Analysis and Design of a Reinforced Concrete Multistory Office Building

Laureano Dávila González
Civil Engineering
Gustavo E. Pacheco-Crosetti, Ph.D.
Department of Civil and Environmental Engineering
Polytechnic University of Puerto Rico

Abstract *— The objective of this project is to analyze and design an existing old structure using actual codes and specifications, locating the structure in a seismic risk zone. This project performs a load analysis of the structure using the International Building Code 2009 specifications, and the reinforced concrete designs using the Building Code Requirements for Structural Concrete and Commentary 2008 specifications. The structural system is a "Special Moment Resistant Frame". The designs of reinforced concrete members included in this project are: beams, columns, slab, joints, walls and foundation. For the selected typical designed elements, serviceability and strength requirements are checked and conclusions and recommendations are given.*

Key Terms *— Analysis, Design, Reinforced Concrete, Special Moment Resistant Frame.*

INTRODUCTION

The following presents a brief description of the background information of the selected existing structure. It also presents the justification of the developed project, and the objectives and scope of the work, together with a general discussion of the methodology adopted to develop the project.

Background Information of the Existing Structure

The Wainwright Building (also known as the Wainwright State Office Building) is an actual 10-story red brick office building located in St. Louis, Missouri. Designed by Dankmar Adler and Louis Sullivan in the Palazzo style and built between 1890 and 1891, it was among the first skyscrapers in the world.

In 1968, the building was designated as a National Historic Landmark and in 1972 it was named a city landmark. The building now houses Missouri stet offices, and along with Guaranty Building of Buffalo, New York, the Wainwright is among only two surviving Adler & Sullivan skyscrapers.

Justification

Reinforced concrete special moment frames are used as part of the seismic force-resisting systems in buildings. Beams, columns, and beam-column joints in moment frames are proportioned and detailed to resist flexural, axial, and shearing actions. Special proportioning and detailing requirements result in a frame capable of resisting strong earthquake shaking without significant loss of stiffness or strength. These moment resisting frames are called "SMF" because of these (ACI 318–Chapter 21 [1]) additional requirements. Puerto Rico is a high risk seismic zone, so the design of "SMF" is mandatory.

Objectives and Scope

The main objective of this project is to perform the analysis and design of a reinforced concrete multistory structure categorized as a special moment resisting frame, located in a high seismic zone area such as PR.

General Procedures and Methods

The following presents a list of the primary tasks conducted during this project:

- **Determine and specify the system requirements:** The type of material is chosen and the use of the system is presented. Location and the type of soil where the system will be built is assumed and presented.
- **Select the structural system and geometry:** The system frame is categorized based on the location and seismic action classification. The structure's geometry is presented including the floor plan describing every element proposed

in the structural frame, dimensions, and height of each floor.

- **Determine the strength and serviceability requirements:** Using the ACI 318-08 Code [1], strength and serviceability for the elements of the structure needs to be checked.
- **Perform a preliminary design:** Preliminary concrete sections were determined and assigned in ETABS program to model the structure for the analysis.
- **Determine the structural loads:** Using the IBC 2009 Code [2], loads applied to the structure were calculated and load combinations were established. Dead, Live, Wind and Earthquake were the loads considered in the load analysis.
- **Analyze the structure:** An analysis of the structure in ETABS was performed to obtain the data for the design.
- **Design frame elements and foundation:** Loads combinations established by the ACI 318-08 Code [1] gives the critical elements for the design. Typical elements of a special moment resisting frame and the foundation were designed manually and using the structural programs ETABS and SAFE.
- **Check compliance with strength requirements:** The typical elements designed need to be checked for strength requirements.
- **Check compliance with serviceability requirements:** The typical elements designed need to be checked for serviceability.

DESCRIPTION OF THE SCHEMATIC DESIGN

The following presents a description of the schematic design. System requirements are discussed, with the presentation of the structural system and geometry proposed. Also a model of the system in ETABS is discussed in details.

System Requirements

This project focuses the analysis and design of a system in a seismic region. The proposed structure is placed on San Juan, Puerto Rico. The structure is located in Hato Rey in a sector called Milla de Oro, a high seismic area (zone 3). Figure 1 shows a top view of the site and localization of the proposed structure.

Figure 1
Site Top View

For the location of the structure a classification of the soil, SD (Stiff Soil Profile) was assumed. The soil was assumed to be sedimentary rock with a soil bearing capacity of 6,000 lb/ft2.

The proposed structure was specified for office usage. Reinforced concrete was chosen to be the material of design.

Structural System and Geometry

Analyzing the specific requirements for this structure, a moment resisting frame was chosen as the structural system for the study. As a structure classified to resists seismic action, the moment resisting frame is analyzed and designed as a special moment resisting frame, where gravity and lateral loads are resisted by the frame.

With the structural system established, the geometry of the structure was proposed; using as references the old structure plans view and details. Figure 2 shows the plan view of the structure proposed, with the principal elements in the special moment resisting frame. This plan view also shows the spacing between these elements.

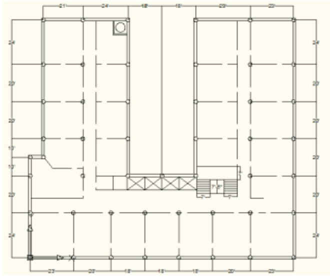

Figure 2
Plan View of the Proposed Structure

The structure is a non-symmetrical reinforced concrete building with a height of 135 ft, proposing 13.5 ft the height of each floor in a 10 story office building. Same plan view is used as typical for all stories. The skeleton or the frame of the structure is composed primarily by columns and girders with spacing shown. Slabs are also part of the structural system. The structure also is composed of four openings for the elevators and an opening for the stairs, both surrounded with walls.

Description of the Model

The full structure was drawn and presented in ETABS. Using references dimensions in the plan view, the structure was modeled with all the elements proposed, ready to be analyzed. The detailed plan view of the structure in ETABS is shown in Figure 3.

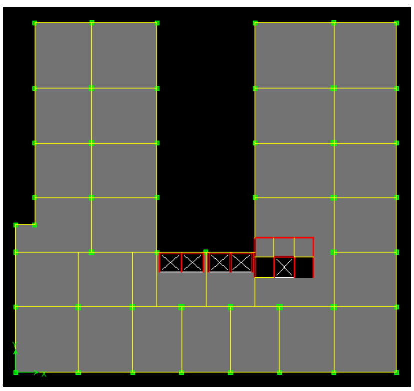

Figure 3
Plan View in ETABS

This plan view presents the location of the columns in the structure with the system of girders that connects every element in the frame. The geometry of the slab is also presented, with the openings for the stairs and the elevator.

Below, a detailed description of the model:

- **Columns:** The columns were modeled as reinforced concrete element with square section. The columns are connected to girders in both directions supporting the slab. The supports in the columns were established as fixed in the structure.
- **Beams:** Two types of beams were modeled for the structure: exterior and interior girders. Girders are the primarily connections to the columns in both directions.
- **Slabs:** The slab in ETABS was modeled as a continuous reinforced concrete slab, resting on the beams and walls. According to the dimensions, the slab is considered as a two way system. The slab in ETABS acts monolithically.
- **Beam-Columns Connections (Joints):** In ETABS, joints connections act monolithically by default. In the case a different type of connection is desired, end releases option has to be modified in the program. For the case of this study, the joints acting like default will be analyzed and designed that way.
- **Elevators:** As part of an office building, elevators were required in the structure. To model the elevators in ETABS, four openings were drawn, surrounded with wall elements representing the core of the elevators. The supports for the core were established as pin supports, given by default in ETABS.
- **Stairs:** In ETABS, the stairs were modeled as ramps resting on the slabs and the walls. The supports for the stairs were established as pin supports.
- **Full System Model:** The proposed complete system is presented in Figures 4 and 5.

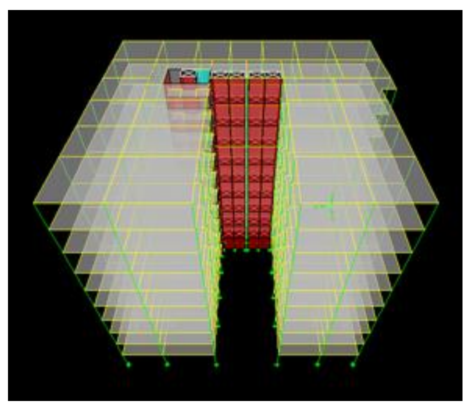

Figure 4
Complete Structural Model

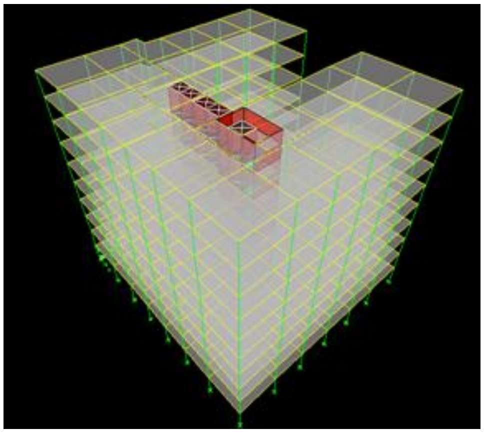

Figure 5
3D View of the Structure

STRENGTH AND SERVICEABILITY REQUIREMENTS

Strength limit states are based on the safety or load-carrying capacity of structures and include buckling, fracture, fatigue, overturning, and so on. Serviceability limit states refer to the performance of structures under normal service loads and are concerned with the uses and/or occupancy of structures and measured by considering the magnitudes of deflections, cracks and vibrations of structures as well as by considering the amounts of surface deterioration of the concrete and corrosion of the reinforcing.

Strength Requirements

Structures and structural members shall be designed to have design strengths at all sections at least equal to the required strengths calculated for the factored loads and forces in such combinations as are stipulated by the ACI 318 Code [1]. The basic requirement for strength design may be expressed as follows by Equations "(1)" and "(2)":

$$\text{Design Strength} \geq \text{Required Strength} \quad (1)$$

$$\emptyset\ (\text{Nominal Strength}) \geq U \quad (2)$$

In the strength design procedure, the margin of safety is provided by multiplying the service load by a load factor and the nominal strength by a strength reduction factor.

The following presents several criteria for strength requirements considered in this project:

- **Required Strength:** The required strength U is expressed in terms of factored loads, or related internal moments and forces. Factored loads are the loads specified in the general building code multiplied by appropriate load factors. Required strength U shall be at least equal to the effects of factored loads presented in Section 9.2 of the ACI 318-08 Code [1].
- **Design Strength:** The design strength of a member refers to the nominal strength calculated in accordance with the requirements stipulated in Section 9.3.2 of the ACI 318-08 Code [1], multiplied by a strength reduction factor ϕ, which is always less than 1.
- **Required Strength for Reinforcement:** The yielding values of f_y and f_{yt} used in design calculations shall not exceed the specifications of Section 9.4 of the ACI 318-08 Code [1].

Serviceability Requirements

To ensure adequate performance at service loads, the requirements are:

- **Control of Deflections:** Reinforced concrete members subjected to flexure shall be designed to have adequate stiffness to limit deflections or any deformations that adversely affect strength or serviceability of a structure according to Section 9.5 of the ACI 318-08 Code [1].

LOAD ANALYSIS

The following presents the structural load analysis for the model, using ETABS. As an actual requirement, IBC 2009 (International Building Code) [2] was used for the determination of the structural loads.

Preliminary Structural Design

Preliminary sizes of elements were established to model the structure in ETABS. With the results of the analysis, the design was refined, designing the typical elements selected, updating and reanalyzing the structure as necessary. For a structure of this size, reasonable estimates of sizes of members were as follows:

- Beams: 18” x 30”
- Columns: 30” x 30”
- Slabs: 6 in
- Walls: 5 in
- Ramps and slabs of the stairs: 6 in
- Beams on stairs: 6” x 6”

Determination of the Structural Loads

For this system, four types of structural loads were used for the analysis and design; Dead, Live, Wind and Earthquake loads. The following presents the discussion of each load:

- **Dead Load:** The dead load considered in the analysis was the weight of materials of construction incorporated into the building; the self-weight of the structure was calculated according to Section 1606 of the IBC 2009 Code [2].
- **Live Load:** The live load considered in the analysis was the load produced by the use and occupancy of the building and do not include construction or environmental loads. The live load was determined according to Section 1607 of the IBC 2009 Code [2] and applied in ETABS to the model.
- **Wind Load:** The determination of wind loads was checked in reference to Chapter 6 of ASCE 7-05 Code [3], according to the Section 1609 of the IBC 2009 Code [2]. Wind was assumed to come from any horizontal direction and wind pressures was assumed to act normal to the surface considered. The data obtained in the ASCE 7-05 Code [3] was entered in ETABS for the wind analysis.
- **Earthquake Load:** The determination of earthquake loads for the structure was computed in accordance to Section 1613 of the IBC 2009 Code [2] with references from ASCE 7-05 Code [3]. A static load case was created in ETABS for the earthquake load using two directions: x and y.

Load Combinations

Load combinations from Section 1605 of the IBC 2009 Code [2] were defined using strength design or load and resistant factor design, and were created and inserted in ETABS for the analysis. The structure and portions thereof shall resist the most critical effects from those load combinations.

Analyzing the Structure

As an overview of the model in ETABS, the following steps were checked:

- **Joint and Member Connectivity:** The defined geometry of the structure was checked to assure members adequate connectivity.
- **Joint Restraints:** The structural supports were specified by restraining the joints at supports. Fixed supports were established for columns and pin supports were assigned to stairs and elevators.
- **Members Properties:** Properties like cross-sectional characteristics and modulus of elasticity for each reinforced concrete member were established and checked before performing the analysis.
- **Loads:** Loads acting on the structure were specified and assigned. In ETABS, the loads acting on the structure were assigned to members and joints, using a global coordinate system for joints and a local coordinate system for members.

The analysis was performed, showing the results and behavior of the structure. Typical elements subjected to critical load combinations from the analysis were selected and results were used for the design of these elements. These typical design sections were used in all the stories in the structure.

The following information was considered in the selection of the results for each member:

- **Results for Beams Design:** A design of an exterior girder and an interior girder were presented in this project. The beams are flexural members in special moment frames, therefore the maximum moment values were selected from the analysis for each typical element and the maximum shear values were checked in the designs.

- **Results for Columns Design:** A design of an interior column, exterior column and corner column were presented in this project. The columns are members in special moment frames subjected to bending and axial loads, therefore the maximum axial forces and moment values were selected from the analysis for the design of each typical element.
- **Results for Slab Design:** Slabs are considered reinforced systems designed for flexure in more than one direction. In this case, the slabs were considered elements with two ways action clamped by beams and columns. A specific critical piece of slab acting two ways was selected as shown in Figure 6. Using the load cases that applied and length dimensions, the design for this specific slab was performed. These results were used as references for the design of the complete slab in each floor. The designed dimensions were established in ETABS and the critical floor was selected with the dimensions and reinforcement references of the manually designed slab and exported to the structural program SAFE. In SAFE, the complete slab was analyzed giving the necessary results for the design, and then designed in the same program.

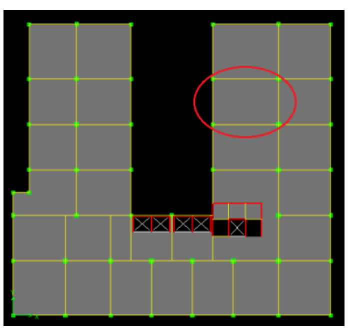

Figure 6
Selected part of Slab for Design

- **Results for Joints Design:** ETABS considered the joins in the structure as monolithically elements. For this project and example of the design of a selected joint was performed using the required data, results and dimensions from the others designs.
- **Results for the Wall Design:** For the walls design, in this case the one surrounding the elevators and stairs, ETABS was used for the analysis and design.
- **Results for the Foundation Design:** For the foundation design, an overview of the base of the structure was made. From the analysis in ETABS, the reaction forces at the supports in the base were evaluated. As discussed before, the supports of the structure were fixed, therefore, vertical axial forces and moments in the base were considered in the design of the footings.

DESIGN OF THE SPECIAL MOMENT RESISTANT FRAME AND FOUNDATION

The following presents and discusses the procedure used for the design of each element in the frame and the foundation design. Each element was designed separately using an adequate procedure following the specification of the ACI 318-08 Code [1] for reinforced concrete.

Design of Beams

Beams are flexural members in a moment resisting frame. Therefore, these members were designed using tension and compression reinforcements, covering the flexure requirements with addition of reinforcement for shear requirements.

The selection of the two different typical beams was: exterior (edge) girders and interior girders. For each of these cases, the members were designed by hand computations for maximum results from the structure analysis for a specific critical load combination. These designs were assigned to the complete structure in the model in ETABS for a final design.

The designs of beams were as follows:

- **Exterior Girders:** 14” x 20” with 3 No. 11 (A_s = 4.68 in^2) and a clear cover of 1.5 in. No. 3

stirrups with No. 4 hangers using 9.25 in for maximum spacing.

- **Interior Girders:** 12” x 26” with 5 No. 9 (A_s = 5.00 in^2) and a clear cover of 3 in. No. 3 stirrups with No. 4 hangers using 11.5 in for maximum spacing.

Design of Columns

Columns are vertical members subjected to bending and compression axial loads in a moment resisting frame. Therefore, these members were designed using compression reinforcement, also covering the requirements for bending. Slenderness in columns was checked and the columns were designed as short columns.

This section presents the complete design for the selection of three different typical columns: interior columns, exterior columns and corner columns. The corner columns, unlike the others, were designed for biaxial bending. For each of these cases, the members were designed by hand computations for maximum results from the structure analysis for a specific critical load combination. These designs were assigned to the complete structure in the model in ETABS for a final design.

The designs of columns were as follows:

- **Interior Columns:** 22” x 22” (A_g = 484 in^2) with 8 No. 18 (A_s = 32.00 in^2) and No. 4 ties at 22 in.
- **Exterior Columns:** 18” x 18” (A_g = 324 in^2) with 4 No. 14 edge bars (A_s = 9.00 in^2) and 4 No. 18 corner bars (A_s = 16.00 in^2) and No. 4 ties at 18 in.
- **Corner Columns:** 17” x 17” (A_g = 289 in^2) with 8 No. 11 (A_s = 12.48 in^2) and No. 4 ties at 17 in.

Design of the Slab

The slab was classified as a two way slab, explaining that bending occurs in two directions; therefore, a design of a part of the entire slab was performed. In this design, the dead and live loads were considered only, supporting the assumption that in the frame these types of loads are supported by the slab and lateral loads by the beams and columns. The procedure used for the design of this slab was the Direct Design Method. This procedure was provided by the ACI 318-08 Code [1] Section 13.6. The design of this part of the slab provided a thickness and reinforcements that were used as reference. This summary information is displayed in Table 1 and Table 2. With this information, the slab thickness was assigned in ETABS and results from the analysis were established. The critical floor was selected and exported to the structural program SAFE. The calculated reinforcements from the Direct Design Method were assigned and with the results from ETABS, the design of the complete slab was performed in SAFE.

Table 1
Summary of the Slab Reinforcement and Spacing for the Column Strip

Column Strip				
	Support		Midspan	
Direction	As/12 in	Bar Size and Spacing (in c-c)	As/12 in	Bar Size and Spacing (in c-c)*
E – W (d = 6.0)	0.28 in^2	No. 4 at 9	0.18 in^2	No. 3 at 7
N – S (d = 5.5)	0.18 in^2	No. 3 at 7	0.10 in^2	No. 3 at 8

*Maximum spacing of bars should not exceed 12 in center to center for crack control.

Table 2
Summary of the Slab Reinforcement and Spacing for the Middle Strip

Middle Strip				
	Support		Midspan	
Direction	A_s/12 in	Bar Size and Spacing (in c-c)	As/12 in	Bar Size and Spacing (in c-c)*
E – W (d = 6.0)	0.21 in^2	No. 4 at 11	0.15 in^2	No. 3 at 9
N – S (d = 5.5)	0.28 in^2	No. 4 at 9	0.15 in^2	No. 3 at 9

*Maximum spacing of bars should not exceed 12 in center to center for crack control.

Figure 7 shows the complete slab reinforcement in SAFE, where selecting or clicking the desired area, shows you the reinforcement in two directions and the number and sizes of bars in the selected region.

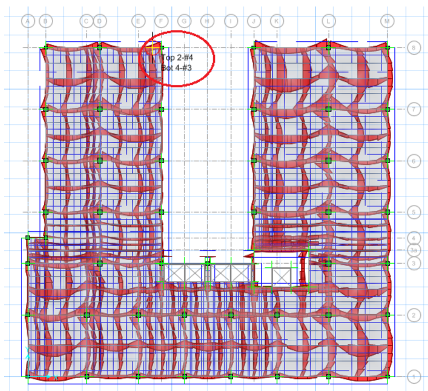

Figure 7
Slab Reinforcement in Two Directions in SAFE

Design of Joints

For the design of joints in this project, an example of a reinforced concrete connection was established. This example shows how the reinforcement is designed and located in the union of a beam and column selected in the model. The joints were considered as one element when connected the beams and columns in the model.

Design of Walls

The walls in this structure do not represent parts of the resistant frame. Walls were modeled as part of the surroundings and cover for the elevators and stairs. Although not part of the main elements, the walls were designed using ETABS and not using an extended procedure like other elements. In ETABS the walls were designed as bearing and shear walls.

Design of the Foundation

The following presents the design of the foundation for the structure presented in this project. The geotechnical data established for the design was assumed based on the location of the structure and soil references. For the location of the structure, the assumed allowable bearing pressure or capacity of the soil was 6,000 psf.

The design of the foundation for this project consisted on three different square footings. The design of these three different square footings were based on the design of the three typical columns in this project; interior, exterior and corner. The material for the square footings was reinforced concrete with a compressive strength of 3,000 psi and Grade 60 bars. Each square footing contains dowels design, to carry some of the load across the column-footing interface. The top of the footings was covered with 6 in of fill with an assumed density of 120 lb/ft^3 and a 6 in basement floor. For this basement floor, an assumed loading of 100 psf was assumed.

The design of the square footings was as follows:

- **Interior Column Footings:** 15 ft square footing and 42 in thick. Using 10 No. 11 each way @ 18 in spacing and 8 No. 10 dowels.
- **Exterior Column Footings:** 11 ft 6 in square footing and 32 in thick. Using 10 No. 9 each way @ 18 in spacing and 8 No. 6 dowels.
- **Corner Column Footings:** 9 ft square footing and 25.5 in thick. Using 7 No. 9 each way @ 18 in spacing and 5 No. 5 dowels.

An evaluation of the design provided above was performed using SAFE. This evaluation was developed for the purpose of checking the results for the design presented, including strength and serviceability requirements and as an alternative design method. A look of the complete foundation modeled in SAFE is presented in Figure 8.

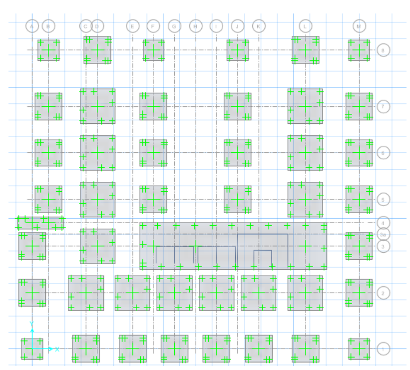

Figure 8
Foundation of the Structure in SAFE

RESULTS ANALYSIS

The following discuss the important results from the modeling, analysis and design of the structure in this project. The structure must be check using the required Codes and engineering approach to meet several criteria taken in consideration in this project.

An analysis of the fundamental period of the final model of the structure was presented and verified with the IBC 2009 Code [2]. An analysis of the behavior of the final model of the structure and modes was presented. An analysis of the Chapter 21 from the ACI 318 Code [1] and requirements for earthquake resistant structures was discussed and taken as reference for the design of the structure in this project, including specific strength and serviceability requirements. A look and analysis of strength requirements for each designed element was presented according to the ACI 318 Code [1]. And a look and analysis of serviceability requirements for the designed elements and complete structure is presented, checking deflections according to the ACI 318 Code [1] and story drifts according to the IBC 2009 Code [2].

SCHEMATIC DESIGN DRAWINGS

This section presents the drawings and plans for the designed members discussed in this project. Programs like AutoCad, ETABS and SAFE were used for the drawings of most of the members. The schematic design drawings were as follows:

- **Beams:** The exterior girder and interior girder drawings are shown in Figures 9 and 10.

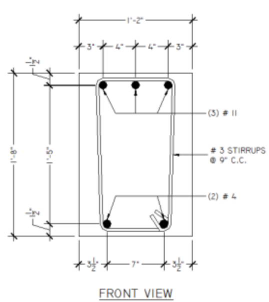

Figure 9
Exterior Girders Design

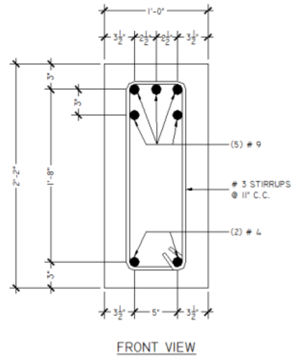

Figure 10
Interior Girders Design

- **Columns:** The interior column, exterior column, and corner column drawings are shown in Figures 11, 12, and 13.

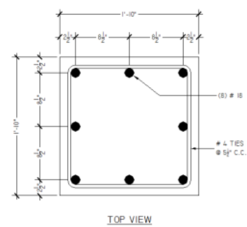

Figure 11
Interior Columns Design

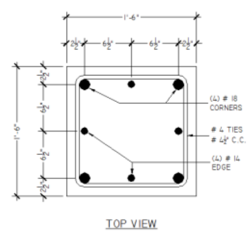

Figure 12
Exterior Columns Design

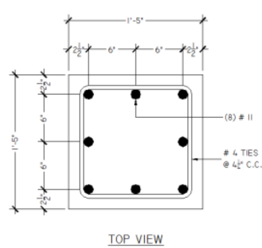

Figure 13
Corner Columns Design

- **Slab:** The slab design drawing is shown in Figure 14.
- **Footings and Foundation:** The square footing for the interior columns, exterior columns, and corner columns are shown in Figures 15, 16,

and 17. A look of the schematic drawing for the foundation of the structure is shown in Figure 18.

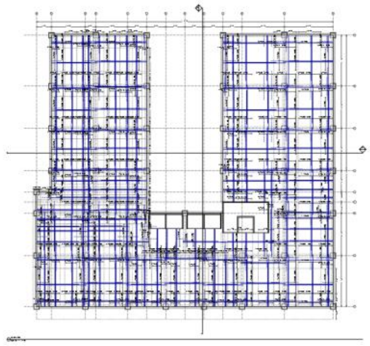

Figure 14
Slab Design

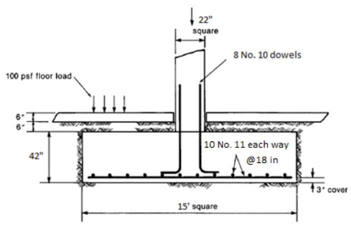

Figure 15
Square Footing for Interior Columns

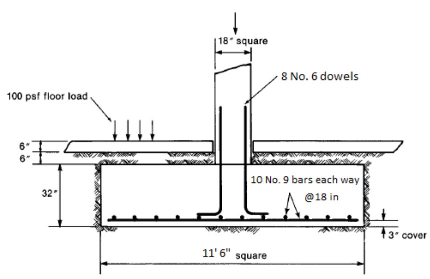

Figure 16
Square Footing for Exterior Columns

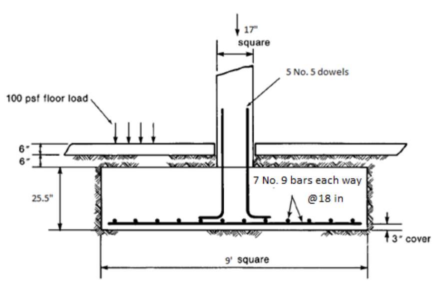

Figure 17
Square Footing for Corner Columns

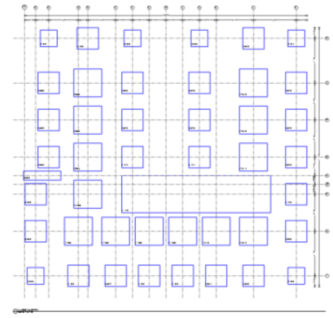

Figure 18
Schematic Drawing for the Foundation

CONCLUSION AND RECOMMENDATIONS

The following presents the general conclusions of the design project:

- The selection of reinforced concrete as the primary material was appropriate according to the strength and serviceability requirements.
- The fundamental period associated to the Mode 1 of the designed structure was considered high with a value of 1.9288 sec, but was acceptable according to the ACI 318 Code [1]. This vibration mode presented a torsional movement in the structure. The size, magnitude, and characteristics of the proposed structure explained this behavior and how the structure acted due to the different types of loads applied in this project.
- The designed structure meets the strength and serviceability requirements required by the ACI 318 Code [1] for reinforced concrete structures. The design also meets the requirements established by the Chapter 21 of the same Code, for structures or frames resisting earthquake loading.
- The proposed and designed structure demonstrated an acceptable behavior due gravitational and lateral forces. The structure was considered an earthquake resistant frame.
- An improvement in the design may consist in increasing the size of members to obtained higher stiffness characteristics in the structure and decrease the period of the structures.
- It is recommended the use of structural design programs to check actual designs and provide

alternative designs for specific members. This procedure will help the user in saving time and in several cases, saving money.

REFERENCES

[1] American Concrete Institute (ACI), *"Building Code Requirements for Structure Concrete (ACI 318) and Commentary"*, 2008.

[2] International Code Council (ICC), *"International Building Code"* (IBC), 2009.

[3] American Society of Civil Engineers (ASCE), *"Minimum Design Loads for Buildings and Other Structures"* (ASCE/SEI 7), 2006.