A COMPARATIVE STRUCTURAL AND ARCHITECTURAL ANALYSIS OF EARTHQUAKE RESISTANT DESIGN PRINCIPLES APPLIED IN REINFORCED CONCRETE RESIDENTIAL BUILDINGS IN TURKEY

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ABSTRACT

A COMPARATIVE STRUCTURAL AND ARCHITECTURAL ANALYSIS OF EARTHQUAKE RESISTANT DESIGN PRINCIPLES APPLIED IN REINFORCED CONCRETE RESIDENTIAL BUILDINGS IN TURKEY

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The aim of this thesis is to demonstrate that it is possible to design earthquake resistant residential structures without significant compromises in the spatial quality and economic viability of the building. The specific type of structural system that this thesis focuses on is the reinforced concrete skeleton system. The parametric examples and key studies that are used in this research are chosen among applied projects in the city of Bolu. This city is chosen due to its location on the North Anatolian Fault and its destructive seismic history.

The structural validity of the hypothesis was demonstrated through an analytical process during which a set of 7 models were tested. 5 of these were designed as idealized parametric models and 2 of them were based on actual buildings destroyed in earthquakes.

The architectural validity of the hypothesis was demonstrated on a set of 3 architectural projects. Projects were subjected to a comparative evaluation between their original states and the modified seismically resistant versions. The architectural comparison between earthquake resistant and non-resistant states was made on a planimetric basis. Comparison parameters were: floor area; size, location and number of rooms; and access to view.

The feasibility of seismically resistant reinforced concrete residential buildings was demonstrated through an approximate cost analysis which has proven that designing earthquake resistant structures only resulted in an acceptable 4-8% rise in the overall building cost.

Keywords: Earthquake, Architecture, Seismic Design, Reinforced Concrete, Residential Buildings

ÖZ

TÜRKİYE'DEKİ BETONARME KONUT YAPILARINDA DEPREME DAYANIKLI TASARIM PRENSİPLERİNİN UYGULANMASININ KARŞILAŞTIRMALI STRÜKTÜREL VE MİMARİ BİR ANALİZİ

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Bu tezin amacı binaların mimari kalitelerinde ve ekonomik yapılabilirliklerinde bir azalma olmadan depreme dayanıklı bir şekilde tasarlanabileceğini göstermektir. Bu tezin ulaşmayı amaçladığı okuyucu kitlesi mimarlardır. Bu tez özel olarak betonarme iskelet yapısal sistemlerle ilgilenmektedir çünkü bu sistem Türkiye'de en yaygın olarak kullanılan strüktürel sistemdir. Bu tezde kullanılan parametrik ve gerçeğe dayalı örnekler Bolu şehri merkezindeki uygulanmış projeler arasından seçilmiştir. Bu şehrin tercih edilme nedeni doğrudan Kuzey Anadolu Fay Hattı üzerinde yer alması ve yıkıcı bir sismik geçmişe sahip olmasıdır.

Tezin savunduğu fikirlerin strüktürel açıdan geçerliliği 5 tanesi idealize edilmiş parametrik model, 2 tanesi de yapılmış gerçek binalara dayalı model olmak üzere toplam 7 analitik model üzerinden test edilmiştir.

Hipotezin mimari geçerliliği ise Bolu şehrinde bulunan yıkılmış 3 adet gerçek proje üzerinden araştırılmıştır. Bu projelerin orjinal halleri ve depreme dayanıklı tasarım ilkelerine gore yeniden tasarlanmış versiyonları arasında karşılaştırmalı bir mimari inceleme yapılmıştır. Bu mimari inceleme esnasında yapıların kat alanı, konutların, oda sayısı, boyutları, manzaraya açıklığı gibi planimetrik özellikleri esas alınmıştır.

Depreme dayanıklı betonarme konut yapılarının ekonomik fizibilitesi yaklaşık strüktürel sistem maliyetlerinin analizi yoluyla araştırılmıştır. Bu araştırmalar depreme dayanıklı strüktürel tasarımın toplam yapı maliyetini sadece %4-8 kadar arttırdığını göstermiştir.

Anahtar Kelimeler: Deprem, Mimarlık, Depreme Dayanıklı Tasarım, Betonarme, Konut Yapıları

To My Family

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PREFACE

> *"… in a single day and night of misfortune, the island of Atlantis disappeared into the depths of the sea."*
>
> From, Timaeus & Critias, Plato 360 B.C.

The sinking of the mythical island of Atlantis reveals how deeply the fear of natural disasters is routed in the collective memory of humanity. Whether the story of Atlantis is merely a legend or if there is some truth in it is yet unknown. However, the possibility of entire cities or communities being destroyed by the unforgiving fury of nature is a well recorded fact of human history.

The people of the antiquity regarded the natural disasters as punishments from their gods for their sinful way of life. According to Plato, Atlantheans were struck with earthquakes and floods because they strode away from the divine values. These values instructed them to live their lives according to the rules of knowledge, science and wisdom. However, in their arrogance, they have chosen to become the slaves to their materialistic ambitions. They have paid the price with their very lives.

Modern science helped us understand the real reasons behind natural phenomena such as earthquakes. We know now that the drift of continental plates and not the fury of gods is the governing reason behind these occurrences. However, after observing how poorly constructed the damaged buildings were or how badly chosen the location of settlements are, one cannot stop thinking that humanity is somehow punished for its irresponsible actions and lack of proper judgment.

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LIST OF SYMBOLS

A	Effective ground acceleration
a	Acceleration of the building
A_o	Effective ground acceleration coefficient
b	Column dimension parallel to bending axis
e	Amount of eccentricity of the structural element
E	Modulus of Elasticity
F	Equivalent earthquake force/Total Load Effect on the Structure
f_{ck}	Characteristic strength of concrete
Fe	Chemical symbol for Iron
f_{yk}	Characteristic yielding strength of steel
g	Acceleration due to Earth's gravity
h	Column dimension perpendicular to bending axis
h_i	The height of the i^{th} floor of the building
h_{i+1}	The height of the $i+1^{st}$ floor of the building
I	Moment of inertia of the structural element
L	Height of the Column
M	Moment
ΔM	Second Order Moment
m	Mass of the building
N	Axial Force
n	Number of Storeys
Mg	Chemical symbol for Magnesium
O	Chemical symbol for Oxygen
P	Applied Point Load
R	Resistance Capacity of the Structure
$R_a(T)$	Seismic Load Reduction Factor
Si	Chemical symbol for Silica

T	Natural period of the building
T_A	Spectrum Characteristic Period
Δ_{max}	Maximum displacement
$(\Delta i)_{max}$	Maximum storey drift
$(\Delta_i)_{ort}$	Average storey drift
η_{ci}	Strength irregularity coefficient
η_{bi}	Torsion irregularity coefficient
η_{ki}	Stiffness irregularity coefficient
ΣA_e	Effective shear area of a floor
ΣA_g	Total area of shear-walls in a floor
ΣA_w	Total area of columns in a floor
ΣA_k	Total area of partition walls without door and window openings in ΣA_w
	Total area of shear-walls in a floor a floor
w	Applied Distributed Load
γm	Material Coefficient
γf	Load Factor

CHAPTER 1

INTRODUCTION

1.1 Statement of The Problem

This thesis demonstrates that it is possible to design earthquake resistant residential structures without significant compromises in the spatial quality and economic viability of the building. The intended audience of this thesis is architects. There are two reasons for this choice. The first reason is the lack of studies on seismic design which specifically address architectural audiences. The other reason is the fact that the majority of architects will have to design residential buildings during the course of their professional carriers.

The specific type of structural system that this thesis focuses on is the reinforced concrete (R/C) skeleton system because this is the dominant type of structural system in Turkey. The parametric examples and key studies that are used in this research are chosen among applied projects in the city of Bolu. This city is chosen due to its location on the North Anatolian Fault and its destructive seismic history.

The context of the thesis is the urban environment in Turkey. More specifically, the established tradition of building R/C residential buildings in Turkish cities located on seismic zones. Although the majority of the arguments of this study are internationally applicable, the conclusions of this research are primarily relevant to the current and future developments in Turkish building industry.

1.2 Aim and Objectives of the Thesis

The objective of this research is to demonstrate to architects that following certain guidelines during the design process significantly improve the earthquake resistance of the building. The main audience of this thesis consists of architects and students of architecture. This is a critical statement for two reasons. First of all, the ratio of scientific studies which are written specifically for architects within all the work done on seismic design is very low. Secondly, this thesis is not just written for architects but also authored by an architect. This is a rare situation considering that the general tendency among architects in Turkey is to seek counsel on seismic design from professionals outside their own discipline.

Presenting an argument for an architectural audience has different requirements than a study addressing an engineering audience. The first of these requirements is to present a valid argument to convince architects that the topic of seismic design is within their domain of responsibility. It is critical for architects to understand that the term “architectural design” implies the preliminary design of the structural system and furthermore, in Turkey, even preliminary structural design requires a special emphasis on the seismic behavior of the building.

The second requirement is to make a thorough definition of the context for the study from an architectural point of view. In this case, the context is the urban environment in Turkey; more specifically, the emergence of the R/C residential block as the dominant architectural typology in Turkish cities. This study will not propose radical changes to the architectural status quo. The structural and architectural arguments of this thesis aim to improve the average building quality in cities located on seismic zones. Therefore this study stays within the boundaries of the conventional R/C construction system.

The third requirement is to convey to the architects certain critical notions about seismic design. This is achieved in two steps. In the first step, contextual information is given in the form of the seismic characteristics of Turkey, the essentials of the country's seismic regulations and a brief overview of the R/C skeleton system. In the second step, key technical concepts such as natural period, the effect of excessive lateral displacements, and the use of axial force-moment diagrams for columns are introduced with a language suitable for the understanding of architects.

The manner in which the main argument is presented is also determined from an architectural perspective. The argument develops in two stages. In the first stage, the validity of the proposed modifications is tested through analytical models and computer simulations. Although the analytical models are prepared as realistic as possible, the primary aim of these analyses is not to obtain accurate numerical results. The objective is to demonstrate the seismic behavior of proposed structural principles within a reasonably precise interval. Understanding the structural behavior of buildings under seismic loads is more important for architects than the ability to perform complicated engineering calculations.

The second stage consists of comparative architectural discussions on the original and modified states of selected building projects. Similar with the previous part where the structural discussions were not allowed to become too technical to blur the clarity of the message, in this stage, architectural discussions are conducted mainly from a pragmatic perspective. In other words, the buildings are compared in planimetric terms such as the floor area, access to view, number and size of rooms, location of openings, etc. The aim of this thesis in not to go into a critical architectural debate about whether the R/C residential blocks still offer a suitable way of life for today's society or not. The aim is simply to improve the seismic resistance of this building typology.

1.3 Materials and Methodology

The materials used for this study can be listed as follows:

- Literature survey conducted in the master and doctoral dissertations database of The Council of Higher Education of the Republic of Turkey – Türkiye Cumhuriyeti Yüksek Öğretim Kurumu.

- Literature survey conducted among available domestic and foreign publications on the subject in the form of books, conference proceedings, articles, seismic regulations, statistical data and internet pages.

- Photographs taken by the author during field studies conducted in various locations of Bolu city center. These locations include downtown area, neighborhoods which were recently opened for development and neighborhoods which consist of permanent residences built by Housing Development Administration of Turkey - Toplu Konut İdaresi (TOKİ)

- Interviews conducted with architects, civil engineers and contractors practicing in Bolu.

- Interviews conducted with architects practicing in Ankara and academicians specialized in the field of seismic design.

- Architectural and Structural drawings of buildings obtained from municipalities, architectural and civil engineering offices. These drawings include buildings destroyed in 1999 earthquakes; seismic strengthening projects for buildings that were heavily damaged during earthquakes, projects for recently built or planned buildings in Bolu.

The methodology of this thesis is as follows:

1. The establishment of the Architectural context for the study:

    - Definition of the role that architects play in earthquake resistant design. The spheres of responsibility of architects and structural engineers. The meaning of the word “design” from both architectural and engineering points of view.

    - A brief overview of the history and general characteristics of urban environment in Turkey.

    - A description of the seismic characteristics of Turkey with special emphasis on the seismic characteristics of the city of Bolu.

    - A concise review of the current Turkish Earthquake Code from an architectural point of view.

2. The definition of critical concepts in the earthquake behavior of reinforced concrete structures:

    - A review of the material properties of R/C. The relevant aspects of the Turkish Standard TS 500

    - The definition of the earthquake load concept. The relationship between the architectural design and the seismic performance of R/C buildings.

    - The effects of critical concepts such as strength, ductility and stiffness.

  - Definition of performance assessment tools for the comparative analytical study. The description of the concept of natural period, the effect of excessive lateral displacements on R/C skeleton systems and the use of Column Interaction Diagrams as an effective way of determining the safety level of R/C columns under earthquake loads.

  - A review of the most commonly encountered types of seismic design faults in R/C residential buildings.

3. The structural evaluation of earthquake resistant design principles applied in reinforced concrete residential apartment buildings:

  - Demonstration of the isolated structural effect of each type of seismic design fault on the earthquake behavior of the structure through a progressive sequence of analytical models.

  - Analysis of Idealized Parametric Models. The sequence begins with the model which has the least favorable structural configuration and ends with the model which has an ideal structural configuration.

  - Analysis of a model based on an actual building with unfavorable structural configuration.

  - Analysis of a model based on an actual building with improved structural configuration.

  - Discussion of the results obtained from the structural analyses.

4. The architectural evaluation of earthquake resistant design principles applied in reinforced concrete residential apartment buildings:

- Establishment of the procedure for a comparative planimetric analysis of R/C residential buildings.

- A comparative architectural analysis of a R/C apartment building with two residential units per floor. The building is first modeled with unfavorable structural configuration and then redesigned with favorable structural configuration.

- A comparative architectural analysis of a R/C apartment building with three residential units per floor. The building is first modeled with unfavorable structural configuration and then redesigned with favorable structural configuration.

- A comparative architectural analysis of a R/C apartment building with four residential units per floor. The building is first modeled with unfavorable structural configuration and then redesigned with favorable structural configuration.

- A comparative cost-based analysis of R/C residential buildings before and after the application of earthquake resistant design principles.

5. Discussion and Evaluation of the results obtained from structural and architectural studies.

- Observations on the current building practices in Bolu city center.

1.4 Disposition

Chapter 2 establishes the architectural context for the study. The spheres of responsibility of architects and structural engineers are explored. The fact that R/C apartment block is the most common building type in Turkey is established through a brief overview of the history and general characteristics of urban environment in Turkey. A description of the seismic characteristics of Turkey is made in order to establish that the threat of a destructive earthquake is a realistic possibility for many Turkish cities. A special emphasis is made on the seismic characteristics of the city of Bolu. The Turkish Earthquake Code 2007 “Specifications for Buildings to be Built in Earthquake Areas” is concisely reviewed from an architectural point of view.

Chapter 3 begins with a review of the material properties of R/C. This section also covers the relevant aspects of the Turkish Standard TS 500 “Requirements for Design and Construction of Reinforced Concrete Structures” which is the principal legal document that sets the framework for the production of R/C in Turkey. The following section provides the definition of the earthquake load concept. The relationship between the architectural design and the seismic performance of R/C buildings is explored in structural terms. The third section of Chapter 3 will provide the working principles of critical concepts such as the concept of natural period, the effect of excessive lateral displacements on R/C skeleton systems and the use of Column Interaction Diagrams as an effective way of determining the safety level of R/C columns under earthquake loads.

The final section of Chapter 3 will focus on the most commonly encountered types of seismic design faults. This thesis is specifically interested in design faults in plan because the R/C apartment buildings are typically produced by the repetition of the same floor plan at each level.

Chapter 4 presents the structural aspect of the main argument of the thesis. The first step is to demonstrate the isolated structural effect of each type of seismic design fault on the earthquake behavior of the structure through a progressive sequence of analytical models. A series of idealized parametric models will be analyzed beginning with the model which has the least favorable structural configuration. Then, the structural system will be gradually improved modifying one parameter at a time. At each step the structural analysis will be repeated and results will be compared to demonstrate the improvements.

The second step is to apply all the findings of the parametric study on an actual building project to explore whether the results obtained in idealized conditions are applicable to existing cases. In this section, a 6 storey structure chosen among buildings which were heavily damaged during the 1999 earthquakes in Bolu, is analytically modeled first in its original structural configuration and then in its modified state.

Chapter 5 will discuss and evaluate the architectural aspect of the main argument
A total of three building projects, all based on buildings, which were heavily damaged during the 1999 earthquakes, are examined. The first example has two residential units per floor. The second and the third examples have three and four residential units per floor respectively. A key requirement for the feasibility of proposed guidelines is to offer a solution that has economic validity in the building market. Therefore, the economic impact of designing seismically resistant structures is discussed in this chapter. However, the scope of this cost analysis is kept limited with the cost of the R/C structural system.

The conclusion chapter begins with a summary of the results obtained in previous chapters. The findings of comparative studies, both structural and architectural, are briefly reviewed in order to demonstrate the validity of the initial assertions. The thesis ends with proposals for further studies.

CHAPTER 2

THE CONTEXT OF THE STUDY

2.1 The Role of The Architect in Structural Design

2.1.1 Architects vs. Engineers: Overlapping Spheres of Responsibility

If we study the history of building construction, we see that there was a time when the “master builder” was responsible for every aspect of creating a new building. The writings of the Roman architect Vitruvius and the studies on the Ottoman Imperial architect Sinan clearly demonstrate that the builder of those times had to assume the roles of the architect, the structural engineer and the mechanical engineer as well as the city planner and the contractor. The ancient architect had to be a true renaissance man.

However, those were times when scientific knowledge and available technology were limited and could be within the grasp of a single person. Over the centuries, the developments in science and technology exponentially multiplied the amount of knowledge necessary for the design and construction of a building. A need for professional specialization has emerged. As a result a rift between architecture and structural engineering became inevitable.[1] As Spyros Raftopoulos states:

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[1] ÜNAY, Ali İhsan, ÖZMEN, Cengiz “Building Structure Design as an Integral Part of Architecture: A Teaching Model for Students of Architecture”, International Journal of Technology and Design Education, 2006, Vol.16, pp.253-271

> *…The developments in the building industry, especially in our recent times, demanded a specialization of the various disciplines. These were also enhanced by the complexity of the market demands. This complexity was very high especially in the engineering field, with all the additional prerequisites of the seismic calculations, the new technological developments and the introduction of computers. This development naturally increased the exclusion of architects from the engineering part of their job, a fact which was evident even before that. Similarly the complexity and the increasing demand of designed buildings, gradually excluded engineers from the architectural field, especially in relation to larger projects.*[2]

This separation of disciplines brought along some advantages and disadvantages. The greatest advantage was that as a result of advanced technology, materials and specialized knowledge, it was now possible to design and construct buildings with stronger, complex, efficient and more economic structural systems. Another advantage was the introduction of group work. Besides the obvious economy of time, the design of the building was now realized with the participation of a larger group of specialists who can support each other's efforts by contributing with their knowledge; and serving as an error-check mechanism. This reduces the possibility of man-made mistakes, which would otherwise be on the shoulders of a single person.

Unfortunately, there were some disadvantages to specialization. In time, some architects and engineers developed a misconception that their responsibilities mutually excluded each other's concerns and sensibilities. For architects, structure was a technical issue which had to be left to engineers who had no saying in the matters of design and should have to work strictly within the boundaries and criteria set by the architects. Engineers, on the other hand, have begun to see architects as mere artists whose, sometimes capricious, demands were in contradiction with the principles of effective and economic structural design.

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[2] RAFTOPOULOS, Spyros, "Educating Architects or Architects-Engineers", Les Cahiers de l'enseignement de l'architecture Transations on Architectural Education No: 5 Architecture and Engineering, The Teaching of Architecture for Multidisciplinary Practice, Maria VOYATZAKI Ed., Thessaloniki, Greece, Art of Text S.A. 1999, p.207

Such separatist visions had effects on the way architects and engineers trained themselves in the ways of the art of building. Some architects have solely focused on theoretical studies and engineers have exclusively sharpened their skills in overcoming structural challenges, such as covering the largest span, designing the tallest building, etc. This is also described by Tom F. Peters in the book 'Bridging the Gap: Rethinking the Relationship of Architect and Engineer' as follows:

> *…While engineering hopes to be moving toward a more comprehensive approach to design and building, and the very nature of the word 'design' in engineering seems to be shifting to mean more 'configuration' than 'dimensioning', architecture is in danger of diversifying into literary and purely graphic pursuits, on occasion so strongly that some architects become mere aesthetic consultants or even abandon building altogether.*[3]

This alienation of professions and the consequent mutual disdain of architects and engineers may perhaps be best characterized by the words of Le Corbusier:

> *…Engineers are healthy and virile, active and moral, happy and useful. Architects are disenchanted or unemployed, or morose. The reason is that soon they will not have anything left to do. We don't have any more money just to maintain historical memories. We need so cleanse ourselves.*[4]

There is a safety mechanism against the total alienation of professions. One of the novelties of specialization is the necessity of group work between professionals of different disciplines. In this system, the architects, as an addition to their traditional role as the designers, had to assume also the role of coordinator between the parties involved in the process of design and construction. To perform their duties as the leader and coordinator of the design group, architects still had to have a certain degree of knowledge in the various fields concerning building construction.

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[3] PETERS, Tom F., Bridging the Gap: Rethinking the Relationship of Architect and Engineer, New York, Van Nostrand Reinhold, 1991

[4] JEANNERET-GRIS, Charles Eduard, Towards a New Architecture, by Le Corbusier, Frederick Etchells Trans. New York, Preager, 1970

2.1.2 Critical Concept: The Meaning of the word “Design”

This thesis is about the close interaction between the “Architectural Design” and the “Seismic Performance” of buildings. Here, the word architecture is consciously emphasized because the concept of “design” has very different meanings depending on the context. A simple example is the difference between the meanings attributed to this word by structural engineers and architects.

Structural engineers almost unanimously agree that structural safety and economy are the two governing principles of engineering design. In addition to these two criteria, some engineers consider “practicality”[5] as the third principle while certain others state that a sense of “aesthetics”[6] is a must in structural design. As one can observe, despite small individual differences, there is a clearly defined consensus on the meaning of the word design among structural engineers.

Architectural design, on the other hand is an entirely different issue. Architecture itself is commonly described as a union of art and science. This union embodies the two major aspects of human psyche. One of these aspects is humankinds’ sentimental side, based on feelings, instincts and intuitions. This is what gives architecture its artistic flavor. The other aspect is the human reason, based on logic and accumulated scientific knowledge of humanity. This is what makes architecture a science.

Unlike the field of structural engineering, this personal and subjective nature of architecture makes it difficult to talk about a widespread consensus on the meaning of the word design. In fact, a large portion of the academic literature of

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[5] ERSOY, Uğur, Reinforced Concrete, Ankara, METU Press, 2000, p.53

[6] ATIMTAY, Ergin, Reinforced Concrete: Fundamentals, 2 Vols., Ankara, Bizim Büro Basımevi, 1998, Vol.1, pp.171-172

the architectural discipline is focuses on the history, current meanings and future of the architectural design concept. Here, it should be emphasized that this thesis will keep itself strictly out of such theoretical discussions. The discussions on the position of architects in today's Turkish building industry is a vital and ongoing area of research and debate. However, the aim of this study is to find a common ground among the majority of architects and convey a critical message about the architects' role in disaster prevention.

Such a common ground can be found in the Vitruvian principles of *Utilitas* (commodity), *Firmitas* (firmness) and *Venustas* (delight) as the three basic requirements that all works of architecture should satisfy.[7] Although the understanding of architecture has immensely evolved through the millenniums that followed the time of Vitrivius, these three simple but quite powerful concepts either consciously or intuitively represented the lowest common denominator of every architectural effort.[8] (**Table 2.1**)

Table 2.1 Various Interpretations of the Vitruvian Trilogy

Vitruvius (1st c. B.C.)	Utility	Firmness	Delight
L. Battista (15th c.)	Commodity	Necessity	Beauty
F. Blondel (17th c.)	Distribution	Construction	Decoration
J. Blondel (18th c.)	Commodity	Solidity	Agreement
H. Guimard (19th c.)	Spirit	Logic	Harmony
P. Nervi (20th c.)	Function	Structure	Form
C. Portzamparc (21st c.)	Perception	Production	Representation

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[7] VITRUVIUS, The Ten Books on Architecture: Mimarlık Üzerine On Kitap, Suna Güven Trans. Şevki Vanlı Mimarlık Vakfı Yayınları, 1993, p.11

[8] "Confrontation par l'architecture de ses propres principes avec ce de Vitruvius", Cours au College de France, http://www.college-de-france.fr/default/EN/all/college/index.htm, Last Accessed Date: 12 February 2006

This trilogy also provides one a chance to draw parallels between the design understandings of structural engineers and architects. It was previously stated that although beauty is not an essential necessity of engineering design, many engineers prefer their works to convey a certain sense of aesthetics. The need for economy can be considered parallel to the principle of commodity. After all, every work of design should be able to fulfill the requirements of the task for which it was conceived. However, there is one concept that is, beyond any doubt, common between engineering and architectural design. That is the principle of safety or firmness.[9]

Firmness, in other words, the ability to stand up is one of the fundamental requirements of existence for any work of architecture. Here, it can be argued that a work of architecture may very well exist in the theoretical or virtual environment without satisfying the condition of firmness. This argument might be correct. However, such works of architecture are out of the scope of this thesis. This study deals with the conditions of the real–life environment, where the ability to stand up is a must.

Some may suggest that there should be no hierarchy among the principles of the Vitruvian approach and that firmness shouldn't be considered as the chief precondition of Architecture. Today's notions of firmness are related with the materials and construction techniques available and, architectural ideas that seem utopian today may become quite ordinary tomorrow. It should be noted here that this thesis has no such claim of hierarchy among the Vitruvian principles. This study simply suggests that if one has the intention of bringing a work of architecture to life without risking the lives of its occupants, the condition of firmness should be satisfied.

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[9] ÜNAY, Ali İhsan, ÖZMEN, Cengiz "Building Structure Design as an Integral Part of Architecture: A Teaching Model for Students of Architecture", International Journal of Technology and Design Education, 2006, Vol. 16, pp.253-271

2.1.3 Intended Audience: Architects

The intended audience of this thesis is architects. Making this statement brings into mind two questions. The first of these inquires the reason behind the selection of architects as the intended audience. The second one asks about the effect of this selection on the scope, structure and the language of the thesis. The first question will be answered in this section and the second one, is already described in the methodology section.

To understand the architects' contribution to the seismic performance one must observe the realization process of a building from the drawing table till the end of the construction phase. Such a remark is necessary because, in public opinion, there is a misunderstanding that earthquake resistance is strictly within the domain of structural design which in turn is solely the concern of structural engineers. The same misunderstanding leads to the idea that structural design is a process that begins once the architectural design phase is over. The actual design process however is quite different.[10]

The life of a building begins as an idea, a concept in the mind of the architect. When the idea reaches a certain maturity, the architect transfers it into a concrete medium. After another period of development in the light of various criteria and the input of several professionals, the design becomes the architectural project of the building. This phase is followed by the articulation and detailing of the project by specialists such as structural, mechanical and electrical engineers, all of whom are bound to work within the framework set up by the architect. The building then becomes ready for construction.

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[10] ÜNAY Ali İhsan, ATIMTAY, Ergin, "Developing Earthquake Consciousness in the Architect", Architecture and Engineering the Teaching of Architecture for Multidisciplinary Practice, Transactions on Architectural Education, No: 05, ed. Voyatzaki, Greece, Art of Text s.a., pp.267-270

As it can be observed from this chain of events, the architects' decisions are critical in the way even the most technical aspects of the building come into being. Therefore one should understand the nature of the architects' decisions to grasp to which extent they affect the seismic performance of the building.

During the architectural design process, the architect makes decisions on the form and the spatial arrangement of the building. Both categories of decisions inevitably have a critical influence on the shaping of the structural system. The form of a building cannot be considered as independent from its structural system. Some structural systems even dictate a certain morphological characteristic to the building. For example, if one desires to have relatively large spans in a strictly masonry building, the use of arches, vaults or domes is inevitable. These very characteristic elements have a profound effect on the overall morphological language of the building.[11]

On the other hand, a building with prismatic shape can be built both with reinforced concrete (R/C) or steel structural system. However, despite the similarity of the overall form, there will be significant differences in architectonic qualities. For instance in R/C system, structural elements will have rather large cross-sections and a certain rhythm of spans in accordance with the constructional characteristics of this structural material. In contrast, steel system will have relatively slender structural cross-sections, a different rhythm of spans and characteristic elements such as cross-bracings. The sum of these minor but critical differences will have a deep impact on the overall architectural expression of the building.

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[11] ÖZMEN, Cengiz, ÜNAY, Ali İhsan, "Commonly Encountered Seismic Design Faults due to the Architectural Design of Residential Buildings in Turkey", Building and Environment, 2007, Volume 42, Issue 3, pp. 1406 – 1416

Architects' contribution to structural design is not limited with decisions on form. The spatial arrangement of the building is the main factor in the configuration of the structural elements. The number, shape, size and location of columns, beams, etc. are determined by the way the spaces of various sizes come together and structural configuration is a critical factor in the seismic performance. A building with an unsuitable structural configuration may be damaged during an earthquake even if there is no deficiency in individual structural members.

Architects' structural duties extend even further into the preliminary dimensioning of structural elements. This is because it is not possible to design any architectural space without having a realistic idea about the sizes of structural elements, so architects are required to have basic structural calculation skills. This is the reason why a certain level of structural calculations is an integral part of architectural education. As Spyros Raftopoulos states:[12]

> *…architectural students are introduced in their profession, in the first stages of their studies, by demanding projects that enhance their creativity and imagination without applying any structural restrictions. The gradual introduction of structural parameters reaches a level of a realistic representation of the design project until the end of the studies …, the system is trying to educate architects to comprehend the requirements of the engineering aspects of the building and encourage the idea of collaboration within a multidisciplinary group…*

As the designer, architects make many of the critical decisions about the structural design of the building. Whether these decisions are about the form, structure or preliminary dimensioning, they have a direct influence on the buildings' seismic performance. It is difficult to build an earthquake resistant building without a consciously prepared architectural design. Therefore, it is critical to make it clear that architects have a major role in earthquake resistant building design.

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[12] RAFTOPOULOS, Spyros, "Educating Architects or Architects-Engineers", Les Cahiers de l'enseignement de l'architecture Transations on Architectural Education No: 5 Architecture and Engineering, The Teaching of Architecture for Multidisciplinary Practice, Maria VOYATZAKI Ed., Thessaloniki, Greece, Art of Text S.A. 1999, p.207

2.2 A Brief History of Urbanization in Turkey: Emergence of Reinforced Concrete Apartment Block as the Dominant Building Type in Turkey.

2.2.1 Urbanization in the Industrialized Countries

In the west, urbanization began with the end of the feudal period and became widespread after the industrial revolution (18th and 19th centuries). During this period, cities that were already the center of monetary economy and commerce also became the centers of heavy industries and mass production. Developing technology allowed mechanization in the agricultural sector which allowed a decrease in the necessary man power. Because of the lack of employment, a large portion of the rural population who were previously employed in agriculture and small crafts had migrated to large cities and became employed in industrial and service sectors.[13]

This transformation might not have been problematic if it had happened in a long period of time; however this migration was rapid and massive in scale. Such a dramatic increase in the city populations created serious problems of dwelling for the workers. City life was complex and difficult, wages were low and living conditions were poor. Moreover, the effects of this population increase were not limited to the newly developed areas and neighborhoods, instead, the whole of the cities were affected and transformed forever in terms of economy, culture and inevitably architecture.[14]

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[13] Bilkent University – Server at knuth.ug.bcc.bilkent.edu.tr, “Türkiye’de Kentleşme Sorunu”, http://knuth.ug.bcc.bilkent.edu.tr/~bbakay/articleA/kent.htm, Last Accessed Date: 15 May 2007

[14] BİLGİN, İhsan, “20.Yüzyıl Mimarisi, Barınma Kültürünün Hassas Dengeleri ile Nasıl Yüzleşti”, http://www.arkitera.com.tr/konut/ihsanbilgin4.htm, Last Accessed Date: 20 March 2008

Despite the initial impact in the 18th and 19th centuries, industrialized countries have evolved economically; culturally and architecturally to absorb the effects of urbanization and to develop means to cope with its various problems. The phenomenon of urbanization has progressed parallel with the evolution of democratic tradition in government.

This was not the case for the young Turkish Republic of 1923 who inherited a land ravaged by centuries of war from the Ottoman Empire. The economy was feeble; agriculture based, and possessed no significant heavy industries. The population of the country was only 13 millions and was far away from providing the necessary manpower for an industrial economy. Furthermore, the ethnic minorities who constituted the financial and cultural elite of the Ottoman Empire were gone after the War of Independence leaving the country without any accumulation of capital, technology or culture to trigger a movement of industrialization.[15]

Nevertheless, the young republic made its best efforts, usually by the hand of the state, to transfer its agricultural income to industrial enterprises. Between 1923 and 1950, there was a slow but steady increase in the industrial capacity of the country. In this period, the industrialization efforts were limited and were realized strictly through national resources. With the increasing industrialization and the founding of the new capital Ankara, there was a limited movement of population from the rural areas to the cities. Because the migration was limited, the lands and buildings necessary for the dwelling and working of the increasing population were easily met by the government and small scale private production mechanisms.[16]

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[15] BİLGİN, İhsan, “Anadolu’da Konut ve Yerleşmenin Modernleşme Süreci”, http://www.arkitera.com/v1/diyalog/ihsanbilgin/anadolu.htm, Last Accessed Date: 25 March 2008

[16] BİLGİN, İhsan, “Anadolu’da Konut ve Yerleşmenin Modernleşme Süreci”, http://www.arkitera.com/v2/diyalog/ihsanbilgin/anadolu.htm, Last Accessed Date: 25 March 2008

2.2.2 Urbanization in Turkey

In Turkey, urbanization and the associated problems have begun with 1950's when an economic model based on capitalist relationships started to develop in the country. In 1948 many countries including Turkey have received the Marshall Aid from the United States of America. America was not able to decrease its production capacity which was extensively enlarged during the World War II, due to conjectural reasons. The surplus of this production was exported to developing countries to prepare the infrastructure for the establishment of capitalist economies. This aid package included many tractors and heavy road building equipment, the use of which has transformed the rural areas of the country and accelerated the rate of urbanization.[17]

The major factors governing the phenomenon of urbanization can be grouped under four topics: Factors that drive people away from the rural areas, factors that attract people to urban areas, Factors related to transportation and Factors related to technology. Factors that drive people away from rural areas are mostly due to the conditions of deprivation in small towns and villages such as the lack of hospitals, schools, cultural facilities and infrastructure. Such factors were highly valid for the villages, towns or even rural cities of the Turkey of 1950's; however they are not enough on their own to explain the rapid urbanization movement.[18]

The second group of factors governing urbanization are those that attract people to urban areas. Cities attract rural populations because of the services and opportunities they provide. It is well known that certain wealthy rural families in

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[17] BİLGİN, İhsan, "20.Yüzyıl Mimarisi, Barınma Kültürünün Hassas Dengeleri ile Nasıl Yüzleşti", http://www.arkitera.com.tr/platform/ihsanbilgihtm, Last Accessed Date: 20 March 2008

[18] Bilkent University – Server at knuth.ug.bcc.bilkent.edu.tr, "Türkiye'de Kentleşme Sorunu", http://knuth.ug.bcc.bilkent.edu.tr/~bbakay/articleE/kent.htm, Last Accessed Date: 15 May 2007

Turkey migrate to urban areas to provide better education for their children among other reasons. Yet these factors may only have limited effect on Turkish urbanization movement because it requires a certain level of prosperity which didn't exist in the rural population of Turkey in those years.[19]

Transportation became easier as a result of the construction of a large network of auto routes with the help of the new heavy equipment received during the Marshall Aid. These routes have connected the rural and urban areas of the country in a previously unseen scale and made it possible for the unemployed masses to migrate to the cities in the hope of finding new employment in the fledgling industrial sector.[20]

Among the factors related to technology one can mention the widespread use of tractors in the agriculture sector. There was a sharp decrease in the required work force. This has revealed the secret unemployment which was previously concealed within the rural family structure. Agricultural lands that were already divided due to inheritance, etc. became insufficient to support families. As a result, there was a migration of unskilled labor to the cities. While it was possible to employ some of these people in the industrial sector some others found work in the informal service sectors such as street venders, porters, doorkeepers, etc. The housing requirements of these masses were met usually by squatter housings and resulted in the uncontrolled growth of urban areas. Certain cities have become overpopulated which resulted in a decrease in the quality of life and services.[21]

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[19] Bilkent University – Server at knuth.ug.bcc.bilkent.edu.tr, “Türkiye'de Kentleşme Sorunu”, http://knuth.ug.bcc.bilkent.edu.tr/~bbakay/articleF/kent.htm, Last Accessed Date: 15 May 2007

[20] BİLGİN, İhsan, “20.Yüzyıl Mimarisi, Barınma Kültürünün Hassas Dengeleri ile Nasıl Yüzleşti”, http://www.arkitera.com.tr/konut/ihsanbilgin4.htm, Last Accessed Date: 20 March 2008

[21] BİLGİN, İhsan, “Anadolu'da Konut ve Yerleşmenin Modernleşme Süreci”, http://www.arkitera.com/v1/diyalog/ihsanbilgin/anadolu.htm, Last Accessed Date: 25 March 2008

There are three reasons why there was no serious opposition to the construction of squatter housings. Firstly, squatter housings solve the problem of housing without spending the already limited government resources. Secondly, the political potential of the significant population of these areas makes it very difficult, if not impossible, for the government officials to pursue an effective prevention policy. Thirdly, because squatter housing is a relatively cheap form of dwelling which is located near the industrial employment zones, it is possible for the employers to keep the labor costs at a minimum level. This is a considerable advantage for the entrepreneurs of an underdeveloped country because the government funds can be transferred to their use without any cutbacks for housing projects.[22]

A well established system of land ownership did not exist in the Ottoman Empire. This has left the Government of the Turkish Republic with an inheritance of a substantial amount of public lands. The production of illegal squatter housings at such a large scale was the result of the expenditure of these lands through populist policies.[23]

After the 1950’s, 250.000 residential units per year were added to the existing building stock. This is a huge increase in scale and cannot be accomplished with the small scale production mechanisms of the past. This new and steady demand for residential units was met through three different types of construction mechanisms. The first of these is the individual production mechanism called the “build and sell” method which has increased the building density in the authorized development zones. This type of production was made possible by the approval of the “Condominium Law – Kat Mülkiyeti Kanunu” in 1954.

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[22] BİLGİN, İhsan, “20.Yüzyıl Mimarisi, Barınma Kültürünün Hassas Dengeleri ile Nasıl Yüzleşti”, http://www.arkitera.com.tr/konut/ihsanbilgin4.htm, Last Accessed Date: 20 March 2008

[23] KEYDER, Ç., “Konut Piyasası: İnformelden Küresele”, <u>Defter</u>, No:35, İstanbul, Metis Yayınları, 1999, pp. 73-93

The success of the method was to bring together the small land owner, the small-scale contractor and the customer within the secure framework of the free market economy. The “build and sell” method allowed the middle classes to invest in small groups in construction projects that they couldn’t afford on their own. The mechanism accorded with the social structure of Turkey so much that nearly 40 – 45% of the buildings in urban areas were built using this method. In “build and sell” method neighborhoods were formed not according to a master plan but building by building as required by parcel owners. This has turned the cities into construction sites for the next 30 years. The individual apartment block became the dominant architectural unit of the Turkish urban pattern.[24]

The above mentioned building method has created two urban forms namely the “adjacent order” and the “separate order”. Unlike the Central European countries, in Turkey, the “adjacent order” was not able to create a homogenous and harmonious façade structure. The reason for this was the lack of rules and regulations in terms of façade openings, rhythms and levels. European cities also had a long established tradition which had its routes in the Baroque architecture of the 19th century.[25]

The “separate order”, when applied in areas where building parcels are similar in size, resulted in a repetition of almost identical apartment blocks creating an urban pattern without meaning or variety. In areas where building parcels are variable in size, the adjacent apartment blocks formed of a string of non-consistent building volumes which were unable to form a harmonious whole. In the formation of urban pattern, the emphasis was generally put on the excessive density requirements. Consequently, the increasing building heights have prevented the

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[24] BİLGİN, İhsan, “Türkiye’de Toplu Konut Üretimi ve Mimarlık”, http://www.arkitera.com.tr/konut/ihsanbilgin2.htm, Last Accessed Date: 12 March 2008

[25] Bilkent University – Server at knuth.ug.bcc.bilkent.edu.tr, “Türkiye’de Kentleşme Sorunu”, http://knuth.ug.bcc.bilkent.edu.tr/~bbakay/articleG/kent.htm, Last Accessed Date: 15 May 2007

potential of the “separate order”, which would otherwise allow the integration of green areas in the urban pattern. The resulting urban pattern consisted of apartment blocks which were neither adjacent nor truly separate enough.[26]

The urban areas which consist of apartment blocks were created by the repetition of certain plan and layout schemes depending on the size of building parcels. The governing principles of these schemes were developed not by the logic of a design discipline but rather through an intuitive process, a middle class living format that the contractors have developed and verified in the course of their practice. Almost all of these apartment blocks which were produced through small-scale production mechanisms possessed R/C skeleton structural systems and brick partition walls. Other equipments of the buildings were chosen among the variety of products that market was able to offer at that period.[27]

The second 40 – 45% of the housing production of the country in this period was realized through illegal production mechanisms such as squatter housings. This form of building production which originated on the surroundings of industrial areas – and later became widespread – was made possible by the populist policies. This method of housing production was preferred by the social classes who had recently migrated to cities from rural areas and didn’t possess the economic means to acquire housing through legal means. It was a dynamic and adaptable process.[28]

The neighborhoods on steep slopes were not able to evolve vertically due to topographic restrictions and retained their rural character. On the other hand, neighborhoods on flat lands were able to develop both horizontally and vertically.

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[26] BİLGİN, İhsan, “Türkiye’nin Modernleşme Süreci İçinde Konut Üretimi”, http://www.arkitera.com.tr/konut/ihsanbilgin1.htm, Last Accessed Date: 10 March 2008

[27] BİLGİN, İhsan, “Sıradan Olanın Yeniden Üretimi ve Konut Sorunu”, http://www.arkitera.com.tr/konut/ihsanbilgin3.htm, Last Accessed Date: 8 March 2008

[28] BİLGİN, İhsan, “Türkiye’de Toplu Konut Üretimi ve Mimarlık”, http://www.arkitera.com.tr/konut/ihsanbilgin2.htm, Last Accessed Date: 12 March 2008

In time, with the additional help of municipal building pardons and excessive new building rights the initially separate settlements have merged and became huge apartment neighborhoods.[29]

Because the squatter housings were realized with insufficient economic resources, the building process usually intersected with the settlement process. Therefore these neighborhoods looked like a giant construction site after the 1950's. Since there were neither legal framework nor deadlines for the completion of the apartments, it was possible to expand the size and the scope of the projects depending on the availability of the resources. The infinite flexibility and opportunity for further expansions created a situation where future expectations were emphasized instead of the requirements of the present. These squatter apartments were also modeled after the middle class living format created by the "build and sell" contractors. Although these squatter apartments realized with lower construction standards and cheaper equipment then the legal counterparts, the same plan and layout schemes were used in their design.[30]

The third and last construction mechanism was the cooperatives which constituted approximately 10% of the housing built during that period. This method appealed to the classes with low but steady and guaranteed income by providing them the opportunity of owning their houses through reasonable loans and cheap building parcels. The comparatively large scale of these projects however have not encouraged the use of advanced construction techniques or sophisticated spatial organization schemes but rather remained limited to the repetition of individual houses or apartment blocks on a large building plot. The large majority of these

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[29] BİLGİN, İhsan, "Türkiye'de Toplu Konut Üretimi ve Mimarlık", http://www.arkitera.com.tr/platform/konut/ihsanbilgin2.htm, Last Accessed Date: 12 March 2008

[30] BİLGİN, İhsan, "Türkiye'nin Modernleşme Süreci İçinde Konut Üretimi", http://www.arkitera.com.tr/platform/konut/ihsanbilgin1.htm, Last Accessed Date: 10 March 2008

housings retained the living standards of the middle-class in terms of size, plan layout, spatial organization and the quality of used appliances and equipment.[31]

After the 1970's Turkish cities were filled with the examples of the negative correlation between quality and quantity of architectural products. In a building market where small-scale contractors provided anonymous apartment flats to anonymous buyers, the architects were merely needed for their signature due to legal reasons. The design of the apartment blocks was reduced to a limited practice where the aim was to provide the contractor with the maximum profit with an optimum plan and volume layout.[32]

The virtually unlimited possibilities of spatial and volumetric layout offered by the R/C skeleton system were ignored by contractors or architects willing to exercise a limited practice. Architects accused the apartment block typology for being an insufficient medium for transforming the built environment; however they used it repeatedly even in mass housing projects where the restrictive fabric of building parcels did not exist. The same plan and mass layouts were used in every region of the country. Buildings with façades superficially decorated with regional architectural motives were constructed. This created a typology that was insensitive to regional climatic conditions, life styles and vernacular architectures. Constant modification of building codes in order to provide higher profits for the building industry have deteriorated the otherwise regular and ordered fabric of urban neighborhoods. This laid foundations for today's chaotic metropolitan areas.[33]

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[31] Bilkent University – Server at knuth.ug.bcc.bilkent.edu.tr, "Türkiye'de Kentleşme Sorunu", http://knuth.ug.bcc.bilkent.edu.tr/~bbakay/articleH/kent.htm, Last Accessed Date: 15 May 2007

[32] BALAMİR, Aydan "Türkiye'de Modern Yapı Kültürünün Bir Profili", Mimari Kimlik Temrinleri – I, http://arkiv.arkitera.com/periodical.php?action, Last Accessed Date: 25 April 2008

[33] BALAMİR, Aydan "Türkiye'de Modern Yapı Kültürünün Bir Profili", Mimari Kimlik Temrinleri – I, http://arkiv.arkitera.com/periodical.php?action, Last Accessed Date: 25 April 2008

2.2.3 Urban Environment in Today's Turkish Cities

Today, there is an emphasis on large scale housing developments by both the government and the private sector. The government has endorsed large-scale housing by means of "Mass Housing Law" and new credit mechanisms such as the "Mortgage System". A new housing market is created through the "Housing Development Administration of Turkey - Toplu Konut İdaresi (TOKİ)". Another public sector to provide mass housing developments is the municipal authorities and cooperative unions. The former "Real Estate Development Bank - Emlak Bankası" had also increased its production capacity before its abolishment in 2001, however has kept its efforts in the line of providing sample projects instead of establishing regulating mechanisms for the market. Despite all the developments in the building industry and architectural market these new mass housing projects reflect the formal and spatial characteristics of the previous generation of apartment blocks.[34]

Despite all the attempts to create a controlled urban development whether by means of the building cooperatives or mass housing projects, the small-scale "build and sell" mechanism is still the dominant building production type of the private sector in Turkey. According to the survey of the Turkish Statistical Institute 90% of all buildings are built by the private sector as opposed to the 4% built by the public sector and 5% built by construction cooperatives. (**Table 2.2**) The results of this survey demonstrate that R/C apartment block typology will continue to be the dominant element of Turkish urban environment for the upcoming decades.[35]

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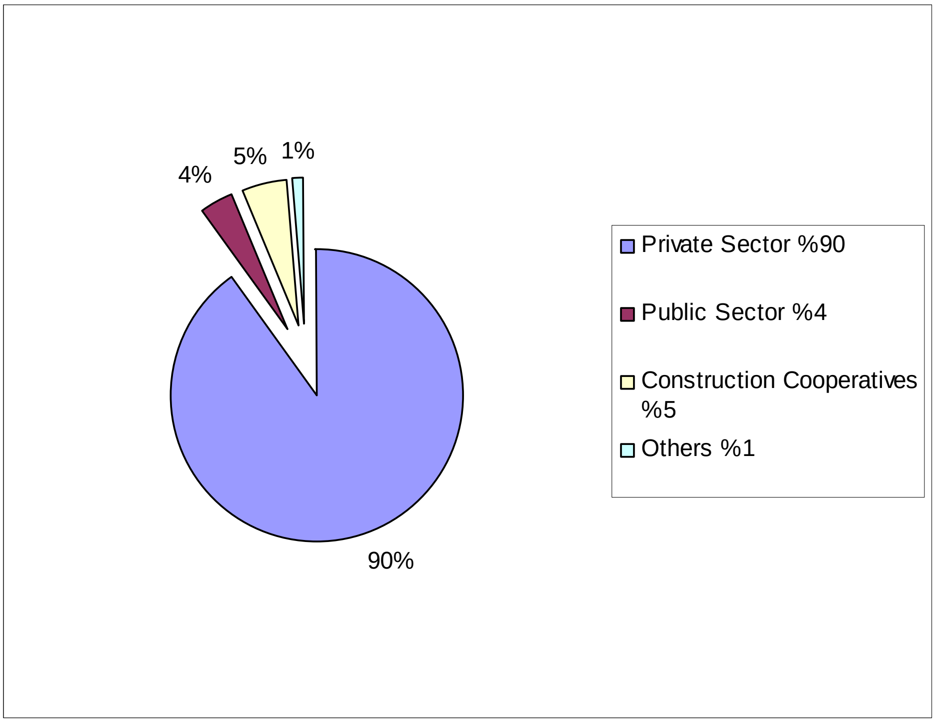
[34] Bilkent University – Server at knuth.ug.bcc.bilkent.edu.tr, "Türkiye'de Kentleşme Sorunu", http://knuth.ug.bcc.bilkent.edu.tr/~bbakay/articleH/kent.htm, Last Accessed Date: 15 May 2007

[35] Building Census 2000, Turkish Statistical Institute-Türkiye İstatistik Kurumu Yayınları, Ankara, 2001, ISBN 975-19 2819 – 2

Table 2.2 The Ratio of Buildings with reference to the Financier Sectors



The same survey also demonstrates that housing production still constitutes the dominant portion the building works in Turkey with almost 75% of all buildings being residential apartment blocks. In addition to this, a large portion of the partially residential buildings (11%) and commercial buildings (6%) also share the same building typology. Overall, it can be concluded that over 90% of all buildings in Turkey are apartment blocks. (**Table 2.3**) According to the same survey almost 80% of urban households live in this type of building. From these results, it is safe to conclude that, in terms of earthquake disaster prevention, it is imperative to establish a seismically secure design notion concerning the apartment typology in the heads of architects, engineers and contractors of private sector.[36]

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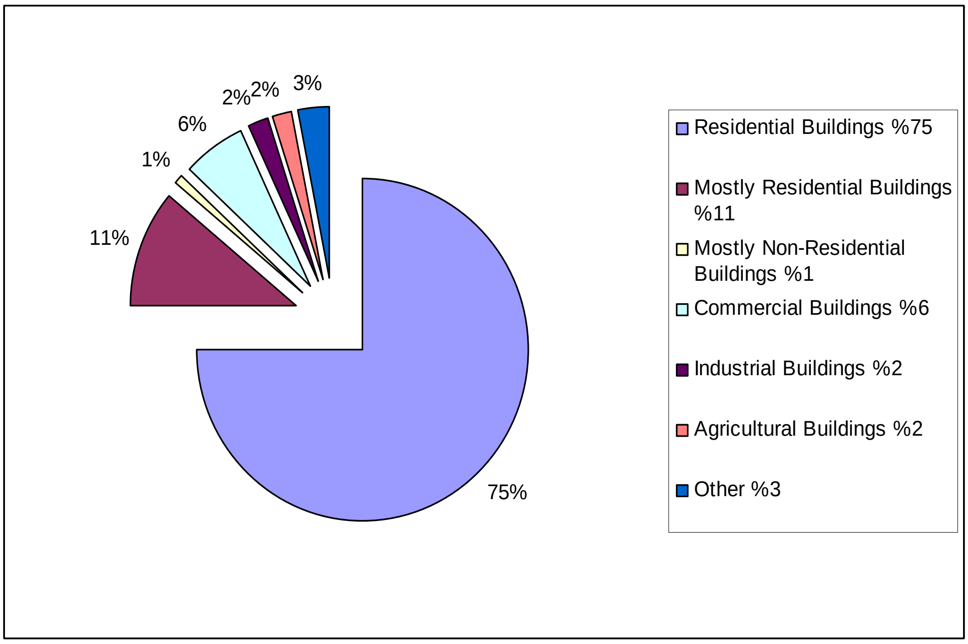
[36] Building Census 2000, Turkish Statistical Institute-Türkiye İstatistik Kurumu Yayınları, Ankara, 2001, ISBN 975-19 2819 – 2

Table 2.3 The Ratio of Buildings with reference to Occupancy Types



The 2000 Building Census states that over 51% of all existing buildings in Turkey have R/C skeleton system. This represents a rise of more than 20% percent in the ratio of this structural system when compared to 1984 Building Census. It can also be assumed that in the 8 years following the 2000 census, this ratio has further increased. Despite the excessive criticism following the poor performance of this structural system in past earthquakes, R/C, with its established industrial and commercial infrastructure, will continue to be the chief construction material in Turkey.[37] (**Table 2.4**)

Parallel with the increase in the country's R/C production capacity and development of the transportation sector, this material is extensively used in not only the urban areas but also even in the most remote rural regions. The steady increase in population results in the rapid development of small towns and even

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[37] Building Census 2000, Turkish Statistical Institute-Türkiye İstatistik Kurumu Yayınları, Ankara, 2001, ISBN 975-19 2819 – 2

villages. The 2000 Building Census shows a significant increase in the ratio of buildings built outside of the country’s traditional metropolitan areas. This development brings along a steep rise in the building stock vulnerable to high seismic risk.[38] (**Table 2.5**)

Table 2.4 The Ratio of Buildings with reference to Structural System Types

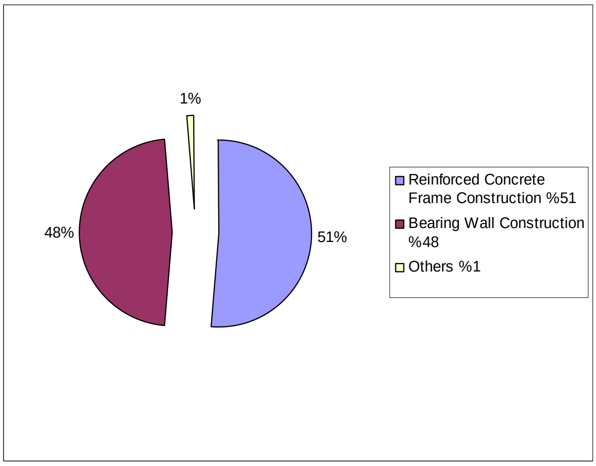
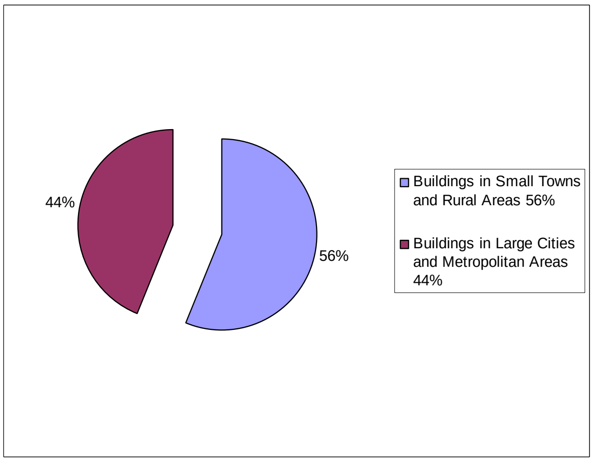


Table 2.5 The Ratio of Buildings in Rural Areas vs. Metropolitan Areas



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[38] Building Census 2000, Turkish Statistical Institute-Türkiye İstatistik Kurumu Yayınları, Ankara, 2001, ISBN 975-19 2819 – 2

2.3 Definition of the Earthquake Phenomenon and The Seismic Characteristics of Turkey

2.3.1 Definition of the Earthquake Phenomenon

The earthquake phenomenon influenced human life since the beginning of history. M. E. Tuna states that the records about earthquakes date back to 2000 B.C. Aristotle (born 384 B.C.) made researches and classifications about earthquakes. The first earthquake recording device was made in China in 132 A.D. John Hoff published an earthquake catalogue, which included the entire world in 1840. Robert Mallet made the first field survey after the 1857 Naples Earthquake. Palmieri produced a primitive seismograph to record the earthquakes in Italy. Oldham solved the equation of P and S waves based on the recordings of seismographs.[39] **(Table 2.6)**

The mechanics of an earthquake are closely related with the inner structure of the earth. R. Yılmaz and R. Demirtaş describe this structure in the form of three layers. These are: the crust (Continental Crust: 25-70 km, Oceanic Crust: 5-10 km) at the outer surface, the core at the center and the mantle in-between. The crust is made of granite and basaltic rocks. The major elements of the mantle are Fe, Mg, Si and O. The crust rests on the solid layer of the upper mantle, which is called the Lithosphere. Under the lithosphere there is the relatively soft layer of the upper mantle. This is the Astenosphere. The composition of the core is 85% Fe. The outer core is of liquid nature but the inner core is solid.[40] (**Figure 2.1**).

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[39] TUNA, Mehmet Emin, Depreme Dayanıklı Yapı Tasarımı. Ankara: Tuna Eğitim ve Kültür Vakfı Pub. November 2000, p.1

[40] YILMAZ, Rüçhan, DEMİRTAŞ, Ramazan. “Depremler ve Türkiye’nin Depremselliği”, Deprem ve Sonrası. ed. Dr. Erhan Karaesmen, Ankara, Müteahhitler Birliği Pub. 1996, p.13.

Table 2.6 Major Earthquakes of the 20th century[41]

DATE	**LOCATION**	**CASUALTIES**	**MAGNITUDE***
04.04.1905	India	19.000	8.6
17.08.1906	Chile	20.000	8.6
16.12.1920	China	200.000	8.6
01.02.1923	Japan	143.000	8.3
02.03.1933	Japan	2.990	8.3
30.05.1935	Pakistan	60.000	7.5
26.12.1939	Turkey(Erzincan)	39.000	7.4
31.05.1970	Peru	66.000	7.8
27.07.1976	China	255.000	8.0
19.09.1985	Mexico	9.500	8.1
17.08.1999	Turkey(Marmara)	45.000	7.4

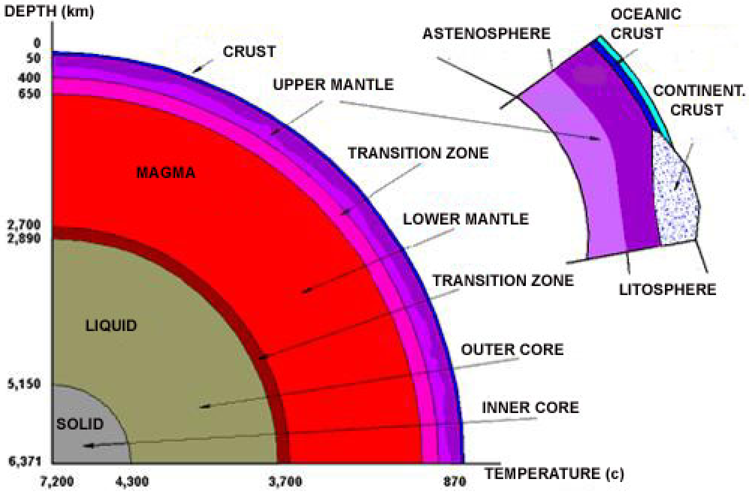

Figure 2.1 The Inner Structure of the Earth[42]

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[41] TUNA, Mehmet Emin, Depreme Dayanıklı Yapı Tasarımı. Ankara: Tuna Eğitim ve Kültür Vakfı Pub. November 2000, p.1

Yılmaz and Demirtaş further state that the heat currents generated from the astenosphere cause cracks on the solid layer above. As a result, the lithosphere is divided to several pieces, which are called tectonic plates (10 major and several minor plates). The plates aren't fixed. They travel on the liquid mantle with a speed of 1-10 cm per year (**Figure 2.2**). The nature of this movement is very complex. The plates may travel away from each other; one plate may go under another one or move side-by-side along their common border. These borders are called seismic faults. The movements cause stresses and deformations along the edges of the plates, which affect the geographical formations. The Himalayas and the Andes came into being as the result of such movements.[43]

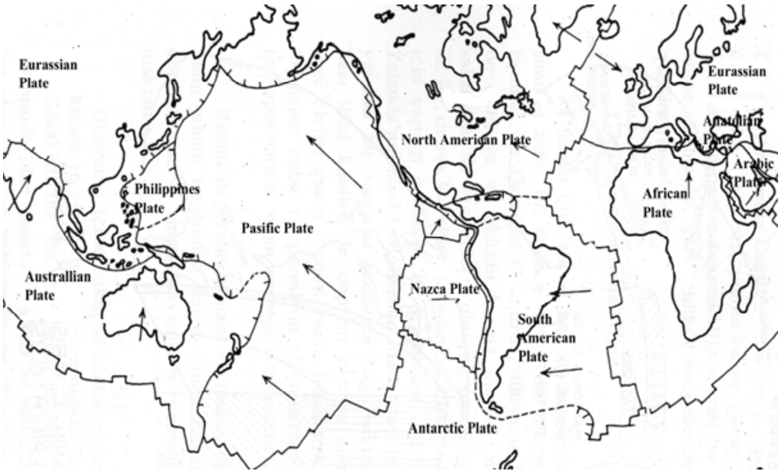

Figure 2.2 Tectonic Plates[44]

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[42] YILMAZ, Rüçhan, DEMİRTAŞ, Ramazan. "Depremler ve Türkiye'nin Depremselliği", Deprem ve Sonrası. ed. Dr. Erhan Karaesmen, Ankara, Müteahhitler Birliği Pub. 1996, p.13.

[43] YILMAZ, Rüçhan, DEMİRTAŞ, Ramazan. "Depremler ve Türkiye'nin Depremselliği", Deprem ve Sonrası. ed. Dr. Erhan Karaesmen, Ankara, Müteahhitler Birliği Pub. 1996, pp.14-15

[44] BAYÜLKE, Nejat. ed. Depremler ve Depreme Dayanıklı Yapılar, Ankara: T.C. İmar ve İskan Bakanlığı Deprem Araştırma Enstitüsü Başkanlığı Pub. 1978, p.4

Earthquakes happen as a result of the movement of the tectonic plates. Tuna states that the majority of the earthquakes occur in the elastic layer (the first 12 km) of the crust. Below that, because the temperature is above 400 ° C, the energy of the movements is absorbed by plastic deformations. The displacements add up to each other through the years. However, due to the friction between the layers of rock, the plates can't move. As a result, a huge amount of energy is stored on the fault lines. When this energy becomes higher than the friction capacity of the rocks, it is suddenly released with the movement of the plates in a very short period of time. This release of energy is called the earthquake.[45] (**Figure2.3**)

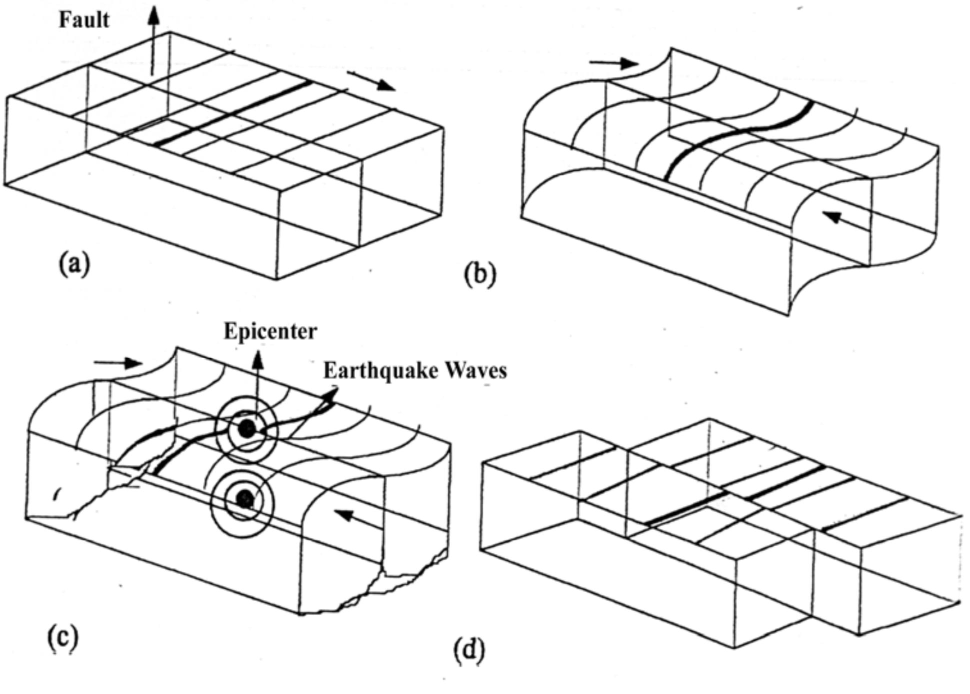

Figure 2.3 Development of an Earthquake[46]

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[45] TUNA, Mehmet Emin, Depreme Dayanıklı Yapı Tasarımı. Ankara: Tuna Eğitim ve Kültür Vakfı Pub. November 2000, pp.2-6

[46] SALARI, Nasrın. Figure 1, "Mimari Form ve Elemanların Depreme Dayanıklı Yapı Tasarımına Etkileri" Graduate Thesis, Trabzon: Karadeniz Teknik Üniversitesi Pub, 1999, p.7

2.3.2 Seismic Characteristics of Turkey

Turkey is located on the Anatolian Peninsula which is at the convergence point of three continents: Asia, Europe and Africa. It is surrounded by the Black Sea in the north, the Aegean Sea in the West and the Mediterranean Sea in the South. The Sea of Marmara and the straits of Bosporus and Dardanelles are also located within the borders of Turkey. Total area of the country is 780.576 km^2. Geographically, 97% of its lands are on Asia and 3% of its lands are on Europe. The population of the country is approximately 70 millions. Its neighbors are Greece and Bulgaria in the west, Georgia, Armenia, Azerbaijan and Iran in the east and Syria and Iraq in the south.

In terms of seismology, Turkey is located on the Alp-Himalayan Seismic Belt, which is one of the most active earthquake areas in the world. This seismic belt starts from the Azores in the Atlantic Ocean and stretches away into the Southeast Asia. Nearly 96% of Turkey is located on highly risky seismic zones and about 80% of the population is exposed to high magnitude earthquakes. Unfortunately, the most economically and socio-culturally developed regions of the country, namely the Aegean and Marmara Regions geographically coincide with the most hazardous earthquake zones.

The seismic activity is very complex around the East-Mediterranean region. Most of the country is on the Anatolian Plate, which is located in the middle of the Eurasian, African and Arabian Plates. The African and Arabian plates travel north and force the Anatolian plate to move west. The majority of the destructive earthquakes take place on the borders of the Anatolian Plate.[47] (**Figure 2.4**)

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[47] YILMAZ, Rüçhan, DEMİRTAŞ, Ramazan. "Depremler ve Türkiye'nin Depremselliği", Deprem ve Sonrası. ed. Dr. Erhan Karaesmen, Ankara, Müteahhitler Birliği Pub. 1996, pp.20-21

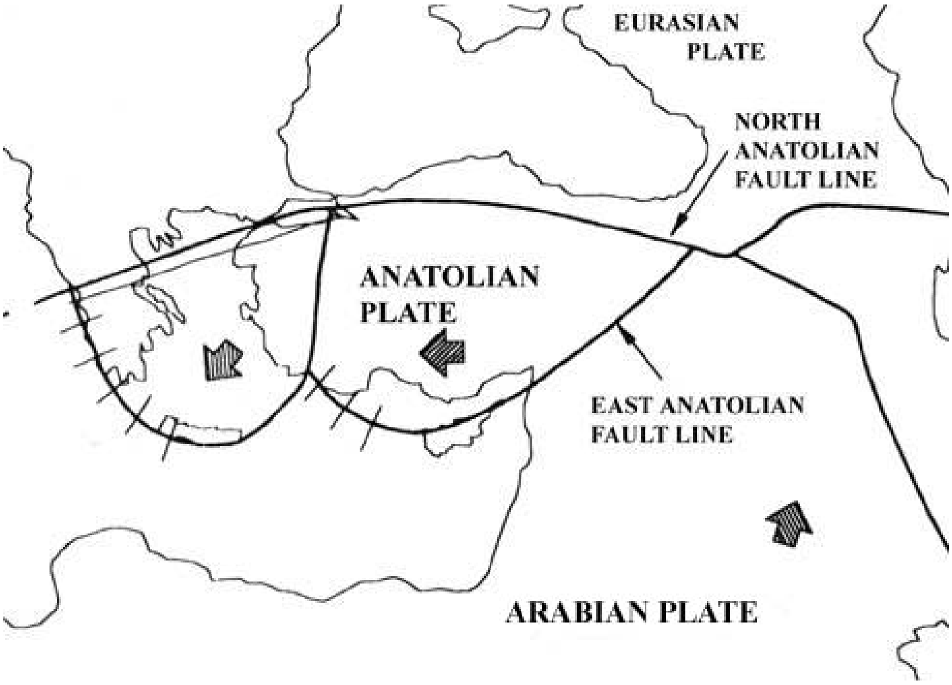

Figure 2.4 Seismic Plates around Turkey[48]

The North Anatolian Fault consists of several shorter fault lines and stretches over 1.000 km. The width of the seismic zones varies between 100 m and 25 km. The annual average slide is about 5-8 mm. The East Anatolian Fault runs 400 km from Karliova to Iskenderun Bay. The width is between 2-3 km and the annual slide is around 6 mm. The most destructive earthquakes take place on these two fault lines. Bitlis compression zone is in a relatively silent state since the beginning of the last century. The Aegean Graben Zone is the reason for the earthquakes in West-Anatolia. In this region, the Anatolian Plate expands in the north-south direction and causes the formation of fault lines in the east-west direction.[49] (**Figure 2.5**)

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[48] CELEP, Zekai. KUMBASAR Nahit. Figure 1.20, Deprem Mühendisliğine Giriş ve Depreme Dayanıklı Yapı Tasarımı, İstanbul: Beta Dağıtım Pub. 2000, p.26

[49] YILMAZ, Rüçhan, DEMİRTAŞ, Ramazan. "Depremler ve Türkiye'nin Depremselliği", Deprem ve Sonrası. ed. Dr. Erhan Karaesmen, Ankara, Müteahhitler Birliği Pub. 1996, pp.21-24

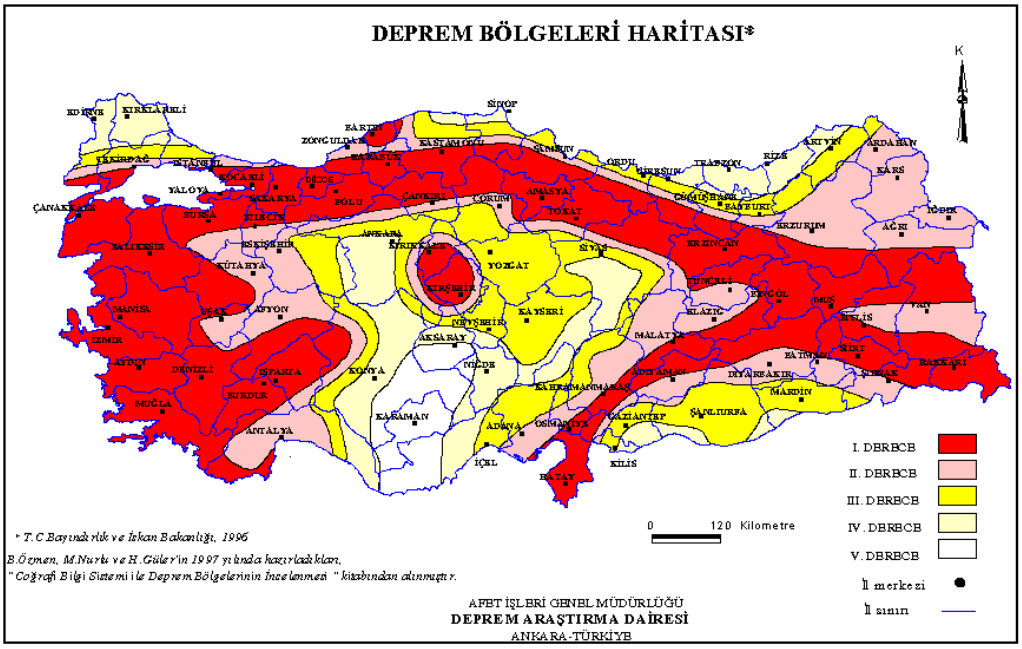

Figure 2.5 Seismic Map of Turkey[50]

Earthquakes should be considered as the most hazardous form of natural disaster. There are three reasons behind this argument. First of all, earthquakes have claimed more lives in Turkey than any other form of natural disaster. Although the country often witnesses other forms of natural catastrophes in the form of floods, landslides and avalanches, only earthquakes reach a national level in terms of the human and material losses they inflict on their environment. Secondly, because of the geographical location of the country, minor earthquakes occur almost on a daily basis and major earthquakes take place very often. As it can be observed from (**Table 2.7**) almost every generation in the last century has witnessed an earthquake of catastrophic proportions. Each time the material losses suffered because of these earthquakes has crippled the country's already fragile economy for many years.

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[50] CELEP, Zekai. KUMBASAR, Nahit. Figure 1.20, Deprem Mühendisliğine Giriş ve Depreme Dayanıklı Yapı Tasarımı, İstanbul: Beta Dağıtım Pub. 2000, p.26

Table 2.7 The list of significant earthquakes in Turkey in-between 1923-2008[51]

Date	Location	Intensity[52]	Magnitude	Casualties	Damaged Buildings
27.12.1939	Erzincan	XI	7.9	32968	116720
27.11.1943	Ladik	X	7.2	4000	40000
01.02.1944	Gerede-Çerkeş	X	7.2	3959	20865
19.08.1966	Varto	IX	6.9	2396	20007
06.09.1975	Lice	VIII	6.6	2385	8149
24.11.1976	Muradiye	IX	7.5	3840	9232
30.10.1983	Erzurum-Kars	VIII	6.9	1155	3241
13.03.1992	Erzincan	VIII	6.8	653	8057
17.08.1999	Gölcük	X	7.8	17480	73342
12.11.1999	Düzce	IX	7.5	763	35519
03.02.2002	Sultandağı	VII	6.4	44	622
01.05.2003	Bingöl	VII	6.4	176	6000
02.07.2004	Doğubeyazıt	VII	5.1	17	1000

The third but maybe the most critical reason is the close relationship between the architectural design and seismic performance of the building. A common anonymous proverb states that "It is the buildings and not earthquakes that kill people." A flood, a landslide or an avalanche can kill a person who merely stands on its way; however, people get injured or killed during earthquakes because of collapsed buildings and not the earthquake itself. Seismic activity is a natural phenomenon but an earthquake is a man made disaster.

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[51] CELEP, Zekai. KUMBASAR, Nahit. Deprem Mühendisliğine Giriş ve Depreme Dayanıklı Yapı Tasarımı. İstanbul: Beta Dağıtım Pub. 2000. pp.19-22

[52] Earthquake intensities are given according to the Modified Mercalli Earthquake Intensity Scale

2.3.3 Seismic Characteristics of the City of Bolu

Bolu is a completely land-bound province located in the Western Black Sea Region in Turkey with an area of 8.294 km^2. The province takes its name from the largest town in its borders, named the City of Bolu. Bolu has a population of 270.654.[53] It is located directly on the North Anatolian Fault Line. As a result, the city is in the First Seismic Zone according to the current Seismic Map of Turkey.[54] (**Figure 2.6**) The history of the town verifies the presence of a serious seismic risk. In the last century, the town was hit twice, in 1944 and 1999, with catastrophic earthquakes, the latter causing a casualty toll of 48 deaths and 354 wounded. The surveys conducted in the aftermath of the 1999 earthquake revealed that 2.399 residential buildings have suffered heavy damage, 5.990 buildings have suffered medium damage and 5809 buildings have suffered light damage. Among the 5.990 medium damaged buildings, 390 were decided to be unsafe and demolished by the municipal authorities.[55] (**Figure 2.7**)

Figure 2.6 Seismic Map of the City of Bolu

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[53] 2000 Genel Nüfus Sayımı Sonuçları – Türkiye İstatistik Kurumu, http://www.yerelsecim.com/DetaySon, Last Accessed Date: 10 March 2008

[54] Türkiye Deprem Haritası, http://www.deprem.gov, Last Accessed Date: 15 March 2008

[55] 1999 Bolu Depremi Kayıpları, http://www.bolu.gov.tr, Last Accessed Date: 12 March 2008

Figure 2.7 Buildings Damaged in 1999 Earthquakes in Bolu

According to a recent survey conducted by the Boğaziçi University, there is a 10% chance of a major earthquake occurring in Bolu in the next 50 years.[56] The same survey states that in case of a major earthquake, approximately 91% of the residential buildings will suffer light or no damage and 7% of the buildings may suffer medium damage. There is a serious seismic risk for the remaining 2% of residential buildings. This number may seem insignificant at first glance, however, according to the 2000 Building census there are 22.612 buildings within municipal areas in the province of Bolu. These buildings contain 48.647 dwelling units.[57] If we consider 2% of all the dwelling units we find that approximately

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[56] Bolu ve Çevresindeki Bölgelerin Kapsamlı Deprem Analizi, http://www.insaatforumu.com/forum/showthread, Last Accessed Date: 10 March 2008

[57] Building Census 2000, Turkish Statistical Institute-Türkiye İstatistik Kurumu Yayınları, Ankara, 2001, ISBN 975-19 2819 – 2

1.000 dwelling units are under serious seismic risk. Assuming that 4 people live in each dwelling unit, it can be concluded that nearly 4.000 lives will be at peril in case of a major earthquake in Bolu. That number is definitely not insignificant.

The dominant building typology in Bolu is R/C apartment block. In the aftermath of the 1999 earthquakes, the buildings in new dwelling areas were only permitted maximum 3 storeys of height. In the following years, buildings were allowed up to 5 storeys. Interviews conducted with building professionals practicing in Bolu have revealed that in the cautious atmosphere of the years after the 1999 earthquakes, due to the lack of knowledge about seismic design, several restrictions were brought to building construction. Large portions of the city were completely closed to building without proper soil analysis. Furthermore, architectural details such as cantilever projections were completely forbidden.

In recent years, with the increasing level of seismic design knowledge and a wider application of the Turkish Earthquake Code, building height and architectonic form restrictions are steadily lifted. Furthermore, due to the economic growth of the city, the market pressure increases on the municipal authorities and it is possible that more areas will be reopened to construction and building height regulations allowing more storeys will be passed.[58]

The city center still consists of 5 to 8 storey high R/C apartment blocks most of which predate the 1997 Earthquake Code. Even though they have survived the 1999 earthquakes, the seismic performance of this building stock is questionable. The concern of this thesis is not the existing building stock but the possible future buildings which will have 5 to 8 storeys. It is assumed that R/C buildings in this height interval will be the most commonly built structures in Bolu city center for the foreseeable future.[58] (**Figure 2.8**)

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[58] ÖZMEN C. "Unpublished Field Study Notes anf Photos", Conducted in Bolu on 23-02-2007

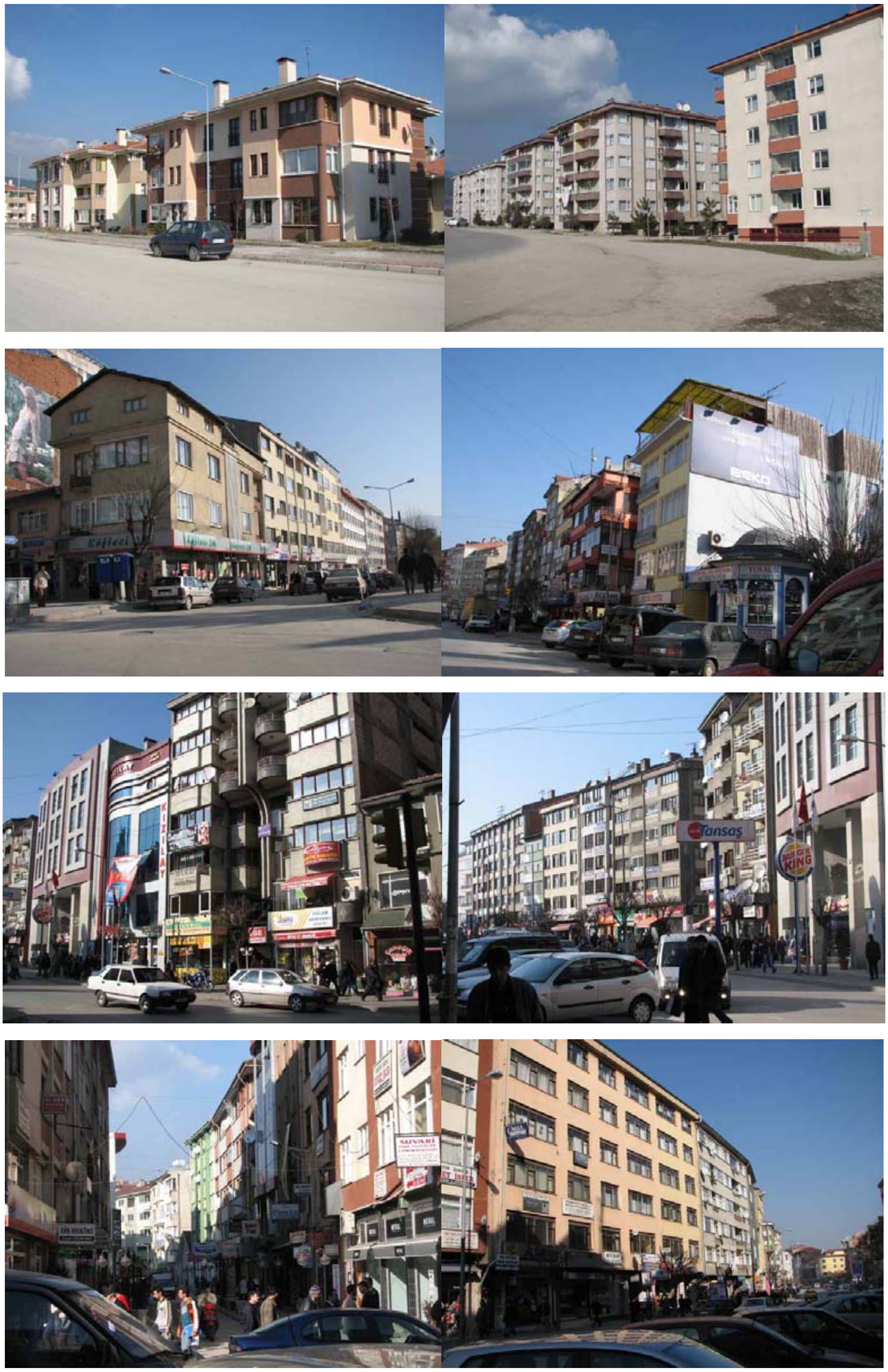

Figure 2.8 Building Typologies in Bolu

2.4 An Overview of the Turkish Earthquake Code

2.4.1 Fundamental Concepts in the Preparation of Earthquake Codes

Earthquake codes and regulations are legal documents, the aim of which is to determine the minimum conditions for the production of seismically safe and functional buildings. The object of these rules is to prevent architects and engineers from making critical design mistakes that will endanger the life of their buildings' occupants.[59]

Observations on significant historical buildings, such as the Hagia Sophia Mosque in İstanbul or the Cathedral of Notre-Dame in Paris, reveal the structural sophistication and insight of the designers and builders of these masterpieces. The fact that these buildings, which were realized without any regulations, were able to withstand many major earthquakes without significant damage during their long life span is impressive. However, one should not reach the conclusion that seismic codes are unnecessary based on that observation. It should not be forgotten that these buildings represent only a minor fraction of all the structures built throughout the course of history, a dominant portion of which was completely destroyed by past earthquakes.[60]

The civil authority of that époque has chosen only the most prominent master builders who had proven themselves through several previous works and a learning process of trial and error. It is natural that such distinguished

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[59] ERSOY. Uğur, Yönetmelikler ve Konut Yapımı, http://www.parlar.com.tr/ersoy/index.html, Last Accessed Date: 17 March 2008

[60] ÜNAY Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002

professionals would create aesthetically beautiful and seismically resistant structures. However, with the emergence of Modern Age, the number of structures – even prestigious ones such as the skyscrapers of Manhattan – to be built has increased exponentially and made it difficult for the owners to choose among a handful of exceptionally skilled builders. Therefore, majority of the building work was conducted by average architects and engineers whose designing skills were questionable. This is how the need for codes and regulation for every aspect of building activity, including seismic design, has become a reality. The aim was to prevent disasters such as the devastations of major earthquakes.[61] (**Figure 2.9**)

Figure 2.9 Museum of Hagia Sophia, Cathedral of Notre-Dame, Skyscrapers of Manhattan, Collapsed Apartment Blocks of Düzce[62]

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[61] ÜNAY Ali İhsan, "A General Overview of the Turkish Earthquake Codes", lecture notes from Earthquake Resistant Building Design Seminar, Ankara Chamber of Architects – Professional Training Seminars, 2007-2008

[62] Pictures taken from: http://www.landoflights.net/, http://www.destination360.com/, http://www.photohome.com/, http://www.ozayegitim.org, Last Accessed Date: 10 May 2008

There are three main sources in the preparation of seismic regulations:

- Results of Experimental and Theoretical Studies.
- Experiences Obtained during Application and Professional Practice.
- Available International and National Regulations.

A careful combination of these sources is necessary to prepare an effective seismic code because none of these sources are enough on their own to secure the widespread application of a newly prepared code. Seismic regulations prepared based on solely experimental and theoretical studies may become well written scientific documents but it should be remembered that these codes are written for application purposes and have to be read and understood even by professionals with average skills. Therefore, it is absolutely imperative that past experiences derived from professional practice and application be included into the preparation of seismic codes.[63]

A common occurrence in the preparation of seismic regulations is the direct borrowing of international or foreign regulations from countries which are believed to be very advanced in the field of seismic design. Such an approach may result in the preparation of an ineffective code due to ignoring the socio-economic conditions of the country for which the code is prepared. Seismic regulations prepared for countries where there is an abundance of skilled labor and vast economic resources may impose expensive and practically inapplicable rules. As a result, practitioners in countries like Turkey may simply choose not to apply them in building construction.[64]

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[63] ERSOY Uğur, Yönetmelikler ve Konut Yapımı, http://www.parlar.com.tr/ersoy1/index.html, Last Accessed Date: 17 March 2008

[64] ERSOY Uğur, Yönetmelikler ve Konut Yapımı, http://www.parlar.com.tr/ersoy2/index.html, Last Accessed Date: 17 March 2008

Another disadvantage of directly applying foreign codes is the possibility of inconsistencies and language confusions between parts taken from different codes. Here, it should be noted once more that seismic codes are prepared to be read understood and applied by everyone involved in the building industry; therefore, the language of these codes must be simple, clear and consistent throughout the entirety of the document.[65]

One of the major aims of the seismic codes is to ensure that all the architects and engineers prepare their projects with respect to the same design guidelines and calculation methods. The reason for this is to make it easy for the authorities who give construction permits to check the projects and calculations for possible errors before the application process. It should not be forgotten that one of the main reasons why the past Turkish Earthquake Code was not widely applied was the deficiency of municipal authorities to employ professionals trained to understand and ensure the correct applications.[66]

In summary, it can be stated that preparation of seismic codes and regulations are closely related with the socio-economic, scientific and technological development level of a country. To create a seismic code that will be accepted and widely applied by the country's building industry; this process must be realized by a joint panel of scientists, practicing professionals and also political authorities. It should not be forgotten that the rules and regulation brought by the seismic code will affect the overall cost, construction time and economic viability of buildings. If one considers the percentage of the building sector in any country's economy, it is evident that the preparation of seismic codes is a matter that requires great attention.

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[65] ERSOY Uğur, Yönetmelikler ve Konut Yapımı, http://www.parlar.com.tr/ersoy3/index.html, Last Accessed Date: 17 March 2008

[66] ÜNAY Ali İhsan, "A General Overview of the Turkish Earthquake Codes", lecture notes from Earthquake Resistant Building Design Seminar, Ankara Chamber of Architects – Professional Training Seminars, 2007-2008

2.4.2 A Brief History of Turkish Earthquake Codes

As stated previously in Section 2.3.2 Turkey has a significant history of major earthquakes. Parallel with the country's seismic history, Turkish Earthquake Code was updated regularly after each major disaster in the light of the experiences obtained from each event. Turkey's first seismic code was completely borrowed from Italy. In time, a system of rules and regulations developed and adapted for the specific socio-economic conditions of the country were created. Today, Turkish Earthquake Code is among the most up to date and comprehensive examples of its kind in the world. Past earthquake codes used in Turkey are:[67]

- 1940 Italian Building Regulation.
- 1944 Building Specifications for Earthquake Areas.
- 1949 Turkish Building Specifications for Earthquake Areas.
- 1953 Specifications for Structures to be Built in Earthquake Areas.
- 1962 Specifications for Structures to be Built in Disaster Areas.
- 1968 Specifications for Structures to be Built in Disaster Areas.
- 1975 Specifications for Structures to be Built in Disaster Areas.
- 1997 Specifications for Structures to be Built in Disaster Areas.

Current earthquake code in Turkey is the **2007 Specification for Structures to be Built in Earthquake Areas**. Unlike the former versions which contained sections on other forms of disasters, this code is completely dedicated to the prevention of the earthquake disaster. It has been prepared in the aftermath of the catastrophic 1999 earthquakes, and the finalized version is put into effect in 2007 after one year of trial period between 2006 and 2007. More detailed knowledge about this code will be given in the following Section 2.4.3.

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[67] Türkiye'de Şimdiye Kadar Uygulanmış Deprem Yönetmelikleri, http://www.parlar.com.tr/yonetmelikler.html, Last Accessed Date: 17 March 2008

2.4.3 Architectural Aspects of Current Turkish Earthquake Code

2007 Specifications for Buildings to be Built in Earthquake Areas differ from its predecessors in several areas. Previous Turkish Disaster Codes included rather short and dysfunctional sections about other forms of disasters such as floods, landslides and fire. These sections have been completely removed until proper specifications for these disaster types were prepared by The Ministry of Public Works and Settlement. As a result the current code focuses solely on the prevention of earthquake disaster. Additionally, the sections on the earthquake design requirements for timber and mud-brick structures were also removed from the code until a detailed specification for these very specific structural systems were prepared. (**Table 2.8**)

In its present form Turkish Earthquake Code focuses on the earthquake resistant design of R/C, steel and masonry structural systems. The current code was prepared in the aftermath of 1999 earthquakes where a substantial amount of R/C buildings have suffered moderate or light structural damage. This resulted in a large operation of damage assessment and strengthening throughout the seismic risk zones. The shear number of buildings to be evaluated and strengthened in a relatively short amount of time has created the possibility of inaccurate or faulty practices. Subsequently, the code now includes an entire section that sets the rules and regulations for such damage assessment and strengthening efforts to guide the ongoing and future operations in this area.

Additionally, because the steel construction system was promoted as a safer alternative than R/C skeleton structures which have performed poorly during 1999 earthquakes, the section on the Earthquake Resistant Design Requirements for Steel Buildings was significantly enlarged including extensive specifications for design calculations and descriptions of production details.

Table 2.8 Table of Contents of 2007 Specifications for Buildings to be Built in Earthquake Areas[68]

SECTION 1: Objective, General Principles and Scope
SECTION 2: Analysis Requirements for Earthquake Resistant Buildings
SECTION 3: Earthquake Resistant Design Requirements for Reinforced Concrete Buildings
SECTION 4: Earthquake Resistant Design Requirements for Steel Buildings
SECTION 5: Earthquake Resistant Design Requirements for Masonry Buildings
SECTION 6: Foundation Soils and Earthquake Resistant Design Requirements for Foundations
SECTION 7: Strengthening Methods and Specifications for Existing Buildings

Although the intended audience of the 2007 Earthquake Code includes both architects and engineers, the scope of the code and the highly technical format clearly addresses engineers rather than architects. This favoring of the engineering audience is a result of the established understanding in Turkey where earthquake resistant design is considered mainly in the domain of structural engineering. This view is not completely inaccurate because a very large portion of the seismic resistance of buildings depends on the correct analysis, design and application of structural details. However, because of the role played by the architect in structural design (Section 2.1), the alienation of the architectural audience from the earthquake code often results in inconsistencies and clashes between the design understandings of architects and structural engineers.[69]

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[68] Specification for Structures to be Built in Earthquake Areas, 2007

[69] ÜNAY Ali İhsan, ATIMTAY, Ergin, "Developing Earthquake Consciousness in the Architect", Architecture and Engineering: The Teaching of Architecture for Multidisciplinary Practice, Transactions on Architectural Education, No: 05, ed. Voyatzaki, Greece, Art of Text. pp.267-270

The 2007 Turkish Earthquake Code along with the codes of several countries worldwide, have accepted the following general principles for the design of earthquake resistant structures in their earthquake codes. These principles are put forward to ensure the creation of a seismically safe building scope within an acceptable range of economic feasibility:[70]

- During a highly probable low-intensity earthquake, structural or non-structural elements should not suffer any damage.

- During a medium-intensity earthquake, the structural system of the building should not suffer any damages. Damages may occur in non-structural elements but these should remain in repairable limits.

- During a high-intensity earthquake which has a low probability of occurrence, the structural system of the building may suffer heavy damages but total or partial collapse of the building is not allowed. The structure can make large displacements within the elastic limit; the priority here is to prevent the loss of lives.

The section of the Turkish Earthquake Code that addresses the most to the architectural audience is the “Definition of Irregular Buildings” article located in “Section 2: Analysis Requirements for Earthquake Resistant Buildings” of the regulation. In this section, various types of geometric arrangements and structural behavior patterns in plans and elevations of buildings are identified as irregularities in terms of seismic design. The codes main advice for the designers is to avoid these irregularities altogether if possible. However, the code also defines the structural calculation assumptions and precautions to be taken in case such irregularities exist in the building. (**Table 2.9**, **Table 2.10**)

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[70] ÜNAY Ali İhsan, “A General Overview of the Turkish Earthquake Codes”, lecture notes from Earthquake Resistant Building Design Seminar, Ankara Chamber of Architects – Professional Training Seminars, 2007-2008

It should be noted here that because the earthquake code is not prepared with an architect-friendly approach, especially the irregularity types created by geometric arrangements such as projections in mass and gallery openings are widely misunderstood and often undeservedly objected by architects. The earthquake code does not forbid the existence of such architectural elements but simply calls for attention to the consequences of using these elements in terms of the seismic behavior of the building.

Table 2.9 Irregularities in Plan According to 2007 Turkish Earthquake Code[71]

A- IRREGULARITIES IN PLAN
A1- TORSIONAL IRREGULARITY: (Figure 2.10, Figure 2.11) The case where *Torsional Irregularity Factor* η_{bi} **,** which is defined for any of the two orthogonal earthquake directions as the ratio of the maximum storey drift to the average storey drift at the same storey in the same direction, is greater than **1.2** $[\eta_{bi} = (\Delta_i)_{max} / (\Delta_i)_{ort\ (average)} > 1.2]$ Storey drifts will be calculated considering the effects of ±5% additional eccentricities.
A2- FLOOR DISCONTINUITIES: (Figure 2.12) In any floor: **I.** The case where the total area of the openings including those of the stairs and elevator shafts exceeds **1/3** of the gross floor area. **II.** The cases where the local floor openings make difficult the safe transfer of the seismic loads to vertical elements. **III.** The cases of abrupt reductions in the in-plane stiffness and strength of floors.
A3- PROJECTIONS IN PLAN: (Figure 2.13) The cases where the projections beyond the re-entrant corners in both of the two principal directions in plan exceed the total plan dimensions of the building in the respective dimensions by more than **20%**.

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[71] Specification for Structures to be Built in Earthquake Areas, 2007

Table 2.10 Irregularities in Plan According to 2007 Turkish Earthquake Code[72]

A- IRREGULARITIES IN ELEVATION
<u>B1- INTERSTOREY STRENGTH IRREGULARITY:</u> (Weak Storey) In reinforced concrete buildings, the case where in each of the orthogonal earthquake directions, *Strength Irregularity Factor* η_{ci}, which is defined as the ratio of the *effective shear area* of any storey to the *effective shear area* of the storey immediately above, is less than **0.80**. $[\eta_{ci} = (\Sigma A_e)_i / (\Sigma A_e)_{i+1} < 0.80]$ *Definition of effective shear area in any storey* : $\Sigma A_e = \Sigma A_w + \Sigma A_g + 0.15\ \Sigma A_k$
<u>B2- INTERSTOREY STIFFNESS IRREGULARITY:</u> (Soft Storey) The case where in each of the two orthogonal earthquake directions, *Stiffness Irregularity Factor* η_{ki} , which is defined as the ratio of the average storey drift at any storey to the average storey drift at the storey immediately above or below, is greater than **2.0**. $[\eta_{ki} = (\Delta_i/h_i)_{ort} / (\Delta_{i+1}/h_{i+1})_{ort} > 2.0]$ **Or** $[\eta_{ki} = (\Delta_i/h_i)_{ort} / (\Delta_{i-1}/h_{i-1})_{ort} > 2.0]$ Storey drifts shall be calculated considering the effects of ± %5 additional eccentricities.
<u>B3- DISCONTINUITY OF VERTICAL STRUCTURAL ELEMENTS:</u> (Figure 2.14) The cases where vertical structural elements (columns or structural walls) are removed at some stories and supported by beams or gusseted columns underneath, or the structural walls of upper storeys are supported by columns or beams underneath.

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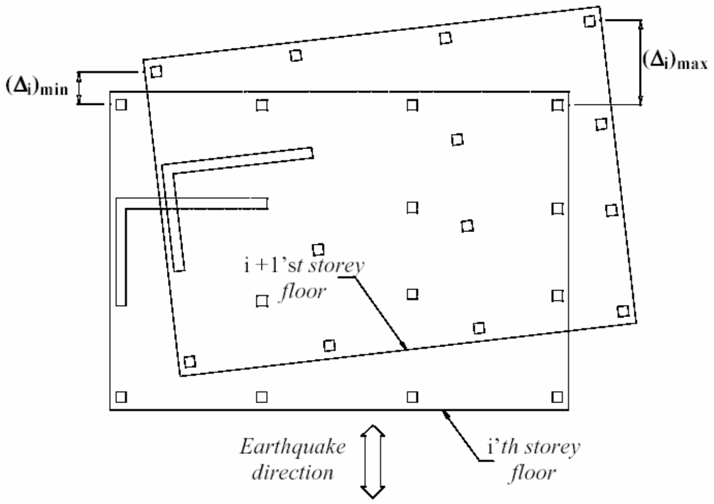
[72] Specification for Structures to be Built in Earthquake Areas, 2007



In the case where floors behave as rigid diaphragms in their own planes:

$$(\Delta_i)_{ort} = 1/2\,[(\Delta_i)_{max} + (\Delta_i)_{min}]$$

Torsional irregularity factor :

$$\eta_{bi} = (\Delta_i)_{max} / (\Delta_i)_{ort}$$

Torsional irregularity : $\eta_{bi} > 1.2$

Figure 2.10 Torsion Irregularity[73]

Figure 2.11 A Building Damaged due to Torsion Eccentricity[74]

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[73] Specification for Structures to be Built in Earthquake Areas, 2007

[74] TUNA, Mehmet Emin, Figure 8.8 Depreme Dayanıklı Yapı Tasarımı. Ankara: Tuna Eğitim ve Kültür Vakfı Pub., November 2000, p.234.

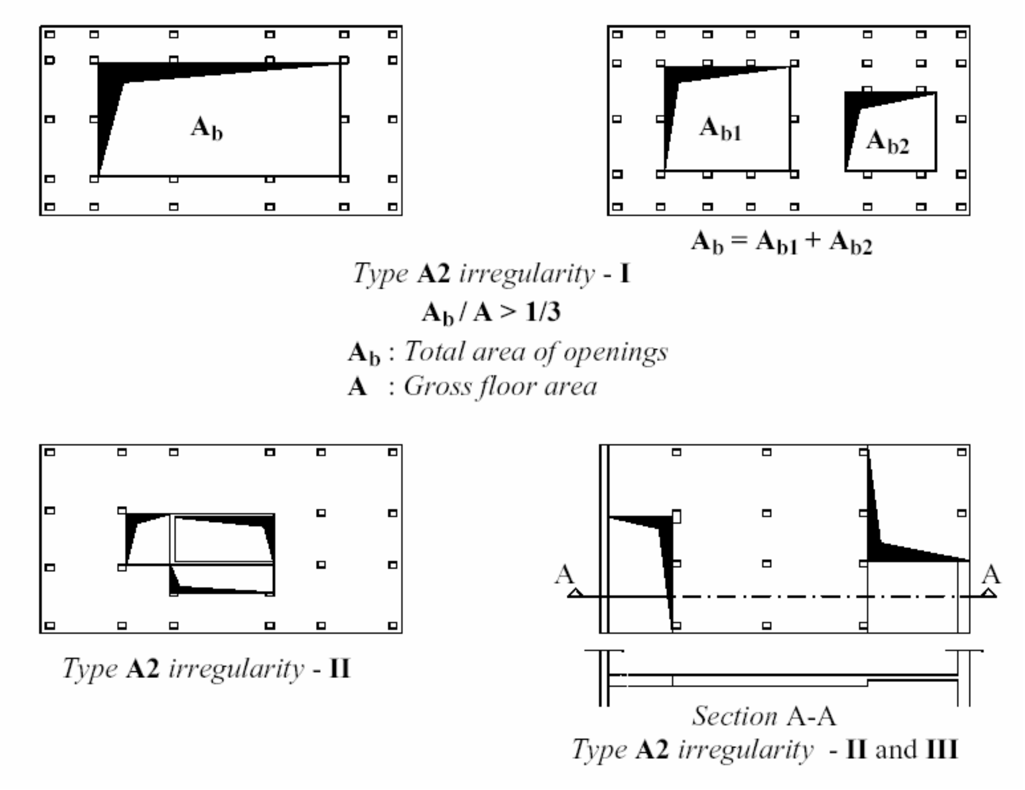

Figure 2.12 Floor Discontinuities[75]

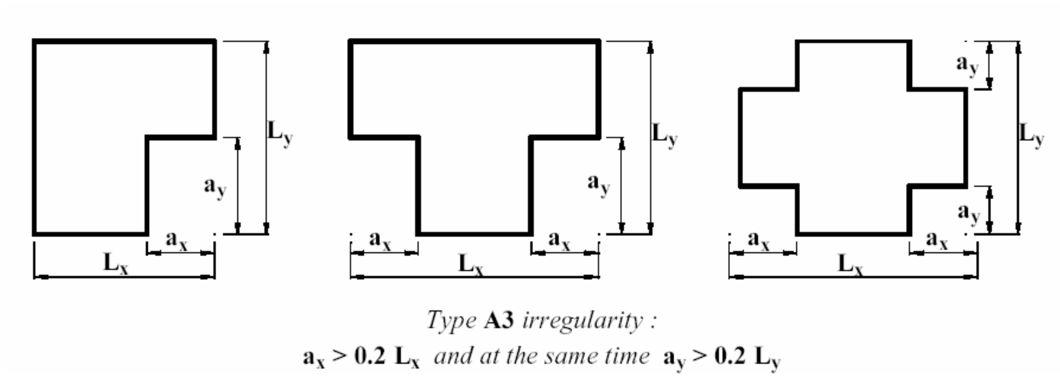

Figure 2.13 Projections in Plan[76]

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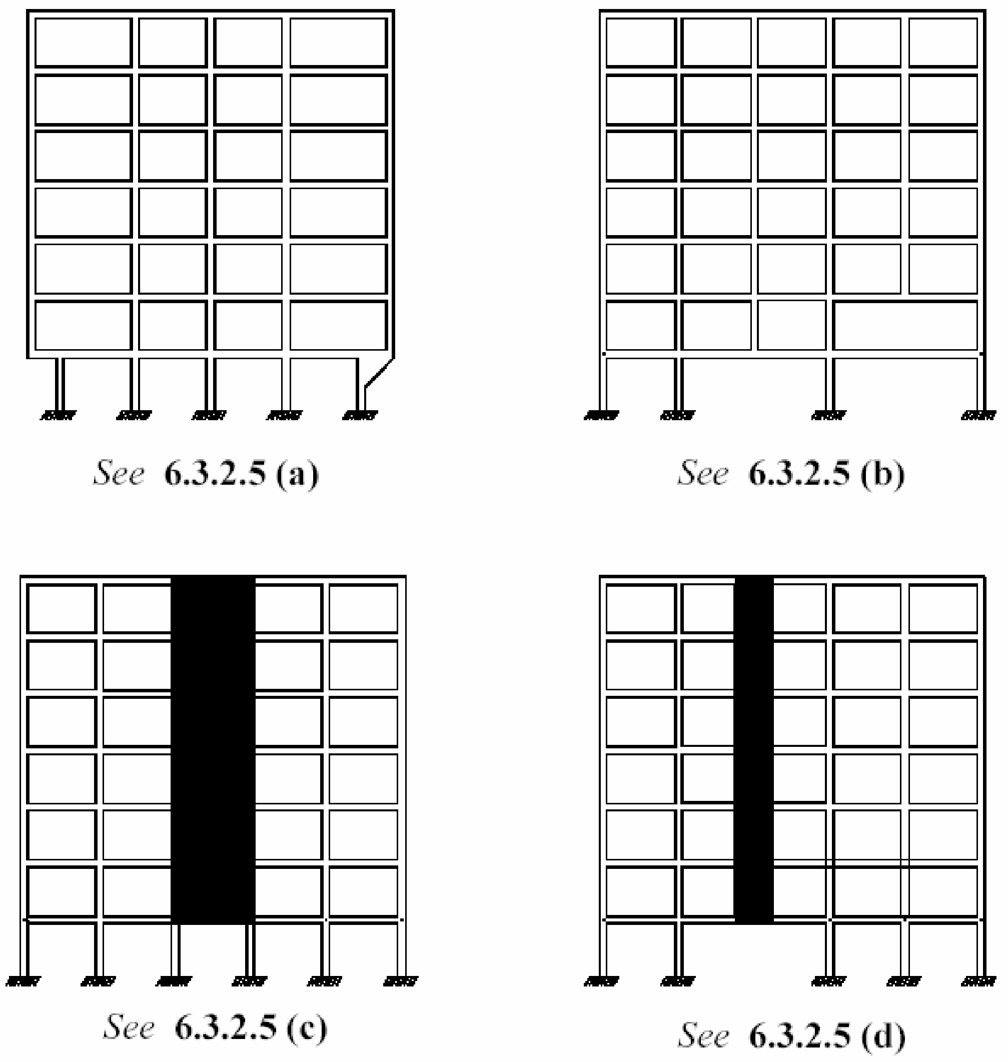
[75] Specification for Structures to be Built in Earthquake Areas, 2007

[76] Specification for Structures to be Built in Earthquake Areas, 2007



See **6.3.2.5 (a)**

See **6.3.2.5 (b)**

See **6.3.2.5 (c)**

See **6.3.2.5 (d)**

Figure 2.14 Discontinuity of Vertical Structural Elements[77]

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[77] Specification for Structures to be Built in Earthquake Areas, 2007

CHAPTER 3

CRITICAL CONCEPTS IN THE EARTHQUAKE BEHAVIOR OF REINFORCED CONCRETE STRUCTURES

3.1 The Material Properties of Reinforced Concrete

Reinforced Concrete (R/C) is the dominant building material in Turkey. It is necessary to have some basic knowledge about the material properties of R/C to understand its seismic behavior. Atımtay states that R/C is a composite material. It is made of concrete, which is very strong in compression forces but weak in tension forces, and steel, which is strong, both in compression and tension forces. The steel is used in the form of bars with circular cross-sections. These bars are called reinforcing bars. The reinforcing bars are used where tension forces occur, to compensate the tensile weakness of concrete.[78] (**Figure 3.1**)

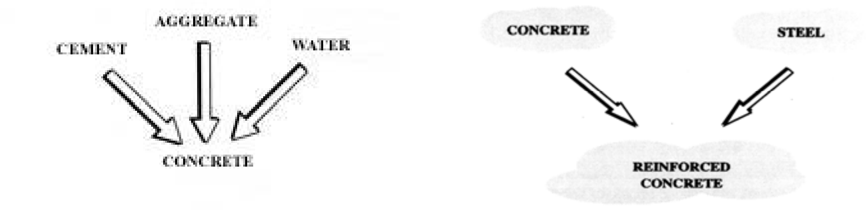

Figure 3.1 Concrete & Reinforced Concrete[79]

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[78] ATIMTAY, Ergin, Reinforced Concrete: Fundamentals, 2 Vols., Ankara, Bizim Büro Basımevi, 1998, Vol.1, p.3

[79] ATIMTAY, Ergin, Reinforced Concrete: Fundamentals, 2 Vols., Ankara, Bizim Büro Basımevi, 1998, Vol.1, pp.5-19

Atımtay further explains the causes of R/C being the dominant building material by economic reasons. The raw materials of concrete (calcium carbonate, aggregates, water) are very plentiful in nature and relatively cheap to obtain. Steel, on the other hand, is an expensive material and the raw materials are scarce; however, the percentage of steel in R/C is only about 1%, which is an economically acceptable ratio.[80]

Concrete is made of cement, aggregate and water. When cement is mixed with water, a chemical reaction called hydration occurs, as a result of which concrete hardens. The hardening of the concrete is called the curing process. During this chemical reaction an important amount of heat is generated. To minimize the volume changes due to this heat generation, aggregates, which are inert to the reaction are added to the mixture. Sometimes additional ingredients called admixtures can be added to modify the speed of curing, the amount of heat generated during hydration, resistance to corrosion, etc.[81]

There are various classes of concrete and reinforcing steel. Concrete classes are determined according to their *characteristic strength* (f_{ck}) and named with capital letter C (XX), while steel classes are determined according to their *characteristic yielding stress* (f_{yk}) and named with capital letter S (XX). For example C20 means that the *characteristic strength* of that concrete is 20 MPa (N/mm^2) and S420 means that the *characteristic yielding stress* of that steel is 420 MPa (N/mm^2). According to the 2007 Turkish Earthquake Code only C20 or higher concrete classes and S420 or lower steel classes can be used in all the earthquake regions in Turkey.[82]

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[80] ATIMTAY, Ergin, Reinforced Concrete: Fundamentals, 2 Vols., Ankara, Bizim Büro Basımevi, 1998, Vol.1, p.3

[81] HASOL, Doğan, Ansiklopedik Mimarlık Sözlüğü, 6th ed. İstanbul, Yapı-Endüstri Merkezi Pub., 1995, p.77

[82] Specification for Structures to be Built in Earthquake Areas, 2007

In Turkey, the production of R/C is subject to Turkish Standard TS 500 "Requirements for Design and Construction of Reinforced Concrete Structures". This standard determines the minimum requirements for material properties of various components of R/C such as the cement, aggregates, water, admixtures, reinforcing steel as well as the properties of the formwork and scaffolding required for R/C application. Quality control methods and rules for the testing of materials and production process are also described in TS 500. Furthermore, this standard determines the methods of calculation for all the structural components found in a R/C structural system such as the beams, columns, shear-walls, slabs and foundations. TS 500 includes a comprehensive set of specifications for all the aspects of R/C production. The latest standard in Turkey concerning the production of R/C is the TS EN 206 which regulates the production and testing procedures for the production of both cast in-situ and ready-mixed concrete types.[83]

The quality of the concrete available in Turkish building market has increased in recent years parallel with the rise in the amount of ready-mixed concrete production. The ready-mixed concrete production, which was approximately 1.500.000 m3 in 1988 has mounted to 70.732.631 m3 in 2006. The number of firms producing ready-mixed concrete has also risen from 25 in 1988 to 409 in 2006. The result of the availability of high quality concrete is an increase in the production quality of R/C buildings. In recent years, even constructions realized in small-towns of Turkey began utilizing ready-mixed concrete. However, the use of high quality concrete does not guarantee the production of an earthquake resistant building. The design of the structural system and the correct application of details are still critical to provide good seismic performance.[84]

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[83] TS-500 Requirements for Design and Construction of Reinforced Concrete Structures, Ankara, Türk Standartları Enstitüsü Yayınları, February 2000

[84] Türkiye Hazır Beton Birliği, 2006 Yılında Türkiye Hazır Beton Sektörü, http://www.thbb.org/Content.aspx?ID=12, Last Accessed Date: 15 March 2007

The calculations in TS 500 are done according to the *Limit State Design Theory*. In this method the main principle is that the *total resistance capacity* (R) should be greater than the *total force effect* (F) acting on the structure. However, to be on the safe side, two separate factors of safety are applied to this equation. The assumed resistance R is divided by a *material coefficient* (γm) and the estimated force effect is multiplied by a *load factor* (γf). These material and load factors are determined based on statistical and empirical data obtained from years of theoretical and practical experience.[85] (**Equation 1**)

$$\mathbf{R / \gamma m \geq F \times \gamma f} \qquad \textbf{(Equation 1)}$$

Terms of the equation are:

R: Resistance Capacity of the Structure
F: Total Load Effect on the Structure
γm : Material Coefficient ≥ 1
γf : Load Factor ≥ 1

In *Limit State Design Theory*, two separate conditions must be satisfied by the structure. The first one is the *Limit State for Load Carrying Capacity*, which determines the maximum load bearing capacity of the element before being completely destroyed, and the second one is the *Limit State for Serviceability*, which determines the allowable limits of conditions such as displacements, cracking and vibrations before the structure becomes unacceptable for the designated type of occupation.[86]

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[85] ERSOY, Uğur, Yönetmelikler ve Konut Yapımı, http://www.parlar.com.tr/ersoy/index.html, Last Accessed Date: 17 March 2008

[86] ATIMTAY, Ergin, Reinforced Concrete: Fundamentals, 2 Vols., Ankara, Bizim Büro Basımevi, 1998, Vol. 1, p.271

3.2 Behavior of Reinforced Concrete Structures under Earthquake Loads

3.2.1 Definition of the Earthquake Load

In the minds of many architects, the concept of earthquake loading is not very different then any other type of conventional lateral loads. It can be represented in the form of force vectors affecting the vertical section of a building and engineers make the necessary calculations by the help certain complex formulas. These may be true to a certain extent. During the process of approximate analysis or in the seismic calculations of small-scale buildings, earthquake forces may be represented in the form of equivalent lateral forces acting on every floor level of the building. However, to understand the earthquake behavior of a building, one must try to see what really happens to a building during an earthquake. (**Figure. 3.2**)

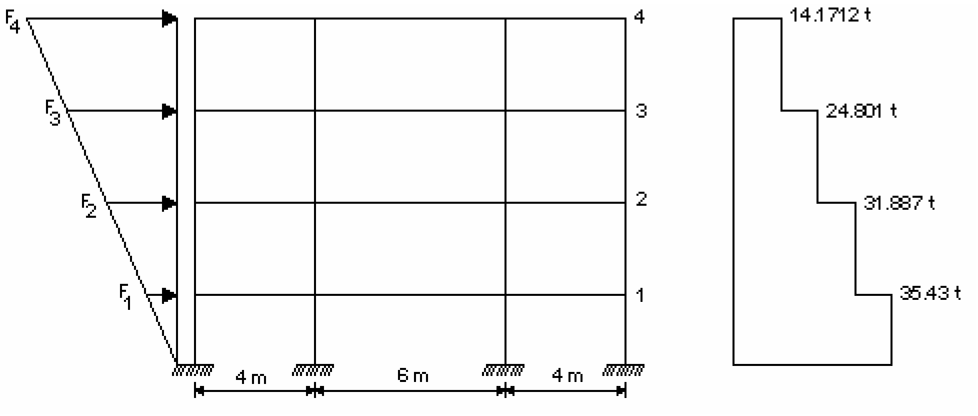

Figure 3.2 Equivalent Earthquake Forces Acting on a Structure[87]

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[87] ATIMTAY, Ergin, Reinforced Concrete: Fundamentals, 2 Vols., Ankara, Bizim Büro Basımevi, 1998, Vol. 1, p.617

It has been previously mentioned in Chapter 2 that an earthquake is a release of energy. According to Atımtay, when this energy travels through the layers of the crust and reaches the foundation of a building, it causes movements in every direction. If we assume that the structure is in a *Cartesian Coordinate System*, the building will make displacements in (x), (y) and (z) directions. The load carrying capacity and the safety factors in the vertical direction are very high in R/C systems; therefore, the forces in the (z) direction are negligible. On the other hand, the movements in (x) and (y) directions cause important accelerations.[88]

Earthquake loads come into existence because of a building's own mass or self-weight. Therefore, it can be stated that heavier buildings are subjected to larger earthquake forces than lighter buildings during the same earthquake. To have a better understanding of this concept, we can imagine the self-weight of every particle of the structure as independent lateral forces acting on that building. However, unlike wind, soil pressure or impact forces, seismic forces are not external loads acting on the structure, they are generated by the building being charged with the earthquake energy transferred from the ground.[89]

Seismic waves released from within the earth's crust during an earthquake, create a vibration when they reach the structure located on the surface. The reaction of the structure against this vibration represents a dynamic behavior. *Forces of inertia* are created as a result of this dynamic behavior. Inertia is the tendency of a physical object to remain still, or to continue moving if it is already moving, unless a force is applied to it.[90]

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[88] ATIMTAY, Ergin, Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 1, p.207

[89] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 p.59

[90] Collins Cobuild English Language Dictionary, William Collins and Sons & Co Ltd., 1987, Great Britain.

A good example to this concept may be the force felt by a passenger traveling in a car which suddenly decelerates. The force felt by the passenger is a *force of inertia* and it is in the same direction with the movement of the car. As demonstrated in the equation below, the *forces of inertia* (F) in a vibrating physical object may be calculated by the multiplication of the *object's mass* (m) with the *applied acceleration* (a).[91] **(Equation 2)**

$$\mathbf{F = m \times a} \qquad \textbf{(Equation 2)}$$

Terms of the equation are:

F: Forces of Inertia
m: Mass of the Structure
a: Acceleration created by the earthquake

Since the forces created in a structure during an earthquake are *forces of inertia*, the magnitude of these forces is related with the dynamic properties of the structure as well as the characteristics of the seismic waves. The dynamic properties of a structure vary according to the total mass, the distribution of the mass in horizontal and vertical planes, the geometrical shape of the structure, the configuration of the structural elements within the whole and the material properties. It should be noted that most of these critical factors which affect the seismic performance of the building are determined during the architectural design phase. Therefore, one of the main requirements of the architectural project of a building is to include an earthquake resistant structural system.[92]

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[91] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 p.60

[92] ÜNAY Ali İhsan, ATIMTAY, Ergin, "Developing Earthquake Consciousness in the Architect", Architecture and Engineering the Teaching of Architecture for Multidisciplinary Practice, Transactions on Architectural Education, No: 05, ed. Voyatzaki, Greece, Art of Text s.a.

3.2.2 The Relationship Between Architectural Design and Seismic Behavior of Structures

The differences between the seismic behaviors of earthquake-resistant and non earthquake-resistant structures must be clearly understood in order to create an architectural design with good seismic performance. In some cases, conditions may dictate for a structural system which contains seismic design faults due to its geometric form and architectural functions, to be relatively improved by the resizing or partial reconfiguration of its structural elements. However, the best seismic performance is obtained when the structural system is designed according to earthquake resistant design parameters from the beginning.[93]

The architectural design criteria affecting the earthquake resistance of structures can be divided into three groups. In reality, these groups are not entirely separate from each other. All groups are interconnected and affect each other; however, studying these criteria under three groups is useful for understanding the interaction in-between. These groups are as follows:[94]

- **Overall Geometric Shape of the Structure:** This concept may be defined as the three-dimensional size, shape and proportions of the entire structure. In addition to this, since the positioning of the building on the site is determined during the architectural design phase, the locations and dimensions of certain critical structural elements which have great effect on the earthquake resistance of the building are also a part of the overall geometric shape.

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[93] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 p.60

[94] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 p.61

- **Architectural Details with Seismic Design Faults:** The configuration and connection details of the individual structural elements may sometimes negatively affect the earthquake resistance of the overall structural system.

- **Non-structural Elements that Generate Seismic Hazard:** Design of the non-structural elements are under the responsibility of the architect. The design of these elements without proper seismic resistance may result in damages during earthquakes. Human or material casualties may occur due to the partial or total collapse of non-structural elements even though there is not damage in the structural system of the building.

The equation **($F = m \times a$)** must be taken into consideration to understand the forces applied on the structure during an earthquake. According to this equation, the earthquake loads acting on a heavy structure will be higher than those acting on a lighter structure with the same geometric configuration. However, the effect of an earthquake on a structure constitutes a complex mechanism; therefore, various factors which affect the seismic behavior of a structure must be simultaneously taken into consideration when examining the possible causes of earthquake damages. These factors are:[95]

- **Direct Load Effect**: During an earthquake, at a certain instant, the structure receives the maximum impact caused by the earthquake. Theoretically, this instant coincides with the largest acceleration created by the earthquake on the surface of the earth. Stresses and deformations are formed within the structure due to the movement created by this acceleration; sometimes the overall stability of the structural system may be disturbed.

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[95] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 p.61

- **Progress of the Small Damage:** The vibration of the structure continues during the entire span of the earthquake. A structural element or a connection may receive damage at the moment of the maximum impact. This initial damage may be small enough not to cause cracks or collapse, however; the extent of the damage may progress due to repeating movement and increasing deformation during the earthquake. As a result, the structure may suffer partial or total collapse.

- **Three-Dimensional Movement Effect:** During the earthquake, buildings make displacements in every direction. As a result, certain structural elements or connections may become exposed to loads and stresses that they wouldn't normally be subjected to. For example, structural elements which were designed for compressive loads may be subjected to tensile loads or elements may be deformed in unpredictable ways incompatible with their original planes of deflection.

- **The Effect of Excessive Deformations:** Excessive deformations that occur during an earthquake may cause partial or total collapse of non-structural elements. Due to the excessive deformations connection points may loose their function and disturb the stability of undamaged structural elements resulting in the collapse of the entire system. The most critical problem created by deformations is the second order moments caused by the strain of the structural elements under excessive stresses.

- **Energy Absorption Capacity:** The most critical parameter for the earthquake resistance of structures is the Energy Absorption Capacity. According to the rules of Statics, the resistance of a structure against earthquakes is determined by forces, stresses and deformations, however; the dynamic properties of the structure which are most critical in terms of its seismic behavior are determined by the Energy Absorption Capacity.

3.2.3 Fundamental Concepts in the Seismic Design of Structures

A structural system should satisfy the following three principles in order to comply with the earthquake resistant design approach described above:

- Strength
- Ductility
- Stiffness

Strength is the ability of a structural element to resist the internal forces created under various loading conditions. Structural elements of a building should satisfy a certain strength level in order to resist the internal forces created by an earthquake. The safest indicator of the strength level is the *Load Carrying Capacity*, (Section 3.1) which can be defined as the limit value of load that can be carried by that element without being damaged.[96]

Ductility is the ability of structural elements to make deformations without major decrease in their load carrying capacity. The concept of ductility, which is not very important under vertical loading conditions, is as critical as the concept of strength under earthquake loads. An experiment is conducted to have a better understanding of this concept. The beam in the figure below is subjected to a force (P). The magnitude of the force (P) is increased from 0 to the point where the beam is broken. The amount of the maximum deflection in the middle of the beam for every increasing value of (P) is plotted on the load-deformation diagram (P-Δ). Three curves are obtained for varying material and section properties. Curve (A) represents non-ductile behavior; curve (B) represents semi-ductile behavior and curve (C) represents ductile behavior. (**Figure 3.3**)

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[96] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 p.62

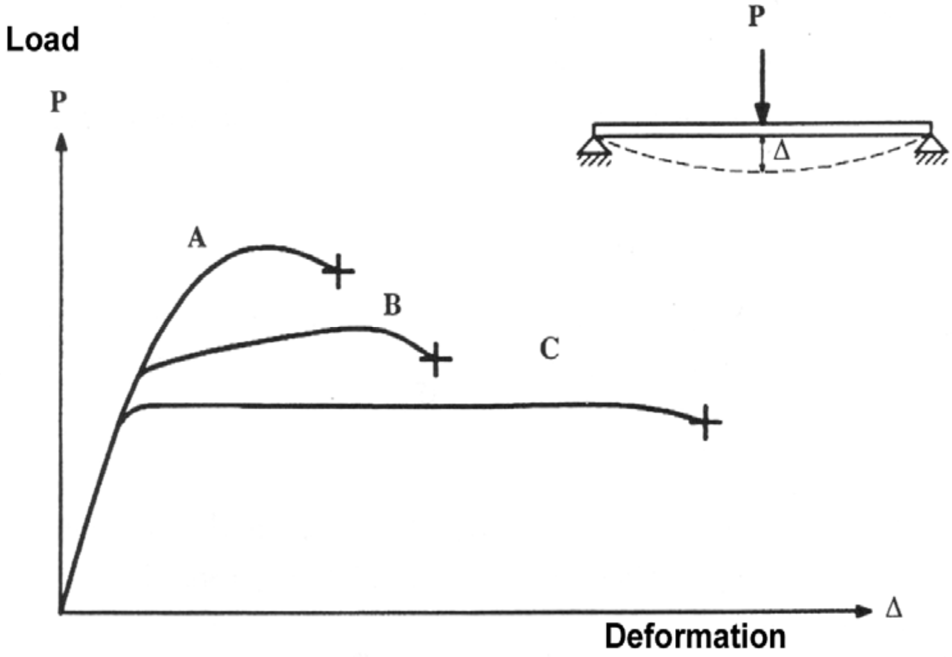

Figure 3.3 Levels of Ductility in a Typical Beam[97]

Ductility is especially important for the good seismic performance of reinforced concrete structures. Past experimental and theoretical researches have proven that it is not economically possible for a reinforced concrete structure to remain within elastic limits during a high-magnitude earthquake. Therefore, the survival of the structure in the face of an earthquake is only possible by the absorption of the released seismic energy. The amount of the energy that can be absorbed by a structure is proportional with the area under the (P-Δ) curve. It is obvious from the diagram that a structural element with ductile behavior (curve C) can absorb considerably more energy than those with non-ductile behavior.[98]

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[97] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 p.63

[98] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 p.63

The amount of seismic force that a structural system receives is closely related with that system's level of ductility. Assume that there is a non-ductile structural system which exhibits a completely elastic behavior. When this system is subjected to earthquake forces (F_E), it will make displacements (Δ) proportional with the amount of load applied until a limit load value (K) and a corresponding ultimate displacement value (Δ_E) after which the system will collapse. Now assume that the same system is designed ductile and exhibits elasto-plastic behavior. In the second system, plastic deformations will start to occur at a certain load value (M) which is considerably smaller than the load value at (K). As it can be seen in the figure below, the system will still be able to carry loads without total collapse until a larger ultimate displacement value (Δ_u) but will be subjected to considerably smaller seismic loads. The ratio of the limit load value at (K) to the limit load value at (M) is called the Seismic Load Reduction Factor (R_a).[99] (**Figure 3.4**)

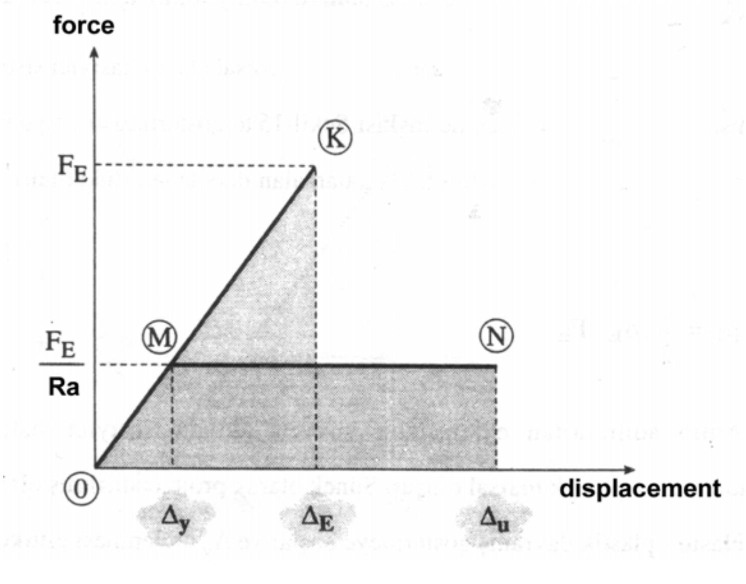

Figure 3.4 Behaviors of Elastic and Elasto-Plastic Structural Systems

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[99] ATIMTAY, Ergin, Açıklamalar ve Örneklerle Afet Bölgelerinde Yapılacak Yapılar Hakkında Yönetmelik: Betonarme Yapılar, 2 Vols. Ankara, Bizim Büro Basımevi, 2000, Vol. 1, p.99

In the Turkish Earthquake Code, it is assumed that the structural elements of a building will demonstrate ductile behavior under earthquakes. That is why the loads that should be considered in earthquake calculations are significantly decreased. Fundamental conditions concerning the ductility level of structural systems are given in the 2007 Turkish Earthquake Code. The code states that, when calculating seismic resistance of a building, *Elastic Seismic Loads*, which are determined according to the linear non-elastic behavior of that specific structural system, should be divided by *Seismic Load Reduction Factor* $\mathbf{R_a(T)}$. In the code the *Seismic Load Reduction Factor* is determined according to *Structural Behavior Factor* **R,** and *Building Natural Vibration Period* **T**.[100] (**Equation 3**)

$$\mathbf{R_a(T) = 1.5 + (R - 1.5)\ T / T_A \quad (0 \leq T \leq T_A)} \qquad \textbf{(Equation 3)}$$

$$\mathbf{R_a(T) = R \ (T > T_A)}$$

The terms of the equation are:

$\mathbf{R_a(T)}$**:** Seismic Load Reduction Factor
R: Structural Behavior Factor
T: Natural Period of the Building
$\mathbf{T_A}$**:** Spectrum Characteristic Period (depends on the soil type)

In the Turkish Earthquake Code, structural systems are classified under two categories, namely, *Structural Systems with High Ductility Level* and *Structural Systems with Low Ductility Level*. In reinforced concrete buildings, the ductility level is determined according to the type of the structural system. The categories are: frame systems, shear-wall systems and hybrid systems that include both frames and shear-walls. Other than the type of the system, ductility level depends on the dimensioning, configuration and the reinforcement ratio of the structural elements.

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[100] Specification for Structures to be Built in Earthquake Areas, 2007

Stiffness can be defined as the resistance of the structural element against displacement and torsional effects. Between two structural elements identical in size, the one that is less deformed under the same loading conditions and external effects has more stiffness than the other. The lateral displacement, under a load (P) applied at the top of a column which acts as a vertical cantilever is calculated through (**Equation 4**).[101] (**Figure 3.5**)

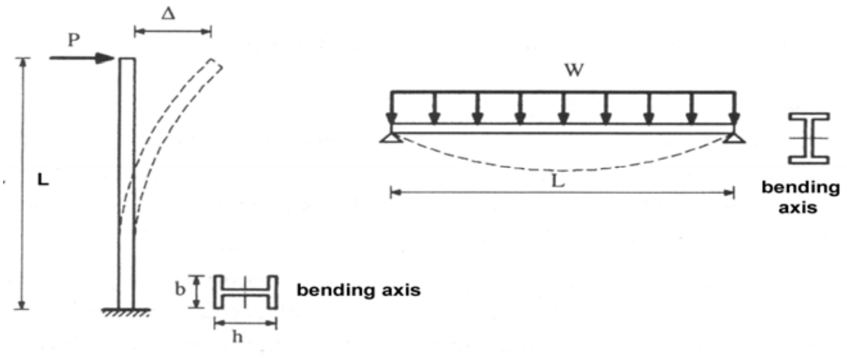

Figure 3.5 The Lateral Displacement of a Free-Standing Column

$$\Delta_{max} = \frac{PL^3}{3EI} \qquad \textbf{(Equation 4)}$$

The terms of the equation are:

Δ_{max}: Maximum displacement
P: Applied Point Load
L: Height of the Column
E: Modulus of Elasticity
I: Moment of Inertia

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[101] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 pp.64-65

Similarly, the maximum vertical displacement in the mid-span of a beam under a uniformly distributed load is calculated through (**Equation 5**).[102] (**Figure 3.5**)

$$\Delta_{max} = \frac{5wL^4}{384\ EI} \qquad \textbf{(Equation 5)}$$

The terms of the equation are:

Δ_{max}: Maximum displacement
w: Applied Distributed Load
L: Length of the Beam
E: Modulus of Elasticity
I: Moment of Inertia

As it can be clearly understood from the equations above, the stiffness of structural elements under earthquake loads is positively proportional with the Moment of Inertia **I**, and negatively proportional with the length or height **L** of the element.

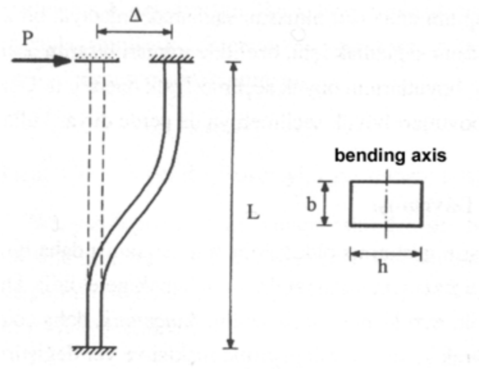

Figure 3.6 The Lateral Displacement of a Fixed-End Column

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[102] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 pp.64-65

It is possible to demonstrate the relation between the height of the column, the cross-sectional dimension of the column perpendicular to the bending axis and the amount of lateral displacement with a simple example. The column shown in the figure above has fixed supports on both ends meaning that the beams at the top and the bottom are assumed to have infinite rigidity. The lateral displacement of such a column under a point load (P) acting at the top end is calculated through **Equation 6**. [103] (**Figure 3.6**)

$$\Delta_{max} = \frac{PL^3}{12EI} \qquad \textbf{(Equation 6)}$$

The terms of the equation are:

Δ_{max}: Maximum displacement
P: Applied Point Load
L: Height of the Column
E: Modulus of Elasticity
I: Moment of Inertia

If we consider that the Moment of Inertia of the column cross-section is equal to:

$$I = \frac{bh^3}{12} \qquad \textbf{(Equation 7)}$$

The terms of the equation are:

I: Moment of Inertia of the Column
b: Cross-sectional Dimension Parallel to the Bending Axis
h: Cross-sectional Dimension Perpendicular to the Bending Axis

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[103] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 pp.64-65

Equation 6 can be re-written as follows:

$$\Delta_{max} = \frac{PL^3}{Ebh^3} \qquad \textbf{(Equation 8)}$$

The terms of the equation are:

Δ_{max}: Maximum displacement, **P:** Applied Point Load,
L: Height of the Column, **E:** Modulus of Elasticity
b: Cross-sectional Dimension Parallel to the Bending Axis
h: Cross-sectional Dimension Perpendicular to the Bending Axis

As it can be seen from Equation 8, displacement increases with the third power of the column height and decreases with the third power of columns cross-sectional dimension perpendicular to the bending axis. It can be concluded that decreasing the column height or increasing the cross-sectional dimension perpendicular to the bending axis will increase the columns stiffness at the same ratio.

Until the recent past, building of structures with high stiffness was avoided because it was thought that structures with less stiffness and more flexibility had a better seismic performance. However, studies in the aftermath of major earthquakes proved that buildings with less stiffness have suffered more damage than the ones with high stiffness. The reason for this damage is the excessive lateral displacements which cause severe damages in non-structural elements such as partition walls, fenestrations and furniture. Another critical type of damage caused by the excessive displacement is the second order moments which create stability problems in the structure and may eventually cause the total collapse of the building.[104]

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[104] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 pp.65-66

3.3 Fundamental Criteria For the Seismic Performance Assessment of Reinforced Concrete Apartment Blocks

3.3.1 The Effect of Natural Period on the Seismic Behavior of Reinforced Concrete Building

Every object in a state of *Free Vibration* has a *Natural Period*. It should be remembered that buildings, which enter into a state of vibration because of the seismic waves created during an earthquake, also have a *natural period* depending on the material and geometric properties of their structural systems. First, the *natural period* of a structure must be determined in order to examine its dynamic behavior. The *natural period* of a reinforced concrete building having a frame skeleton system can be approximately calculated with the following equation:

$$\mathbf{T = 0.1\,n} \qquad \textbf{(Equation 9)}$$

The terms of the equation are:

T: Natural Period, **n:** Number of Storeys

Since the *natural period* of a building is closely related with its stiffness, in cases where the building has enough shear-walls, the period can be decreased by 50 %. As the energy of the earthquake reaches the surface through seismic waves, it also causes vibrations in the ground that the building rests on. If the vibration period of the ground coincides with the *natural period* of the building, *Resonance* is created and the damage in the building will be much higher.[105]

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[105] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 pp.67-68

The seismic vibration of the building decreases in time, depending on the dynamic properties of the structural system. This reduction is related with the type of structural material, the properties of connections, material and physical properties of partition walls filling in-between the beams and columns. This is called *seismic dampening* and is defined as a ratio of the *critical dampening level*, which brings the vibration of the building to a halt. Seismic dampening generally varies between 0,02 and 0,10. It is widely accepted as 0,05 for reinforced concrete structures.[106]

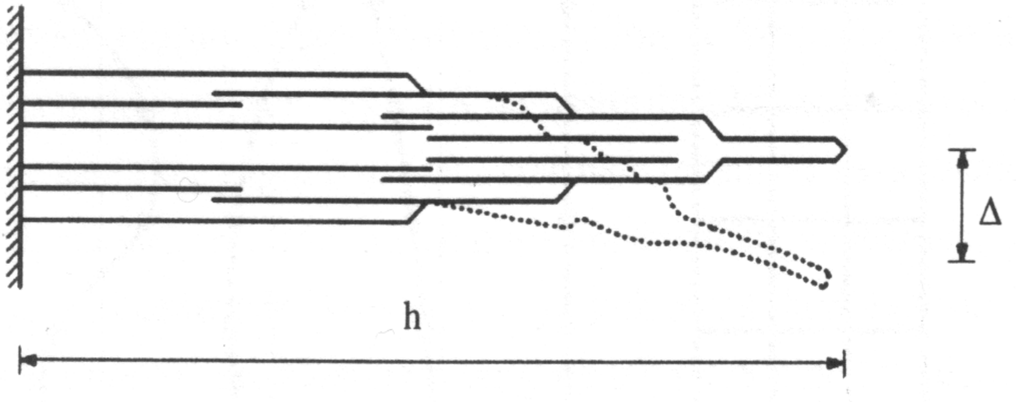

Figure 3.7 Behavior of Structures under Seismic Loads

As can be seen in the figure above, the basic seismic behavior of structures can be assumed similar to the behavior of a cantilever beam under its own weight. (**Figure 3.7**) The weight of a structure can be calculated by the multiplication of its mass with the gravitational acceleration. Similarly, earthquake loads are generated by the ground acceleration interacting with the mass of the building. *Response Spectrums*, which demonstrate the range of the structures' reaction to

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[106] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 pp.64-65

the earthquake, are used to understand the dynamic behavior of the building. As can be seen in the figure below, *Response Spectrum* is a diagram that shows the variation of the *ground acceleration* with respect to the *natural period* of the building. However, since every earthquake is unique in terms of ground acceleration properties, *Normalized Response Spectrums*, which take into consideration several variables such as the probability of earthquake accelerations and ground conditions, are used for structural analysis purposes.[107] (**Figure 3.8**)

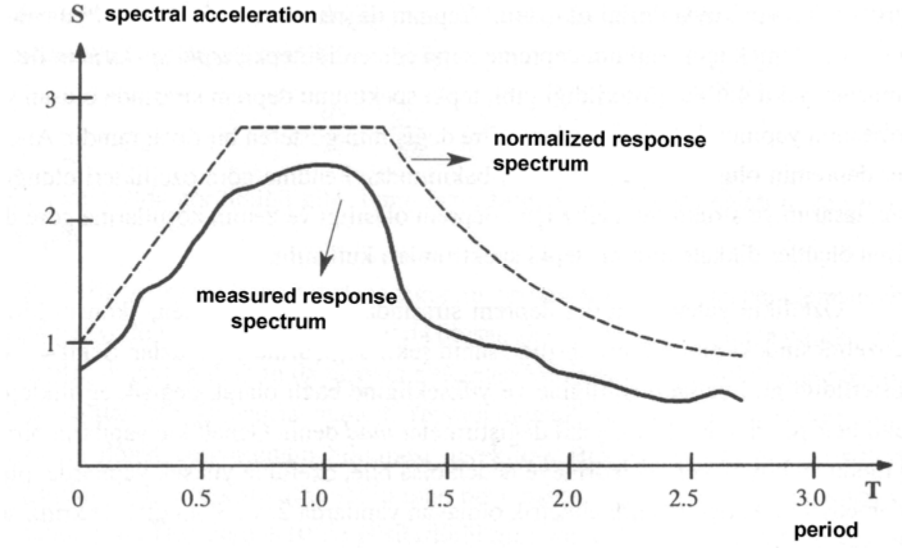

Figure 3.8 Normalized Response Spectrum

Especially tall structures do not exactly behave like cantilever beams, which have a uniform curvature of deflection. As can be seen in the figure below, their deflection curvature is rather uneven depending on the height and the stiffness of the observed section. These different patterns of deflection are called the *Modes* of the structure. Generally the first mode of a structure creates the largest therefore

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[107] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 pp.68-69

the most critical displacement, however; in tall buildings with uneven mass distribution and irregular floor plans, the second and third modes may also be critical.[108] (**Figure 3.9**)

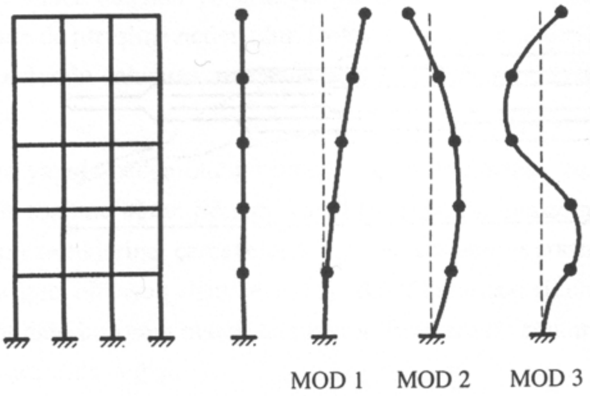

Figure 3.9 Displacements with Respect to Modes

Atımtay states that, there is a close interaction between the *natural period*, level of ductility and received seismic force in R/C structures. In the figure below, assume that the *natural period* of the structure is ($T_{o)}$ at the first impact of the earthquake. The corresponding acceleration will be (a_o) and the respective seismic force will be (F_o). Eventually, this relatively large amount of force will create cracks and subsequent plastic deformations in the system. Deformed structural system will have less stiffness against the action of lateral forces, as a result, the period will get longer and become (T_1). Consequently the corresponding acceleration (a_1) and resulting seismic force (F_1) will decrease and the system will be subjected to a smaller earthquake loading.[109] (**Figure 3.10**)

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[108] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 pp.69-70

[109] ATIMTAY, Ergin, Açıklamalar ve Örneklerle Afet Bölgelerinde Yapılacak Yapılar Hakkında Yönetmelik: Betonarme Yapılar, 2 Vols. Ankara, Bizim Büro Basımevi, 2000, Vol.1, pp.93-94

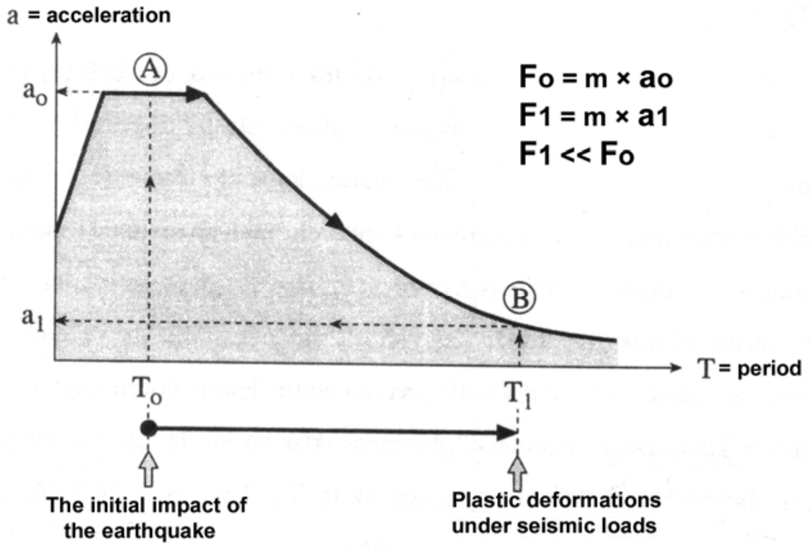

Figure 3.10 Interaction of Natural Period and Ductility

According to Atımtay, there is a critical difference between the structural behaviors of R/C structures having a *natural period* (T) larger than 0,7 seconds and structures having T smaller than 0,5 seconds. In case of structures which have T > 0,7 seconds the *rule of equal displacements* is valid. In this type of behavior, with the increasing magnitude of seismic force (F_E), the non-ductile linear elastic system will reach the point of total failure (K). At this point the displacement of the center of gravity of the structure is equal to (Δu). The area defined by the points 0 – K – Δu will give the amount of energy consumed by the system.[110]

In the same structural system, assume that the system is designed to exhibit ductile behavior. In that case, plastic deformations start to occur at point (M). After the formation of the plastic deformations, the amount of the seismic force acting on the system will remain constant. However, the displacements of the ductile system will continue to increase. This increase in the displacements will

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[110] ATIMTAY, Ergin, Açıklamalar ve Örneklerle Afet Bölgelerinde Yapılacak Yapılar Hakkında Yönetmelik: Betonarme Yapılar, 2 Vols. Ankara, Bizim Büro Basımevi, 2000, Vol.1, pp.97-99

come to an end at point (N) where the system will collapse. The maximum displacement of the elasto-plastic system will also be (Δu). According to analytical and empirical data, for systems having T > 0,7 seconds, maximum displacements will be equal for both elastic and elasto-plastic behaviors.[111] (**Figure 3.11**)

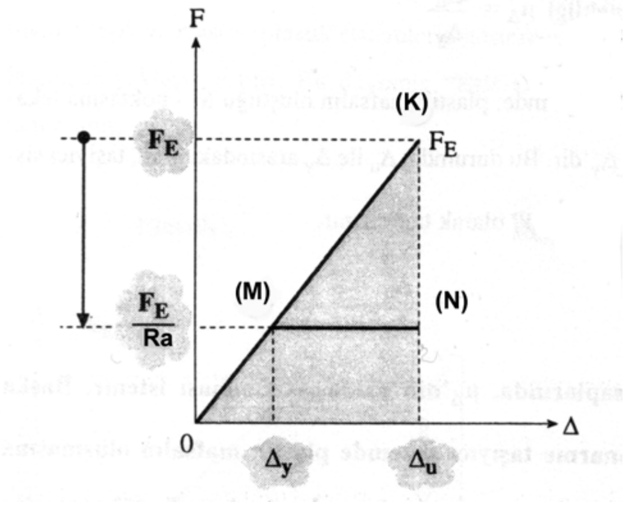

Figure 3.11 F – Δ Diagrams for Systems with T > 0,7 seconds.

For R/C structural systems having natural period (T) smaller than 0,5 seconds, the *rule of equal energy consumption* is valid. Similar to the previous example, in this type of behavior, with the increasing magnitude of seismic force (F_E), the non-ductile linear elastic system will reach the point of total failure (K). At this point the displacement of the center of gravity of the structure is equal to (Δ_E). The area defined by the points 0 – K – Δ_E will give the amount of energy consumed by the system.[112]

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[111] ATIMTAY, Ergin, Açıklamalar ve Örneklerle Afet Bölgelerinde Yapılacak Yapılar Hakkında Yönetmelik: Betonarme Yapılar, 2 Vols. Ankara, Bizim Büro Basımevi, 2000, Vol.1, pp.97-99

[112] ATIMTAY, Ergin, Açıklamalar ve Örneklerle Afet Bölgelerinde Yapılacak Yapılar Hakkında Yönetmelik: Betonarme Yapılar, 2 Vols. Ankara, Bizim Büro Basımevi, 2000, Vol.1, pp.97-99

In case of ductile behavior, the elasto-plastic displacements beginning at point (M) will increase until the point (Δu) where the areas under the diagrams 0 – K – Δ_E and 0 – M – N – Δu are equal. This means that the amounts of energy consumed by the non-ductile and ductile systems are equal. However, the ductile system will be allowed to make much higher displacements without total collapse.

While the failure type of structures with T > 0,7 will be sudden and brittle, the failure of structures with T < 0,5 will be ductile and slow. These structures will be much safer for their occupants during an earthquake because they will be much less likely to collapse and the occupants will have plenty of time to evacuate the building before total failure of the structural system.[113] (**Figure 3.12**)

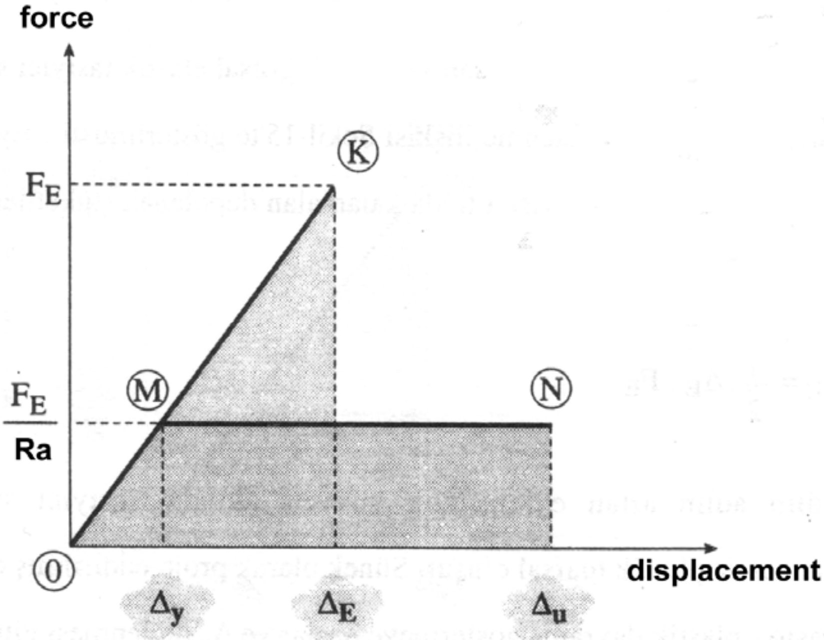

Figure 3.12 F – Δ Diagrams for Systems with T < 0,5 seconds

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[113] ATIMTAY, Ergin, Açıklamalar ve Örneklerle Afet Bölgelerinde Yapılacak Yapılar Hakkında Yönetmelik: Betonarme Yapılar, 2 Vols. Ankara, Bizim Büro Basımevi, 2000, Vol.1, pp.100-102

3.3.2 The Effect of Excessive Lateral Displacements on the Seismic Behavior of Reinforced Concrete Buildings

According to Ersoy and Özcebe, every individual element in a R/C structure is subjected to a certain amount of axial force, shear force and bending moment due to the monolitical nature of R/C skeleton system. From this point of view it is not possible to assume that beams only carry bending moments and columns are only subjected to axial loads. Because columns are connected to beams with rigid connections in skeleton systems, they also carry bending moments in addition to axial loads. In fact, they are also subject to the effect of torsion in certain cases.[114]

Because the cross-sectional dimensions of columns are much smaller when compared to their height, they are usually considered as slender elements. As can be seen in the figure below, the axial force and the bending moment acting on a column can be replaced with an eccentrically (e) applied point load. This load will create a moment called the *first order moment* (M), which is equal to the multiplication of the axial load (N) by the amount of eccentricity (e). $M = N \times e$. The bending effect will create a displacement represented with (y) in the slender column. As a result, there will be an additional moment due to this displacement in addition to the already existing *first order moment*. (**Figure 3.13**)

This additional moment is called the *second order moment* (ΔM), and is equal to the multiplication of the axial load (N) by the displacement (y). $\Delta M = N \times y$. Therefore, the total moment acting on the column will be equal to the sum of the first and second order moments. $M_{total} = M + \Delta M$.[115]

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[114] ERSOY, Uğur, ÖZCEBE, Güney, Betonarme: Temel İlkeler, TS-500 ve Türk Deprem Yönetmeliğine Göre Hesap, Ankara, Bizim Büro Basımevi, 2001, p.323

[115] ERSOY, Uğur, ÖZCEBE, Güney, Betonarme: Temel İlkeler, TS-500 ve Türk Deprem Yönetmeliğine Göre Hesap, Ankara, Bizim Büro Basımevi, 2001, p.324

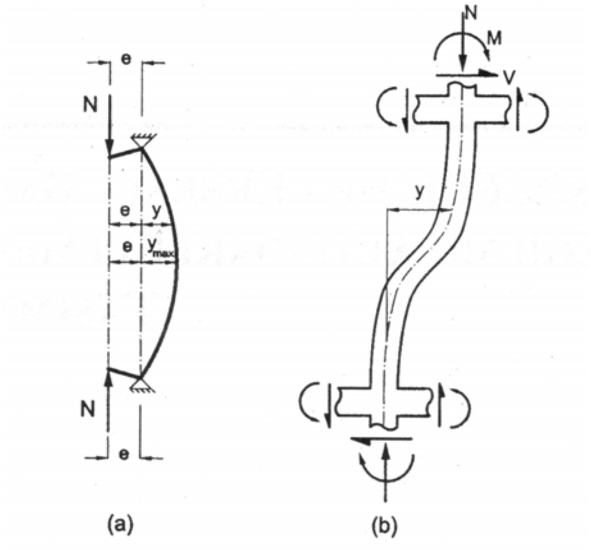

Figure 3.13 Formation of First and Second Order Moments in a Column

The limit conditions and loads acting on real columns are much more complex than those represented in the figure. In cases where there are also lateral loads, such as seismic loads, in addition to the vertical loads and if there are no shear-walls to limit the lateral displacements, significant *second order moments* will occur and may cause unexpected forms of failure, loss of stability and total collapse of the building.[116]

Due to the reasons described above, the Turkish Earthquake Code limits the amount of lateral displacement allowed in-between the floors to satisfy the stiffness of the structural system. Proper dimensioning of the vertical structural elements during the architectural design phase is critical to provide the stiffness condition. The architects should choose large cross-sections for columns or use shear-walls to strengthen their buildings.[117]

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[116] ERSOY, Uğur, ÖZCEBE, Güney, Betonarme: Temel İlkeler, TS-500 ve Türk Deprem Yönetmeliğine Göre Hesap, Ankara, Bizim Büro Basımevi, 2001, p.325

[117] ÜNAY, Ali İhsan, Tarihi Yapıların Deprem Dayanımı, Ankara, METU Faculty of Architecture Press, 2002 p.66

3.3.3 Column Interaction Diagram as a Seismic Capacity Measuring Device for Reinforced Concrete Structure

Column Interaction Diagram is a tool for measuring the load carrying capacity of R/C columns in terms of axial force and bending moment. Atımtay explains the drawing of column interaction diagram as follows: Assume that there are a series of R/C columns with very short height (L) to avoid the formation of *second order moments*. In the first specimen, take the eccentricity of the applied axial load as ($e = 0$) and gradually increase the level of axial load (N) from 0 to the limit value (N_{max}) where the column fails. Note that since eccentricity was 0, there was no bending moment. ($M = 0$).[118] (**Figure 3.14**)

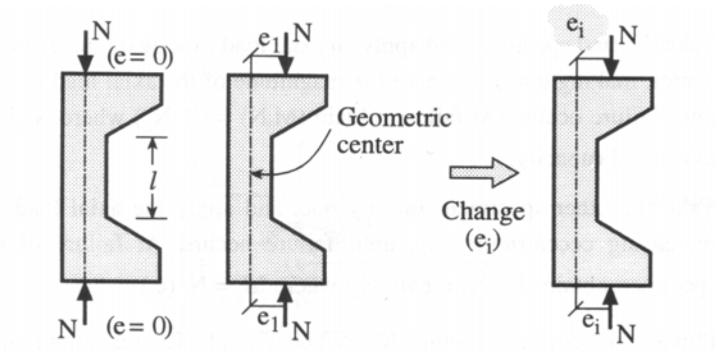

Figure 3.14 Experiment Designed to Draw the Column Interaction Diagram

In the following steps, take the other specimens with increasing eccentricities and apply the same loading process. Plot the corresponding axial force (N) and bending moment (M) values at the failure point of every specimen. When these failure points are connected to each other, the column interaction diagram will be obtained. This diagram defines a safety envelope for the column. Corresponding

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[118] ATIMTAY, Ergin, Reinforced Concrete: Fundamentals, 2 Vols., Ankara, Bizim Büro Basımevi, 1998, Vol.2, p.51

(N, M) values that are inside the diagram mean that the column carries the load safely. If the values are too near the diagram, it means that the column carries the load but there is a risk of exceeding its capacity in case of an unexpected additional load effect.[119] (**Figure 3.15**)

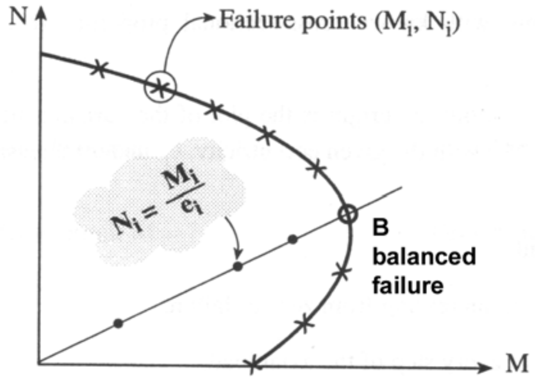

Figure 3.15 Column Interaction Diagram

Column Interaction Diagram is drawn for a specific column with known cross-sectional properties. These properties are: cross-sectional dimensions, percentage of steel, concrete class and steel class. A change in any of these parameters will require the drawing of a new diagram for that column. *Column interaction diagram* is a useful device when measuring the seismic capacity of R/C buildings because other parameters such as the internal force values acting on a specific column are closely related with the level of stiffness of that element. Level of stiffness, on the other hand, changes with any variation in cross-section, height or geometric configuration. Therefore, when similar columns of separate structural systems are compared with each other in terms of seismic performance, using the *column interaction diagram* would give a more objective idea about the safety level of the system.

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[119] ATIMTAY, Ergin, Reinforced Concrete: Fundamentals, 2 Vols., Ankara, Bizim Büro Basımevi, 1998, Vol.2, p.52

3.4 Seismic Design Faults in the Plan Configuration of Reinforced Concrete Buildings

3.4.1 Torsion Eccentricity

In the floor plan, the distance between the *center of gravity* and the *center of rigidity* should be minimum. If eccentricity is large, there will be a *torsion moment* around the center of rigidity due to lateral earthquake forces. This moment will create additional shear forces in the columns, which are already under great shear stress. It is very difficult to change the location of the center of gravity; on the other hand, the center of rigidity can be modified by playing with the cross-sections and the locations of columns and shear-walls.[120] (**Figure 3.16**)

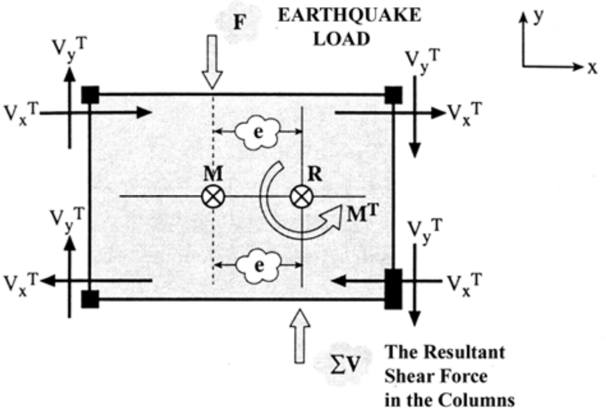

Figure 3.16 Torsion Eccentricity[121]

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[120] ATIMTAY, Ergin. Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, p.499

[121] ATIMTAY, Ergin. Figure 8.23 Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, p.499

The example below shows how the center of gravity and the center of rigidity can be modified by the addition of shear-walls to decrease the torsion eccentricity and the consequent shear forces. (**Figure 3.17**)

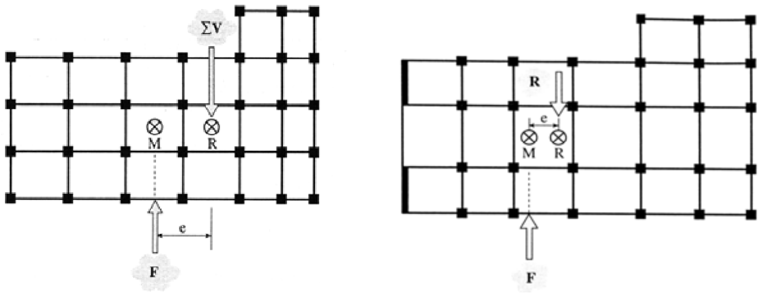

Figure 3.17 Modifying the Center of Rigidity[122]

The building below was damaged due to torsion eccentricity. The shear-walls are located on one corner of the building creating an over-rigid core around which the building has rotated. As a result, the columns have failed. (**Figure 3.18**)

Figure 3.18 A Building Damaged due to Torsion Eccentricity[123]

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[122] ATIMTAY, Ergin. Figure 8.22/8.24 Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, p.499

[123] TUNA, Mehmet Emin, Figure 8.8 Depreme Dayanıklı Yapı Tasarımı. Ankara, Tuna Eğitim ve Kültür Vakfı Pub. November 2000, p.234

3.4.2 Floor Discontinuities

The lateral forces on the structure are transferred to columns and shear-walls through the floor slabs. Generally, in calculations of statics, it's assumed that the floor slabs have infinite in-plane rigidity. However, if there are large openings in slabs or drastic changes in slab rigidity, this assumption will not be valid. Without a rigid floor slab, there will be critical and unpredictable changes in the distribution of lateral loads to columns and shear-walls. Furthermore, the dynamic behavior of the building will be negatively affected. There will be irregular lateral displacements causing additional shear stresses on the columns. If it is absolutely necessary to make discontinuities on the plan, the rigidity of the columns and beams around the opening should be increased or shear-walls should be positioned around the openings.[124] (**Figure 3.19**)

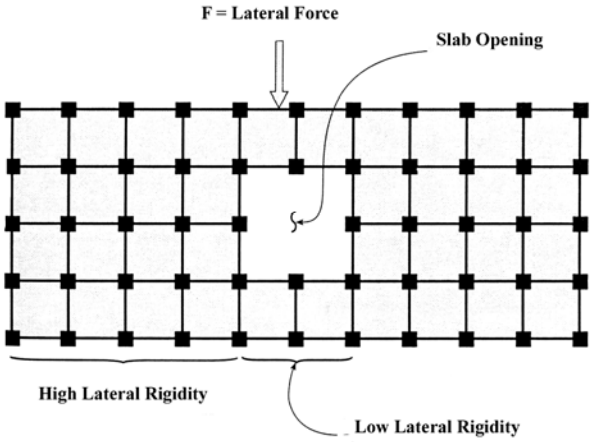

Figure 3.19 Discontinuities in the Floor Slab[125]

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[124] ATIMTAY, Ergin. Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, p.521

[125] ATIMTAY, Ergin. Figure 8.44 Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, p.521

3.4.3 Projections in Plan

Almost all R/C structures and especially residential buildings contain projections in plan due to architectural considerations or functional necessities. The ratio of these projections to the entire plan is very important in terms of seismic behavior of the building. When the projections are too large, they will cause additional stresses on the structure. The most critical shear forces and moments occur in the intersection line of the projection and the main body. Furthermore, there will be torsion eccentricities on the building. If the projections are absolutely necessary, the structural engineers should be consulted for additional reinforcements. If possible, the structure should be divided into several sections with structural joints.[126] (**Figure 3.20**)

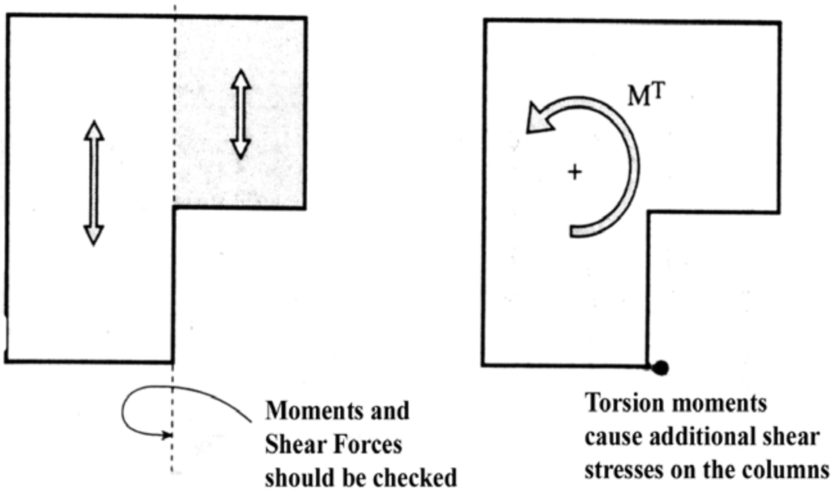

Figure 3.20 Disadvantages of Projections in Plan[127]

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[126] ATIMTAY, Ergin. Açıklamalar ve Örneklerle Afet Bölgelerinde Yapılacak Yapılar Hakkında Yönetmelik, Ankara, Bizim Büro Basımevi Pub. 2000, p.146

[127] ATIMTAY, Ergin. Açıklamalar ve Örneklerle Afet Bölgelerinde Yapılacak Yapılar Hakkında Yönetmelik Ankara, Bizim Büro Basımevi Pub. 2000, p.147.

3.4.4 Non-Continuous Beams

The architect should avoid designing non-continuous beams in the floor plan. Atımtay states that when the beam is not continuous, the lateral forces will be distributed to the vertical elements through the relatively thin floor slab. When the slab looses its structural function as an infinitely rigid diaphragm, it becomes very difficult for the structural engineer to calculate the pattern and the effects of this distribution. If such a configuration is absolutely necessary the slab thickness can be increased or a joist slab can be used. The designer should always keep in mind the lateral displacement properties of the entire design.[128] (**Figure 3.21**)

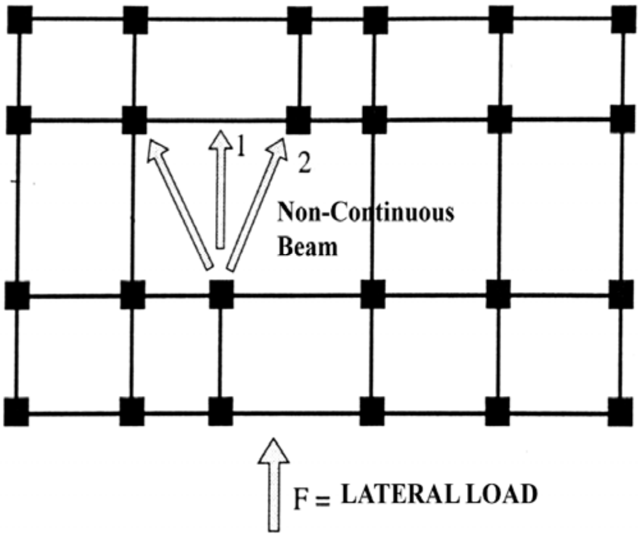

Figure 3.21 Non-Continuous Beam[129]

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[128] ATIMTAY, Ergin. Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, p.495

[129] ATIMTAY, Ergin. Figure 8.19 Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, p.495

3.4.5 Irregular Spans and Beam Cross-Sections

In certain student architectural design juries, the most fervent debates between the architects and the engineers are made because the engineers recommend structures having regular spans. Architects however, find such a limitation to their creative freedom unacceptable. Both sides have reason in their own terms. Nevertheless, there is a simple explanation for this advice of the engineers. Firstly, with irregular spans the lateral rigidity of the entire system will be very unpredictable in an earthquake situation. Besides this, if there are altering beam cross-sections it is very difficult to estimate the critical stresses in the structural elements under lateral loads. Furthermore, the formwork cost will be very expensive. The reinforcement details will be very complicated and difficult to produce especially in Turkey. That is why standard spans and uniform cross-sections are recommended for R/C structures. (**Figure 3.22**)

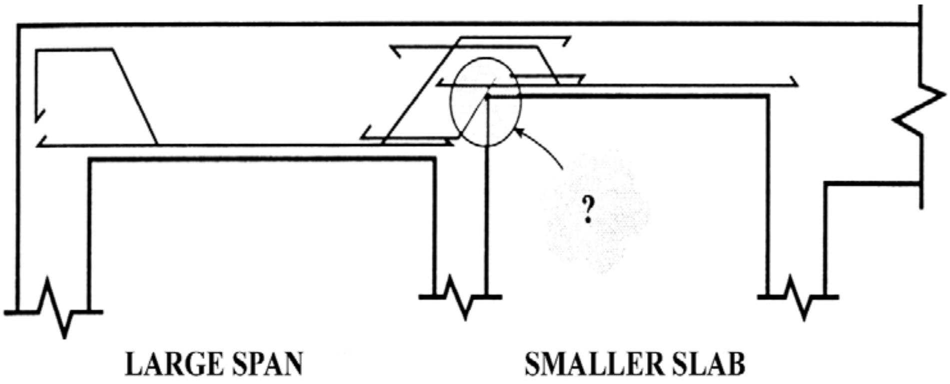

Figure 3.22 Joint Between Beams with Different Cross-Sections[130]

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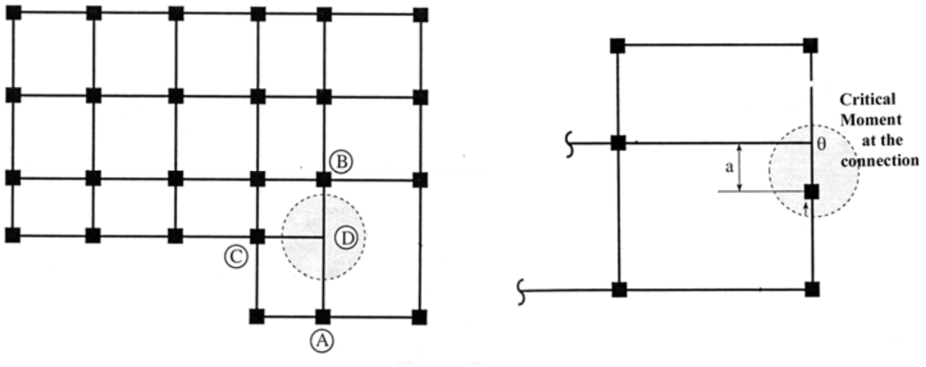
[130] ATIMTAY, Ergin. Figure 8.20/8.21 Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, p.495

3.4.6 Beam-to-beam Connection without Vertical Support

In architectural design projects, sometimes vertical load-bearing members are omitted in beam-to-beam connections due to spatial considerations. Such a configuration may be dangerous under lateral loading (**Figure 3.23 A**). There will be a large point load on the connection point creating critical moments. Large deflections and cracks may occur on the beams. Additional reinforcements plus very large and expensive beam cross-sections will be needed. If such a connection is absolutely necessary the connection point should not be near the support (**Figure 3.23 B**). One should remember that stiffness is negatively proportional with the length of the element. When the span of the beam between the beam-to-beam connection joint and the column becomes very short, very critical torsion moments will occur both on the beams and the column.[131]



A **B**

Figure 3.23 Beams Intersecting Without Vertical Support[132]

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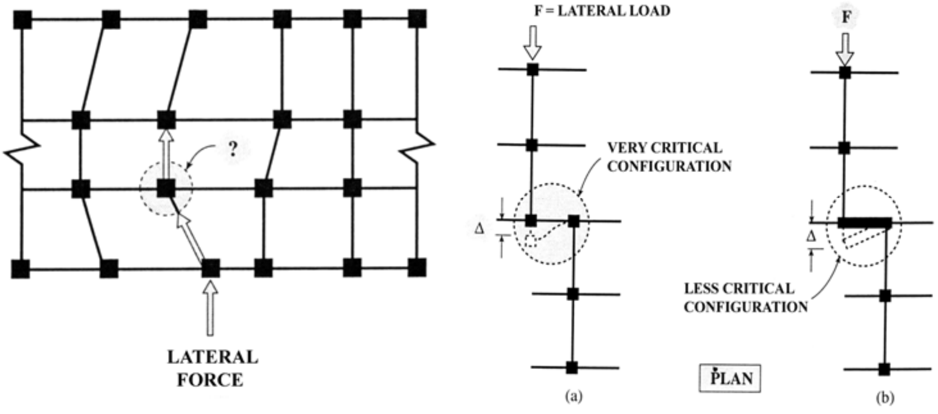
[131] ATIMTAY, Ergin. Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, pp.504-505

[132] ATIMTAY, Ergin. Figure 8.28/8.29 Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, pp.504-505

3.4.7 Beams and Frames with Broken Axis

A structural calculation can be successful only if the engineers are able to make a realistic prediction of the forces applied on the system. Most of the time, three-dimensional structures are represented in the form of two-dimensional frames to make an efficient analysis. As Atımtay suggests, if the frames have broken-axis, it is impossible to handle the system with two-dimensional analysis; therefore, the loads cannot be realistically determined. Furthermore, beams with broken axis are less resistant to lateral forces (**Figure 3.24 A**). Assume that the lateral force received by the structure is transferred through the beams from column to column. If the axes of the columns are not parallel, there will be additional torsion forces acting on both columns and beams. Configurations in (**Figure 3.24 B**) should be avoided due to the formation of a short and over-rigid beam.[133]



A **B**

Figure 3.24 Beams and Frames with Broken Axis[134]

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[133] ATIMTAY, Ergin. Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, pp.508-509

[134] ATIMTAY, Ergin. Figure 8.32/8.33 Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, pp.508-509

3.4.8 Over-Stretched One-Way Slabs

As mentioned before, lateral forces are distributed to vertical elements through floor slabs. It is very difficult to calculate the shear stresses acting on the columns if the slab does not have complete in-plane rigidity. Over-stretched one-way slabs can easily make large deflections under lateral loads. Furthermore, there will be frequent contraction cracks due to the difficulty of placing reinforcements in the long direction. Another disadvantage is breaking the continuity of beams. In architectural design projects over-stretched one-way slabs are often used to create corridors in the R/C residential apartment blocks. The aim is to break the continuity of the structural axes – the rhythm of which is configured according to the dimensions of rooms – so that they do not create a visual obstacle in the ceiling of the corridor. This visual problem can be avoided without creating a structural deficiency by adding suspended ceilings.[135] (**Figure 3.25**)

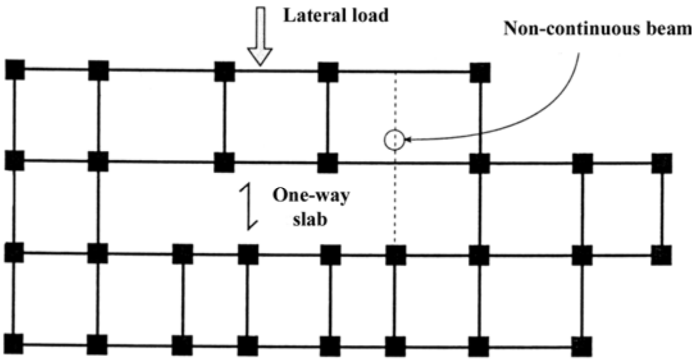

Figure 3.25 Over-Stretched One-way Slab[136]

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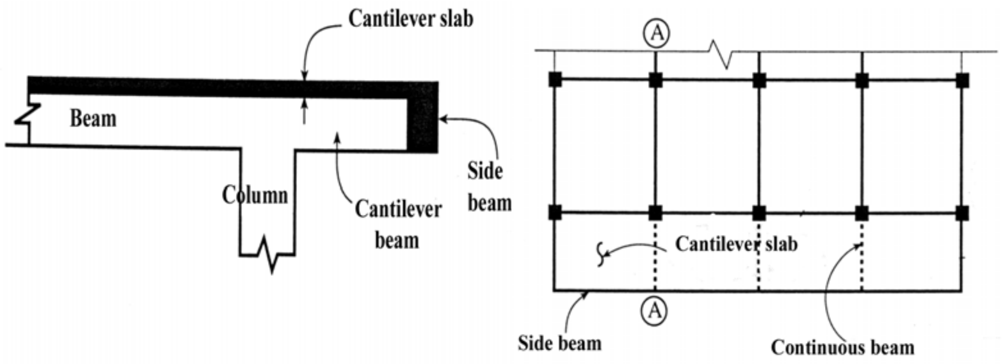
[135] ATIMTAY, Ergin. Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, p.503

[136] ATIMTAY, Ergin. Figure 8.27 Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, p.503

3.4.9 Cantilever Slabs

Open and closed cantilever projections are commonly used to enlarge the rooms and create space for balconies in residential buildings in Turkey. It should be remembered that a long cantilever slab will make a large deflection even when it is not under lateral loads. Under earthquake motion, especially closed projections will make critical displacements, which may lead to a partial collapse. If cantilever projections are to be made, the beams should be continuous under the cantilever slab. A side beam should be designed around the periphery of the projection. (**Figure 3.26 A**.) This way the overall rigidity will be increased and all the separate frames will act uniformly under earthquake loads. Additionally, The columns adjacent to the cantilever should also be connected to each other with a beam. This way the lateral loads will be directly distributed to all the columns without being transferred to relatively less rigid floor slabs.[137] (**Figure 3.26 B.**)



A. **B.**

Figure 3.26 Cantilever Slabs[138]

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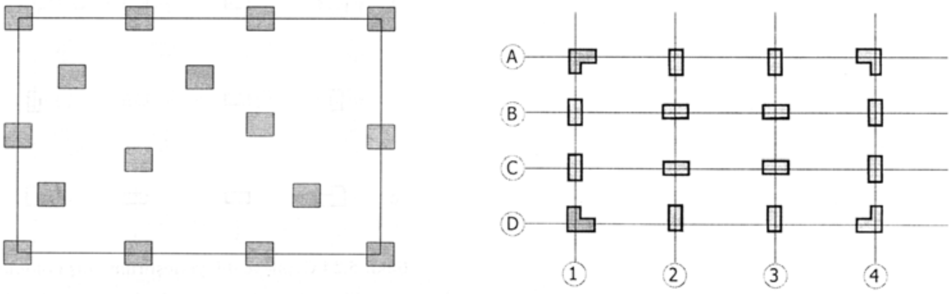
[137] ATIMTAY, Ergin. Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, pp.517-518

[138] ATIMTAY, Ergin. Figure 8.41 Çerçeveli ve Perdeli Betonarme Sistemlerin Tasarımı, 2 vols. Ankara, METU Press, July 2001, Vol. 2, p.517

3.4.10 Column Configuration

Two extreme cases are represented below to explain the advantages of a regular column configuration. It will be very difficult to establish continuous frames in the irregular plan (**Figure 3.27 A.**). The beams will have broken-axis, therefore, the lateral forces will create critical torsion moments on the system. The lateral rigidity of the building will differ throughout the plan thus, uneven displacements will occur. To make such a system resistant to earthquakes, very large and expensive element cross-sections will be needed. On the regular plan (**Figure 3.27 B.**), the columns are organized according to an axial system and distributed evenly for every earthquake direction. The building has high lateral rigidity; therefore, the displacements are limited. Stresses on the elements will be considerably reduced. However, to establish such a rigid and regular structural system may bring difficulties to the flexibility of architectural design. In reality, structural system configuration must be designed somewhere in-between the two examples but must be closer to the regular configuration.



A. **B.**

Figure 3.27 Irregular vs. Regular Configuration of Columns[139]

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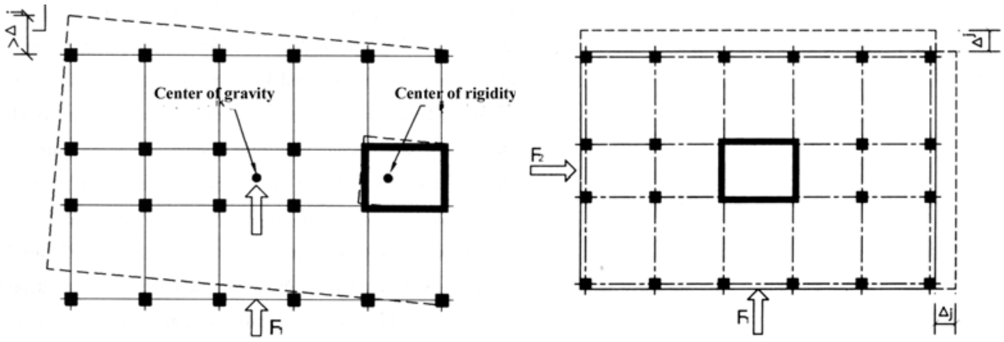
[139] TUNA, Mehmet Emin, Figure 5.22/5.26 Depreme Dayanıklı Yapı Tasarımı. Ankara, Tuna Eğitim ve Kültür Vakfı Pub. November 2000, pp.133-135

3.4.11 Location of Shear-Walls

Shear-walls are the most effective method of making earthquake resistant buildings. They increase the lateral rigidity of the structure and reduce excessive displacements. The location of the shear-walls should be chosen carefully keeping in mind that the centers of gravity and rigidity are supposed to be as near as possible. If the shear-walls are concentrated on one side of the building (**Figure 3.28 A.**), there will be excessive torsion eccentricities and uneven displacements on the structure. Shear-walls should be located symmetrically and near the center of the building. The integration of shear-walls to an architectural project brings along certain difficulties. Because shear walls have to be continuous from the top floor to the foundations they decrease the flexibility of spatial use and make the arrangement of spaces located at mezzanine or basement floors such as shops or parking spaces very difficult. Past earthquakes have demonstrated that shear-walls are life-saving elements during earthquakes. Therefore, architects should be trained to incorporate these structural elements in their designs. (**Figure 3.28 B.**).



A. **B.**

Figure 3.28 Location of Shear-walls[140]

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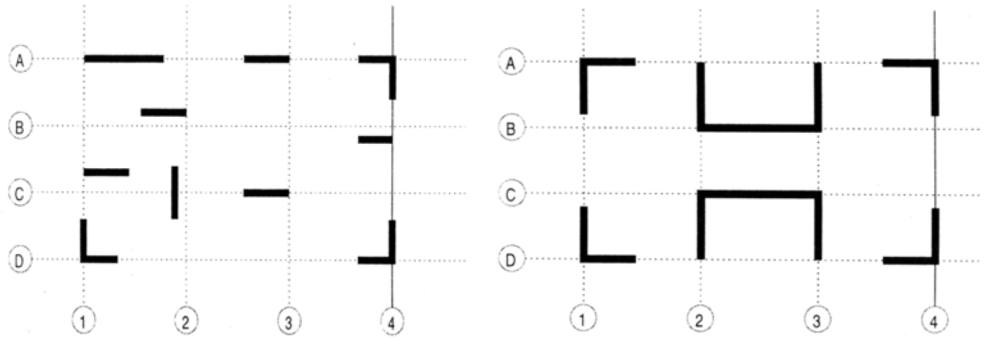
[140] GÖNENÇEN, Kaya. Figure 2/Figure 3A Mimari Proje Tasarımında Depreme Karşı Yapı Davranışının Düzenlenmesi, Ankara, Teknik Yayınevi Pub. 2000, pp.10-12.

3.4.12 Configuration of Shear-Walls

A shear-wall is a vertical load-bearing element whose longer side to shorter side ratio is greater than seven. According to the Turkish Earthquake Code the width of a shear-wall can be 20 cm minimum. Similar to the configuration of columns, it is better if the shear-walls are organized according to an axial system. A symmetrical configuration is the most preferable one. Shear-walls should be distributed evenly for every earthquake direction. It must be remembered that the critical lateral force direction is parallel to the shorter side of the building. Shear-walls should be perpendicular to the building façades in this direction. For architectural purposes, shear-walls can be hidden around staircase and elevator shafts or placed on the façades of the building. (**Figure 3.29**)



A. **B.**

Figure 3.29 Irregular vs. Regular Configuration of Shear-Walls[141]

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[141] TUNA, Mehmet Emin, Figure 5.33/5.34 Depreme Dayanıklı Yapı Tasarımı. Ankara, Tuna Eğitim ve Kültür Vakfı Pub. November 2000, pp.139-140

CHAPTER 4

A STRUCTURAL EVALUATION OF EARTHQUAKE RESISTANT DESIGN PRINCIPLES APPLIED IN REINFORCED CONCRETE RESIDENTIAL APARTMENT BUILDINGS

4.1 Procedure for An Analytical Evaluation of the Structural Principles of Earthquake Resistant Design in Reinforced Concrete Residential Buildings

It has been previously mentioned in Section 2.2.2 that the architectural design of reinforced concrete (R/C) residential blocks was simultaneously determined by the living format of the Turkish urban middle-class and the urban fabric of Turkish cities which are both not very flexible in terms of spatial use. As a result, the architectural design problem at hand is reduced to creating the most suitable planimetric[142] configuration from both spatial and structural points of view. The theoretical framework for the earthquake resistant design of R/C buildings was established in Chapter 3. However, since the aim of this thesis is to render these principles understandable for architects and students of architecture, it is imperative to demonstrate the effect of previously proposed guidelines in a simple analytical and visual format. The aim of this section is to make a progressive demonstration of the effect of these principles on a typical R/C structure.

The analysis consists of 7 mathematical models. It will begin by a set of 5 idealized models representing a R/C structure similar in size to a typical apartment

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[142] Adjective, *having no indications of three dimensional features*, http://www.merriam-webster.com/dictionary/planimetric, Last Accessed Date: 18 March 2008

block that can be encountered in any Turkish city. (Models A to E) The aim of using idealized models in the first steps of the study is to isolate the structural effect of various criteria such as the direction of columns, the variation of cross-sectional dimensions, the use of shear-walls and omitting columns under beam-to-beam connections. In idealized models, the above mentioned parameters can be altered one at a time and the subsequent effect of the alteration on the structural system can be observed clearly.

The idealized model is based on a 6 storey R/C structure similar in size to an apartment block having 2 residential units on one floor. The plan has 6 bays with 3 m span in one direction and 3 bays of 4 m, 3 m and 4 m spans in the other. These spans are chosen to represent the typical spans of a residential block. Floors consist of R/C slabs of 0,12 m in thickness, except the bay in the center which is left void to represent the effect of the vertical shafts and stairs in the building. Floor heights are taken as 3 m except for the bottom floors where they are taken as 4 m to represent the typical use of these floors as shops. The building is assumed to be in the First Degree Earthquake Zone according to Turkish Earthquake Code 2007. (**Figure 4.1**)

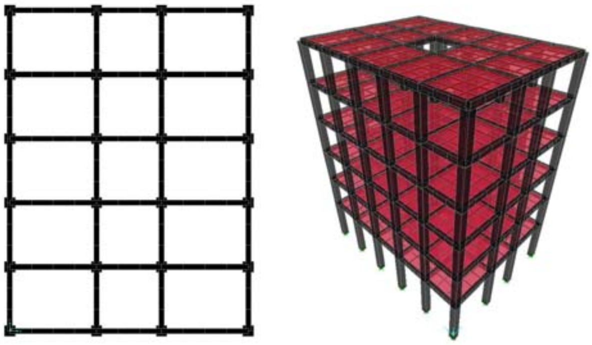

Figure 4.1 Plan and Three-Dimensional Views of a Typical Idealized Model[143]

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[143] Graphichs prepared with SAP2000 Structural Analysis Software

Every model will be observed according to the three comparison criteria defined in Chapter 3. These are: the natural period, maximum displacements and column capacities. In terms of natural period, the periods of the first three critical modes of the buildings will be measured. The first aim is to demonstrate that the proposed improvements reduce the natural period thus taking them out of the undesired interval (T > 0,7 sec.) where *equal displacement principle* is valid and putting them into the safer zone (T < 0,5 sec.) where *equal energy consumption principle* is applied. (See **Section 3.3.1**) The second aim is to check whether the critical first or second modes of the building are dominated by torsion movement, which is very dangerous for R/C structures. (**Figure 4.2**)

Figure 4.2 A Typical Idealized Model in Torsion Mode[144]

The maximum displacements in this type of structural system will occur typically at the top floor of the buildings. Therefore, for each model the displacements of the outermost corner points of the top floor slabs will be measured for each earthquake dimension. This is to see whether the proposed structural alterations

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[144] Graphichs prepared with SAP2000 Structural Analysis Software

are successful in decreasing the amount of maximum displacements and reduce the chance of the formation of critical second order moments which could be potentially fatal for the building. (**Figure 4.3**)

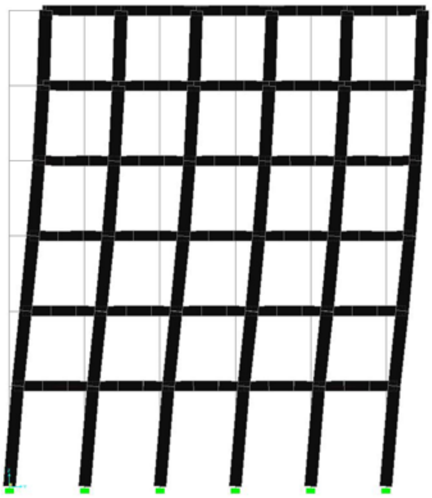

Figure 4.3 Deformed Shape of a Typical Idealized Model under Seismic Loading[145]

In the earthquake resistance of R/C structures the most critical point is the preservation of the system's stability. This is achieved firstly by making the columns stronger than the beams and therefore ensuring the formation of plastic deformations at the extremities of beams and not the columns; and secondly by designing the columns strong enough to withstand the most undesirable combination of gravitational and seismic loading.

The design and analysis of beams depends greatly on the spatial arrangement of a particular project, therefore this analytical study will not deal with the beams but ensure that their cross-sections are always designed weaker than the columns.

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[145] Graphichs prepared with SAP2000 Structural Analysis Software

In a real structural design problem concrete class and steel ratio for the columns would be determined by the structural engineers according to the requirements of each specific element. However, the aim here is to demonstrate the structural behavior of the models to an architectural audience, rather than making precise calculations. As a result, in order to establish a common basis for comparison between models, the columns of the idealized models are designed using C25 class concrete and having the minimum required steel ratio of 1 % according to TS-500 standard.

As mentioned in Section 3.3.3, the safest way of measuring the capacity of R/C columns is to use the *Column Interaction Diagram*. In this type of structural system the maximum axial force-bending moment combination will typically occur in the bottom floor of the building. Therefore, for each model, 8 selected columns with evenly distributed locations on the plan are analyzed in terms of their axial-force – moment capacity. These columns are selected among the ones with the smallest cross-sections therefore most vulnerable to earthquakes. Although some models contain shear-walls, these are assumed to have enough resistance to any load combination and were not included in the comparative study. (**Figure 4.4**)

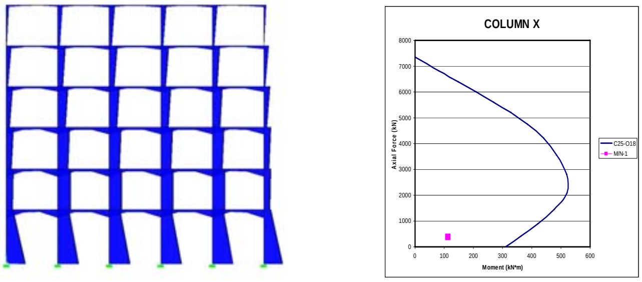

Figure 4.4 Typical Moment Diagram and Column Interaction Diagram for Idealized Models[146]

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[146] Graphichs prepared with SAP2000 Structural Analysis Software and Response 2000 Software

The last 2 models in this analytical study are based on an actual building located in Bolu City Center. (Models F and G) The sample building, which was badly damaged during the 1999 earthquakes, contained several of the design faults and irregularities that were mentioned in Chapter 3. According to the information obtained during the field study in Bolu, the building was demolished by the municipal authority because the damages were beyond repair. Therefore, data about the structure was obtained from existing drawings. The principal characteristics of the structural system were kept the same with only minor alterations.

At first step, the building will be analyzed in its original form to demonstrate the negative structural effect created by the combination of the factors previously mentioned. At the second step, the structural system of the building will be redesigned with improvements, the effectiveness of which are demonstrated in idealized models, and re-analyzed in its new configuration. The re-designed structural system will be considerably improved in terms of natural period, lateral displacements and will be in a much safer zone under seismic loads in terms of column capacities. (**Figure 4.5**)

A. **B.**

Figure 4.5 A. (Original Structural System of the Damaged Building Model F) **B.** (Re-designed Structural System Model G)

4.2 Idealized Parametric Model A: All Columns Are Arranged in the Same Direction

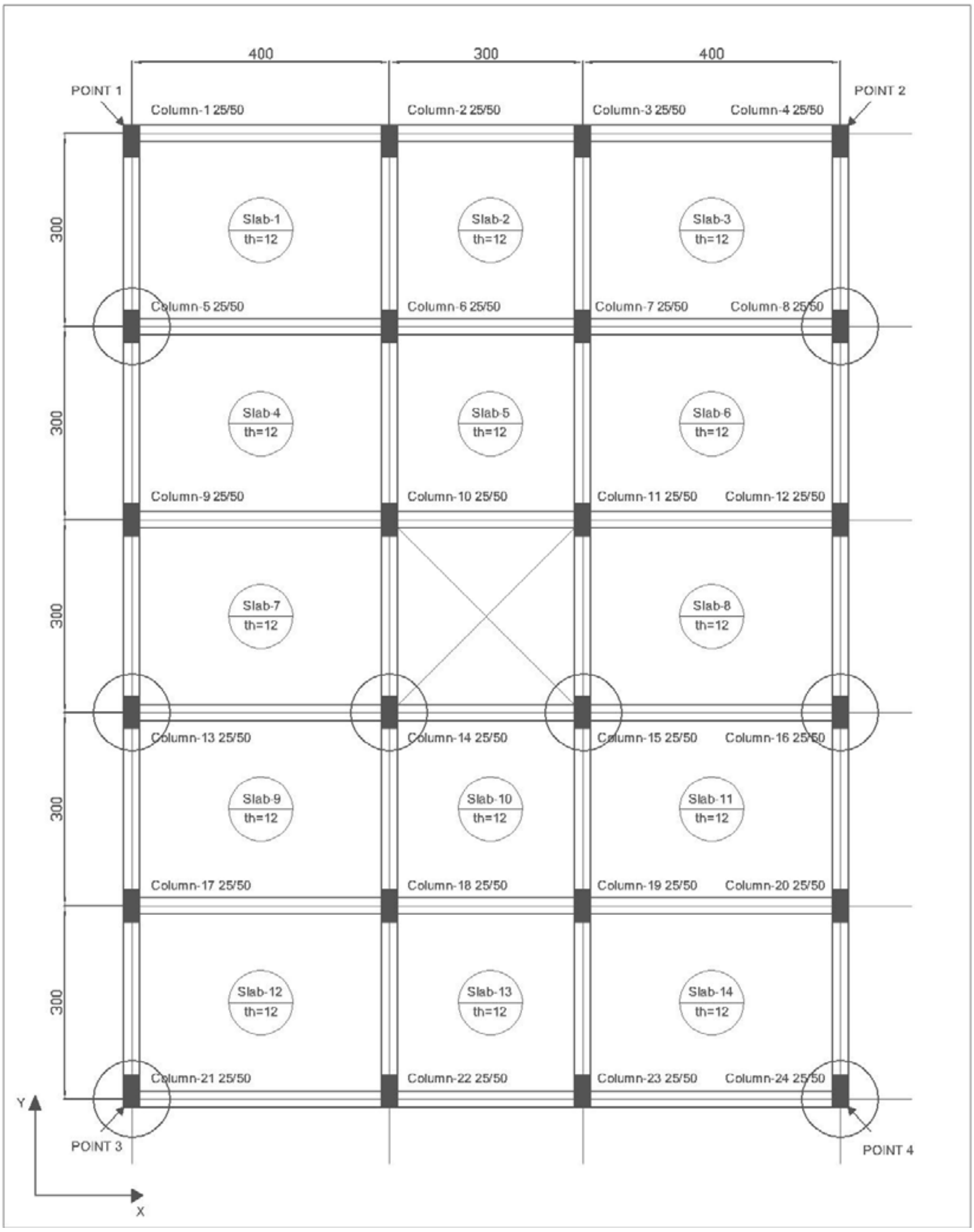


Figure 4.6 Structural Plan of Idealized Parametric Model-A

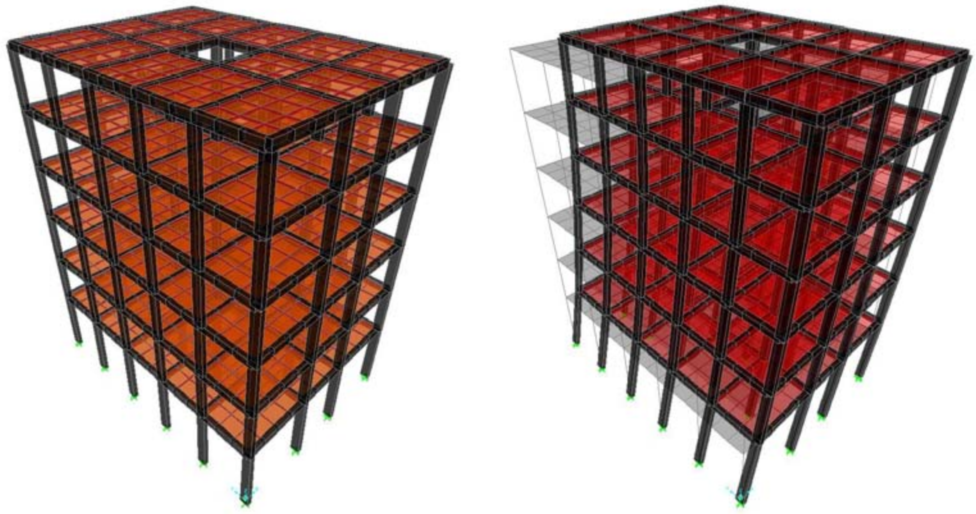
In Model-A, because of the arrangement of columns, the natural period for the critical first mode is obtained well inside the undesired interval. (T > 0,7 sec.) (**Table 4.1**) The second mode of the structure is dominated by torsion which could be potentially dangerous. (**Figure 4.7** and **Figure 4.8**) Considerably large displacements are measured in the top floor corner points in both earthquake directions but especially in the x-direction where the direction of the columns creates a seismically undesirable configuration. (**Table 4.2**)

Table 4.1 Modal Characteristics of Model A

Mode Number	Dominant Movement	Period (sec)
Mode 1	Lateral Displacement (x-dir)	0,84
Mode 2	Torsion	0,57
Mode 3	Lateral Displacement (y-dir)	0,54

Table 4.2 Displacements of Top Floor Outermost Corner Points of Model-A

Point Number	Earthquake Direction	Displacement in x-direction (m)	Displacement in y-direction (m)	Displacement in z-direction (m)
1	**EQ -X**	0,096	0,000009	0,00085
	EQ-Y	0,000008	0,058	0,0013
2	**EQ -X**	0,096	0,000009	0,00085
	EQ-Y	0,000008	0,058	0,0013
3	**EQ -X**	0,096	0,000009	0,00085
	EQ-Y	0,000008	0,058	0,0013
4	**EQ -X**	0,096	0,000009	0,00085
	EQ-Y	0,000008	0,058	0,0013



A. B.

Figure 4.7 A. (Un-deformed Shape of Model-A) **B.** (Deformed Shape Mode 1)

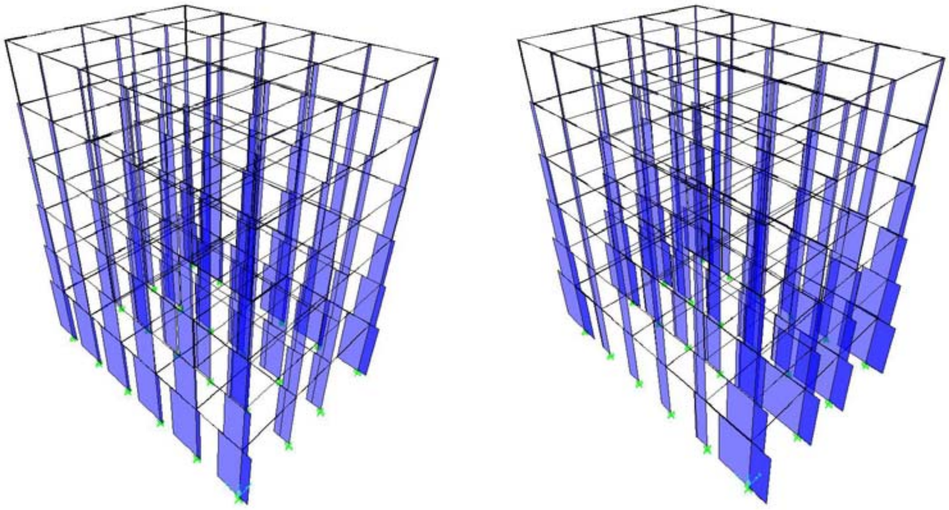
A. B.

Figure 4.8 A. (Deformed Shape Mode 2) **B.** (Deformed Shape Mode 3)

The analysis of Model-A has revealed that the maximum moments and axial forces occur in bottom floor columns for both earthquake directions. (**Table 4.3**, **Figure 4.9** and **Figure 4.10**) The interaction diagrams of the selected columns reveal that columns 5, 8, 13, 14, 15, 16 are far in the failure zone in both earthquake directions. Columns 21, 24 are in the failure zone in x-direction but stay narrowly in safety zone in y-direction. (**Figure 4.11** and **Figure 4.12**) These results demonstrate that this structure would fail under the applied earthquake motion.

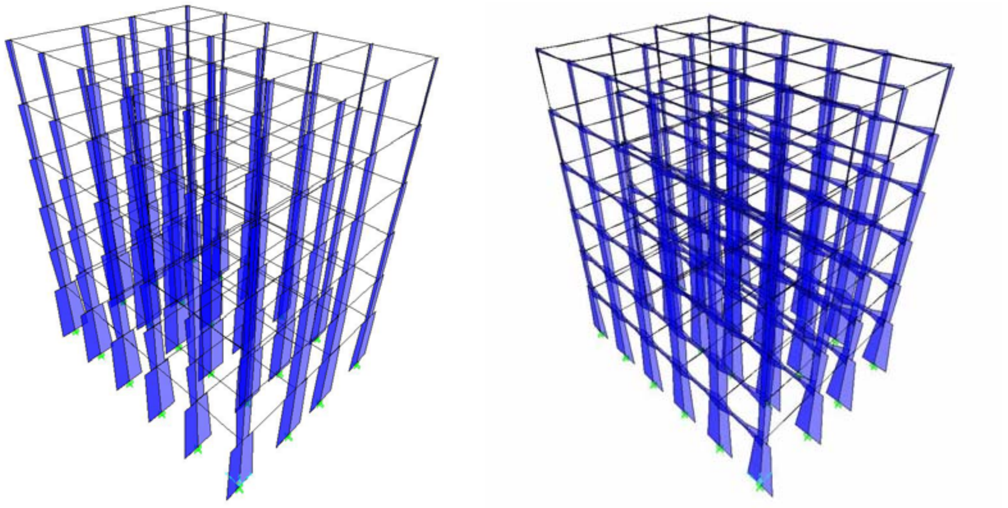
Table 4.3 Axial Force – Moment Combinations in Selected Columns

Column Number	**Load Combination**	**Axial Force (kN)**	**Moment (kN.m)**
5	DL+LL+EQX	629	194
	DL+LL+EQY	281	322
8	DL+LL+EQX	629	188
	DL+LL+EQY	281	322
13	DL+LL+EQX	645	195
	DL+LL+EQY	284	321
14	DL+LL+EQX	452	209
	DL+LL+EQY	446	324
15	DL+LL+EQX	452	213
	DL+LL+EQY	446	324
16	DL+LL+EQX	644	188
	DL+LL+EQY	284	321
21	DL+LL+EQX	498	190
	DL+LL+EQY	701	287
24	DL+LL+EQX	498	187
	DL+LL+EQY	701	287



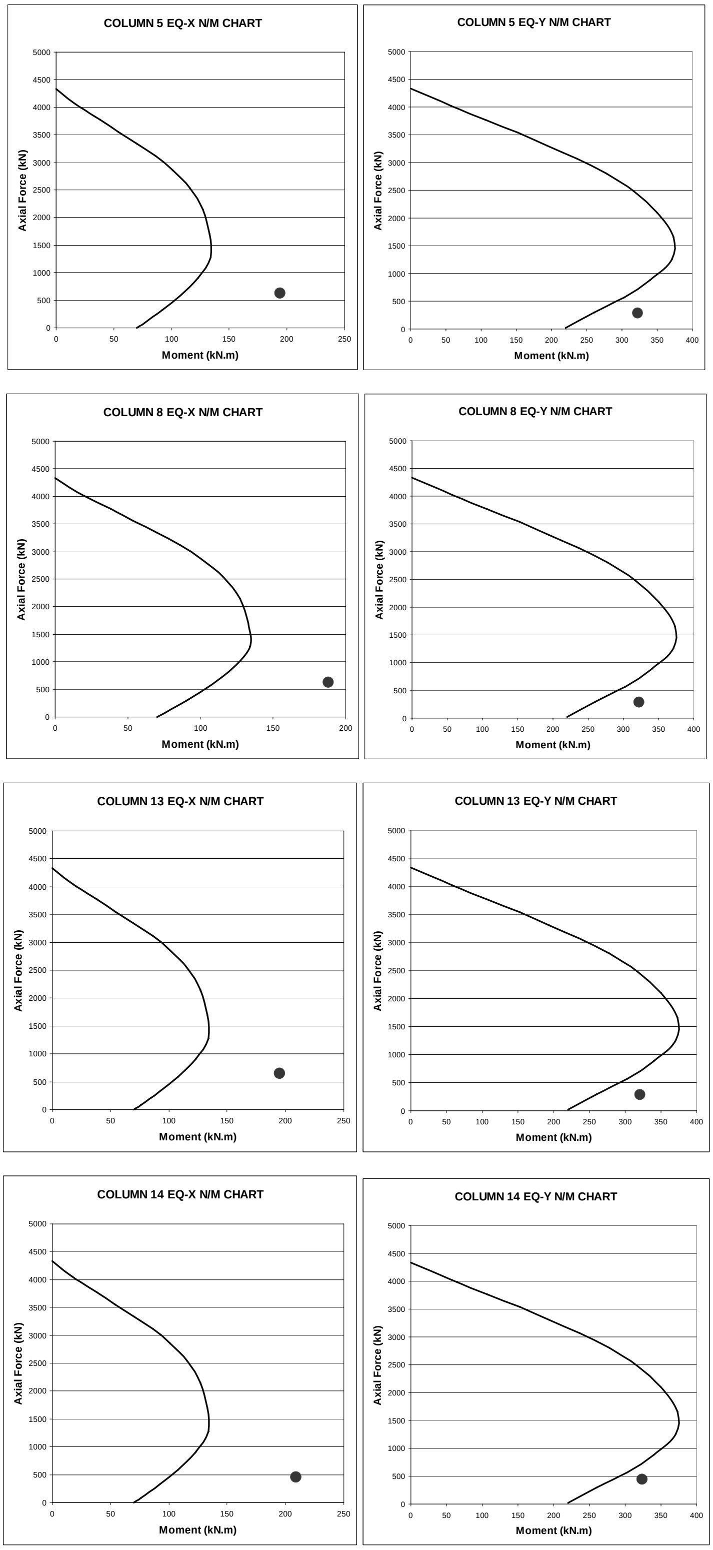
A. **B.**

Figure 4.9 A. (Axial Force Diagram in EQX) **B.** (Axial Force Diagram in EQY)



A. **B.**

Figure 4.10 A. (Moment Diagram in EQX) **B.** (Moment Diagram in EQY)


COLUMN 5 EQ-X N/M CHART

COLUMN 5 EQ-Y N/M CHART

COLUMN 8 EQ-X N/M CHART

COLUMN 8 EQ-Y N/M CHART

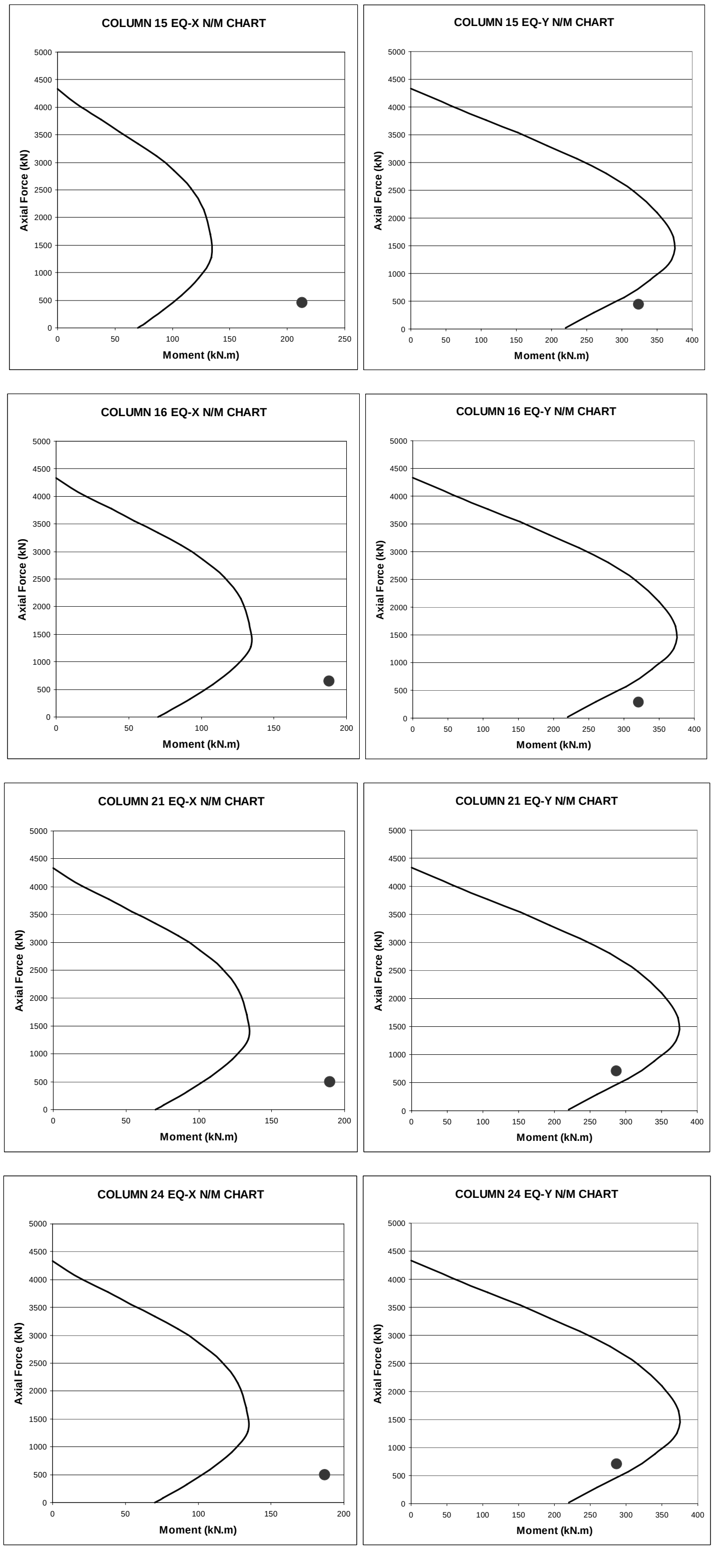
COLUMN 13 EQ-X N/M CHART

COLUMN 13 EQ-Y N/M CHART

COLUMN 14 EQ-X N/M CHART

COLUMN 14 EQ-Y N/M CHART

Figure 4.11 Column Interaction Diagrams of Model-A (Part 1)


COLUMN 15 EQ-X N/M CHART

COLUMN 15 EQ-Y N/M CHART

COLUMN 16 EQ-X N/M CHART

COLUMN 16 EQ-Y N/M CHART

COLUMN 21 EQ-X N/M CHART

COLUMN 21 EQ-Y N/M CHART

COLUMN 24 EQ-X N/M CHART

COLUMN 24 EQ-Y N/M CHART

Figure 4.12 Column Interaction Diagrams of Model-A (Part 2)

4.3 Idealized Parametric Model B: Columns are Distributed Equally in Both Earthquake Directions

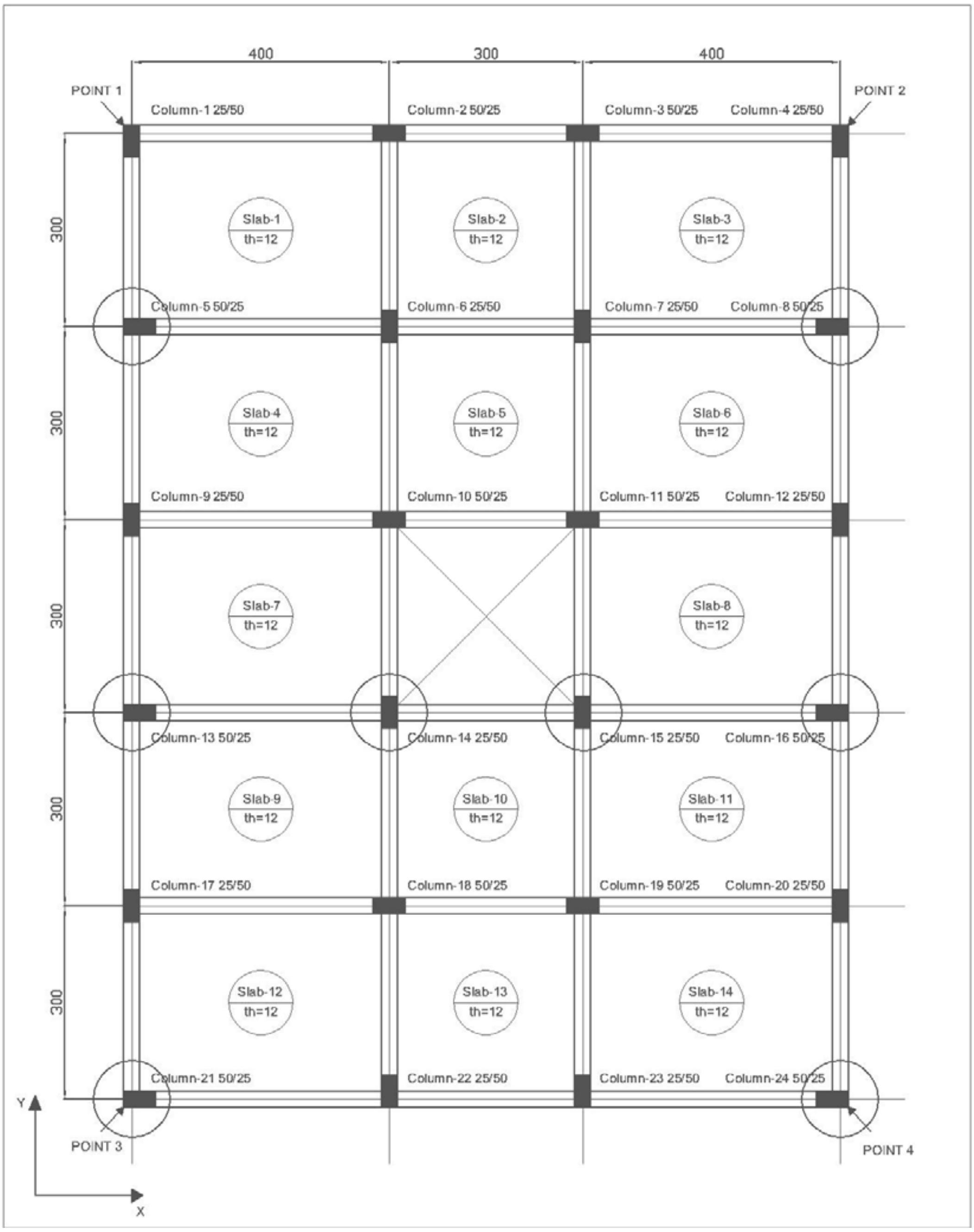


Figure 4.13 Structural Plan of Idealized Parametric Model-B

In Model-B, because columns are distributed evenly in both directions, the natural period for the first mode is reduced with respect to Model-A, but obtained near the undesired interval. (T > 0,7 sec.) (**Table 4.4**) The equal distribution of columns prevents torsion in critical modes. (**Figure 4.14** and **Figure 4.15**) Large displacements are measured in both earthquake directions. The displacements in x-dir. are reduced due to the increasing stiffness in x-dir., the displacements in y-dir. are increased due to the decreasing stiffness in y-dir. (**Table 4.5**)

Table 4.4 Modal Characteristics of Model-B

Mode Number	Dominant Movement	Period (sec)
Mode 1	Lateral Displacement (x-dir)	0,68
Mode 2	Lateral Displacement (y-dir)	0,65
Mode 3	Torsion	0,56

Table 4.5 Displacements of Top Floor Outermost Corner Points of Model-B

Point Number	Earthquake Direction	Displacement in x-direction (m)	Displacement in y-direction (m)	Displacement in z-direction (m)
1	**EQ -X**	0,069	0,0056	0,00098
	EQ-Y	0,000005	0,071	0,0012
2	**EQ -X**	0,069	0,0056	0,00098
	EQ-Y	0,000005	0,071	0,0012
3	**EQ -X**	0,081	0,0056	0,00098
	EQ-Y	0,000008	0,071	0,0012
4	**EQ -X**	0,081	0,0056	0,00098
	EQ-Y	0,000008	0,071	0,0012

A. B.

Figure 4.14 A. (Un-deformed Shape of Model-B) **B.** (Deformed Shape Mode 1)

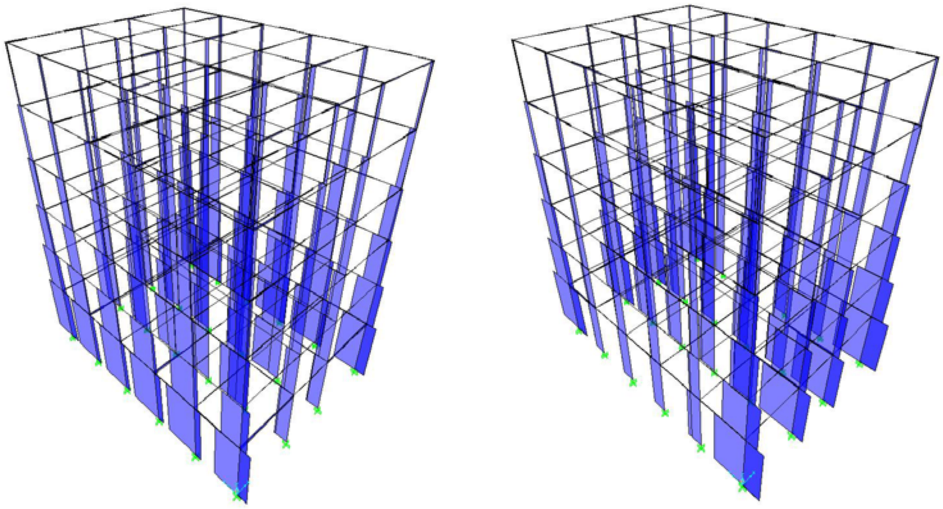
A. B.

Figure 4.15 A. (Deformed Shape Mode 2) **B.** (Deformed Shape Mode 3)

The analysis of Model-B has revealed that the maximum moments and axial forces occur in bottom floor columns for both earthquake directions. (**Table 4.6**, **Figure 4.16** and **Figure 4.17**) The interaction diagrams of the selected columns reveal that all columns are in the failure zone in both earthquake directions. Compared to Model-A, the N/M couples are nearer to the safety zone in x-dir but farther from it in y-dir. This is due to increased stiffness in x-dir and reduced stiffness in y-dir. (**Figure 4.18** and **Figure 4.19**) These results demonstrate that this structure would fail under the applied earthquake motion.

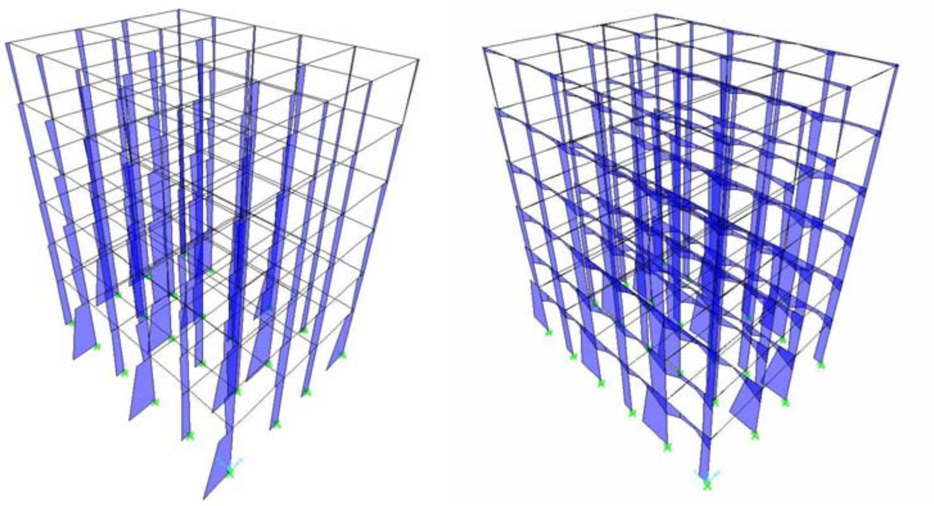
Table 4.6 Axial Force – Moment Combinations in Selected Columns

Column Number	Load Combination	Axial Force (kN)	Moment (kN.m)
5	DL+LL+EQX	677	367
	DL+LL+EQY	288	133
8	DL+LL+EQX	677	357
	DL+LL+EQY	288	133
13	DL+LL+EQX	721	386
	DL+LL+EQY	298	133
14	DL+LL+EQX	428	129
	DL+LL+EQY	433	416
15	DL+LL+EQX	428	132
	DL+LL+EQY	433	416
16	DL+LL+EQX	721	376
	DL+LL+EQY	298	133
21	DL+LL+EQX	519	396
	DL+LL+EQY	671	119
24	DL+LL+EQX	519	390
	DL+LL+EQY	671	119



A. **B.**

Figure 4.16 A. (Axial Force Diagram in EQX) **B.** (Axial Force Diagram in EQY)



A. **B.**

Figure 4.17 A. (Moment Diagram in EQX) **B.** (Moment Diagram in EQY)

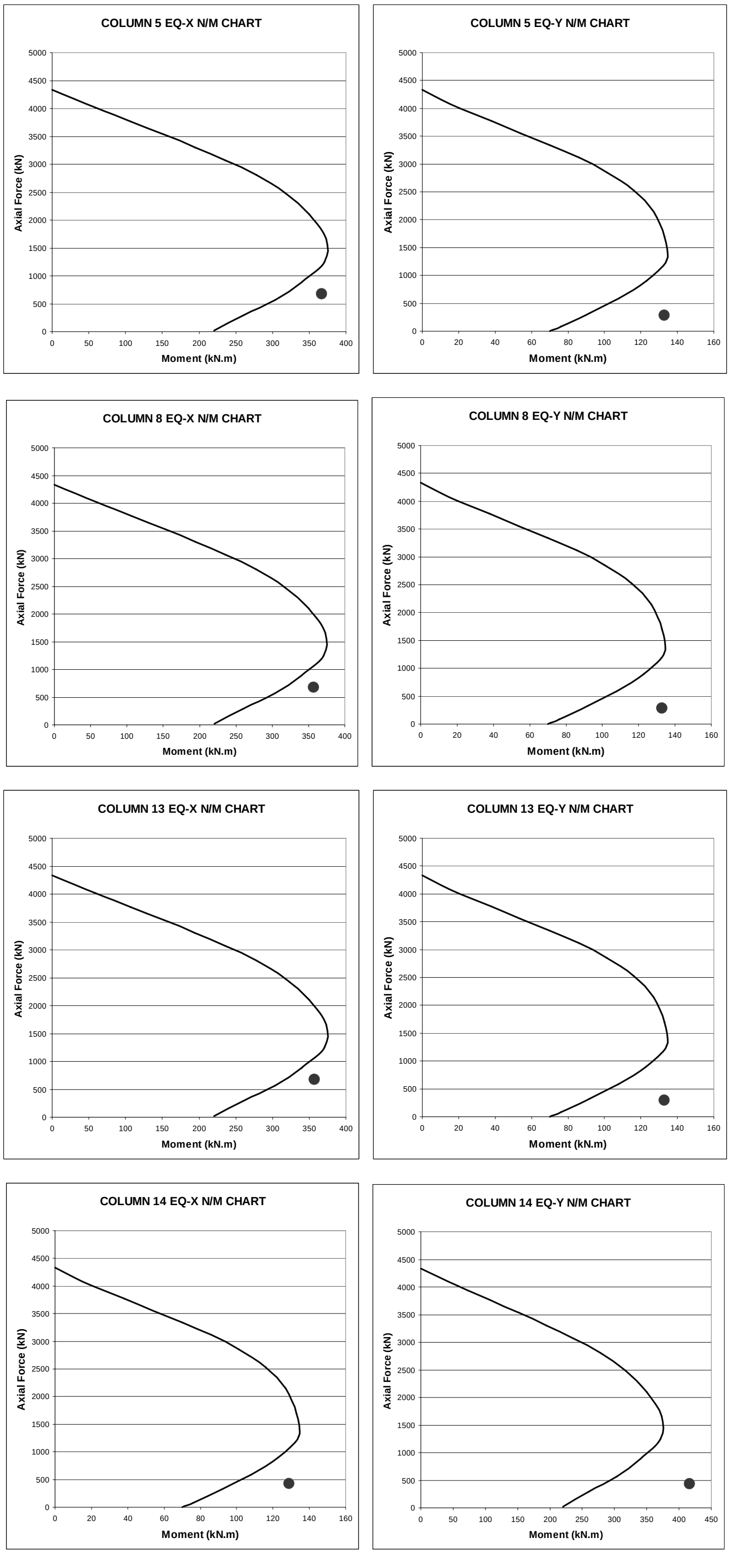


Figure 4.18 Column Interaction Diagrams of Model-B (Part 1)

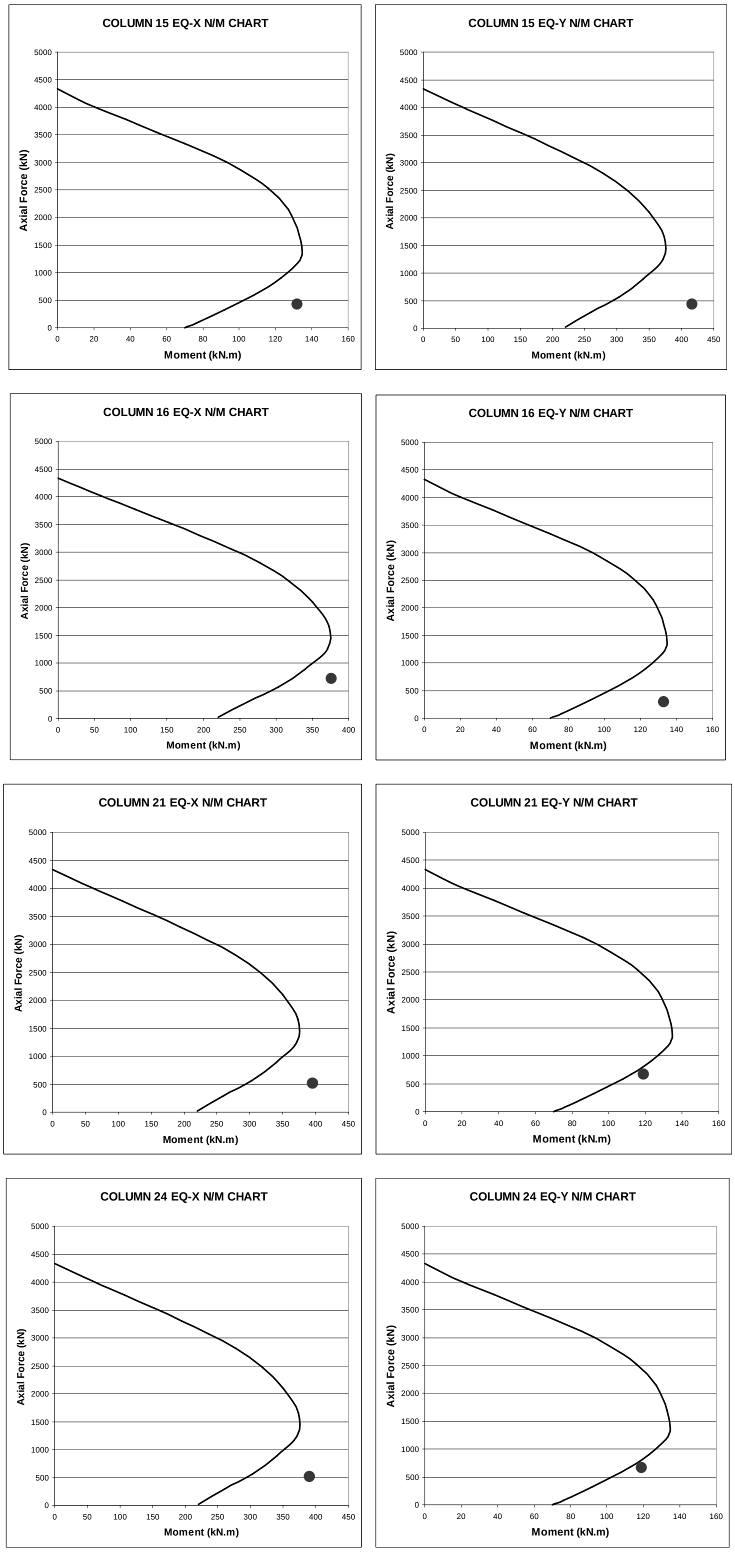


Figure 4.19 Column Interaction Diagrams of Model-B (Part 2)

4.4 Idealized Parametric Model C: The Cross-Sections of Columns are Increased

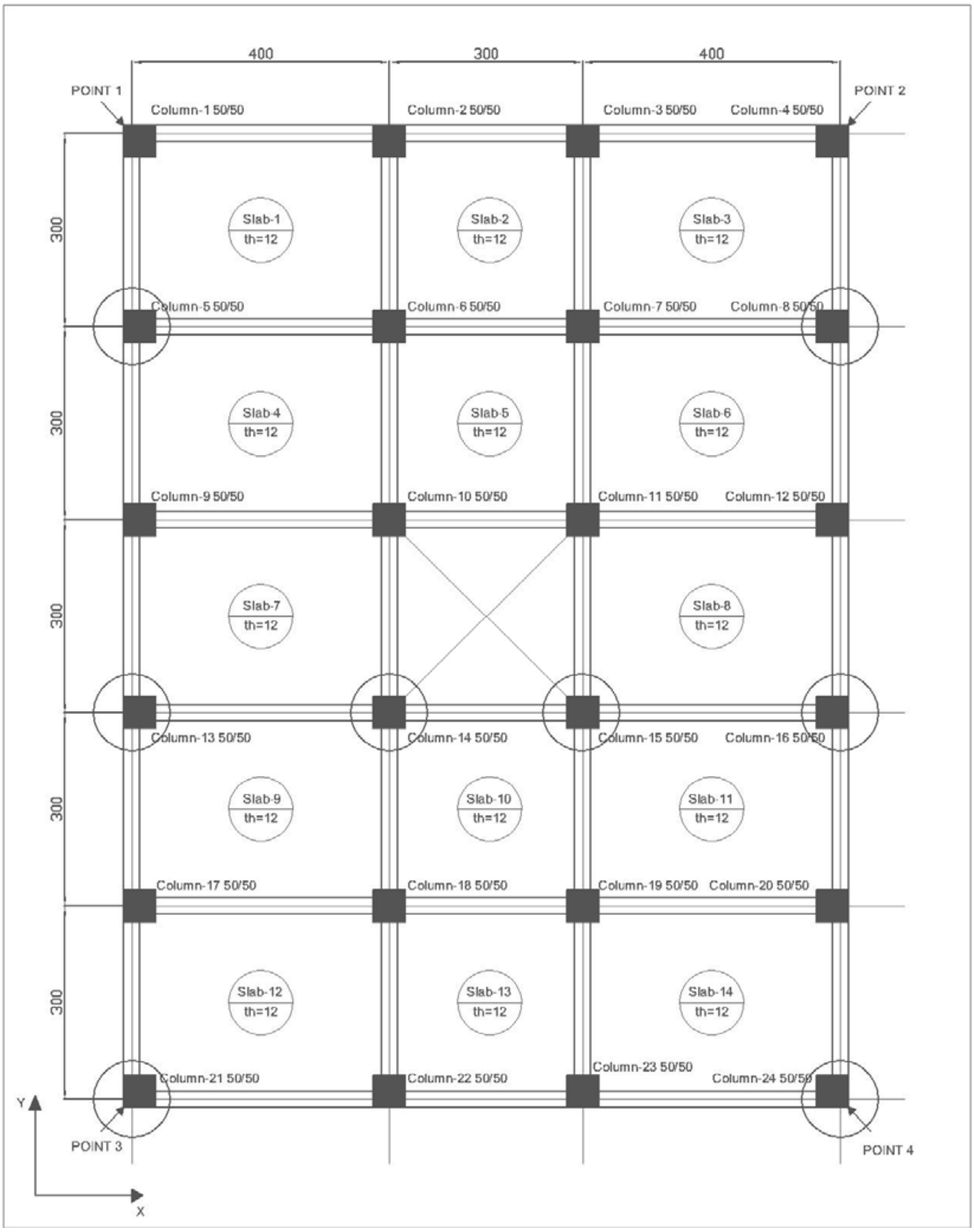


Figure 4.20 Structural Plan of Idealized Parametric Model-C

In Model-C, column cross-sections are increased from 25×50 cm to 50×50 cm. Natural period for the critical first mode is reduced and became very near to the desired interval. (T < 0,5 sec.) (**Table 4.7**) The direction of columns is equally distributed in both directions. This prevents torsion to occur in critical modes. (**Figure 4.21** and **Figure 4.22**) Displacements are reduced in both earthquake directions. The building plan has more column axes in y-direction, the stiffness is higher. The displacements in x-dir. are higher than the ones in y-dir. (**Table 4.8**)

Table 4.7 Modal Characteristics of Model-C

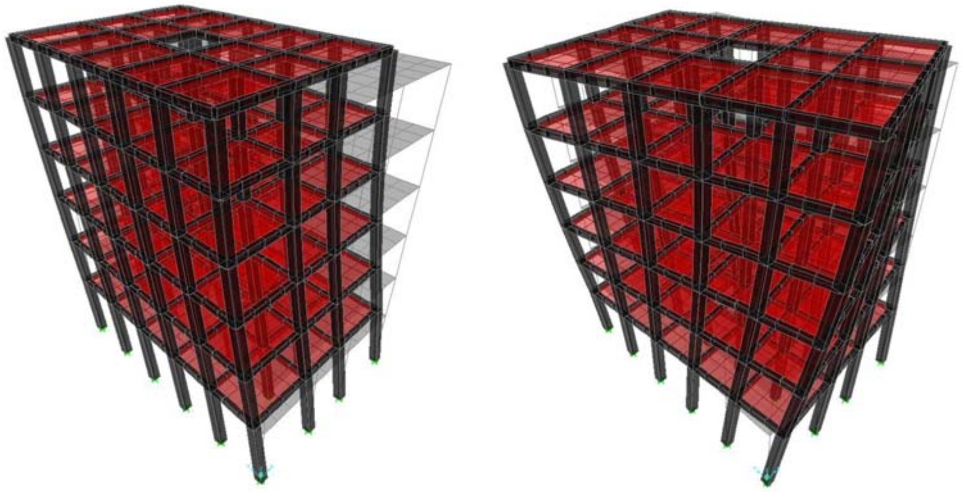
Mode Number	Dominant Movement	Period (sec)
Mode 1	Lateral Displacement (x-dir)	0,51
Mode 2	Lateral Displacement (y-dir)	0,46
Mode 3	Torsion	0,40

Table 4.8 Displacements of Top Floor Outermost Corner Points of Model-C

Point Number	Earthquake Direction	Displacement in x-direction (m)	Displacement in y-direction (m)	Displacement in z-direction (m)
1	**EQ -X**	0,053	0,000011	0,00058
	EQ-Y	0,000008	0,048	0,00077
2	**EQ -X**	0,053	0,000011	0,00058
	EQ-Y	0,000008	0,048	0,00077
3	**EQ -X**	0,053	0,000011	0,00058
	EQ-Y	0,000008	0,048	0,00077
4	**EQ -X**	0,053	0,000011	0,00058
	EQ-Y	0,000008	0,048	0,00077

A. **B.**

Figure 4.21 A. (Un-deformed Shape of Model-C) **B.** (Deformed Shape Mode 1)



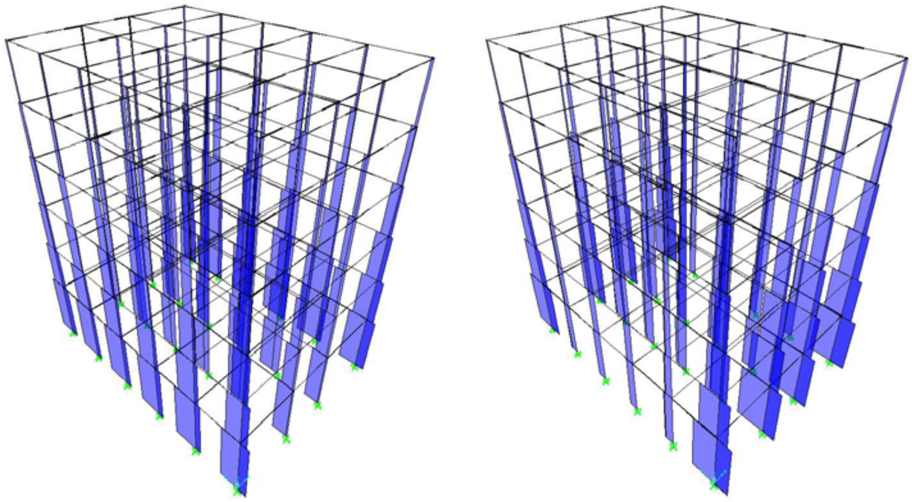
A. **B.**

Figure 4.22 A. (Deformed Shape Mode 2) **B.** (Deformed Shape Mode 3)

The analysis of Model-C has revealed that the maximum moments and axial forces occur in bottom floor columns for both earthquake directions. (**Table 4.9**, **Figure 4.23** and **Figure 4.24**) The interaction diagrams of the selected columns reveal that all columns 14 and 15 are in the failure zone in both earthquake directions. Columns 5,8,13,16 are narrowly in the safety zone in x-dir. but in failure zone in y-dir. Columns 21 and 24 are narrowly in safety zone in both directions. Compared to Model-C, the N/M couples are near or within the safety zone in both directions. (**Figure 4.25** and **Figure 4.26**) These results demonstrate that this structure would fail under the applied earthquake motion.

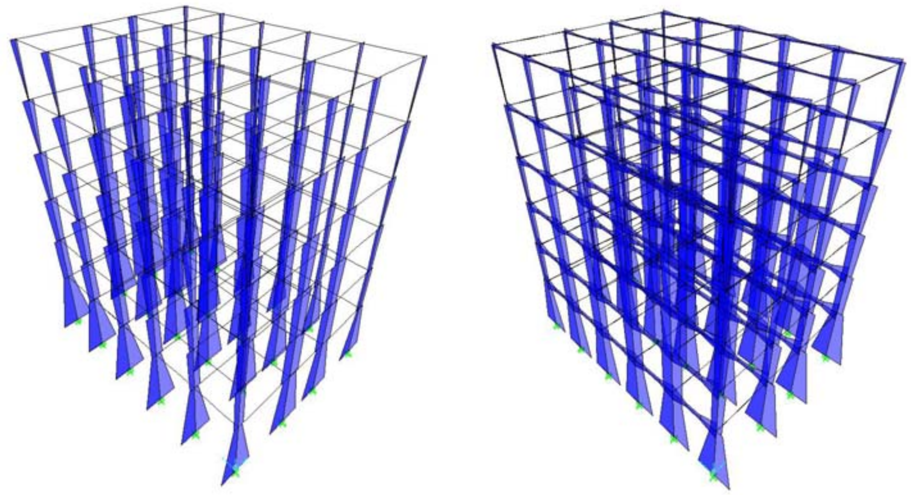
Table 4.9 Axial Force – Moment Combinations in Selected Columns

Column Number	**Load Combination**	**Axial Force (kN)**	**Moment (kN.m)**
5	DL+LL+EQX	749	367
	DL+LL+EQY	291	401
8	DL+LL+EQX	749	357
	DL+LL+EQY	291	401
13	DL+LL+EQX	760	368
	DL+LL+EQY	292	400
14	DL+LL+EQX	584	398
	DL+LL+EQY	445	405
15	DL+LL+EQX	584	405
	DL+LL+EQY	445	405
16	DL+LL+EQX	760	358
	DL+LL+EQY	292	400
21	DL+LL+EQX	583	361
	DL+LL+EQY	752	362
24	DL+LL+EQX	583	355
	DL+LL+EQY	752	362



A. **B.**

Figure 4.23 A. (Axial Force Diagram in EQX) **B.** (Axial Force Diagram in EQY)



A. **B.**

Figure 4.24 A. (Moment Diagram in EQX) **B.** (Moment Diagram in EQY)

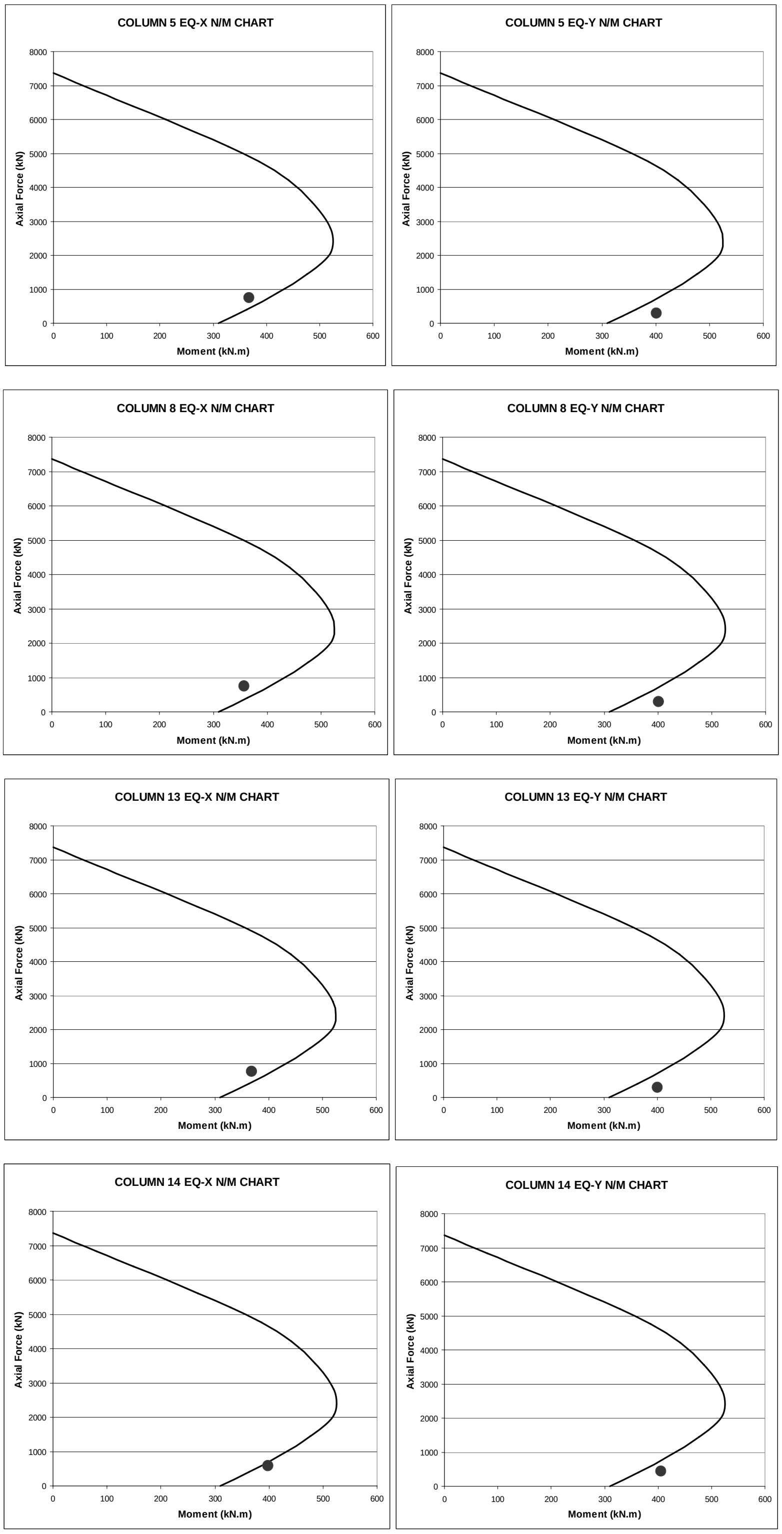


Figure 4.25 Column Interaction Diagrams of Model-C (Part 1)

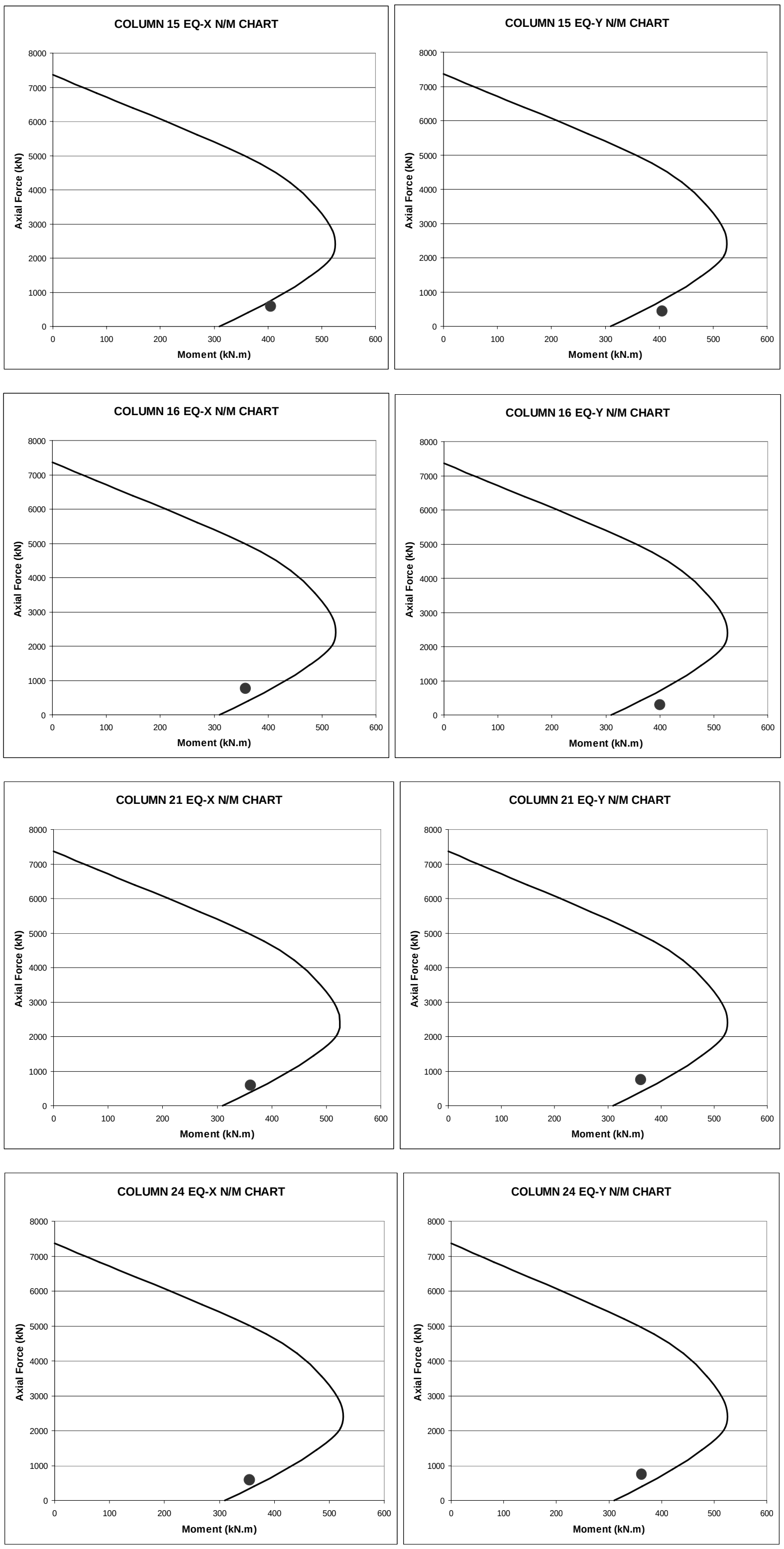


Figure 4.26 Column Interaction Diagrams of Model-C (Part 2)

4.5 Idealized Parametric Model D: The Cross-Sections of Columns are Increased and Shear-Walls are Added

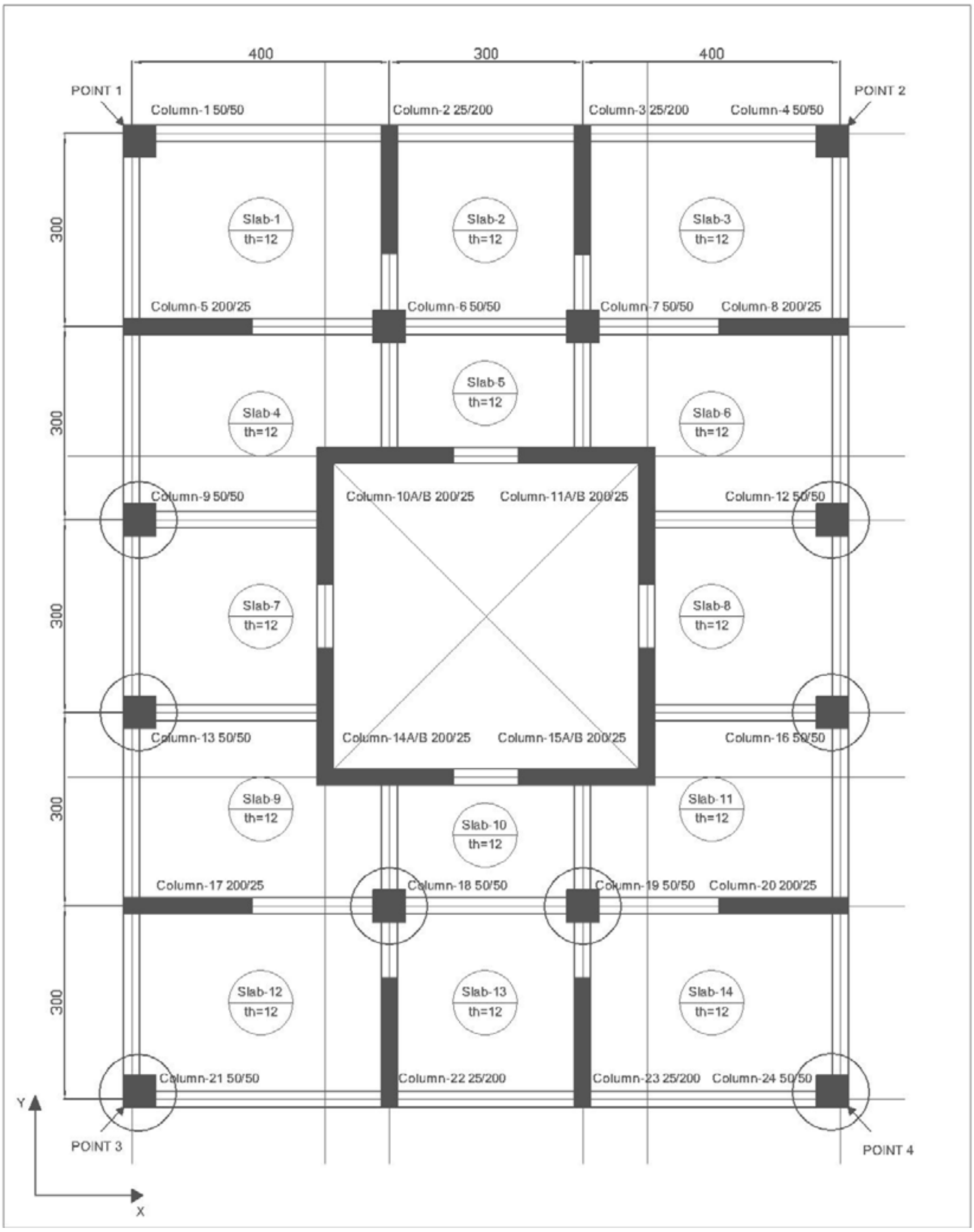


Figure 4.27 Structural Plan of Idealized Parametric Model-D

In Model-D, shear-walls are introduced to the structural system. Natural period for the critical first mode is well within the desired interval. (T < 0,5 sec.) (**Table 4.10**) Columns and shear-walls are distributed equally in both directions. This prevents torsion to occur in critical modes. (**Figure 4.28** and **Figure 4.29**) Displacements are further reduced in both earthquake directions. Because the building plan has almost equal rigidity in both directions, the displacements in x-dir. are nearly equal to the ones in y-dir. (**Table 4.11**)

Table 4.10 Modal Characteristics of Model-D

Mode Number	Dominant Movement	Period (sec)
Mode 1	Lateral Displacement (x-dir)	0,40
Mode 2	Lateral Displacement (y-dir)	0,38
Mode 3	Torsion	0,36

Table 4.11 Displacements of Top Floor Outermost Corner Points of Model-D

Point Number	Earthquake Direction	Displacement in x-direction (m)	Displacement in y-direction (m)	Displacement in z-direction (m)
1	**EQ -X**	0,041	0,000016	0,00047
	EQ-Y	0,0000016	0,038	0,00043
2	**EQ -X**	0,041	0,000016	0,00047
	EQ-Y	0,0000016	0,038	0,00043
3	**EQ -X**	0,041	0,000016	0,00047
	EQ-Y	0,0000016	0,038	0,00043
4	**EQ -X**	0,041	0,000016	0,00047
	EQ-Y	0,0000016	0,038	0,00043

A. **B.**

Figure 4.28 A. (Un-deformed Shape of Model-D) **B.** (Deformed Shape Mode 1)

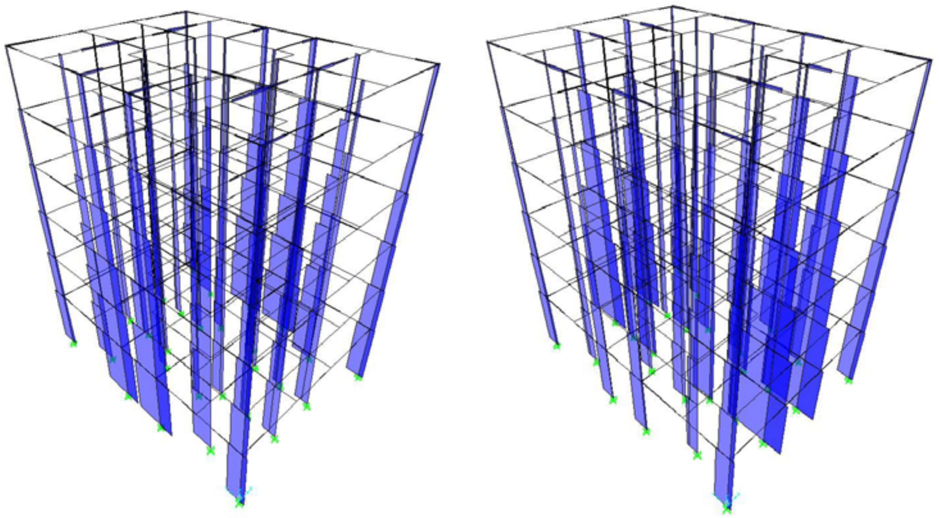
A. **B.**

Figure 4.29 A. (Deformed Shape Mode 2) **B.** (Deformed Shape Mode 3)

The analysis of Model-D has revealed that the maximum moments and axial forces occur in bottom floor columns for both earthquake directions. (**Table 4.12**, **Figure 4.30** and **Figure 4.31**) The interaction diagrams of the selected columns reveal that all columns are soundly within the safety zone in both earthquake directions. The large portion of the bending moments is carried by the shear-walls placed equally in both directions. (**Figure 4.32** and **Figure 4.33**) These results demonstrate that this structure would carry the loads safely under the applied earthquake motion.

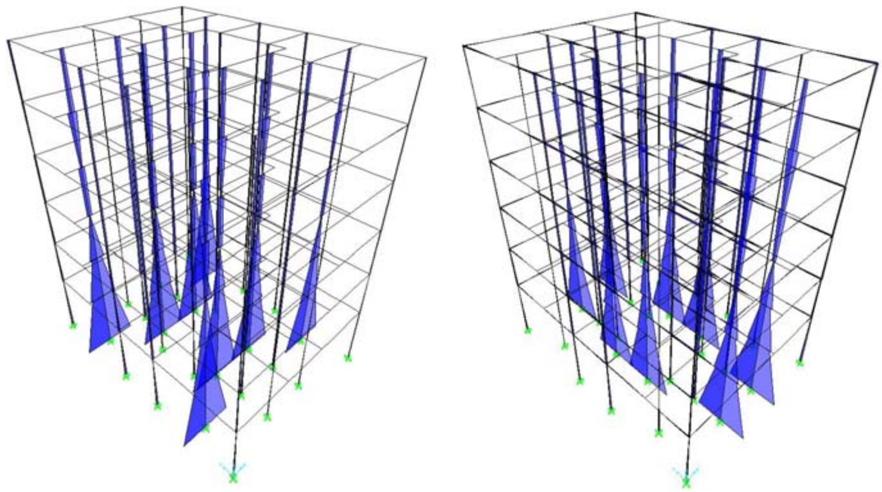
Table 4.12 Axial Force – Moment Combinations in Selected Columns

Column Number	**Load Combination**	**Axial Force (kN)**	**Moment (kN.m)**
9	DL+LL+EQX	908	120
	DL+LL+EQY	467	125
12	DL+LL+EQX	908	115
	DL+LL+EQY	467	125
13	DL+LL+EQX	908	120
	DL+LL+EQY	467	125
16	DL+LL+EQX	908	115
	DL+LL+EQY	467	125
18	DL+LL+EQX	282	133
	DL+LL+EQY	285	141
19	DL+LL+EQX	282	134
	DL+LL+EQY	285	141
21	DL+LL+EQX	447	111
	DL+LL+EQY	422	108
24	DL+LL+EQX	447	106
	DL+LL+EQY	422	108



A. **B.**

Figure 4.30 A. (Axial Force Diagram in EQX) **B.** (Axial Force Diagram in EQY)



A. **B.**

Figure 4.31 A. (Moment Diagram in EQ-X) **B.** (Moment Diagram in EQ-Y)

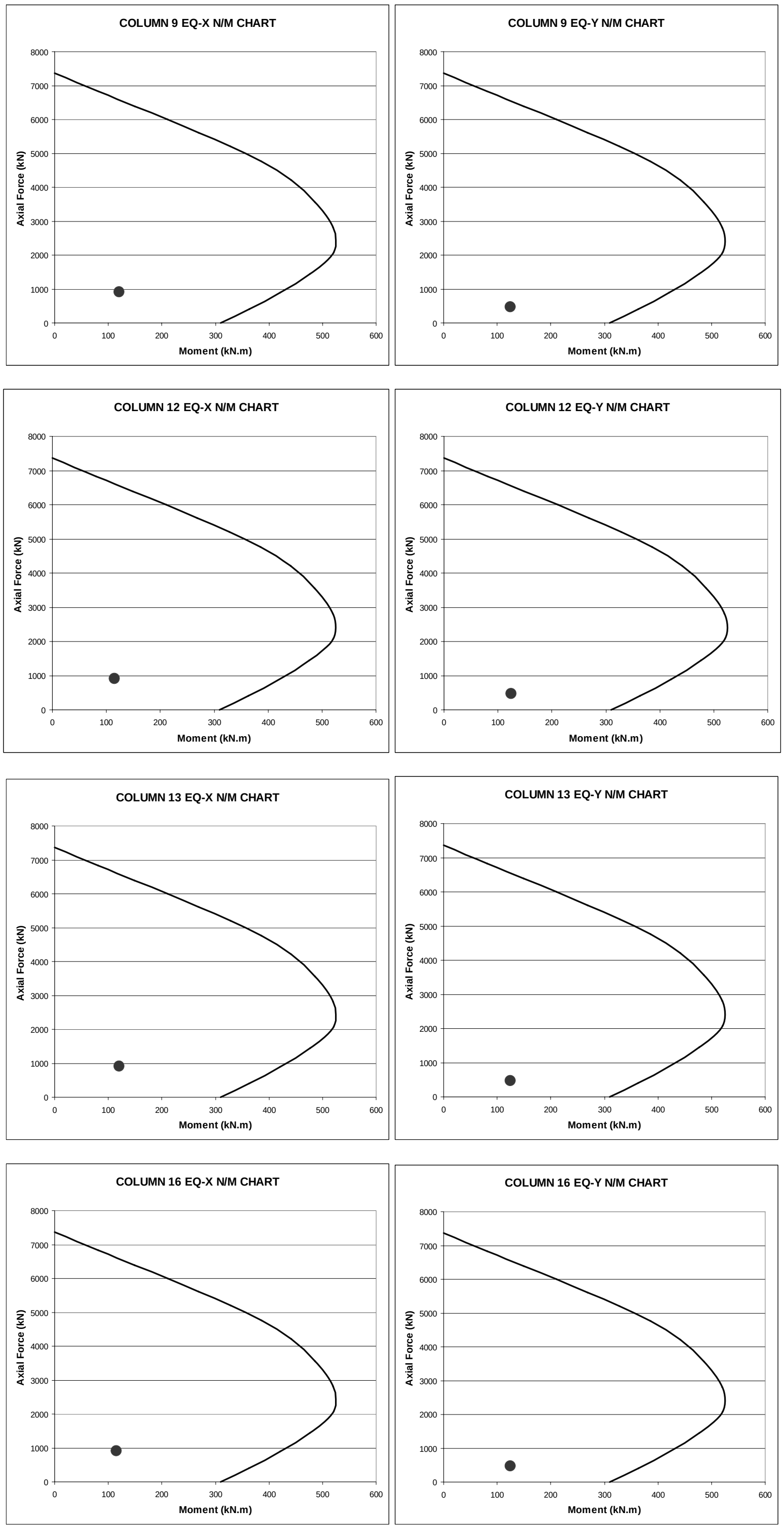


Figure 4.32 Column Interaction Diagrams of Model-D (Part 1)

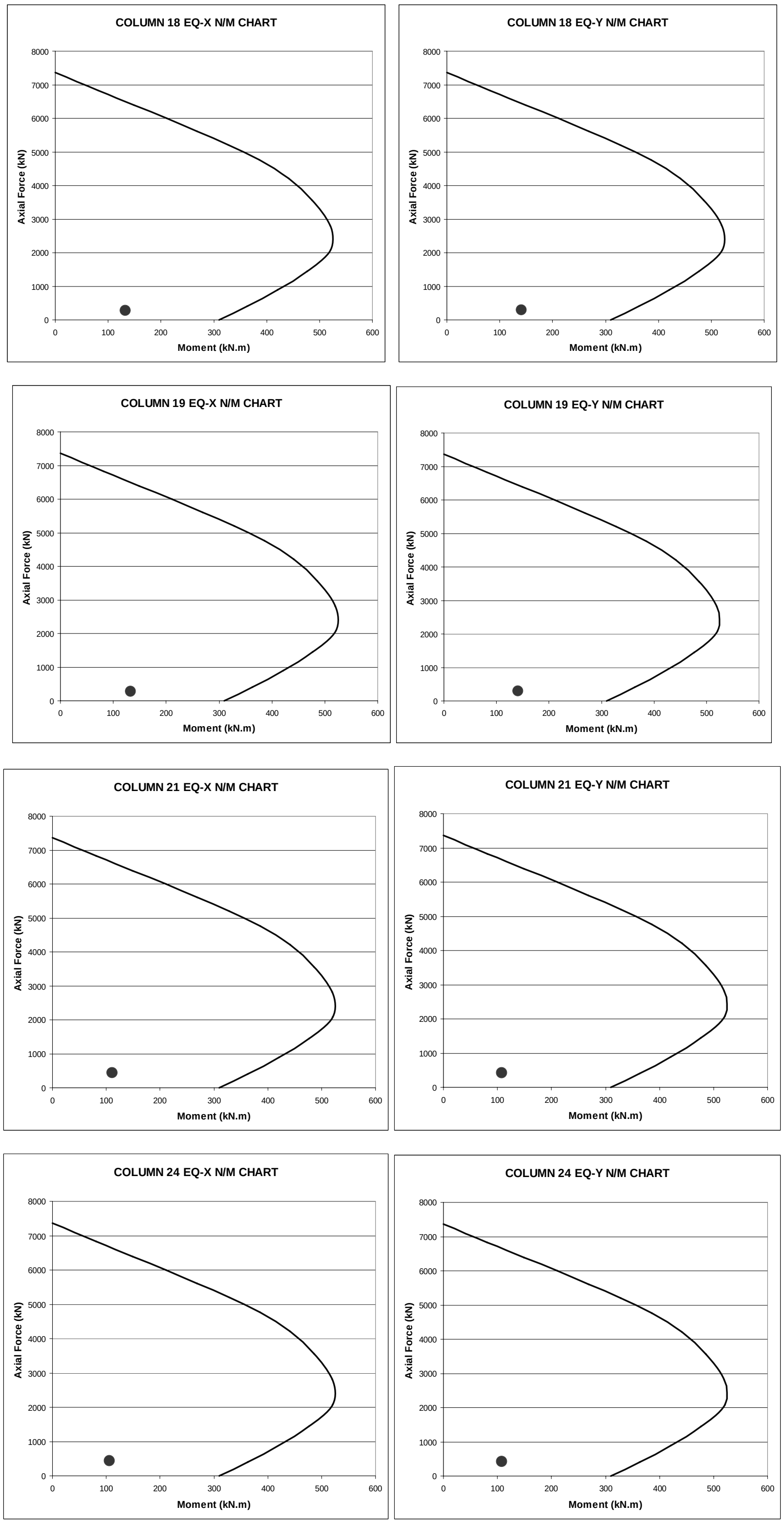


Figure 4.33 Column Interaction Diagrams of Model-D (Part 2)

4.6 Idealized Parametric Model E: Beam-to-Beam Connections without Vertical Support are Introduced to the Structural System

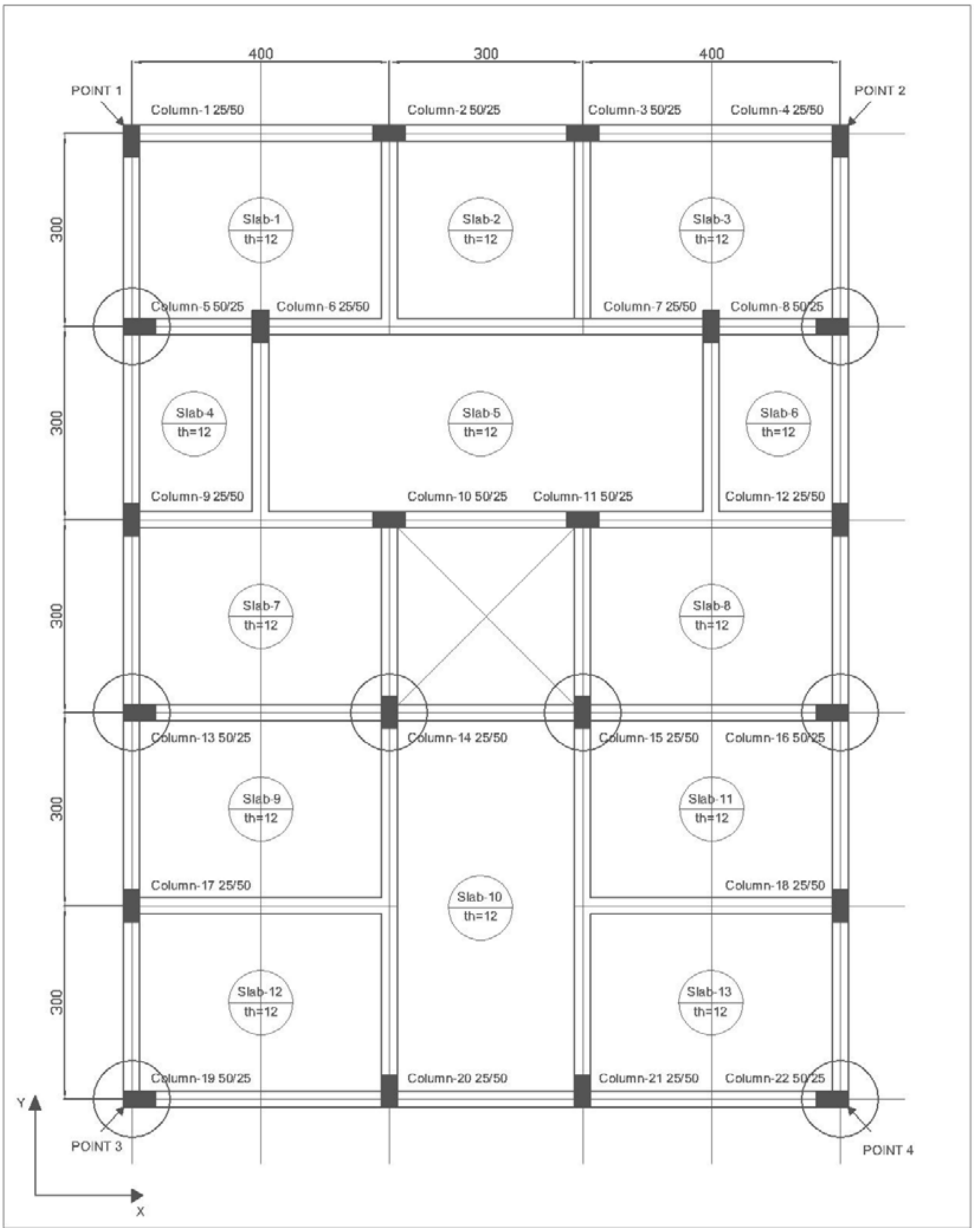


Figure 4.34 Structural Plan of Idealized Parametric Model-E

In Model-E, beam-to-beam connections without columns are introduced to the structural system. Natural period for the critical first mode is well within the undesired interval. (T > 0,7 sec.) (**Table 4.13**) The irregularities in the structural system cause torsion to occur in critical mode. (**Figure 4.35** and **Figure 4.36**) Displacements are similar to the values obtained in Model-B in both earthquake directions. (**Table 4.14**)

Table 4.13 Modal Characteristics of Model-E

Mode Number	Dominant Movement	Period (sec)
Mode 1	Torsion	0,75
Mode 2	Lateral Displacement (x-dir)	0,69
Mode 3	Lateral Displacement (y-dir)	0,56

Table 4.14 Displacements of Top Floor Outermost Corner Points of Model-E

Point Number	Earthquake Direction	Displacement in x-direction (m)	Displacement in y-direction (m)	Displacement in z-direction (m)
1	**EQ -X**	0,058	0,025	0,0011
	EQ-Y	0,000014	0,077	0,001
2	**EQ -X**	0,058	0,025	0,0011
	EQ-Y	0,000014	0,077	0,001
3	**EQ -X**	0,1	0,02	0,0008
	EQ-Y	0,000015	0,077	0,001
4	**EQ -X**	0,1	0,02	0,0008
	EQ-Y	0,000015	0,077	0,001

A. **B.**

Figure 4.35 A. (Un-deformed Shape of Model-E) **B.** (Deformed Shape Mode 1)

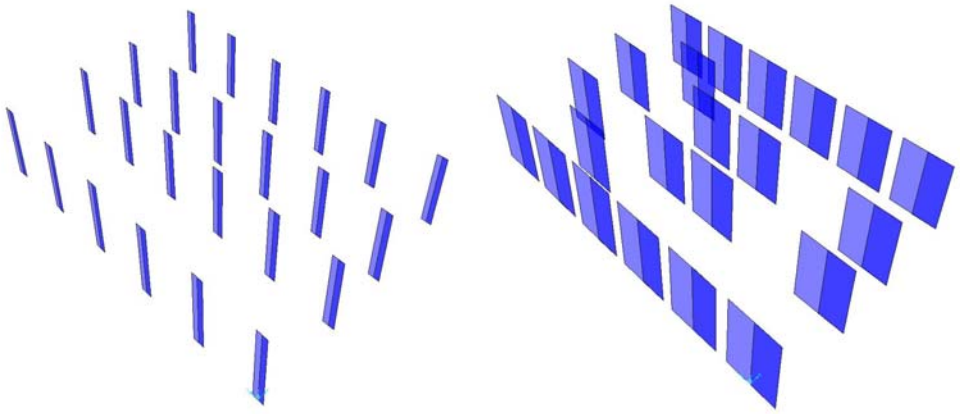
A. **B.**

Figure 4.36 A. (Deformed Shape Mode 2) **B.** (Deformed Shape Mode 3)

The analysis of Model-E has revealed that torsion effect occurs in bottom floor columns. (**Table 4.15**, **Figure 4.37** and **Figure 4.38**) The comparison chart between Model-B and Model-E reveal that due to the existence of beam-to-beam connections without columns there is a significant increase in the amount of torsion that the bottom floor columns are subjected to. It is also revealed that the increase in torsion effect is more critical in x-dir. due to the geometric configuration of the structural system.

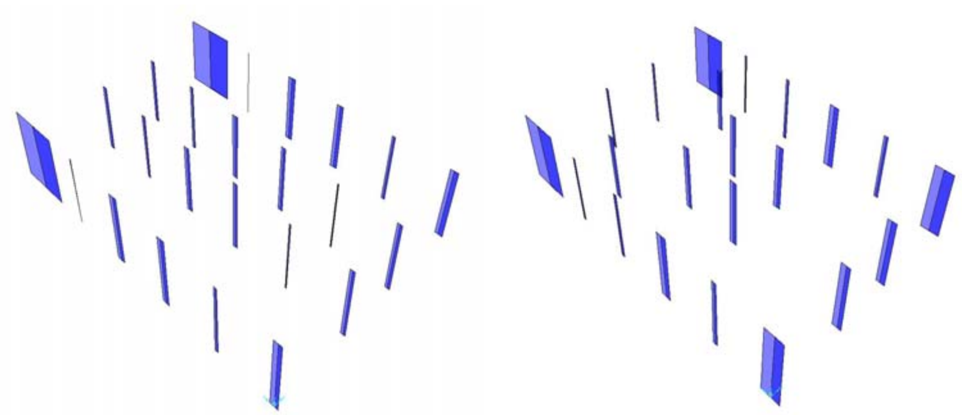
Table 4.15 Comparison Chart between Model-B and Model-E in terms of Torsion in Selected Columns

Load Combination	**Column Number**	**Torsion Model B (kN.m)**	**Torsion Model E (kN.m)**
DL+LL+EQX	**5**	1,32	6,15
DL+LL+EQY		0,001	0,007
DL+LL+EQX	**8**	1,32	6,15
DL+LL+EQY		0,001	0,007
DL+LL+EQX	**13**	1,31	6,15
DL+LL+EQY		0,02	0,02
DL+LL+EQX	**14**	1,31	6,15
DL+LL+EQY		0,01	0,02
DL+LL+EQX	**15**	1,31	6,15
DL+LL+EQY		0,01	0,02
DL+LL+EQX	**16**	1,31	6,15
DL+LL+EQY		0,02	0,02
DL+LL+EQX	**21**	1,21	6,02
DL+LL+EQY		0,02	0,05
DL+LL+EQX	**24**	1,21	6,02
DL+LL+EQY		0,02	0,05



A. **B.**

Figure 4.37 A. (Torsion Diagram in EQX for Model-B) **B.** (Torsion Diagram in EQX for Model-E)



A. **B.**

Figure 4.38 A. (Torsion Diagram in EQY for Model-B) **B.** (Torsion Diagram in EQY for Model-E)

4.7 Model F: An Irregular Structural System Based on A Collapsed Building in Bolu City Center

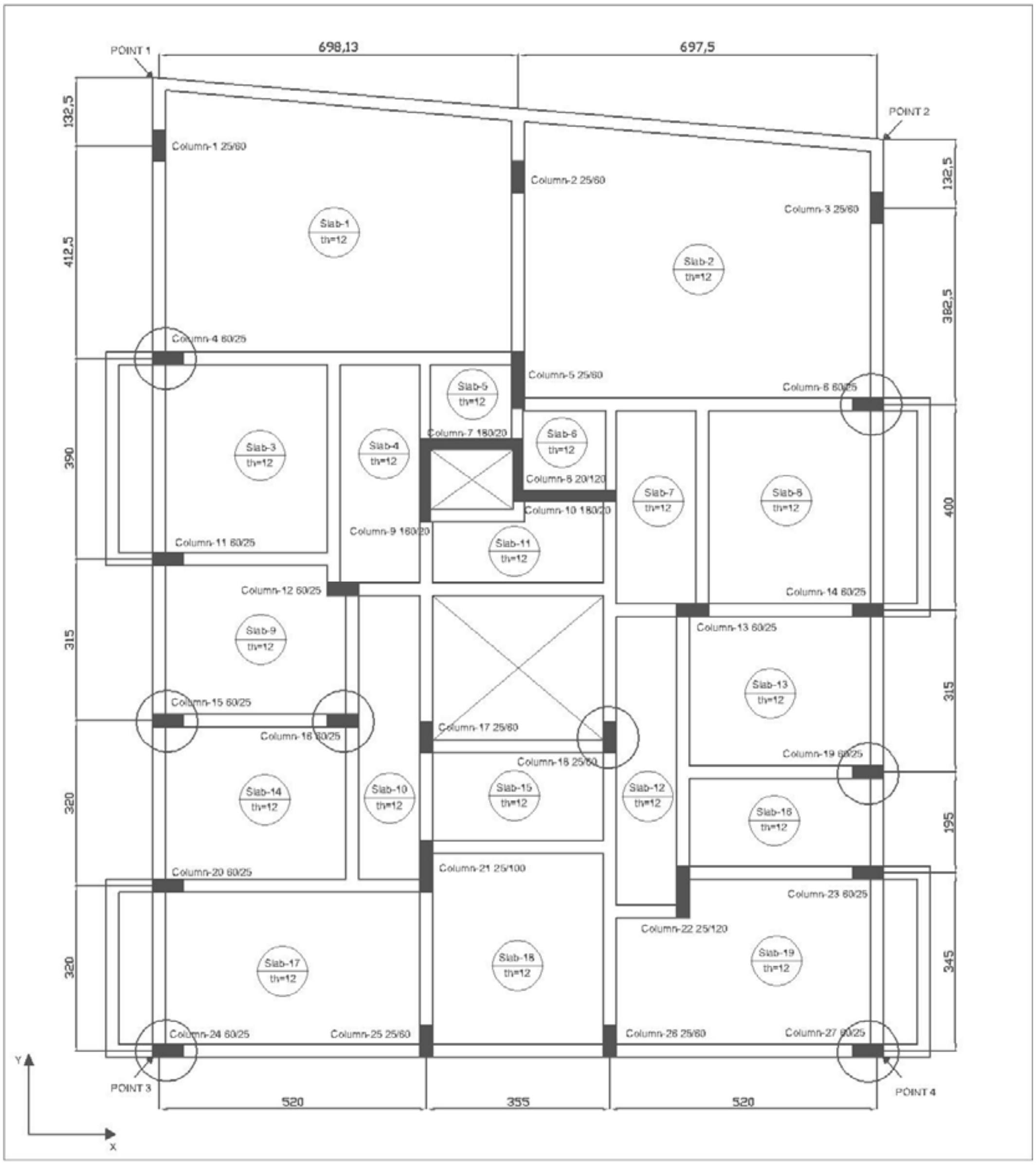


Figure 4.39 Structural Plan of Model-F

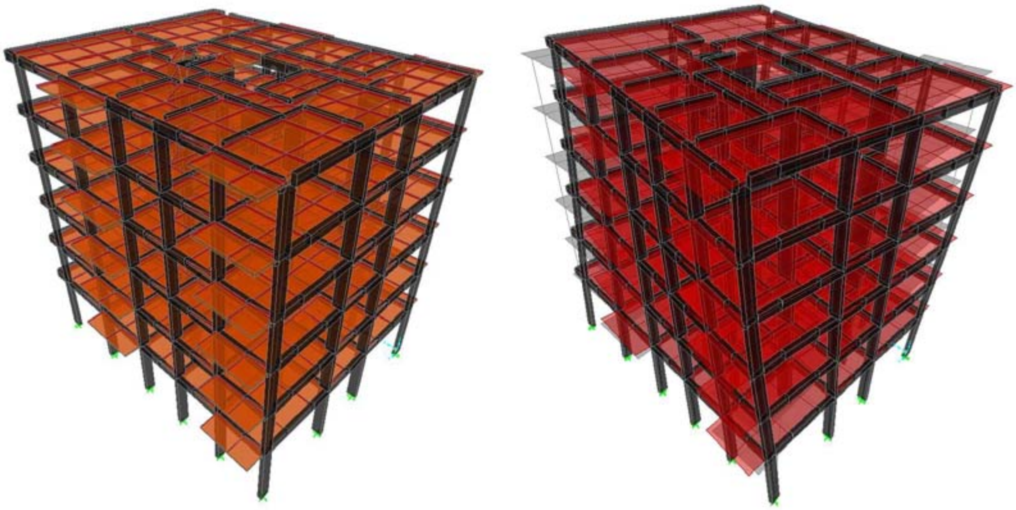
In Model-F, because of the combined effect of the irregularities in the system, the natural period is well within the undesired interval. (T > 0,7 sec.) (**Table 4.16**) Due to uneven distribution of columns, shear-walls and existence of beam-to-beam connections without vertical support, torsion occurs in critical modes. (**Figure 4.40** and **Figure 4.41**) Due to the lack of shear-walls the rigidity of the system is very low; therefore, large and uneven displacements are measured in both earthquake directions. (**Table 4.17**)

Table 4.16 Modal Characteristics of Model-F

Mode Number	Dominant Movement	Period (sec)
Mode 1	Torsion	0,85
Mode 2	Lateral Displacement (y-dir)	0,71
Mode 3	Lateral Displacement (x-dir)	0,66

Table 4.17 Displacements of Top Floor Outermost Corner Points of Model-F

Point Number	Earthquake Direction	Displacement in x-direction (m)	Displacement in y-direction (m)	Displacement in z-direction (m)
1	**EQ -X**	0,091	0,029	0,0009
	EQ-Y	0,01	0,082	0,0009
2	**EQ -X**	0,068	0,029	0,001
	EQ-Y	0,007	0,082	0,004
3	**EQ -X**	0,091	0,024	0,001
	EQ-Y	0,013	0,084	0,0009
4	**EQ -X**	0,068	0,024	0,0008
	EQ-Y	0,007	0,084	0,004



A. **B.**

Figure 4.40 A. (Un-deformed Shape of Model-F) **B.** (Deformed Shape Mode 1)

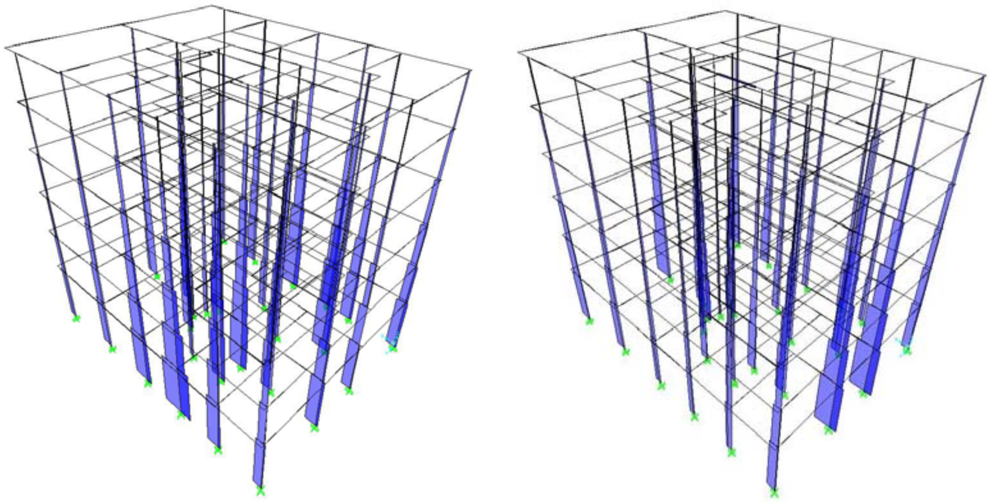
A. **B.**

Figure 4.41 A. (Deformed Shape Mode 2) **B.** (Deformed Shape Mode 3)

The analysis of Model-F has revealed that the maximum moments and axial forces occur in bottom floor columns for both earthquake directions. (**Table 4.18**, **Figure 4.42** and **Figure 4.43**) The interaction diagrams of the selected columns reveal that all columns 4 and 6 are in the safety zone in both earthquake directions. Columns 15, 16, 19, 24, 27 are narrowly in the safety zone in y-dir. but in failure zone in x-dir. Column 18 is narrowly in the safety zone in x-dir. but in failure zone in y-dir. (**Figure 4.44** and **Figure 4.45**) These results demonstrate that this structure would fail under the applied earthquake motion.

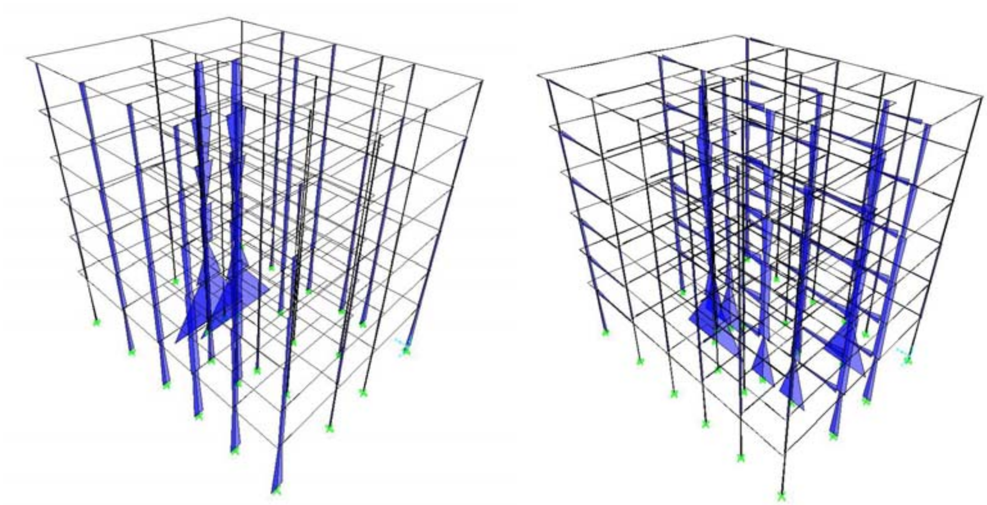
Table 4.18 Axial Force – Moment Combinations in Selected Columns

Column Number	**Load Combination**	**Axial Force (kN)**	**Moment (kN.m)**
4	DL+LL+EQX	1121	262
	DL+LL+EQY	1114	74
6	DL+LL+EQX	1171	241
	DL+LL+EQY	1196	84
15	DL+LL+EQX	1687	441
	DL+LL+EQY	521	71
16	DL+LL+EQX	1049	456
	DL+LL+EQY	452	73
18	DL+LL+EQX	774	81
	DL+LL+EQY	505	379
19	DL+LL+EQX	919	410
	DL+LL+EQY	570	83
24	DL+LL+EQX	701	552
	DL+LL+EQY	686	63
27	DL+LL+EQX	770	550
	DL+LL+EQY	646	72



A. **B.**

Figure 4.42 A. (Axial Force Diagram in EQX) **B.** (Axial Force Diagram in EQY)



A. **B.**

Figure 4.43 A. (Moment Diagram in EQ-X) **B.** (Moment Diagram in EQ-Y)

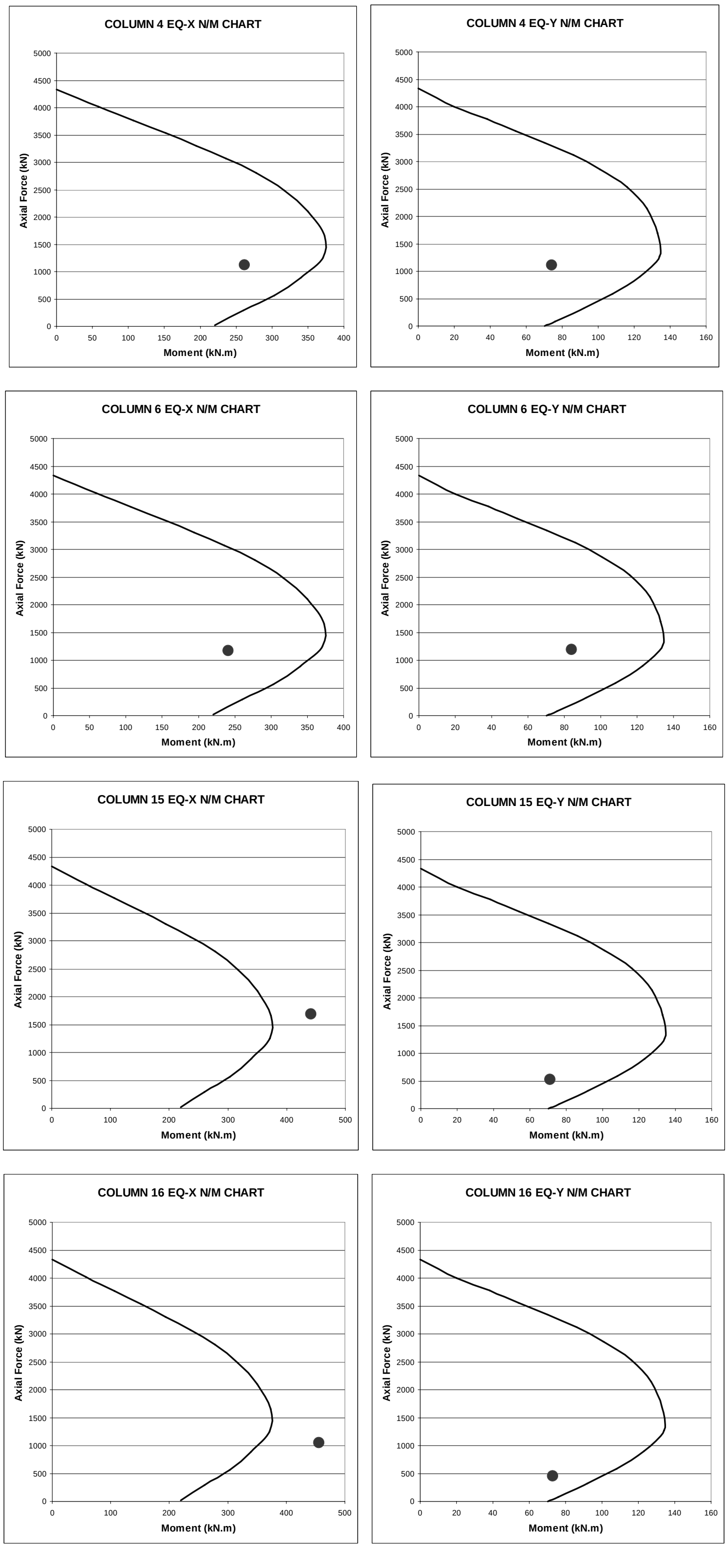


Figure 4.44 Column Interaction Diagrams of Model-F (Part 1)

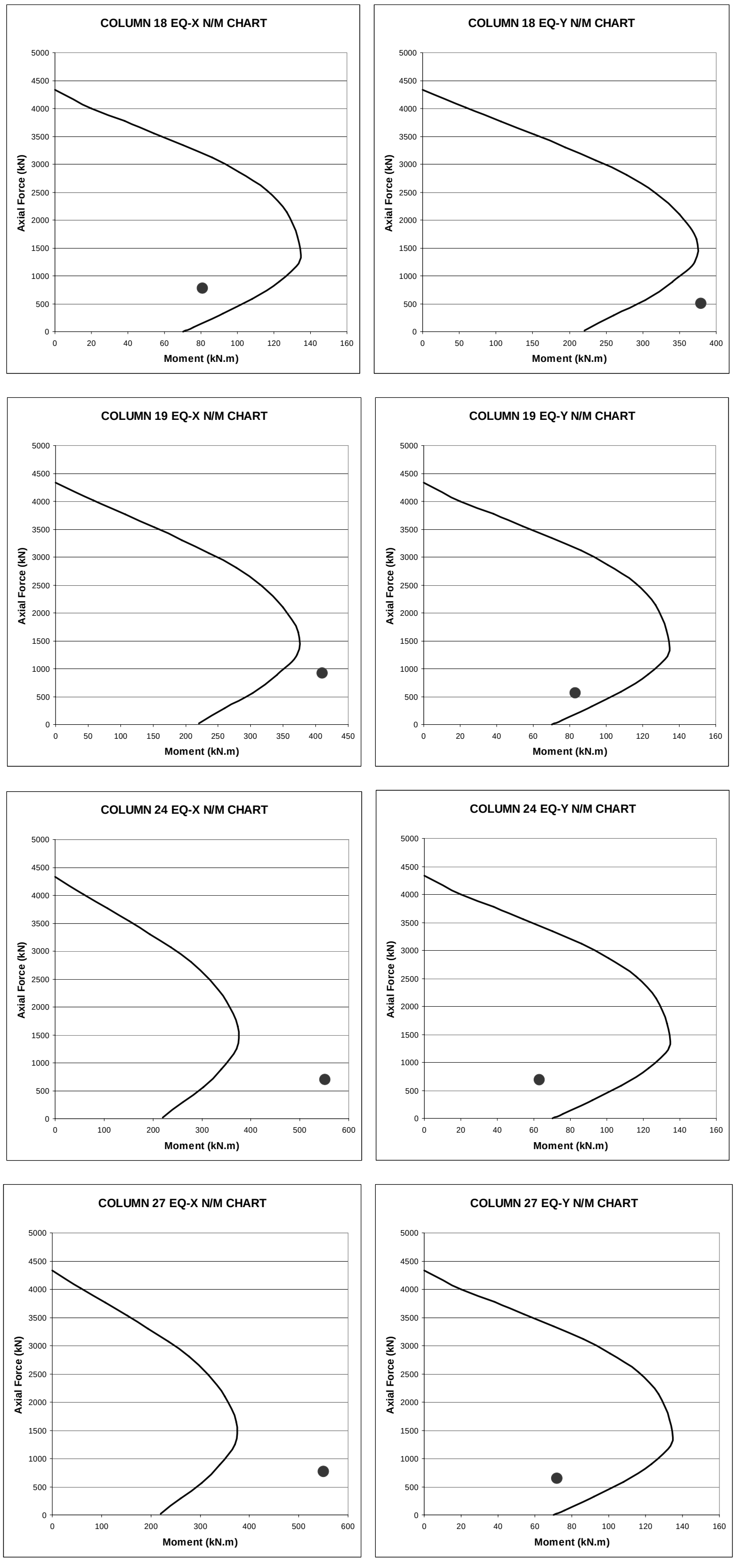


Figure 4.45 Column Interaction Diagrams of Model-F (Part 2)

4.8 Model G: A Regular Structural System Based on Improvements Applied to The Building Represented in Model F

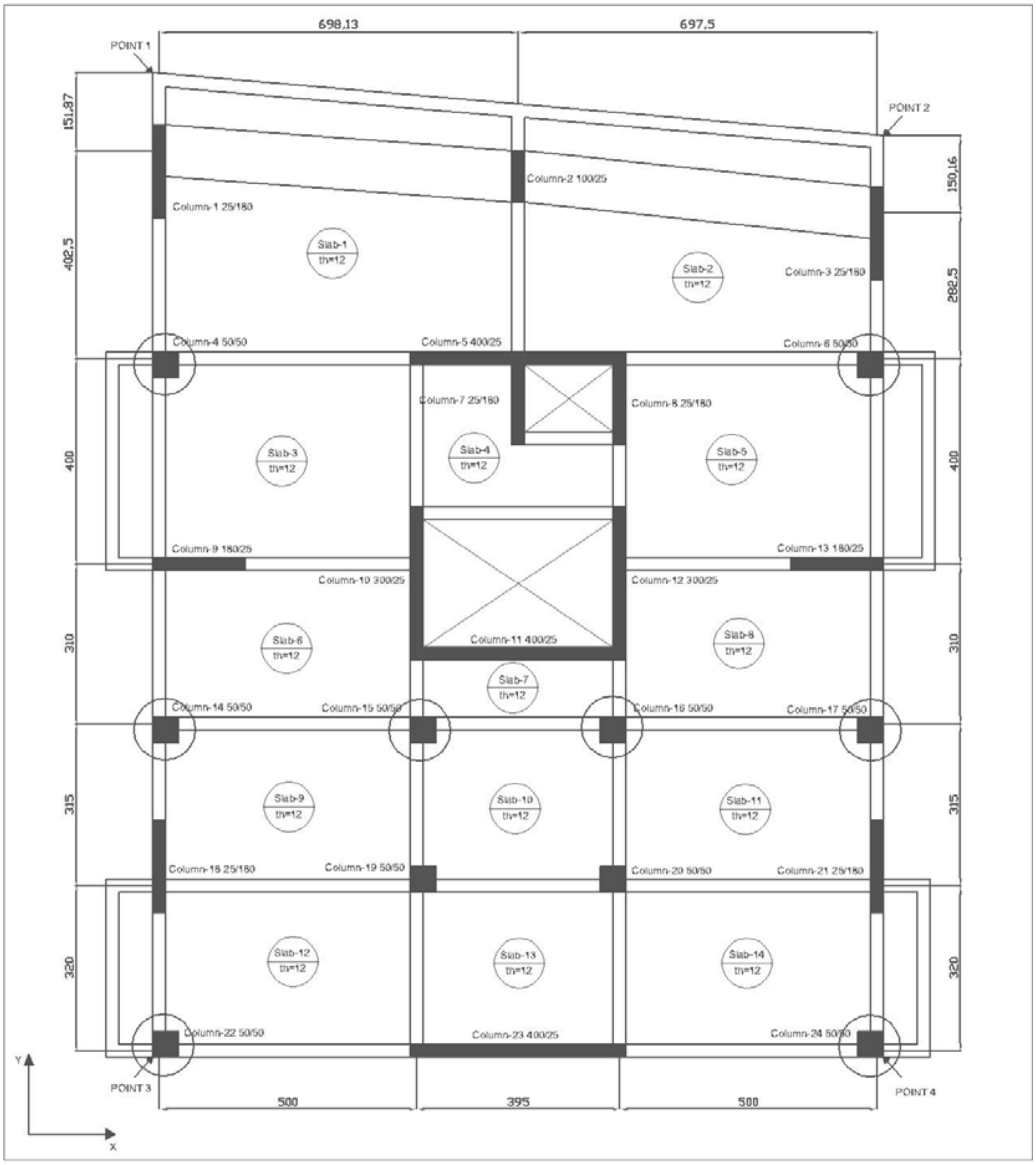


Figure 4.46 Structural Plan of Model-G

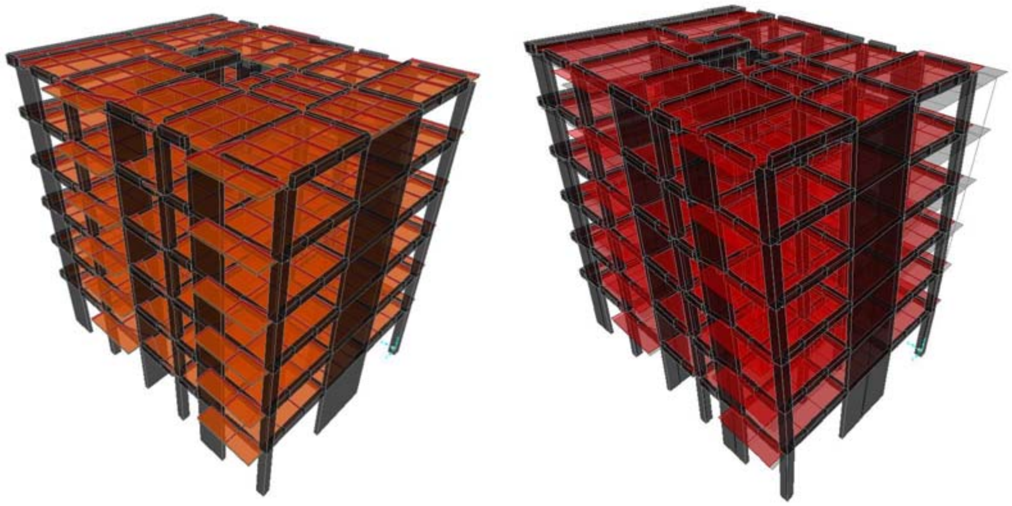
In Model-G, the structural system is completely re-designed including shear-walls, increased column sections and symmetrical configuration. Natural period for the critical first mode is well within the desired interval. (T < 0,5 sec.) (**Table 4.19**) The direction of columns and shear-walls is distributed equally in both directions. This prevents torsion to occur in critical modes. (**Figure 4.47** and **Figure 4.48**) Displacements are reduced in both directions. Due to symmetry, displacements in x-dir. are nearly equal to the ones in y-dir. (**Table 4.20**)

Table 4.19 Modal Characteristics of Model-G

Mode Number	Dominant Movement	Period (sec)
Mode 1	Lateral Displacement (y-dir)	0,47
Mode 2	Lateral Displacement (x-dir)	0,44
Mode 3	Torsion	0,34

Table 4.20 Displacements of Top Floor Outermost Corner Points of Model-G

Point Number	Earthquake Direction	Displacement in x-direction (m)	Displacement in y-direction (m)	Displacement in z-direction (m)
1	**EQ -X**	0,046	0,026	0,0007
	EQ-Y	0,004	0,057	0,00055
2	**EQ -X**	0,054	0,027	0,001
	EQ-Y	0,017	0,057	0,005
3	**EQ -X**	0,045	0,030	0,0007
	EQ-Y	0,004	0,050	0,0006
4	**EQ -X**	0,050	0,030	0,002
	EQ-Y	0,016	0,050	0,004



A. **B.**

Figure 4.47 A. (Un-deformed Shape of Model-G) **B.** (Deformed Shape Mode 1)

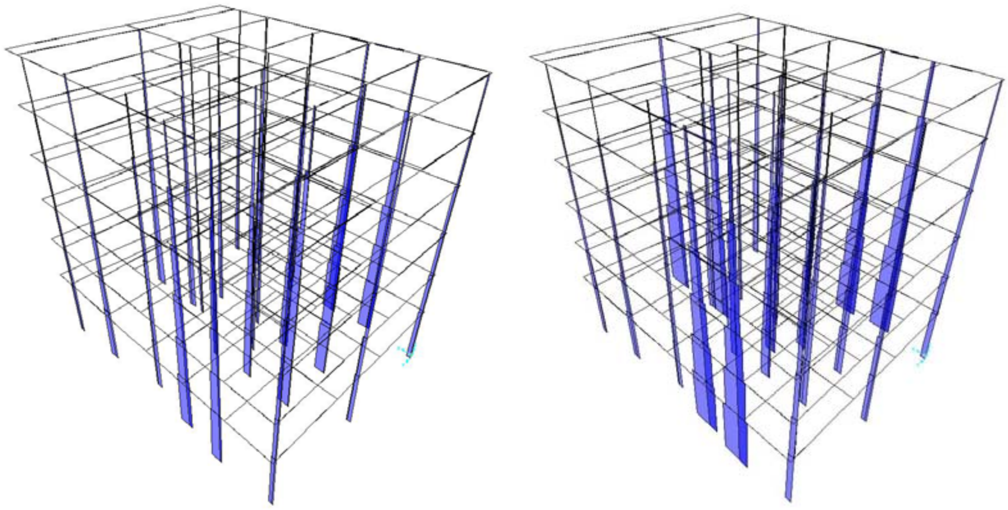
A. **B.**

Figure 4.48 A. (Deformed Shape Mode 2) **B.** (Deformed Shape Mode 3)

The analysis of Model-G has revealed that the maximum moments and axial forces occur in bottom floor columns for both earthquake directions. (**Table 4.21**, **Figure 4.49** and **Figure 4.50**) The interaction diagrams of the selected columns reveal that all columns are soundly within the safety zone in both earthquake directions. The large portion of the bending moments is carried by the shear-walls placed equally in both directions. (**Figure 4.51** and **Figure 4.52**) These results demonstrate that this structure would carry the loads safely under the applied earthquake motion.

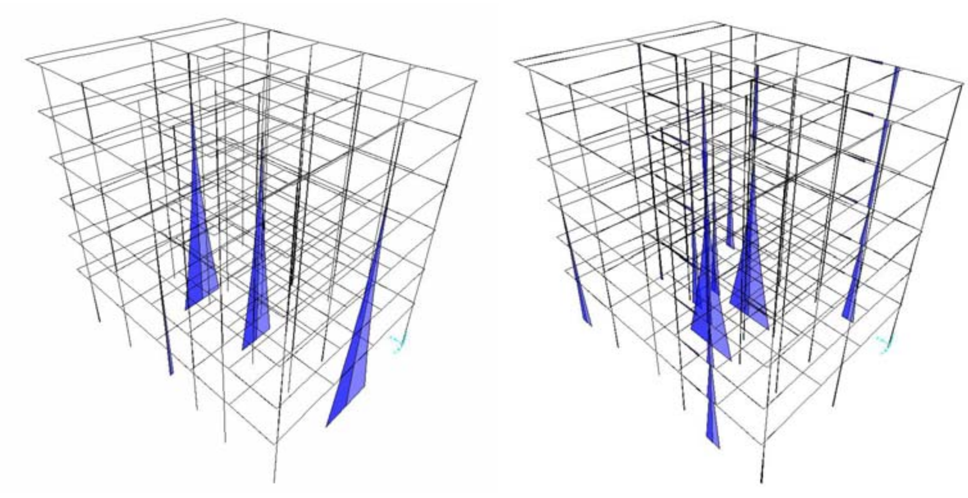
Table 4.21 Axial Force – Moment Combinations in Selected Columns

Column Number	**Load Combination**	**Axial Force (kN)**	**Moment (kN.m)**
4	DL+LL+EQX	1087	120
	DL+LL+EQY	998	140
6	DL+LL+EQX	974	91
	DL+LL+EQY	908	126
14	DL+LL+EQX	1167	89
	DL+LL+EQY	1879	146
15	DL+LL+EQX	868	93
	DL+LL+EQY	1017	134
16	DL+LL+EQX	880	97
	DL+LL+EQY	992	130
17	DL+LL+EQX	1271	71
	DL+LL+EQY	1730	130
22	DL+LL+EQX	458	79
	DL+LL+EQY	578	82
24	DL+LL+EQX	464	63
	DL+LL+EQY	566	73



A. **B.**

Figure 4.49 A. (Axial Force Diagram in EQX) **B.** (Axial Force Diagram in EQY)



A. **B.**

Figure 4.50 A. (Moment Diagram in EQ-X) **B.** (Moment Diagram in EQ-Y)

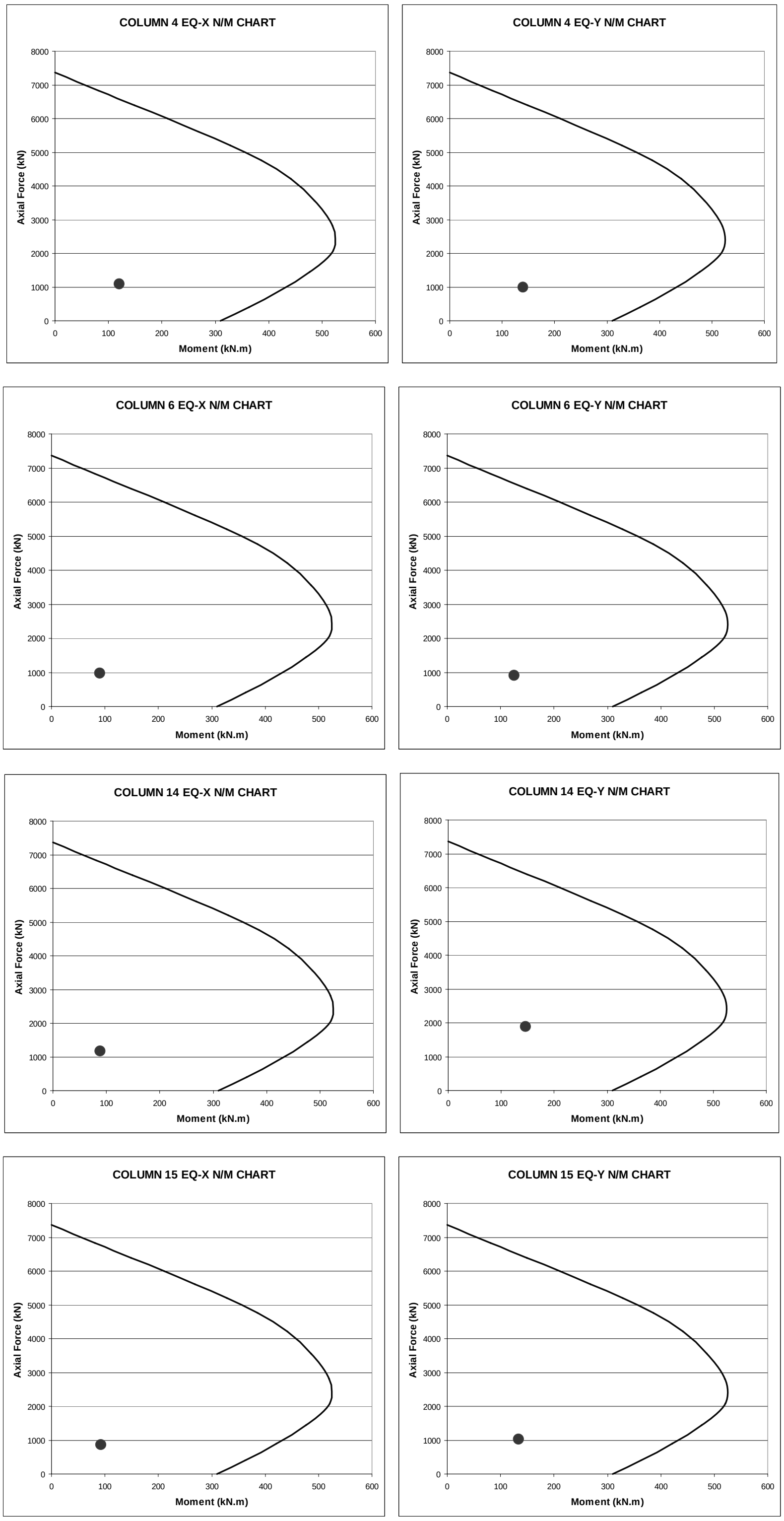


Figure 4.51 Column Interaction Diagrams of Model-G (Part 1)

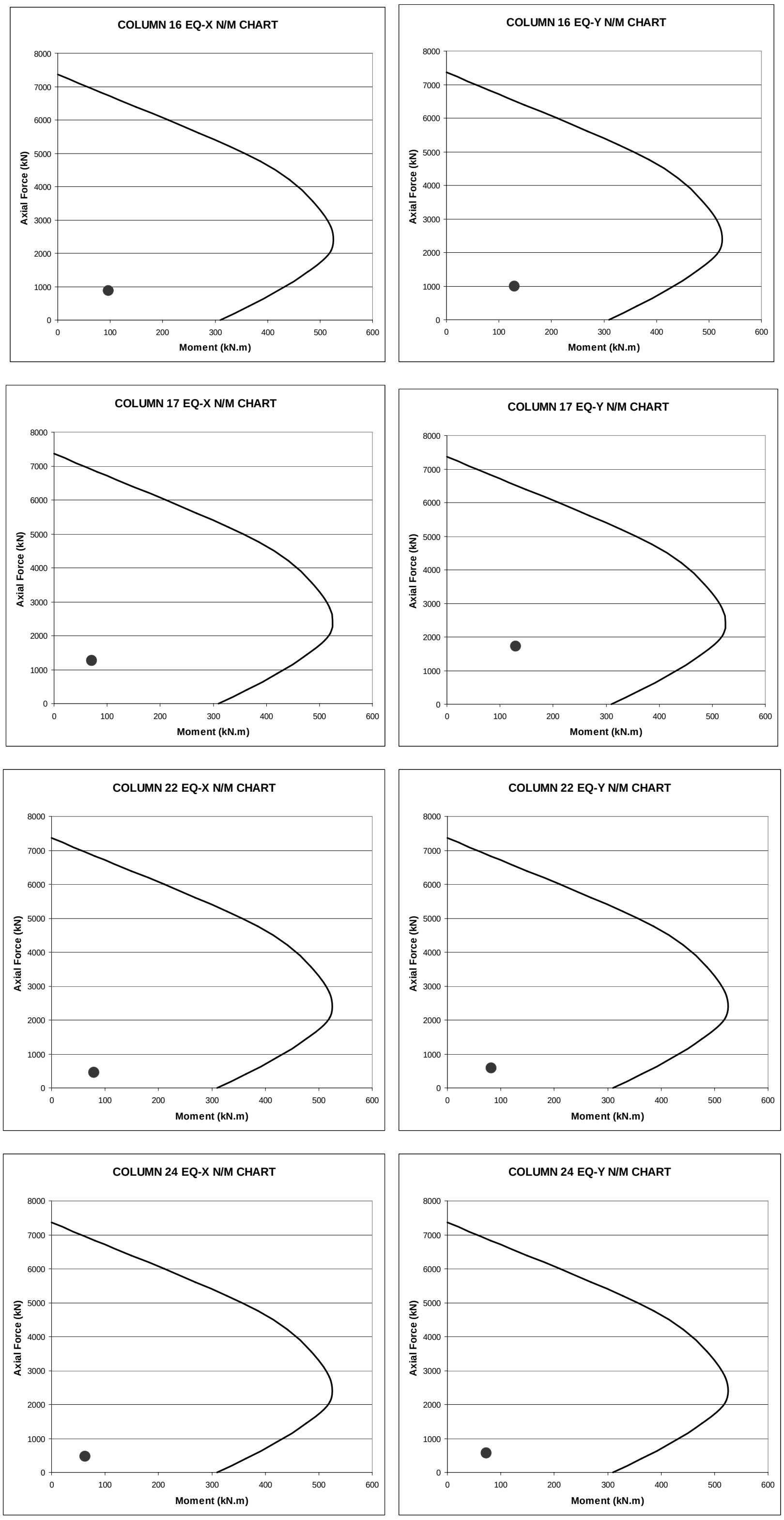


Figure 4.52 Column Interaction Diagrams of Model-G (Part 2)

4.9 Evaluation of The Results Obtained from The Analytical Study

A set of 7 models, 5 of which were idealized parametric models and 2 of which were based on actual buildings were tested during this analytical study. The models were prepared according to principles stated in Chapter 3 and the results were evaluated according to three criteria including the natural period, maximum displacements and column load-carrying capacities. The following conclusions were reached based on the results obtained from the structural analyses:

- The direction of columns has a significant effect on the distribution of rigidity of the overall structural system. If the rigidity of the system is distributed unevenly among the earthquake directions (Model-A), there is a great chance that the system will fail in the weakest direction.

- Distributing the direction of columns evenly in both earthquake directions improves the seismic behavior of the structural system. (Model-B). However, if the cross-sections of the columns are not sufficient to provide adequate lateral stiffness, the system will still not be within the safe zone under earthquake loads.

- Increasing the cross-sections of columns significantly improves the seismic behavior of the structure in terms of natural period, displacements and load-carrying capacity. However, it is not enough by itself to make a structure earthquake resistant. (Model-C) The use of an adequate amount of shear-walls evenly distributed in both earthquake directions is necessary to ensure earthquake safety. (Model-D) The use of shear-walls significantly decreases the amount of internal forces created in the relatively slender columns under earthquake loads.

- Beam-to-beam connections without vertical support introduce undesired torsion effects in the system and must be avoided if possible. If it is inevitable to design such features, it should be realized without disturbing the regularity of the system and continuity of the structural axes.

- The principles of seismic design, demonstrated in idealized parametric models are also effective when applied in actual building structures. (Model-F and Model-G) The seismic behavior of R/C apartment structures, which would otherwise contain the combination of several undesired seismic design features, can be significantly improved with the application of the proposed principles.

- The structural principles of seismic design would have fundamental influence on the architectural design of the building. Therefore the processes of structural and architectural design should go hand-in-hand from the very beginning of the design phase. Architects and Structural engineers should be in close cooperation in every step of the building design.

CHAPTER 5

AN ARCHITECTURAL EVALUATION OF EARTHQUAKE RESISTANT DESIGN PRINCIPLES APPLIED IN REINFORCED CONCRETE RESIDENTIAL APARTMENT BUILDINGS

5.1 Procedure for A Comparative Planimetric Evaluation of Earthquake Resistant Design Principles Applied in The Architectural Design of Reinforced Concrete Apartment Blocks

The validity of the structural principles of earthquake resistant design in reinforced concrete (R/C) apartment blocks was demonstrated in Chapter 4. In this chapter, the impact of the proposed structural design guidelines on the architectural design of the R/C residential buildings will be investigated. As the discussions about the structural principles were kept limited with the correction of design faults in plan, the architectural discussions will also focus on the planimetric arrangements of R/C residential buildings.

R/C residential blocks can be in various sizes ranging from very small buildings with single residential unit on one floor to large-scale mass-housing blocks having several residential units at the same level. Since this thesis is primarily concerned with the building practice in small and middle-size Turkish Cities located on seismic zones, it is logical to establish a limitation for the scale of R/C blocks to focus on. A survey conducted by Saadet Toker[147] in several Turkish cities in

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[147] TOKER, Saadet, Develoing an Innovative Architectural and Structural Solution for Sesimic Strenghtening of Reinforced Concrete Residential Buildings, Ankara, Unpublished Doctoral Thesis-Middle East Technical University, May 2004, pp. 19-26

Anatolia has demonstrated that the majority of the R/C residential buildings in these cities, especially the ones located in newly developing areas, are within 5 to 8 storey range and have 2 to 4 residential units on one floor. (**Figure 5.1**) These findings are consistent with the results of the field study conducted in Bolu as a part of this thesis. (Section 2.3.3) This is the range of R/C structures that this chapter will focus on.

Figure 5.1 Building Typologies from Afyon and Eskişehir[148]

This section consists of three sample projects taken from Bolu, all of which are chosen among buildings that were destroyed either during or immediately after the 1999 earthquakes. All of the projects will first be represented in their original unaltered versions containing several seismic design faults. These projects are adapted from the obtained blueprints with few minor modifications. At the second step, the same apartment block will be represented in its structurally and architecturally modified form. The architectural modifications will be realized staying as loyal as possible to the original design of the building's architect. The aim of this thesis is not to bring a critical approach to apartment block design but to demonstrate that the same or a very similar design could have been achieved in a seismically resistant building.

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[148] TOKER, Saadet, Develoing an Innovative Architectural and Structural Solution for Sesimic Strenghtening of Reinforced Concrete Residential Buildings, Ankara, Unpublished Doctoral Thesis-Middle East Technical University, May 2004, pp. 19-20

The first project is the same structure that was analytically modeled in both its original and altered versions in Chapter 4, under the names Model-F and Model-G. In this chapter, the architectural projects of these two models will be discussed in terms of their planimetric arrangements such as the floor area, number and location of rooms, arrangement of service spaces, access to daylight and vista, etc.

The analytical studies in Chapter 4 have proven the validity of the structural design principles for a R/C structure having two residential units in one floor. Since there is no significant difference in scale between buildings with 2 units per floor and buildings with 3 or 4 units per floor, it is safe to assume that the same structural design principles would also be valid for these type of apartment blocks too. Therefore, the second and third projects will be slightly larger R/C apartments of this type. These two projects will also be discussed both in terms of their structural systems and architectural characteristics.

Although, the primary aim of this thesis is not to make a cost-based discussion, the real-life application probability of any structural or architectural proposal is closely related with its economic feasibility. Therefore, in addition to architectural discussions, there is an approximate cost analysis for each of the projects before and after the proposed alterations. This analysis is based on the ratio of rise in the construction cost of the R/C skeleton system with respect to the total building cost. It is assumed that the cost of the structural system takes approximately 30% of the total cost and that the cost of the remaining parts of the building will remain the same for earthquake resistant and non-resistant structures. The aim of this cost analysis is to demonstrate that the increase in the total cost of the building will be limited to 4-8% which is an economically acceptable ratio.[149]

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[149] TÜRKMEN, M., TEKELİ, H., “Deprem Bölgesi ve Yerel Zemin Sınıflarının Bina Maliyetine Etkileri”, Süleyman Demirel Üniversitesi, Fen Bilimleri Enstitüsü Dergisi, Isparta, Vol.9, No:3, 2005

5.2 Model-1: A Reinforced Concrete Apartment Block with Two Residential Units on One Floor

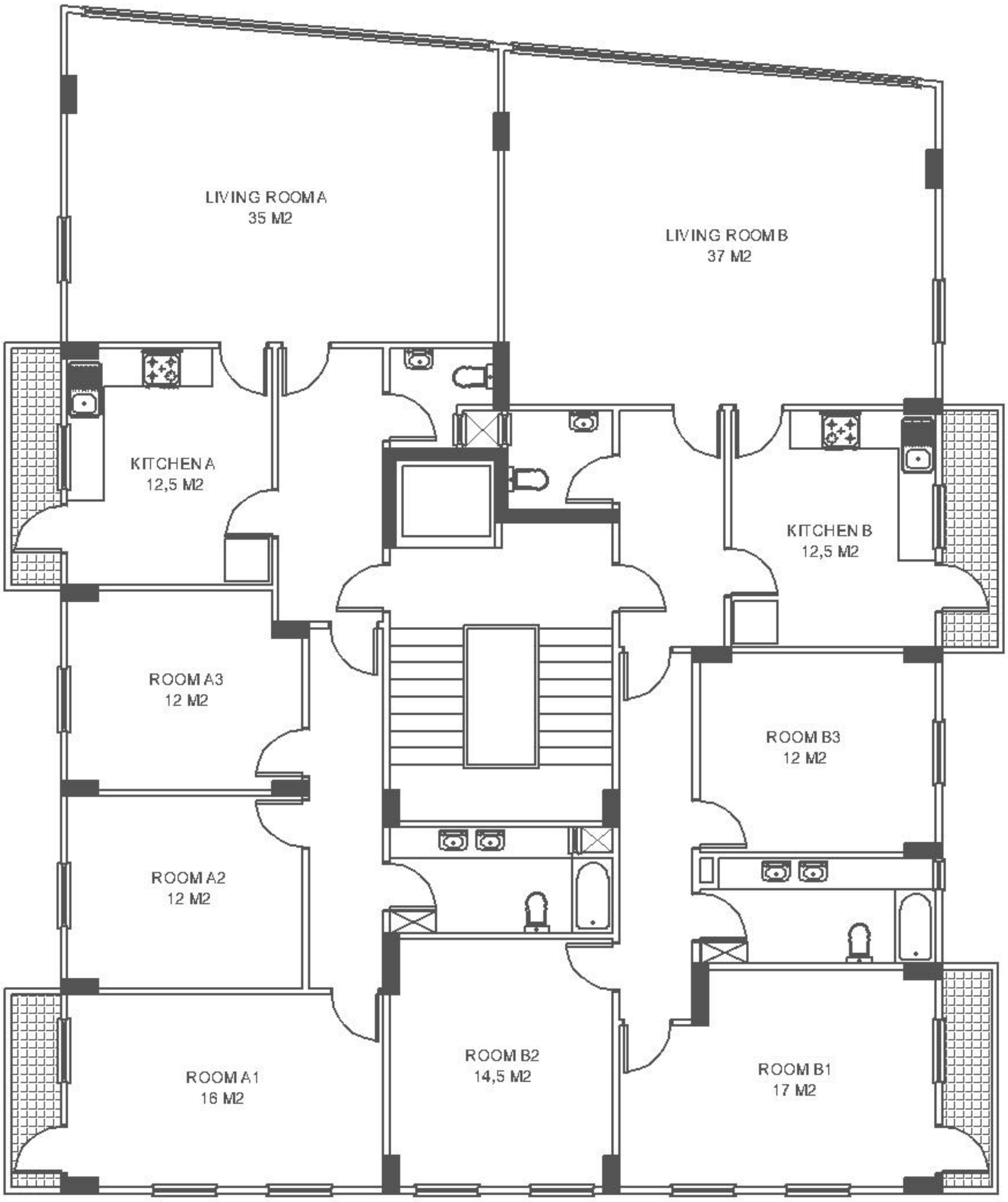

Figure 5.2 Architectural Plan of Model-1 with Irregular Structural System

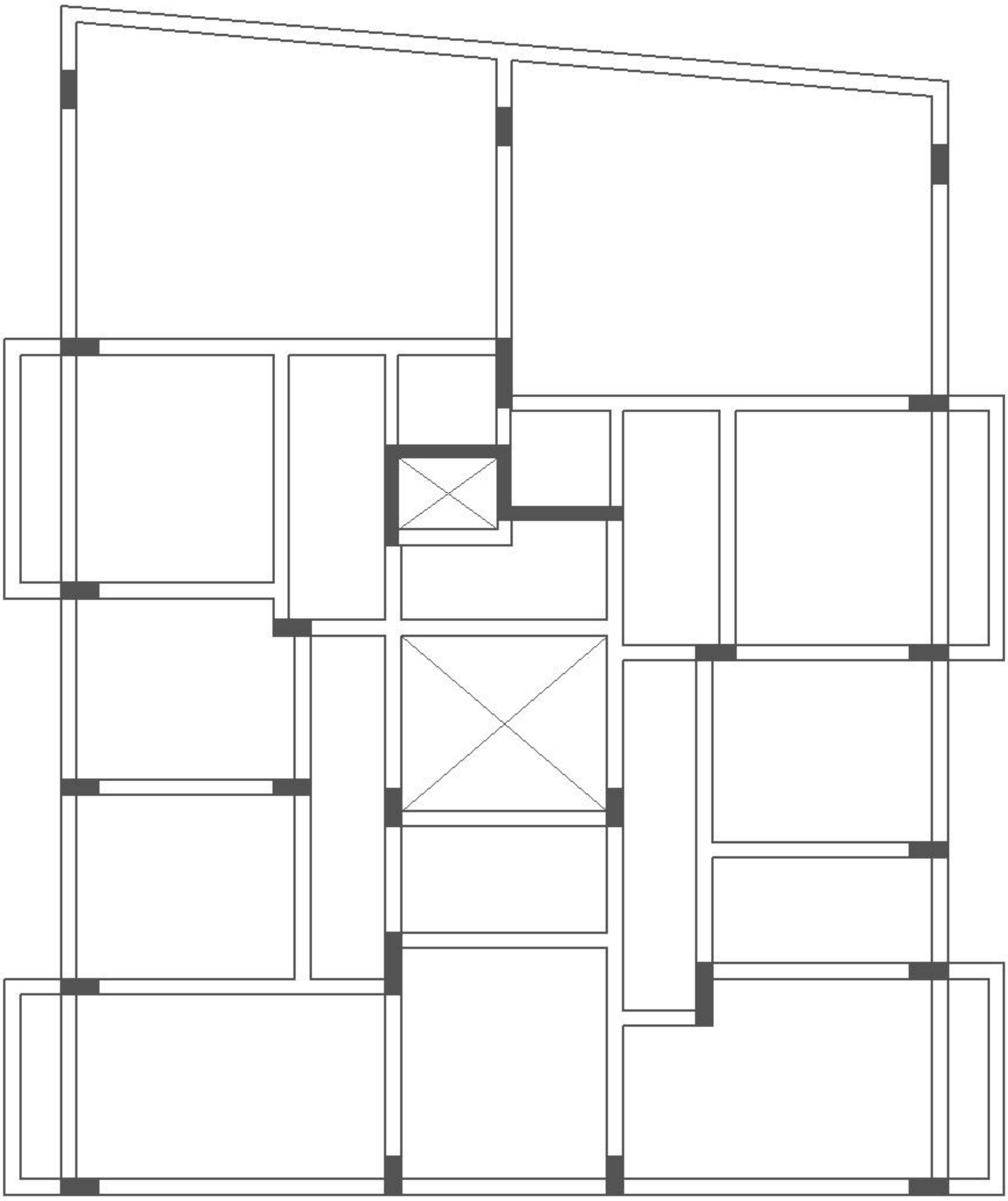

Figure 5.3 Structural Plan of Model-1 with Irregular Structural System

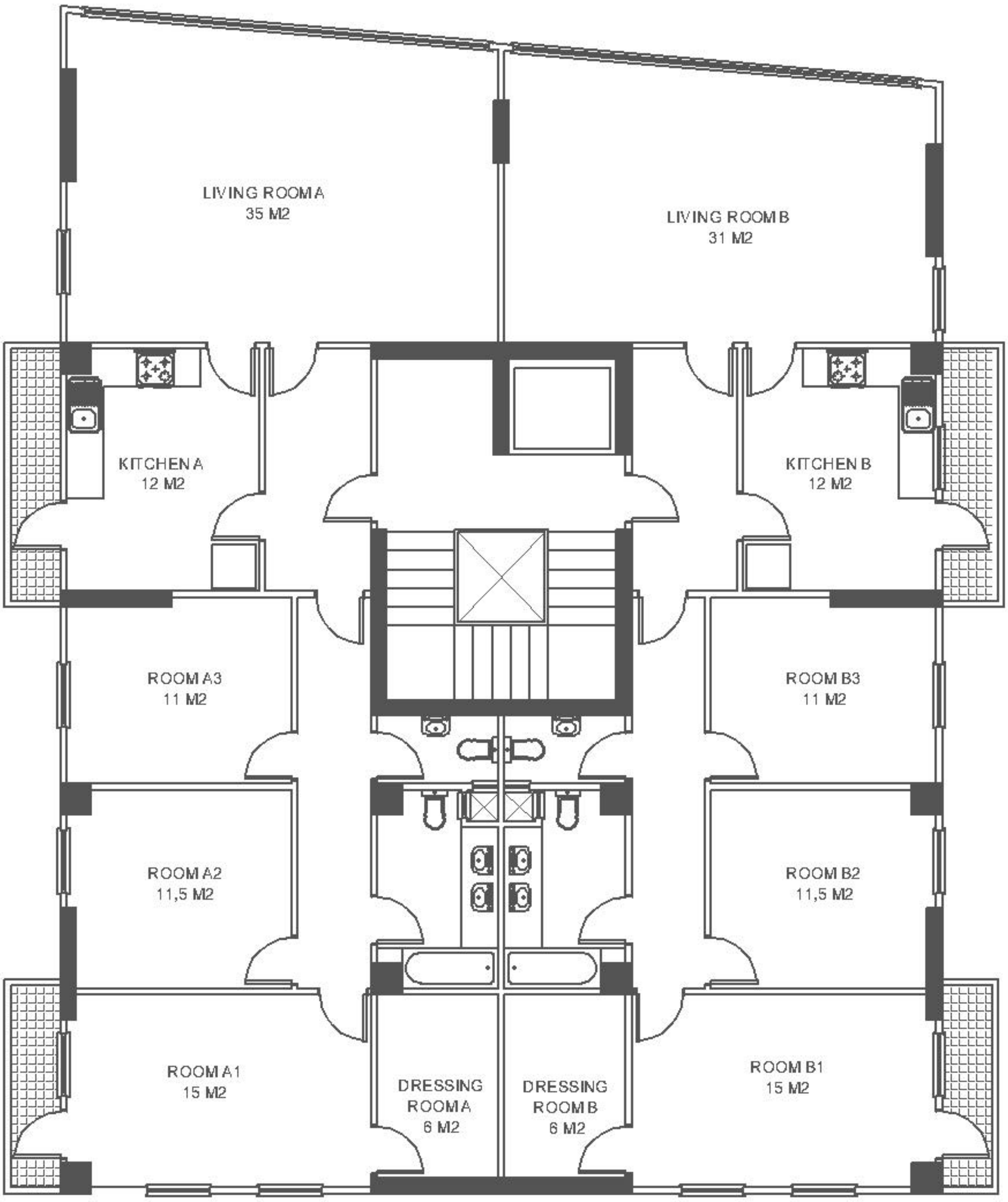

Figure 5.4 Architectural Plan of Model-1 with Regular Structural System

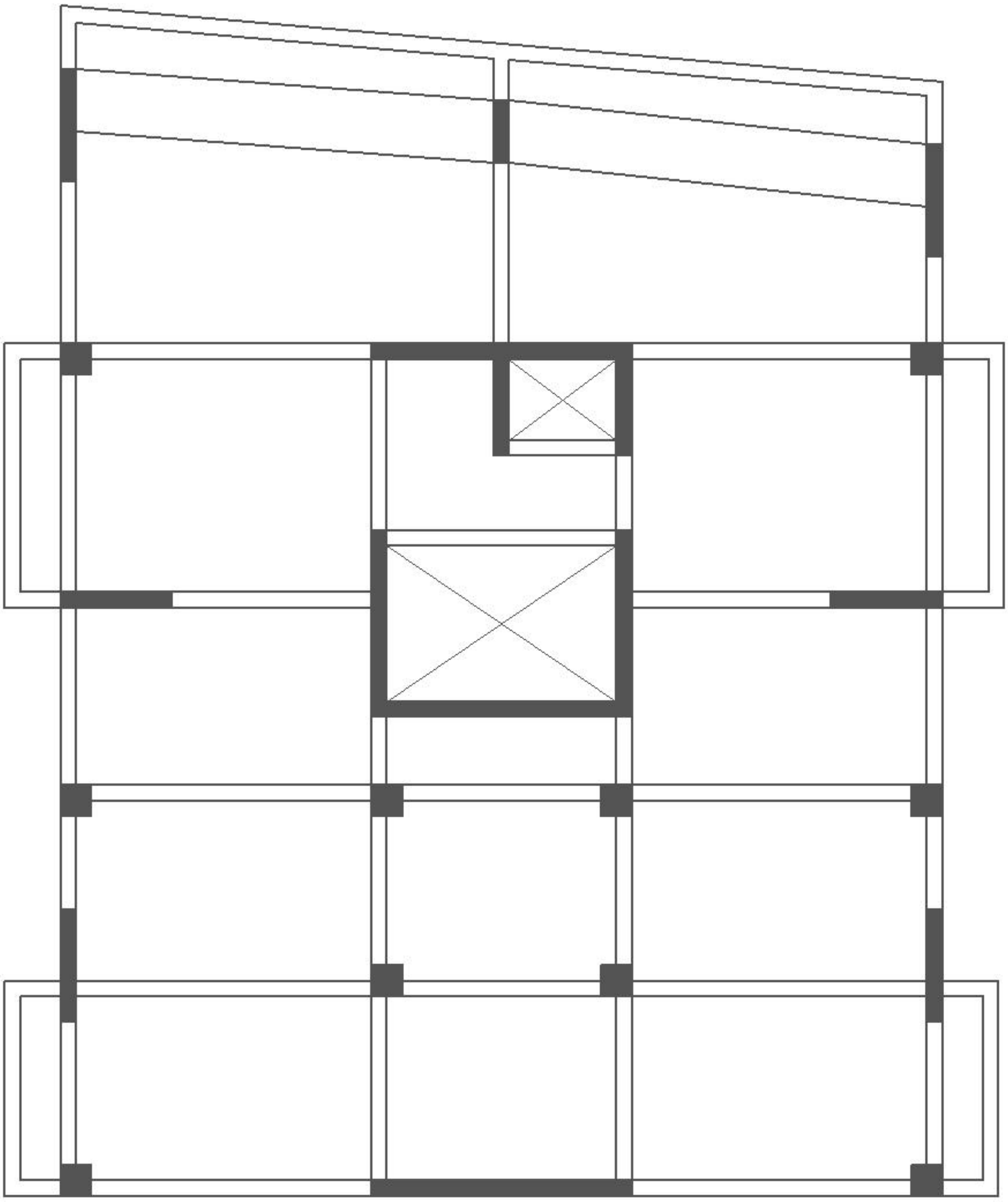

Figure 5.5 Structural Plan of Model-1 with Regular Structural System

Model-1 is based on the same building that was analytically modeled in Chapter 4 under the names Model-F and Model-G. It is a 6 storey R/C building with 2 residential units on each floor. These units are named Unit-A and Unit-B. It is assumed that ground floor has commercial use and therefore is not a part of this study. In the original plan, both residential units have 1 living-room, 3 rooms, 1 kitchen, 1 bathroom and 1 toilet. The kitchen and the master bed-room have balconies in both units. Toilets of both units and bathroom of Unit-A are located around the central axis of the building while the bathroom of Unit-B is located near the side façade of the building.[150] (**Figure 5.2**)

In the original configuration, the effort to create over-sized living-rooms of equal area for both residential units – probably due to marketing reasons – is the main reason behind the structural irregularity. The resulting architectural plan and the subsequent structural system have several discontinuities in structural axes. Another reason for the broken structural axes is the effort to prevent the beams being visible over the corridor spaces. This is a problem that can be avoided easily by the use of a suspended ceiling.

The asymmetry created by the large Living-Room B also prevents the effective use of the area around the central axis of the building plan. Due to lack of space near the side façade for a third room, Bathroom B had to be shifted near the façade and Room B2 was located near the rear façade. This creates inefficiency in the arrangement of wet spaces and introduces a further irregularity to the structural system. The earthquake resistance of the structural system also suffers from the lack of shear-walls and columns with insufficient cross-sections. The columns nearest to the front façade are not connected to each other with beams. This may cause the formation of large stresses in the large floor slabs of Living-Room A & B, and disturb the rigid diaphragm behavior of slabs. (**Figure 5.3**)

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[150] Graphichs prepared with Autodesk-Autocad Architectural Drafting Software

In the modified plan, the continuity of the structural axes in both directions is provided by designing Living-Room B smaller than the original version but still large enough to accommodate the required functions. Together with the introduction of a more compact vertical transportation core, this has allowed the design of identical architectural plans for Unit-A and Unit-B. In the new plan, bathrooms and toilets of both units are efficiently organized around the central axis of the building.[151] (**Figure 5.4**)

Consequently, the structural system was also redesigned in a symmetrical configuration which is known to have better behavior under earthquake loads. The cross-sections of the columns are enlarged and shear-walls are introduced to the system. Shear-walls are placed in both earthquake directions and distributed evenly throughout the building plan to prevent the creation of torsion effect. The continuity of beams is not broken over corridor spaces. The visual problem can be solved by a suspended ceiling. In this case, earthquake safety should be considered more important than aesthetic concerns. Columns nearest to the front façade are connected to each other by beams. These beams are designed with large width and smaller depth so they can be concealed within the slab system. (**Figure 5.5**)

In the modified plan, The floor area of Unit-A has increased by 4,5 m^2. The area of Living-Room A has remained the same. There are small decreases in the areas of Rooms A1, A2, and A3 but these are not significant enough to disturb the functions of these rooms with respect to the original design. The area formerly occupied by Room B2 was turned into Dressing Room A & B. These rooms will provide an excellent utility space for the master bedrooms or if desired they can be converted into private bathrooms. Kitchen A looses 0,5 m^2 without any negative effect to its function. Access to view and circulation spaces function in the same manner with the original design. (**Table 5.1**)

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[151] Graphichs prepared with Autodesk-Autocad Architectural Drafting Software

In the modified plan, The floor area of Unit-B has decreased by 4,5 m^2. The area of Living-Room B has decreased by 6 m^2. This may seem a considerable loss, however, this room was over-sized to begin with and the decrease in the floor area is not large enough to disturb the function. Living Room B is still the largest room in Unit-B. There are small decreases in the areas of Rooms B1, B2, and B3 but these are not significant enough to disturb the functions of these rooms. Room B2 was moved from the rear façade to side façade but still has enough access to daylight. Kitchen B looses 0,5 m^2 without any negative effect to its function. Circulation spaces are decreased by 0,5 m^2. (**Table 5.2**)

Table 5.1 Comparison Chart for Unit-A

UNIT-A	**Original**		**Modified**	
Room	**Area (m^2)**	**Access to View (Façade)**	**Area (m^2)**	**Access to View (Façade)**
Living Room	**35**	Front/Side	**35**	Front/Side
Rooms				
Room A1	16	Side	15	Side
Room A2	12	Side	11,5	Side
Room A3	12	Side	11	Side
Dressing Room	N/A	N/A	8	N/A
Sub-Total:	**40**		**45,5**	
Service Spaces				
Kitchen	12,5	Side	12	Side
Bathroom	6	N/A	6	N/A
Toilet	2	N/A	2	N/A
Circulation	14,5	N/A	14	N/A
Sub-Total:	**35**		**34**	
Grand Total:	**110**		**114,5**	

Table 5.2 Comparison Chart for Unit-B

UNIT-B	**Original**		**Modified**	
Room	**Area (m^2)**	**Access to View (Façade)**	**Area (m^2)**	**Access to View (Façade)**
Living Room	**37**	Front/Side	**31**	Front/Side
Rooms				
Room B1	17	Side	15	Side
Room B2	14,5	Side	11,5	Side
Room B3	12	Side	11	Side
Dressing Room	N/A	N/A	8	N/A
Sub-Total:	**43,5**		**45,5**	
Service Spaces				
Kitchen	12,5	Side	12	Side
Bathroom	6	Side	6	N/A
Toilet	2	N/A	2	N/A
Circulation	13,5	N/A	14	N/A
Sub-Total:	**34**		**34**	
Grand Total:	**114,5**		**110,5**	

An approximate cost analysis has been conducted for the structural system of Model-1 before and after the proposed modifications. The prices have been calculated according to the 2007 unit prices of the Ministry of Public Works and Settlement of Turkey. The cost of the structural system is assumed as 30% of the total building cost. It is also assumed that the remaining 70% of the non-structural system cost remains the same before and after the modifications. According to this analysis, the structural system cost increases by 19% and the total building cost increases by only 5,8% after the proposed modifications. This is an economically acceptable ratio. (**Table 5.3** and **Table 5.4**)

Table 5.3 Cost Analysis for Model-1 with Irregular Structural System

Poz No.	**Work Definition**	**Quantity (m^3, ton, m^2)**	**Unit Price (YTL)**	**Total (YTL)**
16.059	Concrete C25/30)	457 m^3	98,79 YTL	45.147 YTL
21.013	Wrought Shuttering	3.199 m^2	16,58 YTL	53.039 YTL
21.054	Supporting Scaffold	4.798 m^3	2,34 YTL	11.228 YTL
23.014	Steel (Ø8-12)	12,8 ton	1.451 YTL	18.580 YTL
23.015	Steel (Ø14-28)	19,2 ton	1.373 YTL	26.376 YTL
16.059	Casting Concrete	457 m^3	2,89 YTL	1.320 YTL
Total Structural System Cost (30 % of total building cost):				155.690 YTL
Total Non-Structural System Cost (70 % of total building Cost):				363.276 YTL
Total Building Cost:				518.966 YTL

Table 5.4 Cost Analysis for Model-1 with Regular Structural System

Poz No.	**Work Definition**	**Quantity (m^3, ton, m^2)**	**Unit Price (YTL)**	**Total (YTL)**
16.059	Concrete C25/30)	547 m^3	98,79 YTL	54.038 YTL
21.013	Wrought Shuttering	3.829 m^2	16,58 YTL	63.484 YTL
21.054	Supporting Scaffold	5.743 m^3	2,34 YTL	13.468 YTL
23.014	Steel (Ø8-12)	15,2 ton	1.451 YTL	22.064 YTL
23.015	Steel (Ø14-28)	22,8 ton	1.373 YTL	31.321 YTL
16.059	Casting Concrete	547 m^3	2,89 YTL	1.580 YTL
Total Structural System Cost (30 % of total building cost):				185.955 YTL
Total Non-Structural System Cost (70 % of total building Cost):				363.276 YTL
Total Building Cost:				549.231 YTL

5.3 Model-2: A Reinforced Concrete Apartment Block with Three Residential Units on One Floor

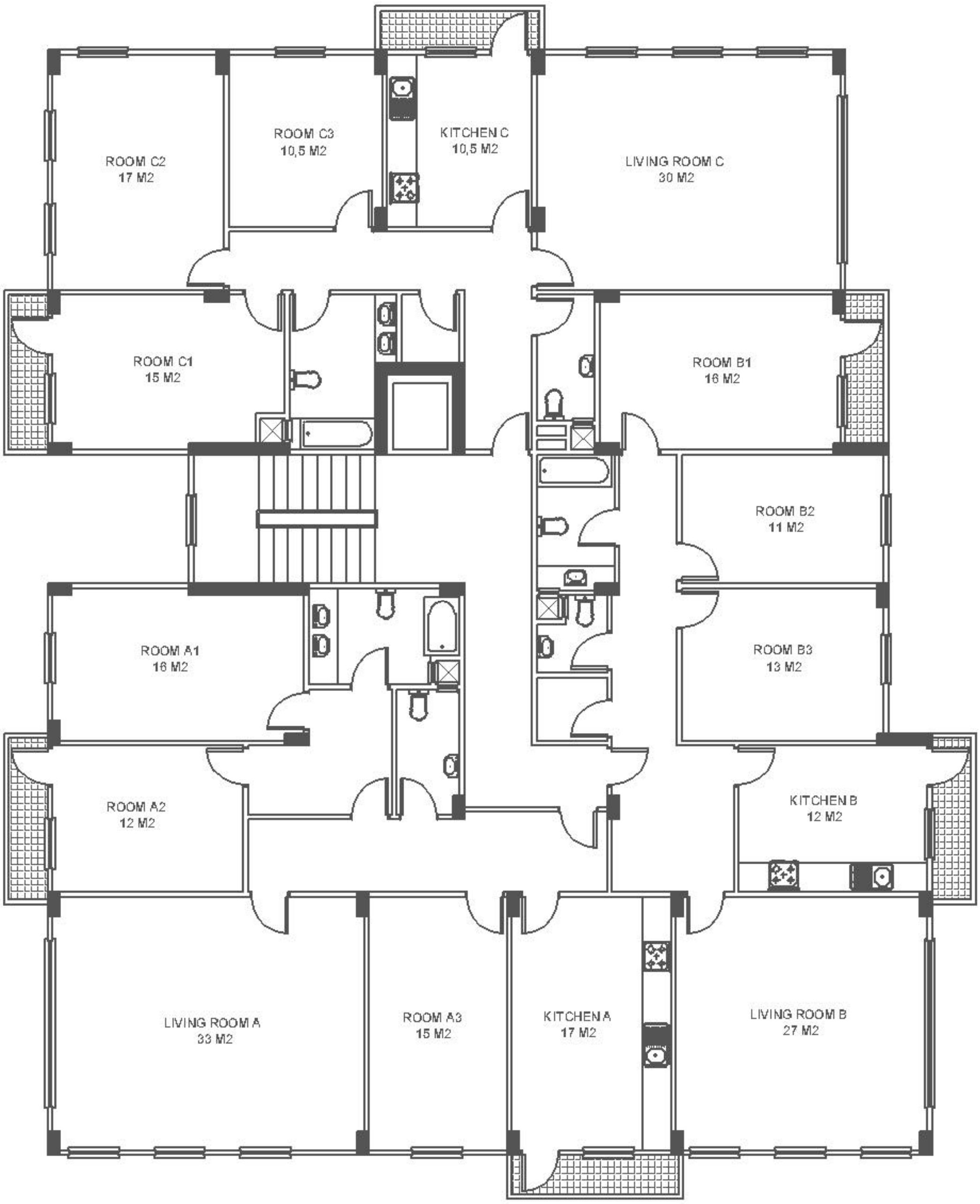

Figure 5.6 Architectural Plan of Model-2 with Irregular Structural System

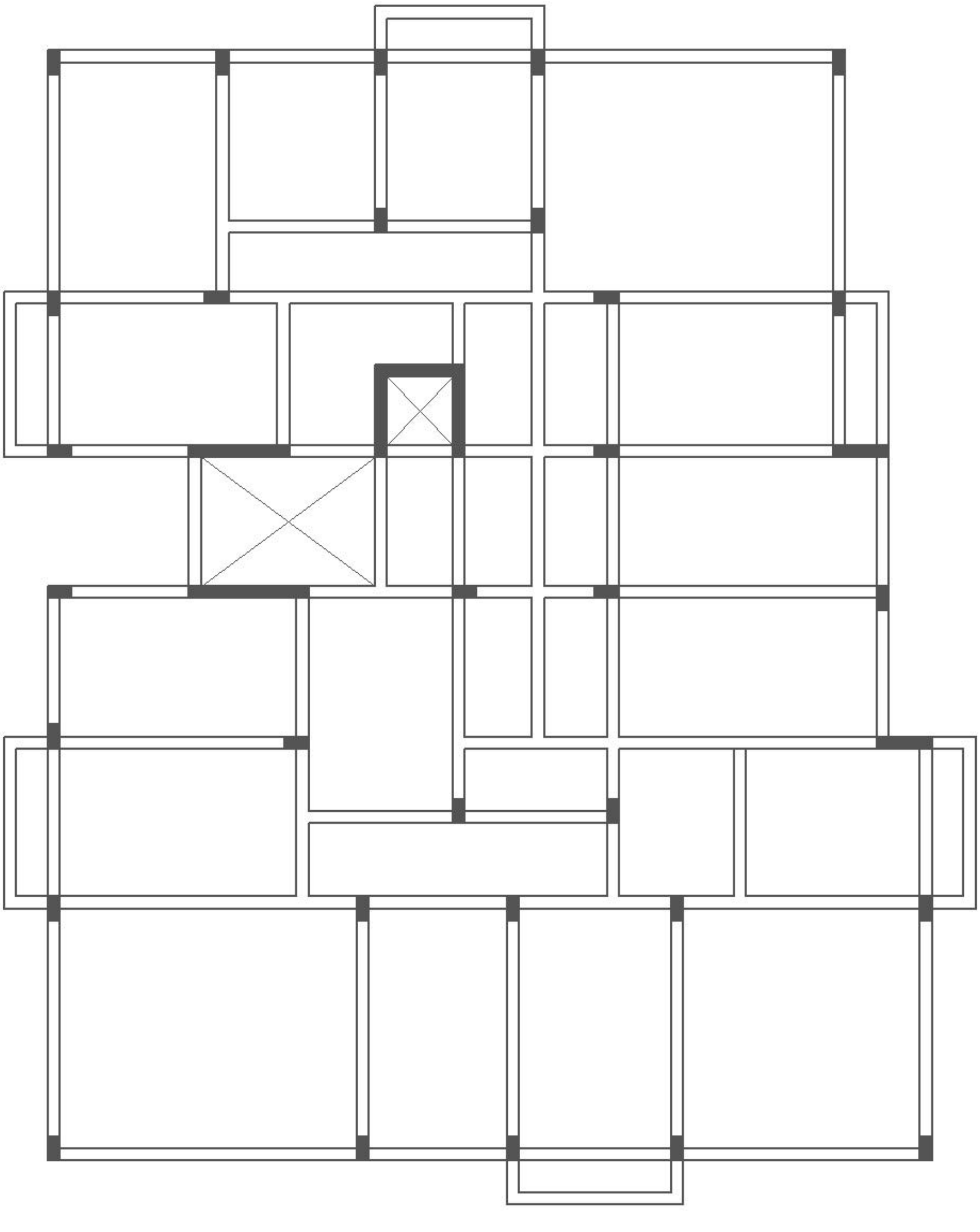

Figure 5.7 Structural Plan of Model-2 with Irregular Structural System

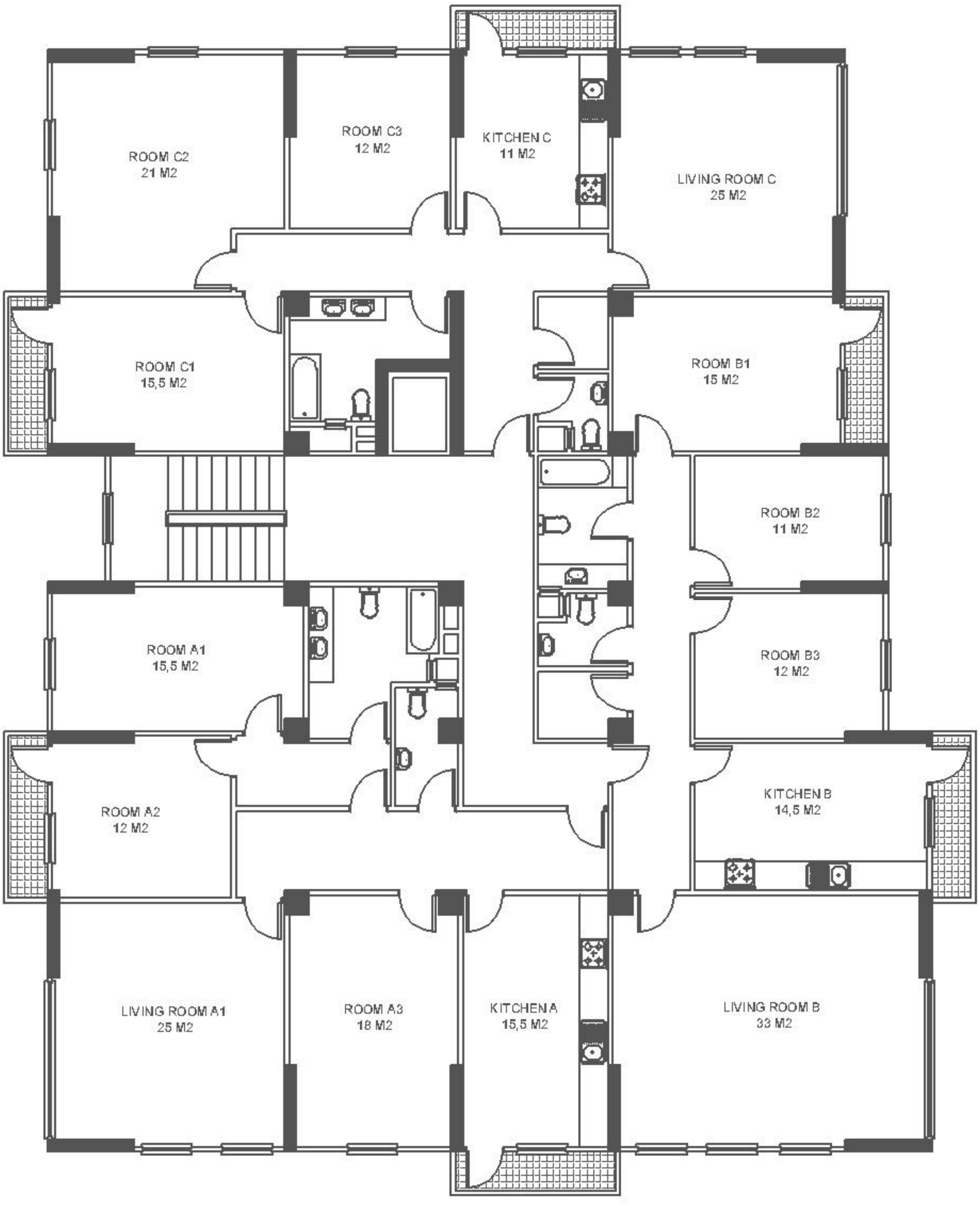

Figure 5.8 Architectural Plan of Model-2 with Regular Structural System

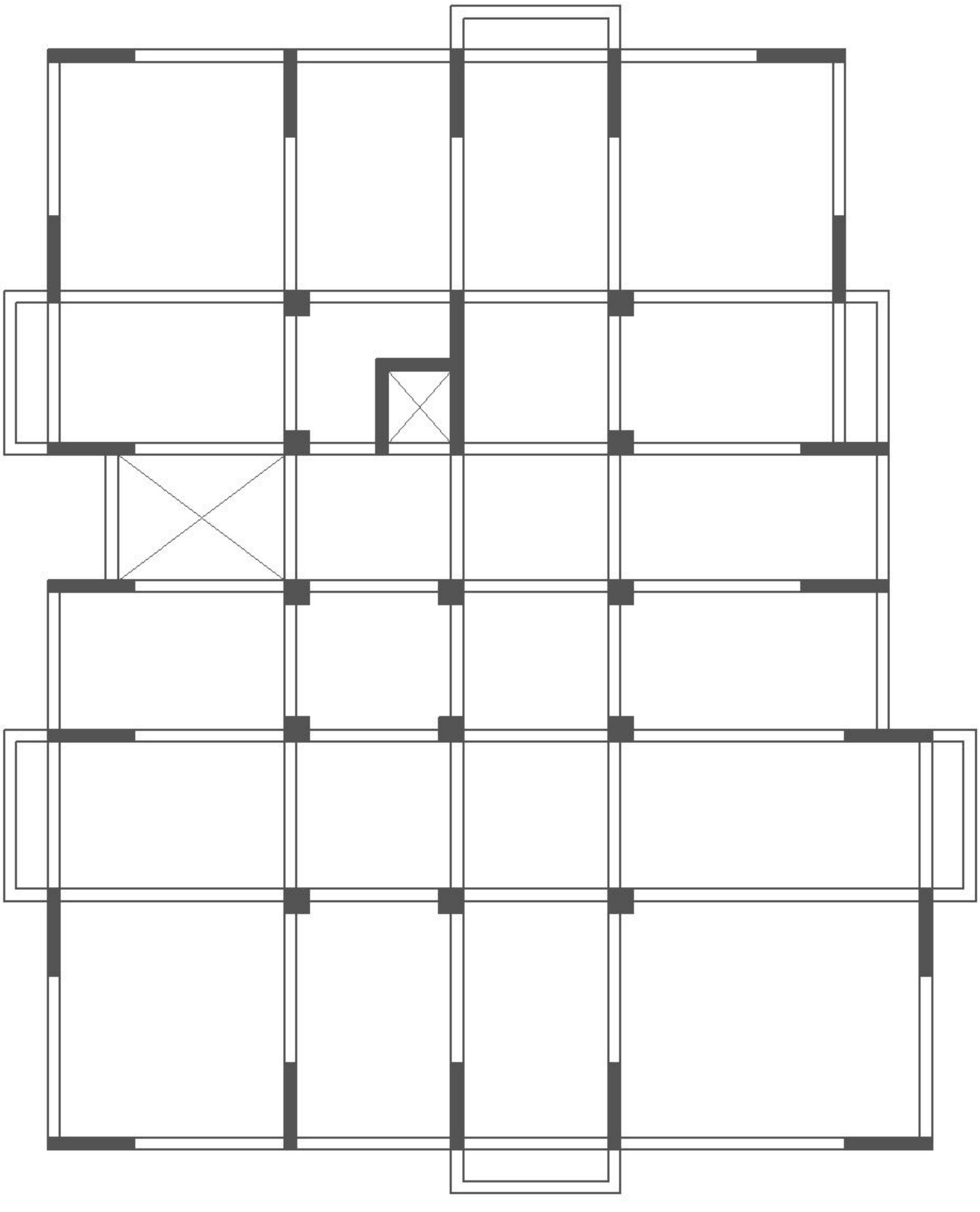

Figure 5.9 Structural Plan of Model-2 with Regular Structural System

Model-2 is based on an actual building which was destroyed in 1999 earthquakes in Bolu. It is a 6 storey R/C building with 3 residential units on each floor. These units are named Unit-A, Unit-B and Unit-C. It is assumed that the ground floor has commercial use and therefore is not a part of this study. In the original plan, all three residential units have 1 living-room, 3 rooms, 1 kitchen, 1 bathroom and 1 toilet. The kitchens and one of the rooms have balconies in all three units. Toilets and bathrooms of all units are located around or near the central axis of the building.[152] (**Figure 5.6**)

In the original configuration, similar with the situation in Model-1, there is an effort to create over-sized living-rooms of equal area for all residential units. This is again the main reason behind the structural irregularity. As a result, the architectural plan and the structural system have several discontinuities in structural axes. Once again, the continuity of the structural system is severely disturbed to prevent the beams being visible over the corridor spaces. There are several beam-to-beam connections without vertical supports which would potentially create large torsion effects on columns.

The effort to configure the structural skeleton according to the individual spatial requirements of every room creates significant asymmetry in the system. In contrast with the general logic of the R/C system designers have tried to place a beam under every partition wall. This increases the number of beam connections without column and increases the irregularity. If the logic behind this effort is to prevent the load of heavy brick walls from acting on slabs, then partition walls can be made of lighter materials such as gypsum wallboards. Today’s material technology allows adequate sound insulation between rooms and even wet-spaces can be constructed with these panels. The earthquake resistance of the structural system also suffers from the lack of shear-walls and columns with insufficient cross-sections. (**Figure 5.7**)

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[152] Graphichs prepared with Autodesk-Autocad Architectural Drafting Software

In the modified plan, the continuity of the structural axes in both directions is provided by designing Living-Room A and C smaller than the original versions but still large enough to accommodate the required functions. Living Room B is larger than it was the original plan. This may compensate whatever marketing disadvantage is caused by the decrease in other units' living rooms. Together with a small modification in the vertical transportation core, a regular structural skeleton is designed without major changes in the original design of the building's architect.[153] (**Figure 5.8**)

Consequently, the structural system was also redesigned in an almost symmetrical configuration. The cross-sections of the columns are enlarged and shear-walls are introduced to the system. Shear-walls are placed in both earthquake directions and distributed evenly throughout the building plan to prevent the creation of torsion effect. The continuity of beams is not broken over corridor spaces. The visual problem can be solved by a suspended ceiling. Due to the shape of the site, the structural elements nearest to the front façade have to have shifting axis. This shift is realized by shear-walls to minimize unwanted torsion effects under earthquake loads. (**Figure 5.9**)

In the modified plan, The floor area of Unit-A has decreased by 7,5 m^2. The area of Living-Room A has decreased by 8 m^2. However, this room is still more than large enough to accommodate the required functions. There is significant increase in the area of Room A3. This compensates the loss in living-room area to a certain degree. There are minor changes in the areas of Rooms A1 & A2. Bathroom is rendered more spacious with a 1 m^2 increase in area. Kitchen A looses 1,5 m^2 without any negative effect to its function. Circulation spaces function in the same manner with the original design, however, 1,5 m^2 less space is lost to circulation in the modified design. Access to view and daylight remains the same with the original plan (**Table 5.5**)

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[153] Graphichs prepared with Autodesk-Autocad Architectural Drafting Software

Table 5.5 Comparison Chart for Unit-A

UNIT-A	**Original**		**Modified**	
Room	**Area (m^2)**	**Access to View (Façade)**	**Area (m^2)**	**Access to View (Façade)**
Living Room	**33**	Rear/Side	**25**	Rear/Side
Rooms				
Room A1	16	Rear	15,5	Rear
Room A2	12	Rear	12	Rear
Room A3	15	Side	18	Side
Sub-Total:	**43**		**45,5**	
Service Spaces				
Kitchen	17	Side	15,5	Side
Bathroom	6	N/A	7	N/A
Toilet	3,5	N/A	3,5	N/A
Circulation	18	N/A	16,5	N/A
Sub-Total:	**44,5**		**42,5**	
Grand Total:	**120,5**		**113**	

In the modified plan, the floor area of Unit-B has increased by 7 m^2. The area of Living-Room B has increased by 6 m^2. This economically compensates for decrease in living room of Unit-A. There are small decreases in the areas of Rooms B1, B2, and B3 but these are not significant enough to disturb the functions of these rooms. With increases in their areas, bathroom, toilet and storage rooms are rendered more spacious and 2 m^2 less space is lost to circulation. Kitchen B gains 2,5 m^2 making it a more comfortable service space. There are no changes in terms of the functioning of circulation spaces. Access to view and daylight remains the same with the original plan. (**Table 5.6**)

Table 5.6 Comparison Chart for Unit-B

UNIT-B	**Original**		**Modified**	
Room	**Area (m^2)**	**Access to View (Façade)**	**Area (m^2)**	**Access to View (Façade)**
Living Room	**27**	Rear/Side	**33**	Rear/Side
Rooms				
Room B1	16	Rear	15	Rear
Room B2	11	Rear	11	Rear
Room B3	13	Side	12	Side
Sub-Total:	**40**		**38**	
Service Spaces				
Kitchen	12	Side	14,5	Side
Bathroom	4,5	N/A	5,5	N/A
Toilet	2	N/A	3	N/A
Storage Room	2	N/A	2,5	N/A
Circulation	15		13	
Sub-Total:	**35,5**		**38,5**	
Grand Total:	**102,5**		**109,5**	

In the modified plan, The floor area of Unit-C has increased by 2,5 m^2. The area of Living-Room C has decreased by 5 m^2. This room was over-sized to begin with and the decrease in the floor area is not large enough to disturb the function. Living Room C is still the largest room in Unit-C. There are significant increases in the areas of Rooms C1, C2, and C3. These compensate more than enough for the loss of floor area in the living room. With increases in their areas, bathroom, and storage rooms are rendered more spacious. There is an insignificant decrease in the area of the toilet. Kitchen C gains 0,5 m^2. There are no major changes in terms of the functioning of circulation spaces. Access to view and daylight remains the same with the original plan. (**Table 5.7**)

Table 5.7 Comparison Chart for Unit-C

UNIT-C	**Original**		**Modified**	
Room	**Area (m^2)**	**Access to View (Façade)**	**Area (m^2)**	**Access to View (Façade)**
Living Room	**30**	Front/Side	**25**	Front/Side
Rooms				
Room C1	15	Rear	15,5	Rear
Room C2	17	Rear/Side	21	Rear/Side
Room C3	10,5	Side	12	Side
Sub-Total:	**42,5**		**48,5**	
Service Spaces				
Kitchen	10,5	Side	11	Side
Bathroom	6	N/A	6,5	N/A
Toilet	3	N/A	2	N/A
Storage Room	1,5	N/A	2	N/A
Circulation	12,5	N/A	13,5	N/A
Sub-Total:	**33,5**		**35**	
Grand Total:	**106**		**108,5**	

An approximate cost analysis has been conducted for the structural system of Model-2 before and after the proposed modifications. The prices have been calculated according to the 2007 unit prices of the Ministry of Public Works and Settlement of Turkey. The cost of the structural system is assumed as 30% of the total building cost. It is also assumed that the remaining 70% non-structural system cost remains the same before and after the modifications. According to this analysis, the structural system cost increases by 15,8% and the total building cost increases by only 4,7% after the proposed modifications. This is an economically acceptable ratio. (**Table 5.8** and **Table 5.9**)

Table 5.8 Cost Analysis for Model-2 with Irregular Structural System

Poz No.	**Work Definition**	**Quantity (m^3, ton, m^2)**	**Unit Price (YTL)**	**Total (YTL)**
16.059	Concrete C25/30)	678 m^3	98,79 YTL	66.979 YTL
21.013	Wrought Shuttering	4746 m^2	16,58 YTL	78.688 YTL
21.054	Supporting Scaffold	7119 m^3	2,34 YTL	16.658 YTL
23.014	Steel (Ø8-12)	19,2 ton	1.451 YTL	27.869 YTL
23.015	Steel (Ø14-28)	28,8 ton	1.373 YTL	39.564 YTL
16.059	Casting Concrete	678 m^3	2,89 YTL	1.959 YTL
Total Structural System Cost (30 % of total building cost): 231.717 YTL				
Total Non-Structural System Cost (70 % of total building Cost): 540.673 YTL				
Total Building Cost: 772.390 YTL				

Table 5.9 Cost Analysis for Model-2 with Regular Structural System

Poz No.	**Work Definition**	**Quantity (m^3, ton, m^2)**	**Unit Price (YTL)**	**Total (YTL)**
16.059	Concrete C25/30)	789 m^3	98,79 YTL	77.945 YTL
21.013	Wrought Shuttering	5523 m^2	16,58 YTL	91.571 YTL
21.054	Supporting Scaffold	8284 m^3	2,34 YTL	19.384 YTL
23.014	Steel (Ø8-12)	22 ton	1.451 YTL	31.934 YTL
23.015	Steel (Ø14-28)	33 ton	1.373 YTL	45.333 YTL
16.059	Casting Concrete	789 m^3	2,89 YTL	2.280 YTL
Total Structural System Cost (30 % of total building cost): 268.447 YTL				
Total Non-Structural System Cost (70 % of total building Cost): 540.673 YTL				
Total Building Cost: 809.120 YTL				

5.4 Model-3: A Reinforced Concrete Apartment Block with Four Residential Units on One Floor

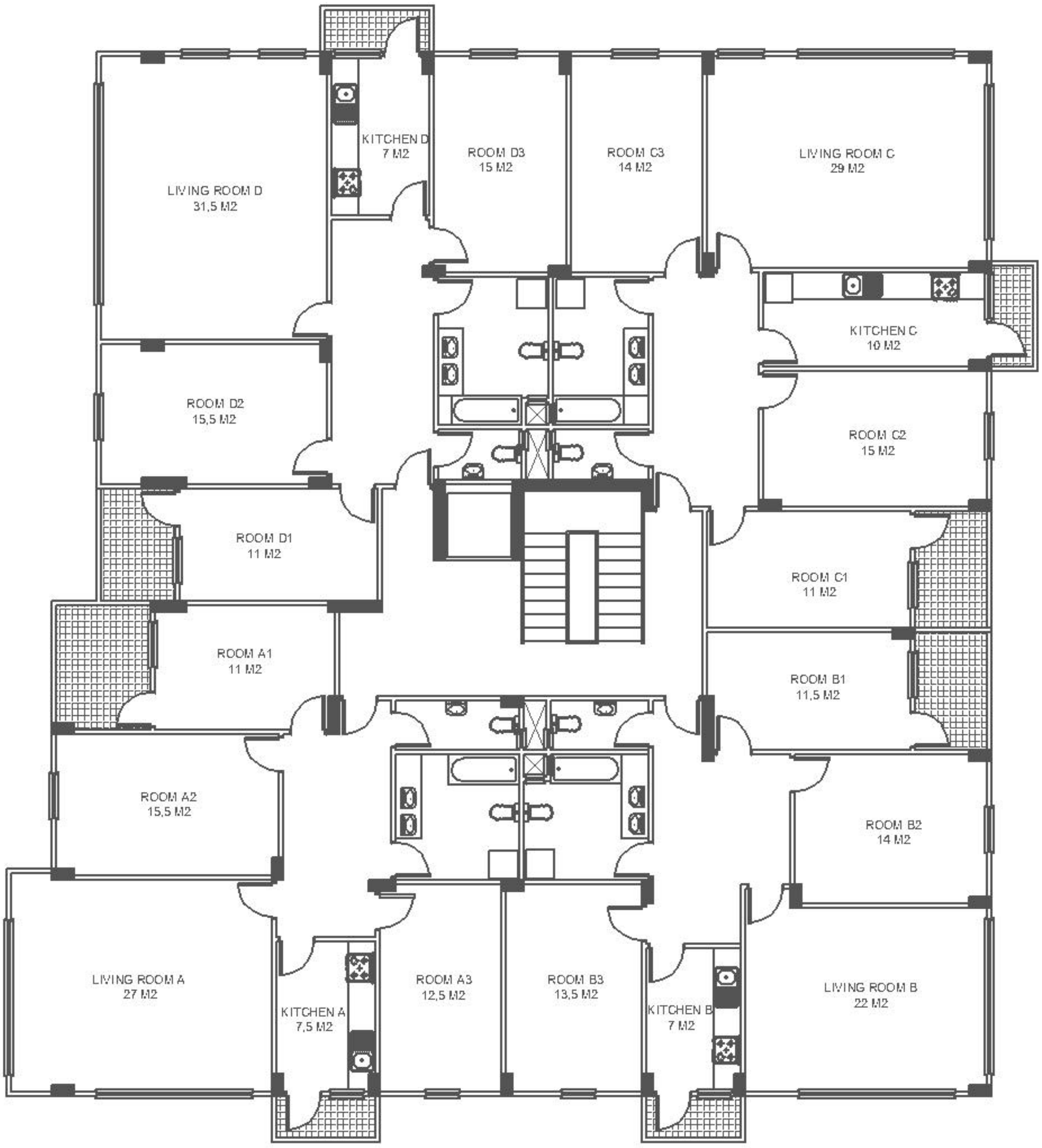

Figure 5.10 Architectural Plan of Model-3 with Irregular Structural System

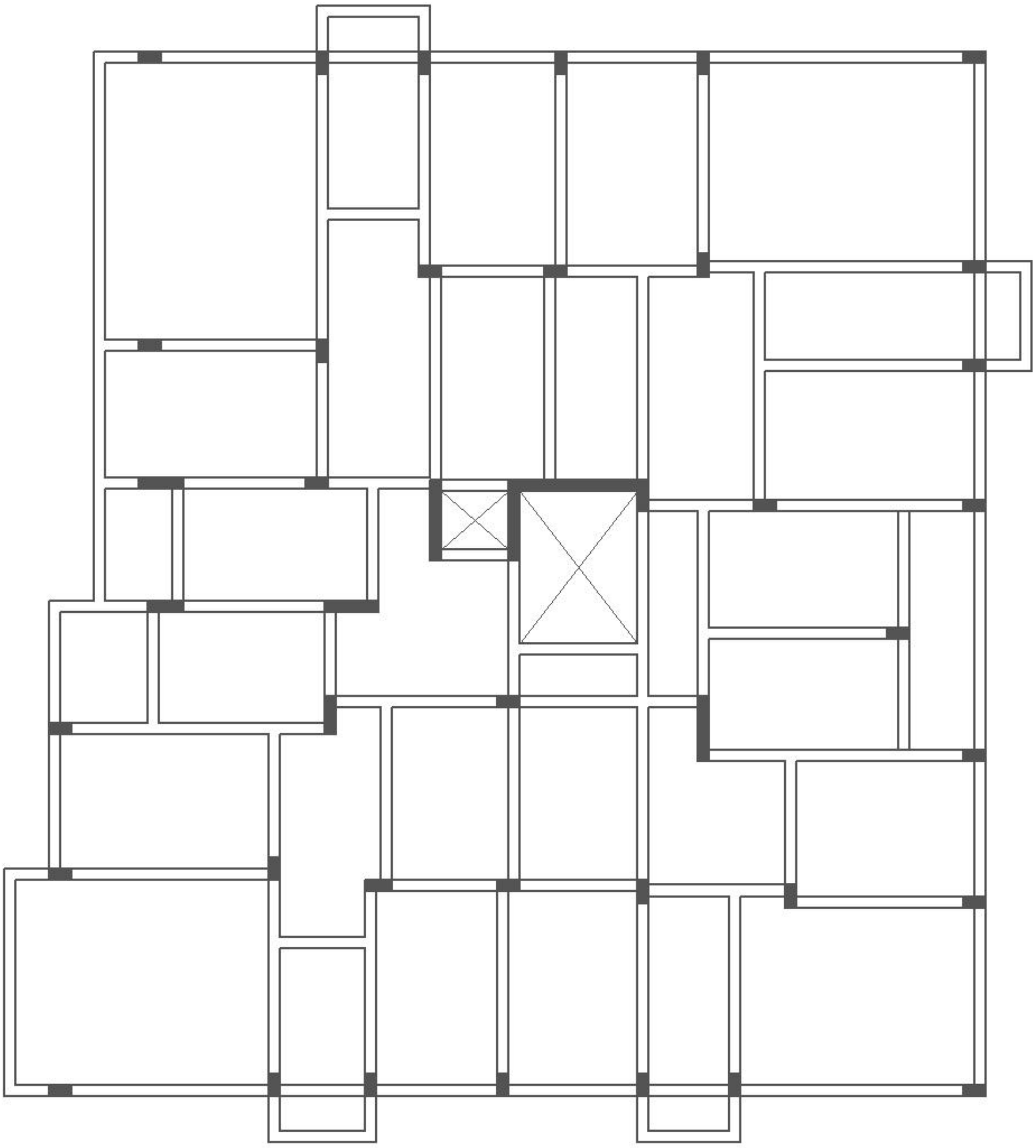

Figure 5.11 Structural Plan of Model-3 with Irregular Structural System

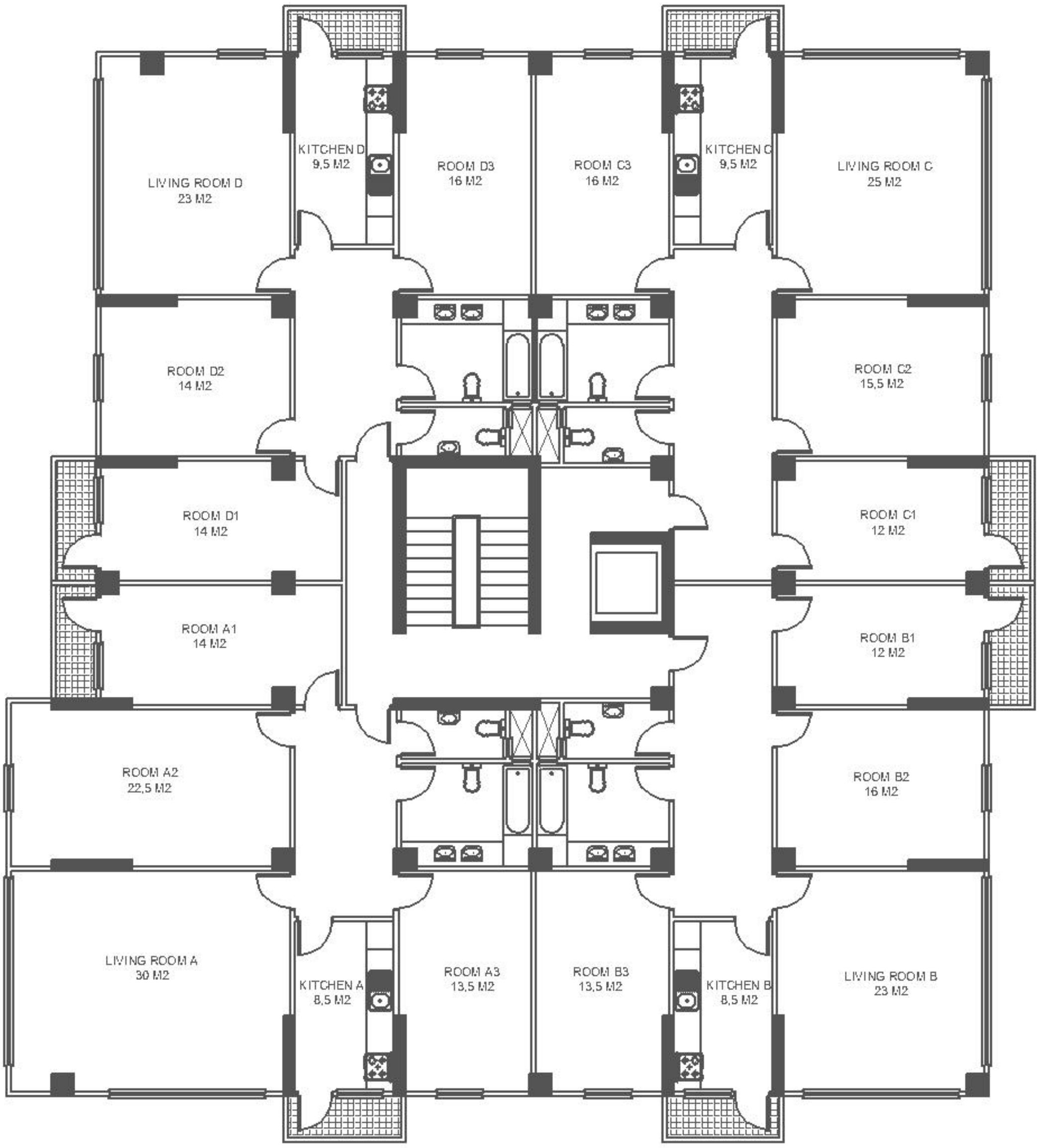

Figure 5.12 Architectural Plan of Model-3 with Regular Structural System

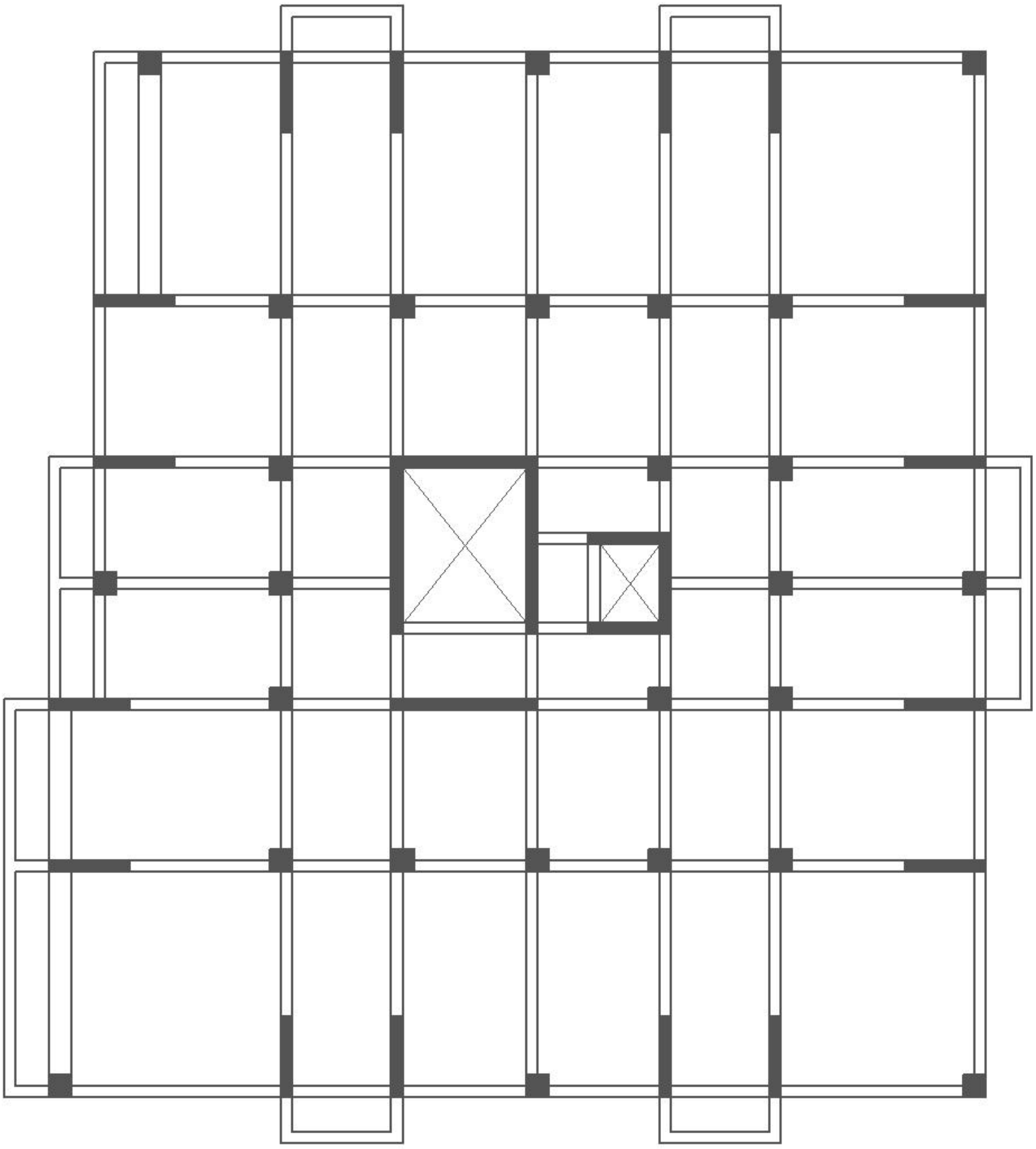

Figure 5.13 Structural Plan of Model-3 with Regular Structural System

Model-3 is based on an actual building which was destroyed in 1999 earthquakes in Bolu. It is a 6 storey R/C building with 4 residential units on each floor. These units are named Unit-A, Unit-B, Unit-C and Unit-D. It is assumed that the ground floor has commercial use and therefore is not a part of this study. In the original plan, all four residential units have 1 living-room, 3 rooms, 1 kitchen, 1 bathroom and 1 toilet. The kitchens and one of the rooms have balconies in all four units. Toilets and bathrooms of all units are located around or near the central axis of the building.[154] (**Figure 5.10**)

In the original configuration, similar with the situation in Model-1 and Model-2, there is an effort to create over-sized living-rooms for all residential units. This is again the main reason behind the structural irregularity. As a result, the architectural plan and the structural system have several discontinuities in structural axes. Similar with previous models, the continuity of the structural system is severely disturbed to prevent the beams being visible over the circulation spaces. There are several beam-to-beam connections without vertical supports which would potentially create large torsion effects on columns.

The effort to configure the structural skeleton according to the requirements of every room creates asymmetry. This is the result of designing the structural system after the completion of the architectural design phase. If two systems were designed together in an interactive process, there would not be such compromises in the seismic resistance of the building. The earthquake resistance of the structural system also suffers from the lack of shear-walls and columns with insufficient cross-sections. The design of balconies as alcoves inserted into the building mass also creates irregularities in the R/C skeleton system. Generally, projections are considered as undesired elements in terms of seismic behavior but in this case designing the balconies as alcoves is more disturbing to the seismic behavior of the building. (**Figure 5.11**)

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[154] Graphichs prepared with Autodesk-Autocad Architectural Drafting Software

In the modified plan, the continuity of the structural axes in both directions is provided by designing Living-Room C and D smaller than the original versions but still large enough to accommodate the required functions. Living Room A and B are larger than they were the original plan. This may compensate whatever marketing disadvantage is caused by the decrease in other units' living rooms. Together with the standardization of room widths, change in the location of Kitchen C and a redesign of the vertical transportation core, a regular structural skeleton is designed without major changes in the original design of the building's architect.[155] (**Figure 5.12**)

Consequently, the structural system was also redesigned in an almost symmetrical configuration. The cross-sections of the columns are enlarged and shear-walls are introduced to the system. Shear-walls are placed in both earthquake directions and distributed evenly throughout the building plan to prevent the creation of torsion effect. The continuity of beams is not broken over circulation spaces. Due to the shape of the site, the structural elements nearest to the front façade have to have shifting axis. This shift is realized by shear-walls to minimize unwanted torsion effects under earthquake loads. (**Figure 5.13**)

In the modified plan, The floor area of Unit-A has increased by 12,5 m^2, making this unit more valuable in marketing terms. The area of Living-Room A has increased by 3 m^2. There are significant increases in the areas of Room A1, A2 and A3. This is achieved by regaining the floor area lost by the design of balconies as alcoves. There are insignificant decreases in bathroom and toilet areas. These losses do not disturb the function of these spaces. Kitchen A gains 1 m^2 making it a more spacious service space. Circulation spaces function in the same manner with the original design, however, 1,5 m^2 less space is lost to circulation in the modified design. Access to view and daylight remains the same with the original plan (**Table 5.10**)

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[155] Graphichs prepared with Autodesk-Autocad Architectural Drafting Software

Table 5.10 Comparison Chart for Unit-A

UNIT-A	**Original**		**Modified**	
Room	**Area (m^2)**	**Access to View (Façade)**	**Area (m^2)**	**Access to View (Façade)**
Living Room	**27**	Front/Side	**30**	Front/Side
Rooms				
Room A1	11	Front	14	Front
Room A2	15,5	Front	22,5	Front
Room A3	12,5	Side	13,5	Side
Sub-Total:	**39**		**50**	
Service Spaces				
Kitchen	7,5	Side	8,5	Side
Bathroom	7,5	N/A	7	N/A
Toilet	3	N/A	2,5	N/A
Circulation	11,5	N/A	10	N/A
Sub-Total:	**29,5**		**28**	
Grand Total:	**95,5**		**108**	

In the modified plan, The floor area of Unit-B has increased by 6,5 m^2, making this unit more valuable in marketing terms. The area of Living-Room B has increased by 1 m^2. There are small increases in the areas of Room B1, B2 and B3. This is achieved by regaining the floor area lost by the design of balconies as alcoves. There are insignificant decreases in bathroom and toilet areas. These losses do not disturb the function of these spaces. Kitchen B gains 1,5 m^2 making it a spacious service space. Circulation spaces function in the same manner with the original design. 2,5 m^2 more space is lost to circulation in the modified design. This does not create disadvantage since there are area gains in other rooms. Access to view and daylight is the same with the original plan (**Table 5.11**)

Table 5.11 Comparison Chart for Unit-B

UNIT-B	**Original**		**Modified**	
Room	**Area (m^2)**	**Access to View (Façade)**	**Area (m^2)**	**Access to View (Façade)**
Living Room	**22**	Rear/Side	**23**	Rear/Side
Rooms				
Room B1	11,5	Rear	12	Rear
Room B2	14	Rear	16	Rear
Room B3	13,5	Side	13,5	Side
Sub-Total:	**39**		**41,5**	
Service Spaces				
Kitchen	7	Side	8,5	Side
Bathroom	7,5	N/A	7	N/A
Toilet	3	N/A	2,5	N/A
Circulation	13,5	N/A	16	N/A
Sub-Total:	**31**		**34**	
Grand Total:	**92**		**98,5**	

In the modified plan, The floor area of Unit-C has increased by 3,5 m^2, making this unit more valuable in marketing terms. The area of Living-Room C has decreased by 4 m^2. The decrease in the floor area is not large enough to disturb the function. There are increases in the areas of Room C1, C2 and C3. This is achieved by regaining the floor area lost by the design of balconies as alcoves. The areas of bathroom and toilet remain the same. However, Kitchen C is relocated from the rear façade to the side façade. Additionally, Kitchen C looses 0,5 m^2 which is insignificant in terms of use. Circulation spaces function in the same manner with the original design, however, 4,5 m^2 more space is lost to circulation in the modified design. Access to view and daylight remains the same with the original plan except the kitchen. (**Table 5.12**)

Table 5.12 Comparison Chart for Unit-C

UNIT-C	**Original**		**Modified**	
Room	**Area (m^2)**	**Access to View (Façade)**	**Area (m^2)**	**Access to View (Façade)**
Living Room	**29**	Rear/Side	**25**	Rear/Side
Rooms				
Room C1	11	Rear	12	Rear
Room C2	15	Rear	15,5	Rear
Room C3	14	Side	16	Side
Sub-Total:	**40**		**43,5**	
Service Spaces				
Kitchen	10	Rear	9,5	Side
Bathroom	7	N/A	7	N/A
Toilet	2,5	N/A	2,5	N/A
Circulation	12	N/A	16,5	N/A
Sub-Total:	**31,5**		**35,5**	
Grand Total:	**100,5**		**104**	

In the modified plan, the floor area of Unit-D has decreased by 7 m^2. The area of Living-Room D has decreased by 8,5 m^2. However, this room is still more than large enough to accommodate the required functions. There are significant increases in the areas of Room D1 and D3. This compensates the loss in living-room area to a certain degree. There is a 1,5 m^2 loss in the area of Room D2. There areas of bathroom and toilet remain the same. Kitchen D gains 2,5 m^2 making it a more spacious service space. Circulation spaces function in the same manner with the original design, however, 3,5 m^2 less space is lost to circulation in the modified design. Access to view and daylight remains the same with the original plan. (**Table 5.13**)

Table 5.13 Comparison Chart for Unit-D

UNIT-D	**Original**		**Modified**	
Room	**Area (m^2)**	**Access to View (Façade)**	**Area (m^2)**	**Access to View (Façade)**
Living Room	**31,5**	Front/Side	**23**	Front/Side
Rooms				
Room D1	11	Front	14	Front
Room D2	15,5	Front	14	Front
Room D3	15	Side	16	Side
Sub-Total:	**41,5**		**44**	
Service Spaces				
Kitchen	7	Side	9,5	Side
Bathroom	7	N/A	7	N/A
Toilet	2,5	N/A	2,5	N/A
Circulation	13,5	N/A	10	N/A
Sub-Total:	**30**		**29**	
Grand Total:	**103**		**96**	

An approximate cost analysis has been conducted for the structural system of Model-3 before and after the proposed modifications. The prices have been calculated according to the 2007 unit prices of the Ministry of Public Works and Settlement of Turkey. The cost of the structural system is assumed as 30% of the total building cost. It is also assumed that the remaining 70% non-structural system cost remains the same before and after the modifications. According to this analysis, the structural system cost increases by 24,9% and the total building cost increases by only 7,4% after the proposed modifications. This is an economically acceptable ratio. (**Table 5.14** and **Table 5.15**)

Table 5.14 Cost Analysis for Model-3 with Irregular Structural System

Poz No.	**Work Definition**	**Quantity (m^3, ton, m^2)**	**Unit Price (YTL)**	**Total (YTL)**
16.059	Concrete C25/30)	777 m^3	98,79 YTL	76.760 YTL
21.013	Wrought Shuttering	5439 m^2	16,58 YTL	90.178 YTL
21.054	Supporting Scaffold	8158 m^3	2,34 YTL	19.089 YTL
23.014	Steel (Ø8-12)	22 ton	1.451 YTL	31.934 YTL
23.015	Steel (Ø14-28)	33 ton	1.373 YTL	45.533 YTL
16.059	Casting Concrete	777 m^3	2,89 YTL	2.245 YTL
Total Structural System Cost (30 % of total building cost): 265.539 YTL				
Total Non-Structural System Cost (70 % of total building Cost): 619.591 YTL				
Total Building Cost: 885.130 YTL				

Table 5.15 Cost Analysis for Model-3 with Regular Structural System

Poz No.	**Work Definition**	**Quantity (m^3, ton, m^2)**	**Unit Price (YTL)**	**Total (YTL)**
16.059	Concrete C25/30)	975 m^3	98,79 YTL	96.320 YTL
21.013	Wrought Shuttering	6.825 m^2	16,58 YTL	113.158 YTL
21.054	Supporting Scaffold	10.237 m^3	2,34 YTL	23.954 YTL
23.014	Steel (Ø8-12)	27,2 ton	1.451 YTL	39.482 YTL
23.015	Steel (Ø14-28)	40,8 ton	1.373 YTL	56.049 YTL
16.059	Casting Concrete	975 m^3	2,89 YTL	2.817 YTL
Total Structural System Cost (30 % of total building cost): 331.780 YTL				
Total Non-Structural System Cost (70 % of total building Cost): 619.591 YTL				
Total Building Cost: 951.371 YTL				

5.5 Evaluation of The Results Obtained from Comparative Architectural Study

A set of three architectural projects chosen among buildings destroyed in Bolu city center due to the 1999 earthquakes were studied in this chapter in terms of earthquake resistant design. Projects were subjected to a comparative evaluation between their original states and the modified seismically resistant versions. The modifications to make the buildings earthquake resistant were made in the light of the principles proven to be valid in Chapter 4. The architectural comparison between earthquake resistant and non-resistant states was made on a planimetric level, meaning according to floor area; size, location and number of rooms; and access to view. The evaluation was also supported by an approximate cost analysis to prove the economic feasibility of proposed changes. The following conclusions were reached as a result of the architectural evaluation:

- The study has demonstrated that it is possible to design R/C residential buildings in a seismically resistant manner without significant changes in the architectural characteristics.

- The principles demonstrated in Chapter 4 for idealized models and small residential buildings are applicable to larger R/C residential buildings.

- The principal reason why structural irregularities occur in R/C residential buildings is because architects do not consider preliminary design of the structural system as their responsibility. Structural configuration is decided after the architectural design phase is completed. The sizes and locations of columns are decided according to the individual spatial requirements of every room. The resulting R/C skeleton is an irregular grid which is most of the time deficient in terms of seismic resistance.

- In many occasions, structural irregularities are created by aesthetic concerns. To prevent beams and columns being visible especially in circulation spaces and living rooms discontinuous structural axes are created or column cross-sections are designed too small for earthquake resistance. Aesthetic concerns can not be overlooked by architects because beauty is one of the main requirements of architectural design. However, designing R/C buildings in a seismically safe manner should be important too. Firmness is also one of the main requirements of architecture. Large column cross-sections and overhanging beams can be dealt with using modern building materials such as gypsum board panels.

- Architectural elements such as over-sized living rooms are often designed to increase the market appeal of R/C apartment blocks. The difference in scale of these rooms with the rest of the units usually creates structural irregularities. Often, the space requirements of the functions attributed to these rooms can be solved in smaller volumes. Furthermore, the increase in the size of the living room is generally at the expense of the rest of the rooms. In the comparative study, it is observed that in earthquake resistant versions of the models, there is a better balance between the living-room and the rest of the rooms in terms of floor area.

- The design of the R/C structural system according to earthquake resistant design principles causes an economically acceptable rise within the range of 4-8% in the overall building cost. Since the earthquake survivability of these buildings without major damage is very high, it can be assumed that there will be no further repair and strengthening costs during the lifetime of these buildings. This further increases the economic feasibility of these structures.

CHAPTER 6

CONCLUSION

6.1 Summary

The aim of this thesis is to demonstrate that it is possible to design earthquake resistant Reinforced Concrete (R/C) residential buildings within economically feasible limits and without significant compromises in the aesthetic, functional and spatial quality of the architectural project. The main audiences of this thesis are architects and students of architecture. This thesis approaches the topic of earthquake resistant design from both structural and architectural points of view. Since this thesis is written by an architect for architects, the structural discussions are kept within a behavioral perspective. The aim is not to make precise calculations for specific cases but demonstrate the working principles of basic concepts governing the seismic behavior of R/C apartment structures.

Within this framework, the first objective was to establish the architectural context for the problem at hand. Architectural design is never independent from its surroundings. It is an interactive process taking place in the present time however; it is rooted firmly in the past and its products inevitably affect the future. Therefore the first task was to make a compelling case for the architects that the task of structural design is well within their domain of responsibility. This was achieved first by describing the historical development of architectural and structural engineering professions. It was stated that although these are separate professions today, this was not always the case and due to the nature of the construction business these two domains will always be inevitably intertwined.

The second step was to demonstrate the differences and similarities of meaning for the concept of design from architectural and engineering points of view. Since the members of these professions are destined to work together, they should have an understanding of each others concerns. Finally, the architectural design process was explored in detail to demonstrate that the preliminary design of the structural system was an inseparable part of the architectural design and therefore well within the scope of responsibilities of architects.

This thesis focuses on the R/C residential apartment block typology; therefore it is essential to demonstrate why the earthquake resistant design of this type of building is especially important in Turkey. Since the emergence of R/C apartment block is directly related with the urbanization movement in Turkey, it was important to state a brief history and the governing characteristics of this phenomenon along with the reasons why R/C apartment blocks will continue to be the dominant building type in Turkey for the foreseeable future.

The nature of the earthquake phenomenon and the seismic characteristics of Turkey are also an integral part of the context for this study. It is critical to demonstrate how earthquakes happen and specifically how they happen in Turkey to understand how they affect the built environment. This is why the fundamental definitions about earthquakes and the seismic history of Turkey were reviewed in this thesis. A specific emphasis was made to the seismic characteristics of the city of Bolu. This middle-sized Turkish city which is located directly on the North Anatolian Fault was selected for the field study from which the sample projects used in structural analysis and architectural discussions were obtained.

The Turkish Earthquake Code is the main legal document that sets the framework for the construction of earthquake resistant buildings in Turkey. Therefore it is critical to understand the underlying principles of this code. Since the Turkish Earthquake Code primarily addresses the engineering audience, it is necessary for architects to understand which portions of the code is directly related with their design work. This why a brief overview of the 2007 Specification for Structures to be Built in Earthquake Areas was conducted to underline the portions of the code most relevant to architectural design process.

After the establishment of the architectural context, it was necessary to provide basic definitions about the nature of R/C both in terms of material properties and characteristics of its seismic behavior. The architectural audience was provided with the fundamental concepts about the definition of earthquake load, the interaction between architectural design and seismic resistance and the governing principles of the seismic behavior of R/C structures.

Since the thesis also contains a chapter which consists of a comparative analytical study of the seismic behavior of various R/C structures, it was also necessary to offer the architectural audience tools to measure and compare the seismic performance of R/C structures. That is why the concept of natural behavior, the effects of excessive lateral displacements and the function of column interaction diagrams were explained in a manner suitable for the understanding of architects. Additionally, the audience was provided with information about the types of commonly encountered seismic design faults in plan for R/C structures.

The working principles of these seismic design faults was demonstrated through an analytical process during which a set of 7 models, 5 designed as idealized parametric models and 2 based on actual buildings, were tested. The models were prepared according to the principles stated in Chapter 3 and the results were evaluated according to three criteria including the natural period, maximum displacements and column load-carrying capacities. The results of this analytical process have demonstrated that the direction of columns has a significant effect on the level of stiffness of the overall structural system. Designing larger and stronger cross-sections for columns also significantly improves the seismic behavior of the structure in terms of natural period, displacements and load-carrying capacity. However, using larger columns is not enough by itself to make a structure earthquake resistant. The use of an adequate amount of evenly distributed shear-walls is necessary to ensure earthquake safety.

It was also demonstrated that beam-to-beam connections without vertical support has introduced undesired torsion effects in the system and must be avoided if possible. The principles of seismic design, demonstrated in idealized parametric models were also effective when applied in actual building structures. The seismic behavior of R/C apartment structures could be significantly improved if the design of the structural system were realized simultaneously with the architectural design phase.

The architectural implications of the structural principles of seismic design were demonstrated on a set of 3 architectural projects chosen among buildings destroyed in Bolu city center due to the 1999 earthquakes. Projects were subjected to a comparative evaluation between their original states and the modified seismically resistant versions. The modifications to make the buildings earthquake resistant were made in the light of the principles proven to be valid in Chapter 4. The architectural comparison between earthquake resistant and non-resistant states was made on a planimetric level, meaning according to floor area; size, location and number of rooms; and access to view.

The study has demonstrated that it is possible to design R/C residential buildings in a seismically resistant manner without significant compromises in the architectural characteristics. The principles demonstrated for idealized models and small residential buildings were applicable to larger R/C buildings. The feasibility of seismically resistant R/C residential blocks was demonstrated through an approximate cost analysis which has proven that designing earthquake resistant structures only resulted in an acceptable 4-8% rise in the overall building cost.

6.2 Concluding Remarks

According to the results of the 2000 Building Census there were 7.838.645 buildings in Turkey. Among these buildings, 5.872.808 were used exclusively as residential buildings and there were an additional 863.005 mixed-used buildings in which residential use constituted the majority. Considering the pace of the ongoing urbanization movement in the country, it is only logical to assume that these numbers have significantly increased since the 2000 census. These statistics demonstrate that there is a thriving building market in Turkey. This environment presents a great opportunity for architects, structural engineers and other building professionals to create remarkable achievements in architecture and construction. The statistics also show that the design of residential buildings does and will constitute the largest portion of architectural activities in Turkey.[156]

However, there is also a grim aspect to the statistics. Numbers also state that during the catastrophic 1999 earthquakes 34.275 residential buildings were completely destroyed in Kocaeli killing nearly 10.000 people, 16.666 residential buildings collapsed in Düzce costing the lives of nearly 1.000 people and 2.399 residential buildings were destroyed in Bolu with significant human losses. What these numbers tell is that the fact that there is a lot of building work does not mean that these works should be realized in a way which jeopardizes human lives. Earthquakes will always be a reality of living and building in Turkey. It is the responsibility of everyone involved in construction business to do their part to prevent disastrous outcomes causing similar statistical results.[157]

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[156] Building Census 2000, Turkish Statistical Institute-Türkiye İstatistik Kurumu Yayınları, Ankara, 2001, ISBN 975-19 2819 – 2

[157] 1999 Bolu Depremi Kayıpları, http://www.bolu.gov.tr, Last Accessed Date: 15 March 2008

The aim of this thesis is to demonstrate that designing earthquake resistant reinforced concrete residential buildings does not necessarily mean spending enormous amounts of money or creating compromised and inefficient architectural designs. Of course building an earthquake resistant structural system will require additional efforts in the design process, construction phase and expenditures. Some aspects of seismic design may pose new challenges to architects in terms of spatial arrangement or architectonic qualities of their buildings. However, this thesis demonstrates that there is a viable solution to all of these problems within architecturally and economically acceptable limits. In any case, if one remembers that the alternative to constructing seismically resistant buildings means the loss of human lives, it should be easy to conclude that there is simply no alternative at all. It is the professional and ethical duty of everyone to make buildings safe for their occupants.

It is fortunate to see that, in recent years, the principles of earthquake resistant design are being applied in the building practice in Turkey, and especially in the cities on seismic zones. The field study conducted in Bolu has revealed that the designers in this town have begun to create their projects according to the principles which were advocated in this thesis. Buildings with structural irregularities in their plans are leaving their places to seismically resistant structures. (**Figure 6.1** and **Figure 6.2**) Even though with the fading of the memories of the 1999 earthquakes, builders become bolder and the number of storeys increase, seismic safety measures such as attention to the continuity of structural axes, the use of columns with large cross-sections and utilization of shear-walls are not forgotten in newly built projects. (**Figure 6.3**)

The effort of this thesis is to effectively play its role in the education of the present and future generations of architects about a topic as crucial as seismic design. In Turkey, fine architecture should mean earthquake resistant architecture.

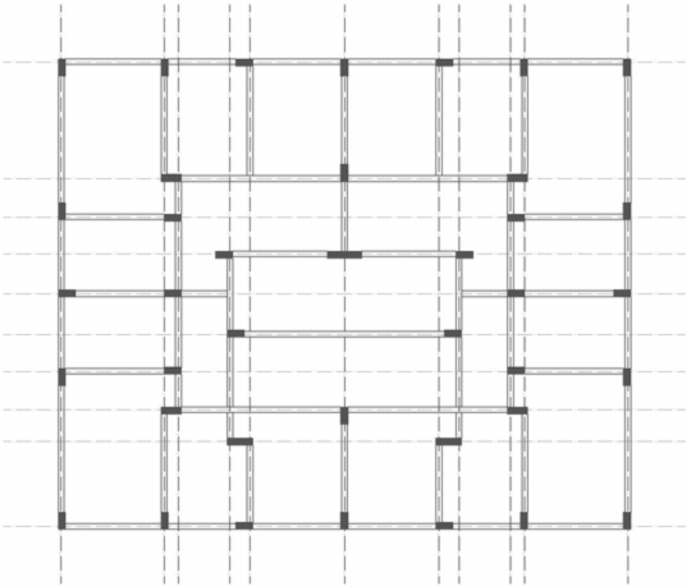

Figure 6.1 A Building in Bolu with Irregular Structural System before 1999

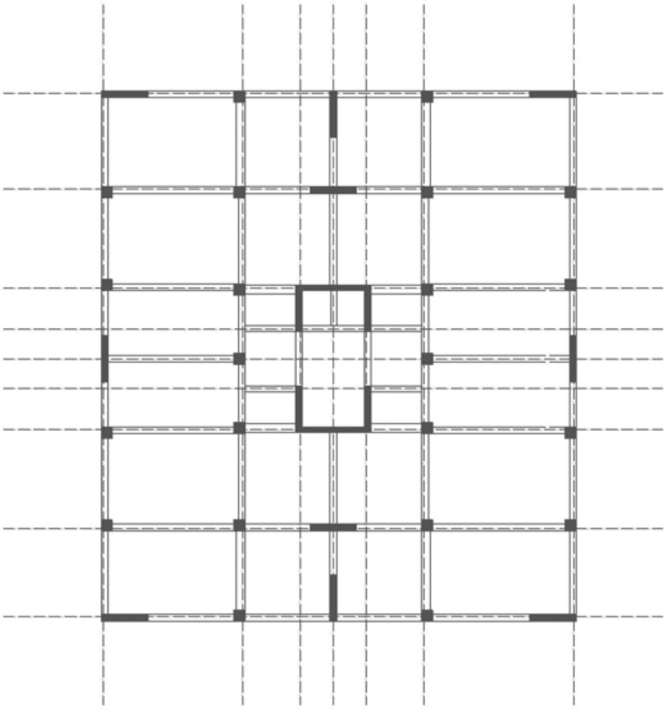

Figure 6.2 A Building in Bolu with Regular Structural System 2008

Figure 6.3 A Building Construction in Bolu with Regular Structural System 2008

6.3 Proposals for Further Studies

This thesis should be considered as a continuation of the efforts which have begun in the master thesis submitted to Middle East Technical University in June 2002 by the same author titled “Commonly Encountered Seismic Design Faults in Reinforced Concrete Residential Architecture in Turkey”. In that thesis the objective was to prepare a concise catalogue, for architects, of design faults to avoid and of design features to include in their projects in order to provide seismic resistance. That thesis was a document based on the observations conducted in the immediate aftermath of 1999 earthquakes.

The aim of this thesis is to take the study one step further and demonstrate the validity of the mentioned principles by actively engaging in the process of structural and architectural design. In other words, bring the theoretical principles within the realm of reality and demonstrate that all of them are applicable in professional practice. However, because this thesis addresses the present situation in the building market, the discussion had to stay within the scope of conventional design practices. The proposed structural and architectural principles address the present way of building R/C residential buildings.

Future studies in this subject may address more innovative ways of utilizing the R/C structural system in residential architecture. The material and structural properties of R/C can be explored in detail within the light of the latest scientific developments throughout the world. New typologies of seismically resistant residential buildings can be developed. The established living format of the Turkish middle-class can be critically analyzed in terms of seismic design requirements. Radical spatial solutions which may even suggest changes in the way Turkish people use their residences can be offered. The next step should include thinking outside the conventional notions.

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