleaned of dust with an air compressor and cleaned with a nylon brush. Steel profiles will be mounted by gluing with epoxy resin.

### 4.5.2 Structural Analysis

After implementing the aforementioned repaired and structural strengthening, the same structural analysis was done, this time with the improvements.

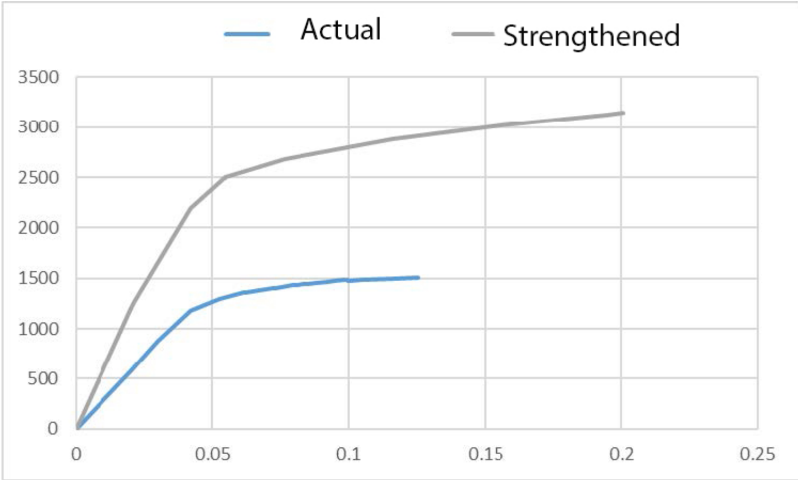



*Figure 46 Capacity Curve According to Longitudinal Direction*

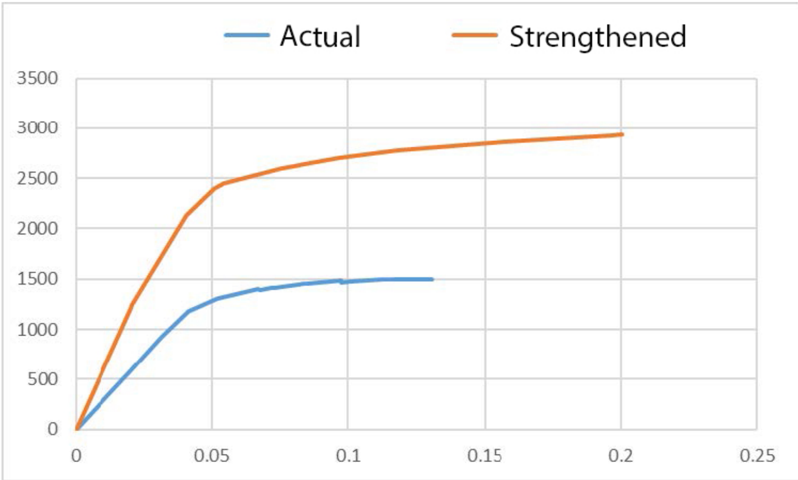



*Figure 47 Capacity Curve for the Transversal Direction*

It can be seen from the above results that the capacity of the structure has increased by about 100% in the longitudinal direction and by about 100% in the transverse direction, while the border displacement has increased by 35% compared to the existing situation.

*Table 9 Static Participation After Strengthening*

| Direction | Static Participation (%) | Dynamic Participation (%) |
|---|---|---|
| X | 99.833 | 92.9476 |
| Y | 99.830 | 92.892 |
| Z | 15.180 | 2.12 |

The following are tables of the sum of the effective modal measures taken into account in the calculation and of the mass participation for each mode.

***Table 10 Sum of the Effective Modal Measures After Strengthening***

| Mode | Period | UX | UY | UZ | RX | RY | RZ |
|---|---|---|---|---|---|---|---|
| 1 | 0.532 | 59.11% | 15.46% | 0.00% | 0.90% | 3.41% | 6.95% |
| 2 | 0.483 | 18.44% | 62.20% | 0.00% | 3.51% | 1.02% | 0.64% |
| 3 | 0.322 | 3.78% | 3.69% | 0.00% | 0.25% | 0.24% | 74.28% |
| 4 | 0.283 | 5.35% | 4.58% | 0.00% | 5.97% | 6.93% | 1.53% |
| 5 | 0.277 | 5.42% | 6.15% | 0.00% | 7.39% | 6.64% | 0.01% |
| 6 | 0.236 | 0.62% | 0.75% | 0.01% | 1.29% | 1.13% | 9.45% |
| 7 | 0.222 | 0.10% | 0.05% | 0.45% | 0.40% | 0.26% | 0.28% |
| 8 | 0.197 | 1.00% | 0.01% | 0.43% | 0.52% | 0.68% | 0.00% |
| 9 | 0.194 | 0.00% | 2.70% | 0.05% | 0.13% | 0.14% | 0.00% |
| 10 | 0.192 | 0.12% | 0.00% | 0.71% | 1.02% | 1.95% | 0.02% |
| 11 | 0.191 | 0.00% | 0.00% | 0.34% | 0.13% | 0.54% | 0.00% |
| 12 | 0.190 | 0.00% | 0.00% | 0.02% | 0.02% | 0.16% | 0.01% |

***Table 11 Period and Frequency After Strengthening***

| Mode | Period | Frequency (Hz) | Radial frequency (rad/s) |
|---|---|---|---|
| 1 | 0.532 | 1.879 | 11.806 |
| 2 | 0.483 | 2.070 | 13.006 |
| 3 | 0.322 | 3.105 | 19.509 |
| 4 | 0.284 | 3.527 | 22.162 |
| 5 | 0.278 | 3.599 | 22.614 |
| 6 | 0.236 | 4.231 | 26.586 |
| 7 | 0.222 | 4.501 | 28.278 |
| 8 | 0.197 | 5.07 | 31.854 |
| 9 | 0.195 | 5.136 | 62.267 |
| 10 | 0.192 | 5.208 | 32.723 |
| 11 | 0.192 | 5.216 | 32.774 |
| 12 | 0.191 | 5.241 | 32.932 |

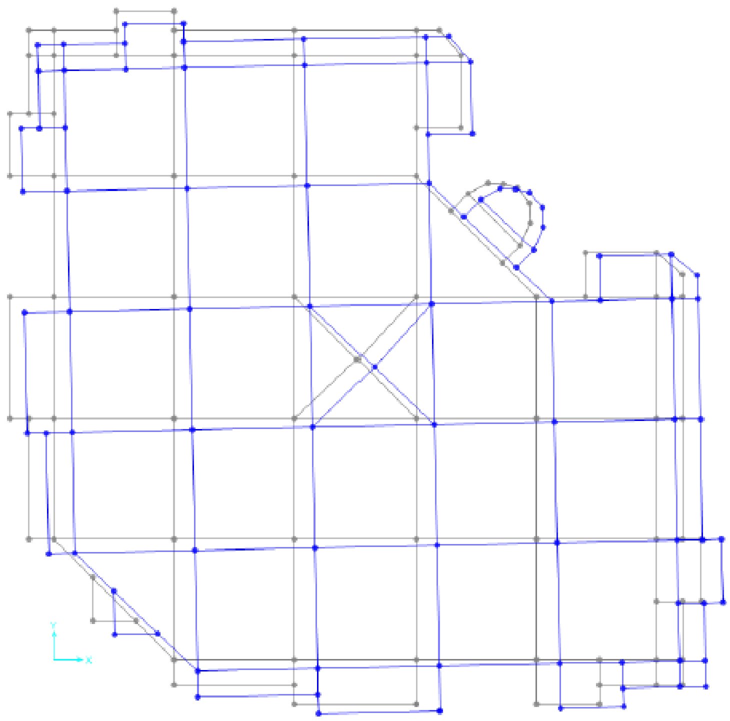



***Figure 48 First Modal Displacement After Reinforcement***

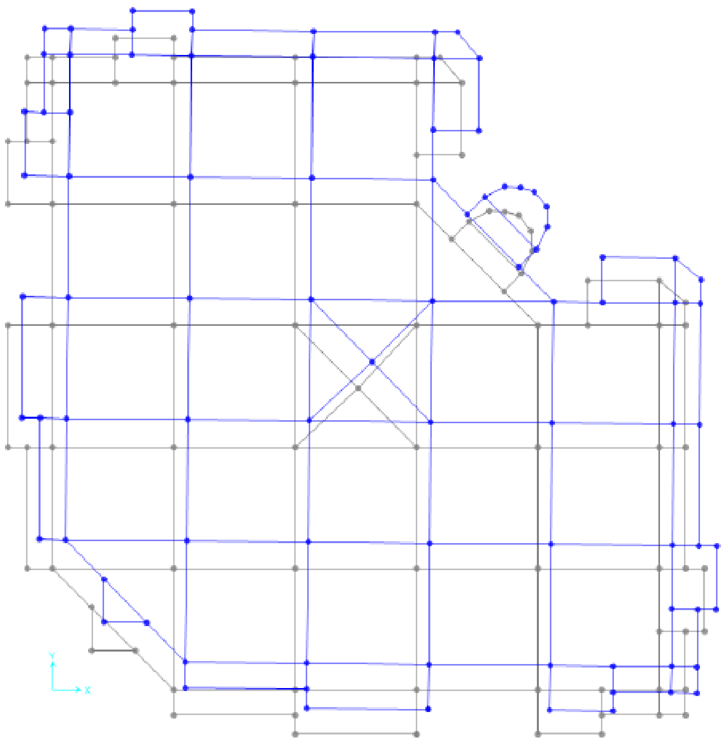



***Figure 49 Second Modal Displacement After Reinforcement***

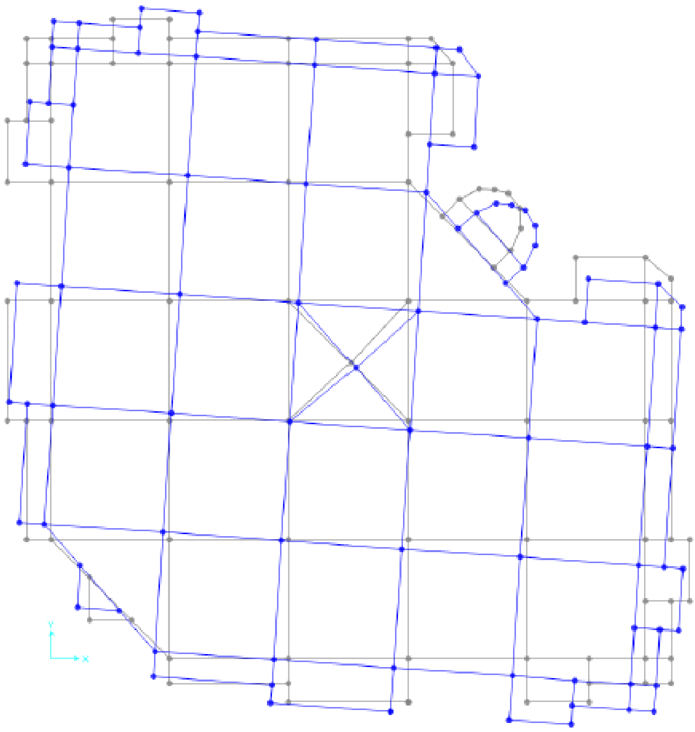


*Figure 50 Third Modal Displacement After Reinforcement*

As it is observed, the first two tones are rectilinear, the first in the shortest direction and the second perpendicular to the first, the third mode is in rotation. Thus, we can say that reinforced structure has very good dynamic behavior.

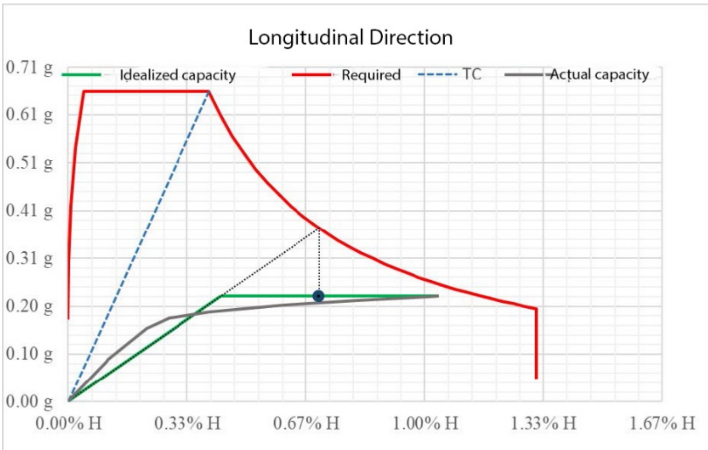



*Figure 51 Displacement According to the Longitudinal Direction*

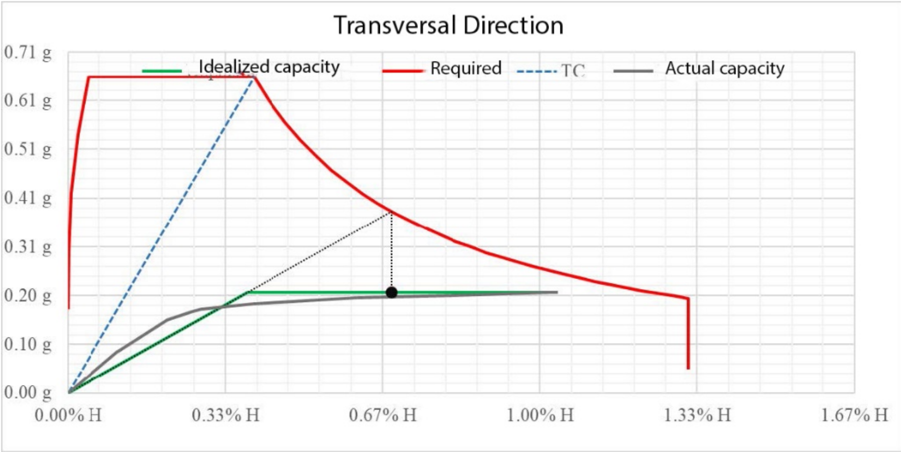



***Figure 52 Displacement According to the Transverse Direction***

***Table 12 Longitudinal and Transversal Displacement After Strengthening***

| Direction | Targeted Displacement (m) | Limitational Displacement (m) |
|---|---|---|
| Longitudinal | 0.135 | 0.150 |
| Transversal | 0.132 | 0.150 |

As can be seen from the graphs and table above, in each direction the building will pass into the plastic phase, but the intended displacement is less than the boundary displacement of the boundary state of significant damage. With the found values of the target displacement we can control the mechanism created.

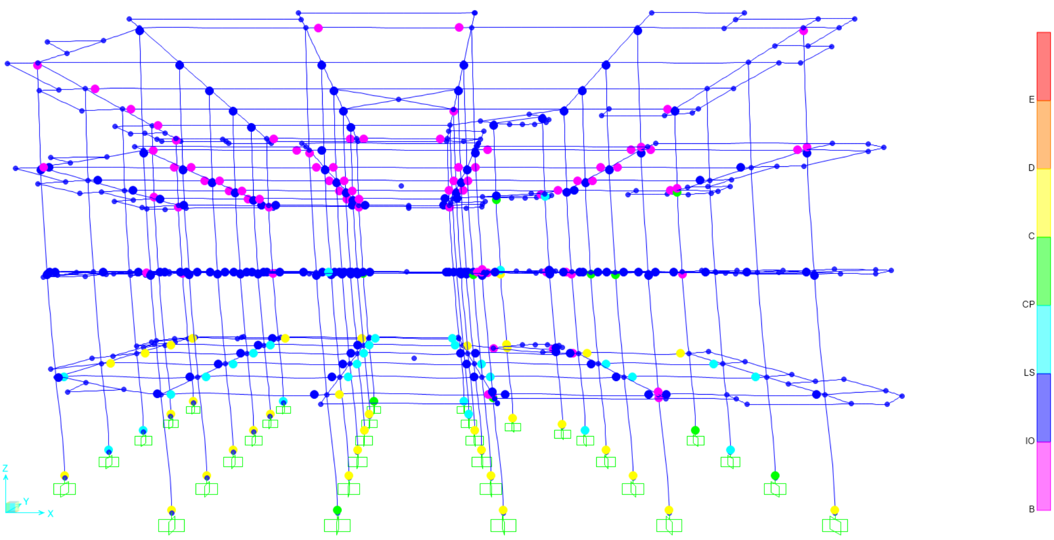



***Figure 53 Collapse Mechanism According to the Longitudinal Direction***

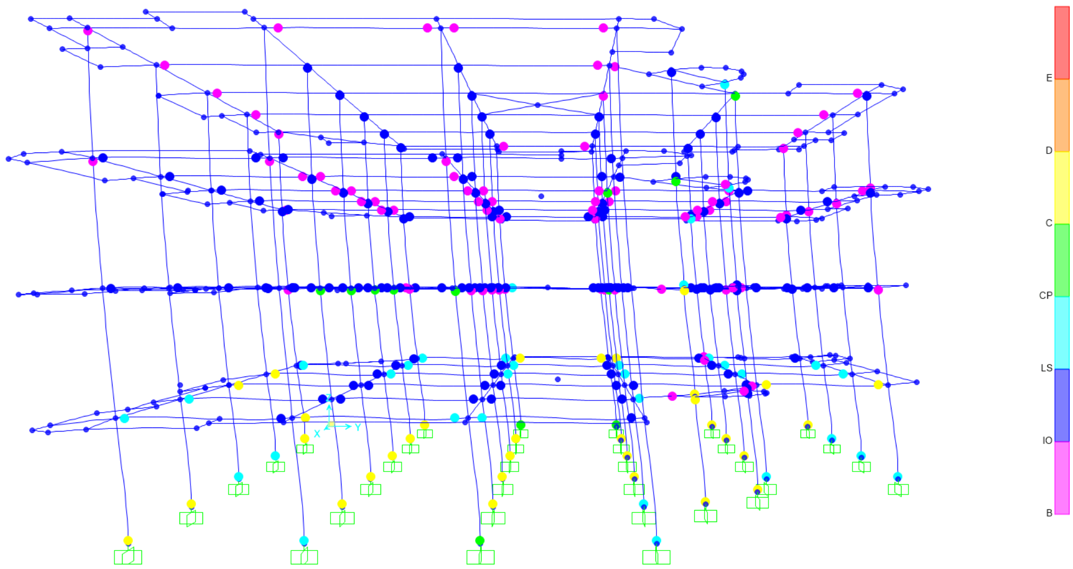



***Figure 54 Collapse Mechanism According to the Transversal Direction***

The plastic hinges are created at the ends of the beams and then at the base of the ground floor columns, so the destruction mechanism is in accordance with the criteria given in SSH EN 1998-1. Also, the condition of the created plastic cracks does not exceed the condition of significant damage.

| Damage | Damage distribution according to scales |
|---|---|
| Slight Damage | 1.0% |
| Damage Limitatio | 25.0% |
| Damage Significant | 53.0% |
| Near Collapse | 21.0% |

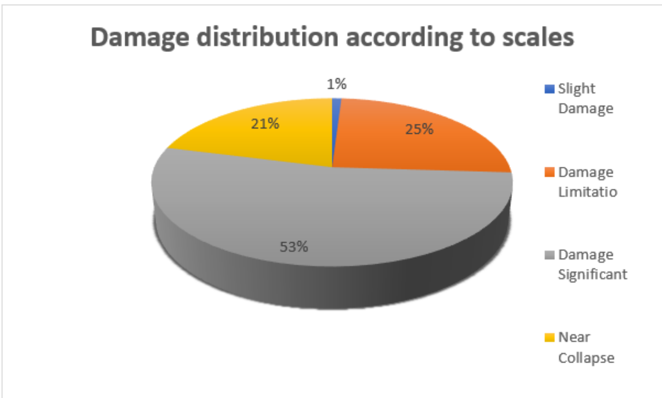



***Figure 55 Damage Distribution After Strengthening According to Eurocode 8.3 Standards***

Referring to the capacity of the structure and based on the vulnerability curves, an assessment of the degree of damage was conducted. Figure 5. is a graphical presentation of the distribution of damage according to the degree of damage, for seismic action according to the seismic study and the requirements of Eurocode. (seismic action is the same as the seismic action given in the in-depth analysis report).

After completing the strengthening of the structure, when compared to the initial damage distribution, the damage distribution after the strengthening, shows that the strengthening has greatly reduced the percentage of Near Collapse of the structure. Thus, it is safe to say that the concrete jacketing and steel plates used in strengthening the building, have fulfilled their purpose.

# CHAPTER 5

# CONCLUSIONS

## 5.1 Conclusions

This thesis investigated the strengthening and repair methods for reinforced concrete structures. A study of the materials used in repairing and strengthening was done in chapter 2 with description on how they are made and how they are used. Chapter 3 conducted a research on the methods of the implementation of the materials. Chapter 4 explained the techniques for repairing and strengthening reinforced concrete structures by using concrete jacketing, steel plates, steel braces and FRP materials and their pros and cons.

It can be concluded that epoxy injections are fare easier to be used and very effective in repairing cracks. They reduce deflection, control cracks and slightly increase beam weight. Resins are cheaper and easy to use. For disintegration and spalling the best method of repair is reinforced concrete jacketing which although increases the cross section of the beam, greatly improves the structural load bearing capacity. Using FRP materials is relatively new compared to using traditional concrete and other more researched materials but it is a promising new solution for improving and/or repairing reinforced concrete structures.

By restoring structural stiffness and increasing its deforming capacity, the structural capacity can be improved. Using FRP materials for strengthening is a very good alternative compared to other retrofitting methods. Albeit a bit expensive, it is very easy to implement, increases structural capacity greatly, is esthetic and is a great way to ensure that the structure will maintain a good seismic behavior.

In the case study taken in consideration in this thesis, the chosen method of repairing was by using steel plates and reinforced concrete jacketing. The structure had clear damages by the 26$^{th}$ November 2019 earthquake. One of the reasons why the structure was damaged by the earthquake was the intervention on the structural members by the residents. According to primary design plans, the structure used to have shear walls that were removed by the residents. Nevertheless, the method chosen proved to be an improvement in increasing structural capacity.

## 5.2 Recommendations for future research

When conducting further research on the methods of repairing and strengthening reinforced concrete structures, some more focused studies should be undertaken for structures that are built on aqueous soil where seismic activity is present.

# REFERENCES


[1] E. Gdoutos, "Cementitious Materials," in *Fracture Mechanics*, 2020.

[2] J. E. W. M. J. Provis, "Supplementary Cementitious Materials for Concrete," 2012.

[3] W.B.Long, "Grouting," *The Maintenance of Brick and Stone Masonry Structure,* 2020.

[4] P. P. A. Jain, "Charachteristics of Silica-Fume Concrete," 2015.

[5] https://www.constrofacilitator.com/theory-and-applications-of-fibre-reinforced-concrete-frc/. [Online].

[6] K. K. S. Maiti, "Polymer Impregnated Concrete," 1986.

[7] https://civilwale.com/polymer-concrete/. [Online].

[8] A. B. J. Beaudoin, "Polymer modified concrete," 1985.

[9] S. Roy, "Fiber Reinforced Concrete and Overlays," 2019.

[10] A. K. M. O. S.E. Gunaslan, "Properties of FRP Materials for Strengthening," 2014.

[11] https://civildigital.com/fiber-reinforced-concrete/. [Online].

[12] J. R. A. W. G. Tsiatas, "Durability of Crack Repair Systems," 2001.

[13] https://theconstructor.org/concrete/types-cracks-concrete-columns/26433/. [Online].

[14] http://www.civilengineeringforum.me/methods-crack-repair-concrete-2/. [Online].

[15] I. G. &. G. Association, "Stitching Concrete Pavement".

[16] https://theconstructor.org/concrete/methods-of-crack-repair/886/.

[17] https://decorativeconcreteneworleans.com/keeping-small-issues-from-becoming-big-problems-with-concrete-crack-repair/.

[18] http://www.civilengineeringforum.me/surface-scaling-spalling-concrete/. [Online].

[19] K. Eberhardt, "Repairing concrete deterioration," 2009.

[20] M. Elreedy, "Concrete Structures Repair," 2020.

[21] https://www.velco.de/en/Concrete-gunning/Rotor-gunning-machines/rotamat-tb.html. [Online].

[22] A. D. I. T. E. M. P. Isaac, "Retrofitting for reinforcement," 2011.

[23] M. Y. A. Ghobarah, "Modeling of reinforced concrete structural walls," 1999.

[24] I. K. B. A. S. K. S. K. S. Aykac, "Strengthening and Repair of Reinforced Concrete Beams Using External Steel Plates," 2013.

[25] M. Zaky, "Repair and Strengthening of Reinforced Concrete Structures," 2013.

[26] https://es.horseen.com/index/customer_case/index?page=22. [Online].

[27] N. M. A. B. F. D. M. Ghannam, "Strengthening and repairing of an existing steel bridge using post tensioning," 2014.

[28] https://theconstructor.org/structural-engg/types-bracing-systems-multi-storey-steel-structures/19559/. [Online].

[29] I. K. K. K. T. S. I. O. M. Nakada, "Mechanical Properties and Material Design of Glass/Aramid/Carbon Hybrid FRP Laminates," 1993.

[30] N. C. Balaji, "Reinforced Concrete Jacketed Column and Its Formwork," 2019.

[31] https://ascelibrary.org/doi/10.1061/%28ASCE%29CF.1943-5509.0000700. [Online].

[32] A. Hoffmann, "Polymer-modified cementitious materials for concrete repair systems," 2008.

[33] E. D. E. B. K. Habel, "Structural elements of Advanced Cementitious Materials and Concrete," 2020.

[34] C. P. J. S. I. F.-C. J.d.Brito, "Repair Techniques," 2020.

[35] "https://www.finehomebuilding.com/2016/08/28/floating-drypack-shower-pan," [Online].

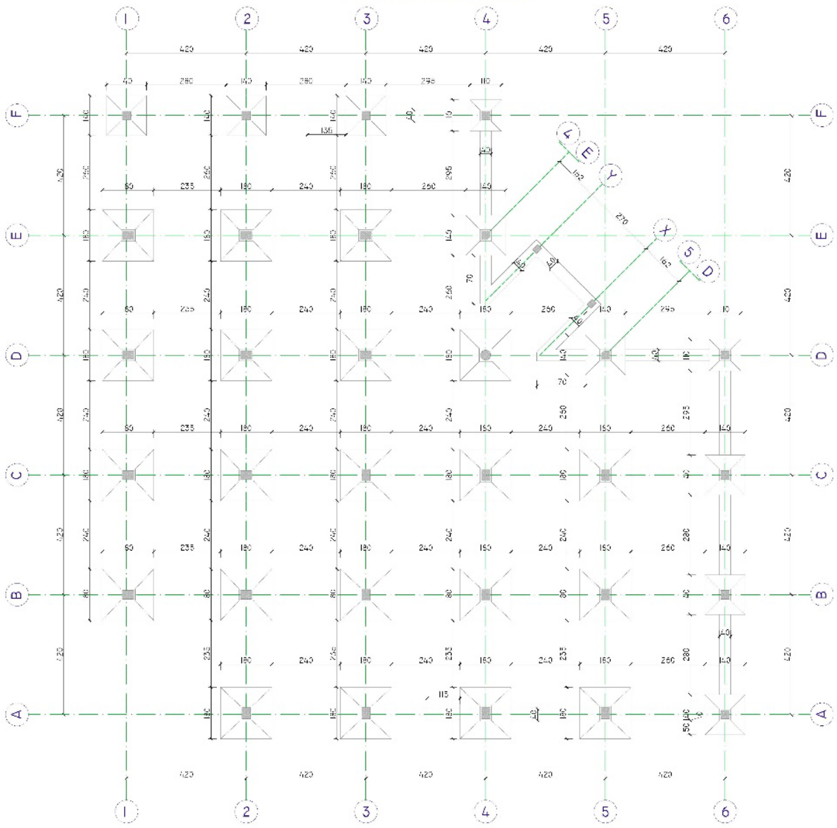
[36] https://ctech-llc.com/en/products/injection-epoxy-resin. [Online].

[37] https://theconstructor.org/structural-engg/improve-ductility-rcc-beams-frp-bars-methods/15862/. [Online].

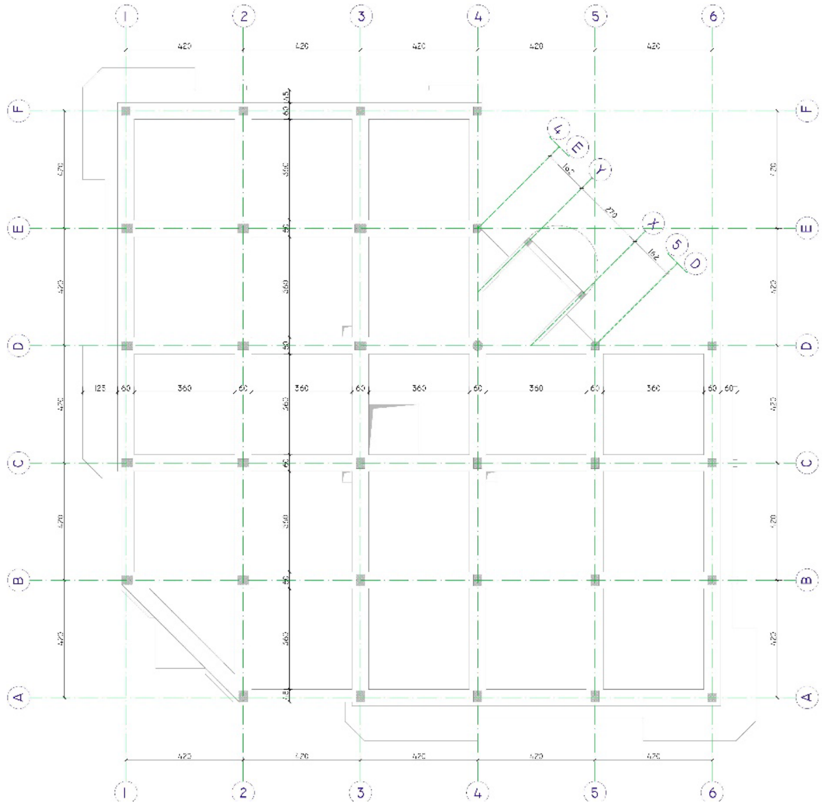
# APPENDIX A

## PLANS OF THE STRUCTURE AS BUILT

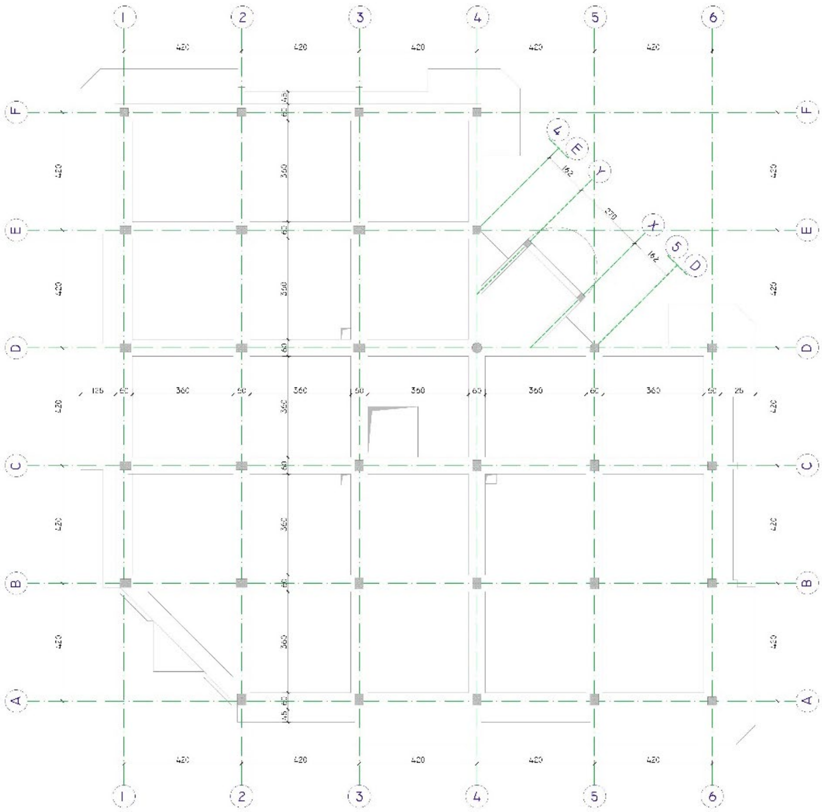
PLANI I THEMELEVE EKZISTUES



PLANI I STRUKTURAVE EKZISTUES -0.05; +3.01




PLANI I STRUKTURAVE EKZISTUES +6.07



PLANI I STRUKTURAVE EKZISTUES +9.13