T.C.

İSTANBUL KÜLTÜR UNIVERSITY

INSTITUTE OF GRADUATE STUDIES

LIFE CYCLE ASSESSMENT OF REINFORCED CONCRETE BUILDINGS IN SEISMIC REGIONS

Masters of Applied Science Thesis

Zabihullah Halim

1700001076

Department: Civil Engineering

Programme: Structural Engineering

Supervisor: Assist. Prof. Dr. Erdal COŞKUN

JUNE 2021

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ABSTRACT

LIFE CYCLE ASSESSMENT OF REINFORCED CONCRETE BUILDINGS IN SEISMIC REGIONS

Zabihullah Halim

The structural engineering profession has been developed significantly over the last decades as new systems, design methods, and other integrated approaches come to the field. From the 1950s and 60s onwards, cities throughout the world have expanded rapidly, high rise buildings increased, and cities expanded their occupied areas; in such circumstances, serious demand for sustainable development approaches can be observed, such as needs for setting some standards applicable in the local and global level. An integrated approach can help us properly address these debated issues.

Experts from the sustainability field point out that materials and energy resources are limited, and the construction sector consumes a large portion of these remaining resources unquestionably. These points should be the main motivation for insisting on sustainable development approaches. However, it is a well-known fact that structural design engineers do not have a fundamental role in sustainable construction topics yet.

Many approaches mainly focus on some specific topics of sustainability like environment and economy, whilst there is a need for an integrated approach to maintain a balance between all components of sustainability. There are many challenges that structural engineers face now a day, but the global environmental challenge is the most prominent of them.

Within the scope of this thesis, it is aimed to determine and define how buildings in seismic regions affect sustainability by comparing steel and reinforced concrete frame structures. This comparison will be made using Athena Impact Estimator and SAP2000 by taking into account the environmental effects for the entire life cycle of reinforced concrete and steel frames in seismic regions.

Keywords: Reinforced Concrete, Buildings, Seismic Regions, Sustainability, Environmental Impacts, Greenhouse gases, Athena Impact Estimator

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KISA ÖZET

SİSMİK BÖLGELERDE BETON BİNALARININ YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ

Zabihullah Halim

Yapı mühendisliği; yeni sistemler, tasarım yöntemleri ve diğer entegre yaklaşımlar sayesinde son on yılda önemli ölçüde gelişim göstermiştir. 1950'li ve 60'lı yıllarından itibaren çok katlı yapıların sayısının artması ve yerleşim alanlarının genişlemesi ile dünya çapında şehirler hızlı bir gelişme kaydetmiştir. Bu gibi durumlarda, yerel ve küresel düzeyde uygulanabilir standartların belirlenmesi gibi sürdürülebilir kalkınma yaklaşımlarına yönelik ilgi artışı gözlemlenmektedir. Entegre bir yaklaşım, bu tartışmalı konuları doğru şekilde ele almamıza yardımcı olabilir.

Sürdürülebilirlik alanında uzmanlar kişiler, malzeme ve enerji kaynaklarının sınırlı olduğuna dikkat çekerek, kalan bu kaynakların büyük bir kısmını inşaat sektörünün tüketmekte olduğunu belirtmektedirler. Bu gerçekler, sürdürülebilir kalkınma yaklaşımlarında ısrar etmenin ana motivasyonu olmalıdır. Fakat, yapısal tasarım mühendislerinin sürdürülebilir inşaat konularında kilit bir role henüz sahip olmadığı bilinmektedir.

Pek çok yaklaşım, esas olarak çevre ve ekonomi gibi bazı belirli sürdürülebilirlik konularına odaklanırken, sürdürülebilirliğin tüm bileşenleri arasında bir denge sağlamak için entegre bir yaklaşıma ihtiyaç vardır. Yapı mühendislerinin her gün yüz yüze kaldığı pek çok zorluk var, ancak küresel çevre sorunu bunlardan en önemlisidir.

Bu tez kapsamında, sismik bölgelerdeki binaların çelik ve betonarme karkas yapılarının karşılaştırılmasıyla çevresel sürdürülebilirliği nasıl etkilediklerinin belirlenmesi amaçlanmaktadır. Bu karşılaştırma Athena Impact Estimator ve SAP2000 kullanılarak, sismik bölgelerdeki betonarme ve çelik çerçevelerin tüm hayat döngüsü için çevresel etkiler dikkate alınarak yapılacaktır.

Anahtar Kelimeler: Betonarme, Binalar, Sismik Bölgeler, Sürdürülebilirlik, Çevresel Etkiler, Sera gazları, ATHENA programı.

LIST OF FIGURES

Figure 1.1: Multiple Dimensional Decision Model of Project Appraisal 10

Figure 1.2: Components of Life Cycle Assessment (LCA) 11

Figure 1.3: Phases and applications of a life cycle assessment (LCA)..... 13

Figure 2.1: Desired Life Cycle of Construction Materials..... 19

Figure 2.2: Energy consumption by different sector in Turkey..... 26

Figure 2.3: Number of conducted graduate studies in research universities in Tureky 27

Figure 2.4: Cement Production in the World 32

Figure 2.5: World Cement Production 2017 33

Figure 2.6: Steel and Iron Role in Energy Consumption in Turkey. 35

Figure 3.2: Turkey Seismic Map - TDTH Website. 43

Figure 3.2: Construction Site in the Map 47

Figure 3.3: Reinforced Concrete Frame..... 49

Figure 3.4: Detailing of Beam (a), Column (b), and Frame (c)..... 50

Figure 3.5: Variation of K according to the structure period 53

Figure 3.6: Kobe-Japan1995 Earthquake Ground Acceleration in Horizontal-1 57

Figure 3.7: Kobe-Japan1995 Earthquake Ground Displacement in Horizontal-1 57

Figure 3.8: El Centro1940 Earthquake Ground Acceleration in Horizontal-1.... 58

Figure 3.9: El Centro1940 Earthquake Ground Displacement in Horizontal-1.. 58

Figure 3.9: Friuli, Italy-1976 Earthquake Ground Acceleration Horizontal-1..... 58

Figure 3.10: Friuli, Italy-1976 Earthquake Ground Displacement H-1 59

Figure 3.11: Site Response Spectrum Curve..... 59

Figure 3.12: Steel Frame 60

Figure 3.13: Illustration of tapered sectional dimensions..... 60

Figure 3.14: Pushover Curve (NUST-2020) 64

Figure 3.15: Capacity Spectrum Curve (NUST-2020) 65

Figure 3.16: Determination of Performance Point (NUST-2020) 66

Figure 3.17: Capacity Spectrum Curve (NUST-2020) 67

Figure 4.1: Lateral Drift of the Frame 68

Figure 4.2: Dead Loads Maximum Moment and Shear Diagrams 69

Figure 4.3: Live Loads Maximum Moment and Shear Diagrams 69

Figure 4.4: Earthquake Loads Maximum Moment and Shear Diagrams 69

Figure 4.5: Wind Loads Maximum Moment and Shear Diagrams 70

Figure 4.6: Lateral Drift of the Steel Frame 71

Figure 4.7: Dead loads Maximum Moment and Shear Diagrams 71

Figure 4.8: Live loads Maximum Moment and Shear Diagrams 72

Figure 4.9: Earthquake loads Maximum Moment and Shear Diagrams 72

Figure 4.10: Wind loads Maximum Moment and Shear Diagrams 73

Figure 4.11: Moment Values` Differences in RC and Steel Frames 73

Figure 4.12: Shear Force Values` Differences in RC and Steel Frames 74

Figure 4.13: Kobe of Japan1995 Earthquake Abs. Acceleration Graph 74

Figure 4.14: Kobe of Japan1995 Earthquake Abs. Displacement Graph 75

Figure 4.15: El Centro Imperial-1940 Earthquake Abs. Acceleration Graph..... 75

Figure 4.16: El Centro Imperial-1940 Earthquake Abs. Displacement Graph... 76

Figure 4.17: Friuli, Italy-1976 Earthquake Abs. Acceleration Graph..... 76

Figure 4.18: Friuli, Italy-1976 Earthquake Abs. Displacement Graph..... 77

Figure 4.19: Kobe of Japan1995 Earthquake Abs. Acceleration Graph 77

Figure 4.20: Kobe of Japan1995 Earthquake Abs. Displacement Graph 78

Figure 4.21: El Centro Imperial-1940 Earthquake Abs. Acceleration Graph..... 78

Figure 4.22: El Centro Imperial-1940 Earthquake Abs. Displacement Graph... 79

Figure 4.23: Friuli, Italy-1976 Earthquake Abs. Acceleration Graph..... 79

Figure 4.24: Friuli, Italy-1976 Earthquake Abs. Displacement Graph..... 80

Figure 4.25: Creation of Hinge in RC Frame, Step-1 81

Figure 4.26: Creation of Hinge in RC Frame, Step-2 81

Figure 4.27: Creation of Hinge in RC Frame, Step-3 81

Figure 4.28: Creation of Hinge in RC Frame, Step-4 82

Figure 4.29: Creation of Hinge in RC Frame, Step-5,6..... 82

Figure 4.30: Creation of Hinge in RC Frame, Step-8 82

Figure 4.31: Pushover Curve of RC Frame, Base Shear vs Roof Displacement 83

Figure 4.32: Capacity Spectrum of RC Frame 83

Figure 4.33: No Creation of Hinges in Steel Frame in Steps-1, 2, 3..... 84

Figure 4.34: Creation of Hinge in Steel Frame, Step-4..... 85

Figure 4.35: Creation of Hinge in Steel Frame, Step-5..... 85

Figure 4.36: Creation of Hinge in Steel Frame, Step-6..... 85

Figure 4.37: Creation of Hinge in Steel Frame, Step-7..... 86

Figure 4.38: Creation of Hinge in Steel Frame, Step-8..... 86

Figure 4.39: Pushover Curve of Steel Frame, Base Shear vs Roof Displacement 86

Figure 4.40: Capacity Spectrum of Steel Frame 87

Figure 4.41: Environmental Impact Categories of Concrete Frame..... 88

Figure 4.42: Environmental Impact Categories of Steel Frame 89

Figure 4.43: Comparison of GWP of RC & Steel Frames In Different LCA Stages 90

Figure 4.44: Comparison of Primary Energy Consumption in Different Stages 91

Figure 4.45: Comparison of Acidification Potential in All Stages 92

Figure 4.46: Comparison of Ozone Depletion Potential in Different Stages 92

Figure 4.47: Comparison of Eutrophication Potential in different stages 93

Figure 4.48: Comparison of Smog Potential in Different Stages 94

Figure 4.49: LEED LCA Measure Comparison Report Cradle-to-Grave..... 94

LIST OF TABLES

Table 2.1: World Cement Production including Turkey 33

Table 2.2: The Projection of Cement Production and Corresponding CO_2 Emissions in Turkey 34

Table 3.1: The Response Modification Factor (R) 40

Table 3.2: Seismic Coefficients 47

Tabel 3.3: Structural and Non-structural Fuetures of RC Frame. 48

Tabel 3.4: Structural Element Essential Properties 49

Table 3.5: Ground Motion Records of Three Different Earthquakes 57

Table 3.6: Materials Specifications 61

Table 3.7: Sizes of the Steel Column at the Top 61

Table 3.8: Sizes of the Steel Column at the Bottom 61

Table 3.9: Beam 1-2 61

Table 3.10: Beam 2-2 62

Table 3.11: Beam 2-3 62

Tabel 3.12: Structural Element Essential Properties 62

Tabel 4.1: Maximum Abs. Acceleration and Maximum Abs. Displacement of Frames From Time History Analysis of 3 Different Earthquakes 80

Table 4.2: Environmental Impact Categories of Concrete Frame 88

Table 4.3: Environmental Impact Categories of Steel Frame 89

Table 4.4: Comparison of GWP in Different LCA Stages 90

Table 4.5: Comparison of Primary Energy Consumption in Different Stages 91

Table 4.6: Comparison of Acidification Potential in Different Stages 92

Table 4.7: Comparison of Ozone Depletion Potential in Different Stages 93

Table 4.8: Comparison of Eutrophication Potential in Different Stages. 93

Table 4.9: Comparison of Smog Potential in different stages 94

Table 4.10: LEED Measure Comparison Report Cradle-to-Grave 95

TABLE OF CONTENT

ACKNOWLEDGEMENT i

ABSTRACT ii

KISA ÖZET iii

LIST OF FIGURES iv

LIST OF TABLES vii

TABLE OF CONTENT viii

LIST OF ABBREVIATIONS xi

LIST OF SYMBOLS xiii

CHAPTER 1 1

INTRODUCTION 1

1.1 Background 1

1.2 Background and Literature Review 4

1.3 Life Cycle Assessment (LCA) Development 7

1.3.1 Single Criterion Evaluation Assessments 9

1.3.2 Multi-Criteria Assessment Method 10

1.3.3 Life Cycle Assessment (LCA) Procedure 12

1.3.4 Life Cycle Cost Assessment (LCCA) 13

1.3.5 Weighting 15

1.3.6 Limitations of the Environmental Building Assessment Methods 16

1.4 Thesis Structure 20

CHAPTER 2 19

SUSTAINABILITY IN CONSTRUCTION INDUSTRY 19

2.1 Life Cycle Environmental Impact Assessment (LCEIA) 19

2.2 Life Cycle Structural Performance Assessment 21

2.3 Life Cycle Assessment of Reinforced Concrete Buildings 22

2.4 Sustainability in the Construction Industry of Turkey 23

2.5 Sustainability in the Higher Education Sector 26
2.6 Life Cycle Assessment and Building Materials 27
2.7 Building Materials 29
2.7.1 Concrete 29
2.7.2 Cement 31
2.7.3 Steel 34
CHAPTER 3 37
STRUCTURAL MODELING 37
3.1 Equation of Motion 37
3.2 Motion Parameters 38
3.2.1 Ground Motion 38
3.2.2 Stiffness 38
3.2.3 Damping 38
3.2.4 Natural Frequency and Period 39
3.2.5 Base Shear 39
3.3 Static Design 41
3.4 Dynamic Design 41
3.4.1 Response Spectrum Analysis (RSA) 41
3.5 Earthquake 41
3.5.1 Service Level Earthquake (SLE) 41
3.5.2 Design Basis Earthquake (DBE) 42
3.5.3 Maximum Capable Earthquake (MCE) 42
3.5.4 Earthquake in Turkey 42
3.6 Environmental Impact Estimation 44
3.6.1 Athena Impact Estimator for Buildings 45
3.6.2 Impact Assessments 46
3.7 Models` Information 46
3.7.1 Concrete Frame 48
3.7.2 Equivalent Lateral Force Analysis (ELF) 51
3.7.3 Vertical distribution of Seismic Force 53

3.7.4 Lateral Drift 55
3.7.5 Time History Analysis 55
3.7.6 Steel Frame 59
3.7.6 Pushover Analysis 63
CHAPTER 4 68
RESULTS 68
4.1 Concrete Frame 68
4.2 Steel Frame 70
4.3 Environmental Impacts 87
4.3.1 Concrete Frame Environmental Impact Assessment 87
4.3.2 Steel Frame Environmental Impacts 88
4.3.3 Environmental Impacts Comparison of RC and Steel Frames 90
CHAPTER 5 96
DISCUSSION, CONCLUSION AND RECOMMENDATIONS 96
5.1 Discussion 96
5.2 Summary and Conclusion 99
5.3 Limitations and Recommendations 100
REFERENCES 103

LIST OF ABBREVIATIONS

ABGR : Australia Building Greenhouse Rating
AP : Acidification Potential
BASIX : Building Sustainability Index
BEPAC : Comprehensive Environmental Performance Assessment Scheme
ÇEDBİK : Turkish Green Building Council
EE : Embodied Energy
EIA : Environmental Investigation Agency
EP : Eutrophication Potential
EPD : Environmental Product Declaration
EPD : Environmental Product Development
GBC : Green Building Challenge
GBTool : Green Building Tool
GHG : Greenhouse Gas
GWP : Global Warming Potential
INDC : Intended Nationally Determined Contribution
IPP : Integrated Product Policy
ISO : International Organization for Standard
LCA : Life Cycle Assessment
LCC : Life Cycle Cost
LCCA : Life Cycle Cost Assessment
LCEIA : Life Cycle Environmental Impact Assessment
LCI : Life Cycle Inventory
LCSPA : Life Cycle Structural Performance Assessment
LEED : Leadership in Energy and Environmental Design
OE : Operational Energy
OECD : Organization for Economic and Co-operation and Development
PCR : Product Category Rule
RC : Reinforced Concrete
SAIC : Scientific Applications International Corporation
SBAT : Sustainable Building Assessment Tool
SÜRATAM : Sustainable Innovation and Research
TCMA : Turkish Cement Manufacturers` Association
TEC : Turkish Earthquake Code
TRMCO : Turkish Ready Mixed Concrete Organization
TÜSAİD : Turkish Industrial and Business Association

UNEP : United Nations Environmental Program
UNFCCC : United Nations Framework Convention on Climate Change
USGBC : United States Green Building Council
VAT : Value-Added Tax
VOC : Volatile Organic Compound

LIST OF SYMBOLS

Mt	: Mega Tone
$GtCO_2eq$	: Giga Tone of CO_2 Equivalent
Gt	: Giga Tone
HWh	: Kilo Watt Hour
S_s	: Spectral Response Acceleration Parameter at Short Periods (s)
S_1	: Damped, Spectral Response Acceleration Parameter at A Period of 1s (s)
S_{DS}	: The Design Spectral Response Acceleration Parameter at Short Periods (G)
S_{D1}	: The Design Spectral Response Acceleration Parameter at A 1-s Period (m/s2)
$f`_c$	: Concrete Compressive Strength (Kg/m^3)
f_y	: Maximum Yeild Stress
f_u	: Minimum Tensile Stress
f_{ye}	: Expected Yeild Stress
f_{ue}	: Expected Tensile Stress
E	: Modulus of Elasticity
υ	: Poisson Ratio
m	: Mass of The Structure
c	: Damping Coefficient
k	: Stiffness
$ü_t$	: Total Acceleration
$ü_r$	: Relative Acceleration Or Structural Acceleration
$ü_g$	: Ground Motion Acceleration
$u̇$	: Relative Velocity
u	: Relative Displacement
m	: Mass of The Structure
c	: Damping Coefficient
β	: Damping ratio
ω	: Natural Period
V_B	: Base shear
C_s	: The Seismic Response Coefficient
W	: The Effective Seismic Weight of The Building
I	: Importance Factor
R	: Response Modification Factor
D_D	: Design Displacement
D_T	: Total Displacement
Cs	: Seismic Response Coefficient

T_a	: Fundamental Period
C_{vx}	: Vertical Distribution Factor
W_i, W_x	: Portion of The Total Effective Seismic Weight Of The Structure (W) Located or Assigned To Level *i* or *x*
h_i, h_x	: Height From The Base to The Level *i* or *x*
δ_x	: Deflection At Level x
C_d	: Deflection Amplification Factor
δ_{xe}	: Deflection at The Level Determined by Elastic Analysis

CHAPTER 1

INTRODUCTION

1.1 Background

Seismic hazards on civil infrastructures especially, on RC buildings, are the motivation behind this thesis to find out a proper way of reducing the devastating consequences of these hazards on cost, environment, and social impact, which in terms are the components of sustainability.

In seismic regions, buildings require more attention to be strengthened and to act stable against earthquakes and other natural events; the structural designers consider different methods to ride on such issues. They are increasing dimensions or increasing marks of materials; in both cases, the embodied energy, CO_2, and other emissions to the atmosphere increasing significantly. To acquire exact knowledge about embodied energy and CO_2 footprint for such buildings, it requires holding an exact science to accurately determine the part these used materials are responsible for. The figures reveal the significance of the construction sector and its role in sustainable development, such vast projects influence all aspects of our life by different meanings; hence, considering life cycle assessment is needed while facing issues of such kinds.

Turkey, with its special Mediterranean location, is hardly prone to earthquakes and other natural disasters. Many parts of Turkey locate in the belt of intensive earthquakes, experienced intensive shakes. On the other hand, researches reveal that ignoring environmental issues will rigorously harm the people across the globe. In the case of Turkey, it is estimated that, if the level of water rises 1m, it will affect more than 3 million people and will cost around 12 billion dollars in the capital.

The concerns over the lack of specialists in the field are crucial to further enhance structural design methodologies. Some fundamental steps have been taken so far by different sides like ISO-14000, LEED, and other local institutions. They provide tools to identify and control industries' impacts on the environment. Rating systems emerged; the aim is to decrease the environmental impacts and

pave the way for having more sustainable buildings (Dekkinche, & Taileb, 2016). Engineers, designers, and architectures believe that this is not a matter of impossibility; environmentally-friendly buildings can be built (Navaei, 2015). They started a remarkable work, but still more efforts needed to comprehensively address the point and outline a roadmap for local and international industries' consideration. A good step has also been taken by the American Society of Civil Engineering ASCE; they included sustainable development as one of the seven fundamental principles of the code of ethics (ASCE, 2209a).

According to global energy agencies, worldwide buildings are responsible for about 25-40% of total energy use (IEA-2005). The residential and commercial building sectors are consuming approximately 30% of primary energy and greenhouse gas emissions in OECD countries (OECD-2003). According to the data from residential buildings in 2010, the EU countries were accounted for around 27% of energy consumption (Stuart & Freire 2013).

The experts insisting that, attention shall be drawn to the design strategies as they are important for all RC buildings, their consideration increases the sustainable potential of RC structures and incorporate with the degree of environmental impacts. Currently, one-third of all buildings in the world have been reported “sick” by U.S environmental protection agency EPA (Tikul & Srichandr, 2011). Embodied energy and CO_2 footprint can be reduced through consideration of different methods and strategies, such as using novel building materials, those who have fewer carbon contents, and are recyclable materials. The reduction of CO_2 footprint can also be achieved through the optimized designing of reinforced concrete structural designs. The other issue for design engineers to be noticed is that buildings with high durability require fewer repairs during their life cycle, and it would take a longer span of time to demolish the building and replace it with a new building.

In recent years, one of the most effective methodologies to assess and evaluate sustainability is the Life Cycle Assessment (LCA). With the help of this methodology, sustainable structural systems can be obtained. This methodology also assesses the environmental impacts of structure designs. LCA considers the impact of the whole life of a structure from Cradle-to-Grave.

Studies show that, the concept of sustainability first come into existence in literature in 1994 in the United States (Yu *et al.,* 2018). According to the environmental protection agency, nearly 50% of CO_2 emissions are stemmed

from the built environment (Means and Guggemos, 2015). This method is on the way to fill its weaknesses; a shortage of statistical data to tell about the environmental impacts of materials, structures, and buildings throughout the whole life cycle are the weak points. On the other hand, low awareness about the importance of life cycle assessment and having a sustainable building among investors is another barrier; most of them consider nothing but costs and revenues from construction projects. There is also a realization process complexity in the method.

For now, the assessment tools are in progress to overcome their multiple limitations. For doing a rigorous LCA of RC buildings; more data is required, therefore, the assessment process involves huge expenses for data collection and its updating. Quantification is an inexact science; it requires a very long view of the entire life cycle assessments. A systematic approach is required to standardize the calculation of embodied energy, establish calculation procedure, and database generations are essential steps for those active in life cycle assessment of buildings.

LCA can be employed to buildings on different levels, including materials, products, building elements, and different parts, the whole building at once or the neighborhoods. As mentioned before, buildings have a remarkable part in releasing overall greenhouse gases and energy emissions to the atmosphere; this amount is about 40-50% globally (Asif, M. *et al.,* 2007). When talking about life cycle assessment of buildings, it covers both embodied energy (EE) and operational energy (OE). The amount of embodied energy of building materials, including concrete, is significant but different from country to country.

As final words to this part, a movement prompted towards a sustainable approach in design, construction, and operation in recent years as concerns increased rapidly about the environmental impacts of civil and industrial infrastructures. Sustainable buildings become equivalent to decrease their negative impact on the environment while still taking full advantage of their strength (Puskaa. & Moga 2015).

1.2 Background and Literature Review

The overall construction, operations, and maintenance of buildings are accountable for about 40-50% of all energy consumption, and greenhouse gas emissions globally (Miller, Dane, *et al.,* 2014). It is expected that nearly three-quarters of the world`s population will urbanize in developing parts in the near future. It is also estimated that, in order to satisfy the housing needs of these people, around 30 million units will be needed from 2000 to 2010 and this number will rise to 39 million units from 2010 to 2020 (Moroz, Lissel, 1999). A quite large number of structural and design engineers underestimate their vital role in sustainable industry (Nengmou, & Hojjat, 2013). On the other hand, Bastos Stuart A. Batterman Fausto Freire also getting the similar results that the construction industry as all particularly the buildings have an enormous side in global warming; the use phase is considered to be accountable for 81-89% of energy consumption and 80-81% for Global Warming Potential; the construction phase is responsible for 12-18% in energy consumption and 19-20% for Global Warming Potential. The end of life phase is accountable for less than 5% of total environmental impacts (Stuart & Freire, 2013). Household`s air pollution causing 4 million deaths every year (Wu *et al.,* 2020).

2010 data reveals that 45% of world energy and 50% of water is used by the building sector. The environmental effects are huge, causing 23% of air pollution, 40% of water pollution, 50% of GHG emissions, and 40% of waste in urban areas (Yilmaz & Bakis, 2015).

Grace K. C. Ding from Australia studied sustainable building materials; the study states that “construction is not an environmentally friendly process and it has major impacts on the depletion of natural resources and GHG emissions as a result of fossil fuel combustion. In the United States, the construction sector is the third-largest industry in terms of contribution to GHG emissions.” (Ding, *et al.,* 2010). Due to the increment in greenhouse gas emissions, global temperature has grown up by 0.5 ºC. Studies also predicted that in the absence of collective struggles at the global level, the atmospheric temperature will further rise by up to 6 ºC till the end of this century. On the other hand, it is also estimated that the annual growth of CO_2 emissions rises by 2.5% and 107% for commercial and residential buildings, respectively. They also release a significant amount of another non-CO_2 GHGs (Asif, Hamoud, *et al.,* 2017).

The remarkable figures mentioned above have brought attention to resilience design practices. Mostly, the efforts are relying on the design stage, which in terms are insufficient for achieving sustainable development goals (Ding, 2007). A truly sustainable design needs access to the best ever available data on materials, products, and processes (Sodagar, *et al.*).

A report from U.S Green Building Council reveals that by applying sustainable building design 24-50% of energy, 30% of CO_2 emissions, 40% of water and 70% of solid water use can be decreased. Structural system is also an effective factor while designing sustainable buildings (Nengmou, & Hojjat, 2013).

Grace K. C. Ding, in his study about LCA of sustainable building materials stating that the stage in which materials can be selected is the feasibility stage, where different technological and environmental aspects of materials can easily be determined; this will give a wide view to the decision makers to consider and address environmental impacts accurately.

Experts from the field believe that engineering and architectural techniques can change the future by presenting environmentally friendly designing methods. The tall buildings which mostly dominating the urban areas are responsible for a massive consumption of energy during their lifetime. Thus, focus should be drawn while considering sustainable designs. With such attitude toward buildings, the factors harming environment will be minimized in the early designing stage. On the other hand, the design processes of such buildings are quite complex since the structural engineer should understand the factors and variables affecting performance of the building. Going with this method bringing some benefits; like energy efficiency in the building, resource conservation, design flexibility, and indoor environmental convenience (Farzad, 2015).

Nengmou W. and Hojjat A. studied sustainable building design; argue that, for having sustainable buildings, hybrid and semi-active vibration controller tools should be used along with smart structural technology. This will result in substantially lighter buildings, leading to effective responses of buildings to literal loads including the earthquake. As the division sustainability components have been done for sustainable construction, the authors divided sustainable design strategies into three categories such as structural materials, structural systems, and design optimization (Nengmou & Hojjat, 2013).

Galbraith studied different sustainable design strategies adding that, along with other measurements, appropriate detailing can save 10-15% of steel and

increasing the usage of post-tensioning structural members in buildings can reduce concrete and steel quantity (Kerry, 2008).

Tamboli A. studied three major tall buildings from structural sustainability design perspective. The buildings are in Taiwan, Malaysia and in the United States with height of 508m, 452m, and 206m, respectively. The buildings have been designed for great strength to withstand against natural hazards including typhoon and other lateral loads. In the meantime, some other environmentally friendly materials like fly-ash and recycled steel have been used. Random House Tower in New York is one of the most innovative sustainable structural designs in the U.S. that uses tuned liquid column damper (TLCD) instead of traditional damping systems to properly resist and reduce the lateral vibrations. The authors determined that, with installing TLCDs not only the deflections and accelerations are reducing at the top floors but also decreasing the amount of materials needed for traditional dampers; the water from TLCDs can also be used for firefight purposes (Tamboli *et al.,* 2008).

Sustainable structural designing is divided into three categories: Structural materials, structural systems, and optimization. From the material perspective light-weight composite materials are advised; besides this, focus should be drawn to other aspects of designing like façade design, solar, wind, natural ventilation and day lighting (Nengmou & Hojjat, 2013).

The overall reduction of CO_2 can be achieved through optimized design procedures, the cost will surely be 5-15% higher than that of ordinary designs, depends on assumed parameters (DongHun, 2015).

Antonin L., *et al.,* (2015) studied buildings` design strategies for low embodied energy and focused on reusing of building structures, giving optimized plan and layout to buildings, working on flexible designs, using lightweight construction materials, paying attention to low-maintenance design strategies, and extending service life of buildings. After studying, the authors stated that replacing normal mix concrete frames with precast RC frames with hollow core slabs resulted in 30% reduction of raw materials` consumption (Antonin, *et al.,* 2015).

Abrahão B. R. and Mônica R. G. (2018) in a case study found that the production stage has more contribution to environmental impacts; transportation on the other hand, has upper hand during construction stage for depletion of stratospheric ozone depletion. The authors stated that, increasing the compressive strength of structural members leads to the decreasing of

environmental impacts and associated costs; it also increases the service life of structural members (Abrahão & Mônica, 2018).

1.3 Life Cycle Assessment (LCA) Development

From a structural point of view, every structure is built to ensure functionality throughout its service life and to withstand all external disturbances. One of the foremost objectives of any building is to demonstrate resilience against extreme loads, including earthquakes.

Structural resilience is the ability of any structure to provide sudden forces that a structure may experience so it will protect itself from the level of collapse in which the structure will still be adaptable, usable, and so on the service life of the structure will be increased. Resilience and sustainability are two different topics from technical point of view; resilience concerns with adequate structural performance when structures face sudden or sustained loads, whereas, sustainability focuses on balancing the three components of LCA, economic, environment, and society. It is requested from sustainable structures to show enough resilience and let minimum damages to the structure while facing extreme events. Amr Sourani quoting a detailed definition from Raynsford about sustainable constructions “Sustainable construction is the set of processes by which a profitable and competitive industry delivers built assets (buildings, structures, supporting infrastructure and their immediate surroundings) which enhance quality of life and offer customer satisfaction, offer flexibility and the potential to cater for user changes in the future, provide and support desirable natural and social environment, and maximize the efficient use of resources.”. The other comprehensive definition of sustainability in construction sector has been presented by other construction experts adding that, sustainable development is “all about ensuring a better quality of life for everyone, now and for generations to come; through social progress which recognizes the needs of everyone, maintenance of high and stable levels of economic growth and employment, whilst, protecting and if possible enhancing the environment, and using natural resources prudently. Sustainable development embraces the three broad themes of environmental, social, and economic accountability, often known as the triple bottom line.” (Sourani, & Sohail).

Grace K. C. Ding also presents a well understandable definition for LCA, “LCA is a methodology used to analyze complex processes which focus on dealing with the input and output flows of materials, energy, and pollutants to and from the environment from a life cycle perspective (Ding, 2013).

Others define it as the prediction of our consumption habits over time without harming the quality and standards of current life (Mustafa Yılmaz, Adem Bakış 2015). Sustainability cannot be imagined without resilience when natural hazards are part of the discussion. Unless, the sustainable structure may undergo extensive damage or sometimes even it may collapse in the extreme situation as a consequence of unsatisfactory structural performance.

There are dozens of tools available right now, use for sustainability analyzing of building materials; such as LISA from Australia, Ecoquantum from the Netherlands, Envest from the Uk, Athena from Canada and SimoPro. (Ding, 2017). Every one of these tools has advantages and disadvantages, some of them are using locally while others could be used beyond specific borders as well.

The accepted way to correctly manage the issue is to consider sustainability assessment in the stages at an early feasibility stage; it will enable the experts then to include environmental issues in the decision-making process. Considerable steps are taken so far by experts for systems development to easily measure buildings life cycle environmental impacts. Long way discussions conducted, first practical step was taken in the 1990s when the Building Research Establishment Environmental Assessment Method (BREEAM), a comprehensive building performance assessment was presented as a method (Ding, 2007). Ahn, Y. H. *et al*., studied LCA of industrial buildings stated that, the best way to achieve sustainability is practicing sustainable designs and works on the reduction of construction waste in the whole life cycle of a building (Ahn & Kim, 2015). BREEAM developed a system, it was launched as a credit awarding system for buildings, were rating the buildings with fair, good and excellent rating scheme; it remained as a widely used system and has been updated constantly, it was behind all alerting to the owners of buildings to inform them about the importance of environmental issues in the construction industry. The method expanded globally, other countries like Canada, Australia, and Hong Kong using BREEAM as a base and developing their own environmental building assessment methods accordingly (Ding, 2007). Other assessment methods

developed in different countries such as ABGR (Australia Building Greenhouse Rating), BASIX (Building Sustainability Index), BEPAC (Building Environmental Performance Assessment Criteria), CEPAS (Comprehensive Environmental Performance Assessment Scheme), LEED (Leadership in Energy and Environmental Design), SBAT (Sustainable Building Assessment Tool) and many others. Some of the methods are running by the governments, while others are private or voluntary (Ding, 2007).

In the last few decades, sustainability has changed to one of the hottest topics; now, after all, researches have been done by different researchers. Sustainability got the way to be the focal point in global stages. It became a qualified brand not only in engineering fields but in all other parts. Some characteristics make one thing to be labeled “sustainable” like marketability, cost efficiency, and reduced environmental impacts. When someone says this or that product is sustainable, it means that there are undisputed benefits.

1.3.1 Single Criterion Evaluation Assessments

Evaluation of projects requires complex data collection, this process going more complex when big projects are on the way, and millions of dollars are in between; in such cases, there is a tendency for simplification of the data collection process, one of the ways is to simplify the objective of the project into a single criterion. This technique came to practice since WWII, and they were mostly involved with economic efficiency. The tool using for this evaluation is Cost-Benefit Analysis (CBA), it is used in both private and public developments. In this system, everything is converted to currency or money, and according to various alternatives, they are choosing the more appropriate one. An important point about this system is that projects with the best financial returning cannot be counted as environmentally friendly and cannot be an appropriate option in all cases. On the other hand, many environmental and social issues cannot be converted to money/currency. The other single criterion technique uses for evaluation is “energy”; it could be titled as energy efficiency or energy rating approach (Ding, 2007).

1.3.2 Multi-Criteria Assessment Method

There is a high tendency for multiple criteria and objective incorporation in building environmental assessment approaches; the criteria researchers are trying to consider and include them in the approach, they are environmental and social criteria. Young (1997) describes sustainability as a three-legged stool, which a leg representing ecosystem, society, and economy; any leg missing would mean instability in the overall sustainability stool. These three different aspects of sustainability are then called the Triple Baseline; in this concept, the focus is not on one side like economic, but equally on environmental and social values. For an organization to be sustainable, it must be financially secure, minimize the negative environmental impacts resulting from its activities, and can form social expectations (Ding, 2007).

As discussed earlier, the need for developing a proper multi-dimensional assessment approach is vital; it will help to make appropriate decisions about structural projects.

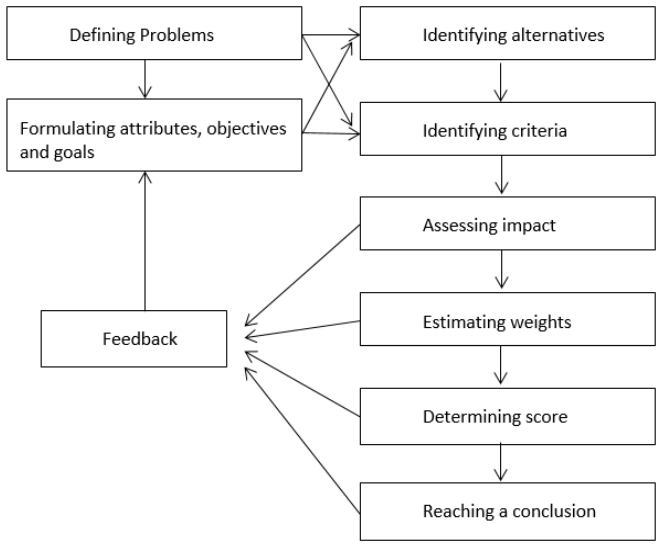

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Figure 1.1: Multiple Dimensional Decision Model of Project Appraisal (Nijkamp)

Environmental building assessment methods are predominantly concerned with environmental protection and resource efficiency with only limited ability to assess socio-economic sustainability (Hossain, 2013). 195 countries adopted the first-ever global climate deal in Paris; they agreed to avoid what happens to the climate by changing the policies and limiting global warming to below 2ºC (Asif *et al.,* 2017). The United Nations conference on environment and

development in Rio de Janeiro on 3-4th June 1992 recognized to accept all three components of sustainability in an equal weight; it was a big achievement. According to other studies, the conference was in 1989 in which the first definition for the environment has been published (Yılmaz, & Bakış, 2015). The figure below illustrates the components of life cycle assessment:

Figure 1.2: Components of Life Cycle Assessment (LCA) (World Steel Association)

Sustainability development principles are closely associated with the building industry; as an accepted term, it is quite clear now that the building industry is the lifeblood of the economy of developed or developing countries. The contribution of the building industry in the US has valued over 1 trillion dollars, while it provides 6.5 million jobs (Chang *et al.,* 2009); in Saudi Arabia, the recent data shows that the ongoing construction project is also valued over 1 Trillion dollars. In Europe, this contribution is ever higher, the building industry contributes 7.5% employment, the same trends going globally (Asif, Ammar *et al.,* 2017).

In the social aspect, the building industry provides structurally safe buildings, providing a good indoor environment of living, low vibration, protection from environmental hazards, wind, rain, sound, fire, etc. The losses resulted from seismic events in 2011 are 20.000 lives, while the total monetary loss due to

earthquake hazards is between 500-700 billion dollars (Daniell & Verveck, 2012). In the meantime, the current thread of economic development model caused the overconsumption of natural materials and so on during their lifetime; such a mind-set discredited the real wealth of environment and standards of living (Yılmaz & Bakış, 2015).

For the environmental impacts, there are no quantifiable benefits to count them; but, the overall studies show that the building industry is accounted for 40-50% of all energy usage and greenhouse gases (GHG) emissions globally. The construction industry has been blamed for many problems causing to the environment in the past decades, as this sector consumes an excessive amount of global resources and is responsible for pollution during construction and operation. Around 40% of raw stones, gravel, and sand consumption globally are related to the building sector alone as well as 25% of virgin wood. Each year buildings use 40% of the energy and nearly 16% of water worldwide especially, during their operational activities (Hossain, 2013). It has also been estimated that 80-90% of the energy is consumed in the use phase, the material extraction phase is also involved for 10-20% and the demolition or end-of-life phase is only responsible for less than 1% (Khasreen *et al.,* 2009).

As a result, it is a known fact that environmental building assessment is a multi-dimensional process; the single-dimensional approaches are insufficient; to properly evaluate the complex nature of sustainability in buildings. There is a demand for greater communications, interactions, and further discussions for improving building assessment methods to get a broad system.

1.3.3 Life Cycle Assessment (LCA) Procedure

Life cycle assessment is a methodology analyzing processes, focusing on input and output of materials, consumption of energy, emission of greenhouse gases, environmental pollution, and other environmental affecting factors. Based on the international organization for standards ISO 14040, LCA assessment has four different stages; the first stage is the scope and goal definition, the second stage is the inventory analyzing stage, the third stage is the assessment of environmental impacts while the fourth and last stage is called analyzing the results. Every stage dealing with its special area and required data, based on that analyzing the impacts. Figure 1.3 explains the different stages of LCA.

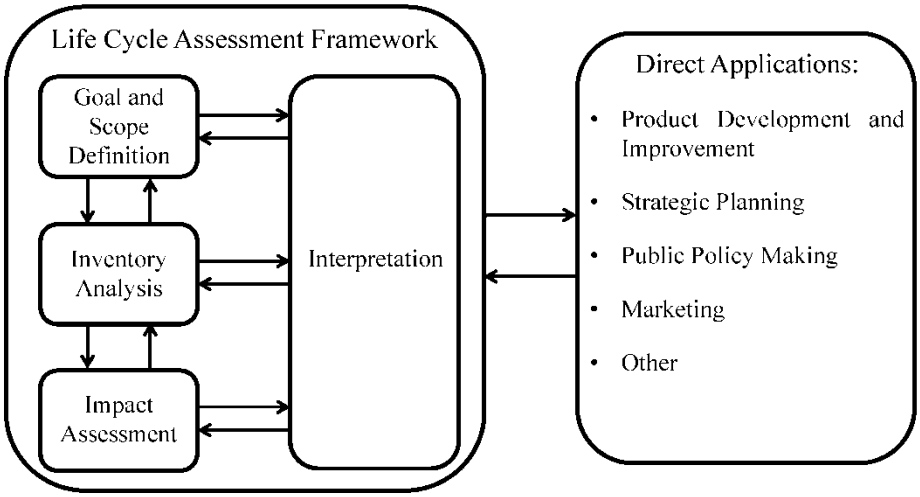


Figure 1.3: Phases and applications of a life cycle assessment (LCA)

1.3.4 Life Cycle Cost Assessment (LCCA)

On the global stage, demands for remarkable changes in the construction sector are increasing day by day; to comprehensively address the issue, multidimensional changes are required (Ricardo, & Arriagada, 2019). LCCA aims to define the total costs of a structure; the total cost is the summation of different life-cycle stages (Hossain, 2013). Sanchez – Silva *et al.,* 2013 also defines the life cycle cost analysis as a framework that provides supports for the allocated resources to the design, construction, and operation phases of a building or facility. He further insists on life cycle cost assessments of buildings, especially in seismic regions (Silva *et al.,* 2013).

The life cycle cost assessment of a building can be easily explained with the following equation:

$$Z(x) = B(x)\, C(x) - D(x) \quad \ldots\ldots\ldots\

Adem Atmaca defines life cycle cost assessment as a method of estimating the total cost of ownership. It is useful when different materials satisfy the same performance requirements; it helps us to select the one with more avenues (Atmaca, 2016). In other words, LCCA in buildings can be defined as the sum of all expected costs from construction to the end of the structure`s life span, mines the present value of the building. LCCA is particularly useful for comparing different alternatives that meet in terms of performance but vary in terms of the initial or total cost. The life cycle cost also refers to buildings subjected to hazard and the future possible monetary losses due to the unsatisfactory performance of the building under forces with random occurrence and intensity during its life span (Hossain, 2013).

Yeo *et al.,* studied optimum structural environmental performances and found that it is possible to achieve a minimized emission building with only 2.8% higher cost (Yeo *et al.,* 2015). The procedure is to minimize the life-cycle cost and to ensure better seismic risk management. The expected cost from probable damages obtained for an earthquake with specific magnitudes for the fixed source; these all obtained through simulation of source mechanism, the characteristic of ground motion, types of structural responses, and damage cost generations.

Adem Atmaca carried out a detailed case study on life cycle assessment and cost analysis of residential buildings in the southeast of Turkey, focusing more and talking about using insulation materials in the external walls. Findings after calculation reveal that, by using proper insulation materials in external walls, the total energy consumption can be reduced by up to 22.8% - 23.4%, according to studied cases. The study also comes up with results that, differences coming in urban and rural buildings, causing different amounts of GHG emissions. Mostly related to building structures and living standards, the urban buildings consume 25–29% more energy and release more CO_2 (Atmaca, 2016).

Mitropoulou *et al.,* (2001) found some significant results and reported by Hossain, 2013, when an RC building was assessed with life-cycle cost assessment; the building was optimally designed. The seismic action on the building was taken into consideration; internal static and dynamic analyses were used for assessing the seismic capacity of the building. The study found that the effects of the enter-story drift are more vital than that of maximum floor acceleration when computing LCC. The study also found that, symmetric

structures have lower LCC due to less susceptibility to damage compared with structures that have asymmetric shapes. Finally, they overcame with the result that uncertainty in the modeling of structures influencing LCC. Structural responses of buildings also affecting LCC; the other important side is that LCCA can be used to manage and maintain aging and deterioration processes of infrastructures, it is obtained as a percentage of the initial cost (Hossain, 2013).

1.3.5 Weighting

Weighting is the main part of the assessment approach; it helps to understand the outcomes of the process easily. “Weighting is the heart of all assessment schemes since it will be dominating the overall performance score of a building being assessed” (Ding, 2007). Sustainability needs to be introduced correctly, terms of introduction could be varied, but it should allow the decision-makers to easily compare alternative designs; weighting or sustainability quantification of buildings is significantly complicated in comparison with other products or processes; the reason behind this complication is that, different kinds of materials present complex manufacturing and product processes, multiple and changing functionality, long product design life compared with a limited service life of a component, constant interaction with users and environment, non-standardized processes, and insufficient data.

Quantification of buildings` sustainability needs overall and systematic assessment of the sub-components of sustainability (Cost, Environment, and Social impacts). The framework should be developed to consider the whole life-span of a building. However, there is no default method for weighting. The main concern is the absence of an agreed theoretical and non-subjective basis for achieving the weighting factors (Ding, 2007).

The characterization model is a set of values through which environmental impacts of specific materials are obtaining. All substances that erupted to air are converted to an equivalent amount of a reference substance. One of such models is Product Category Rules (PCR), in this model; the impact of 1Kg of a specific substance is evaluated and then converting it to $1m^3$ of concrete, doing the same process for the whole building (Horáková *et al.,* 2017).

Finally, the indicators calculated in LCA do not represent any measurable and real impacts; the environmental impacts discussed here are potential impacts; they have been calculated in standardized and hypothetical conditions, defined by each one of the impact models of characterization (Sigrid Reiter, 2010).

1.3.6 Limitations of the Environmental Building Assessment Methods

Environmental building assessment methods have a remarkable part in the perception of relationships between buildings and the environment. However, there are still numerous unknowns; the methods have limitations, which can be translated to that these limitations are obstacles for proper assessment of the environmental impacts of buildings.

There are still misconceptions about the most useful stage of the environmental assessment methods, some put it in the design or even later stages and count it as a design tool, which does not have favorable results. The most effective way of achieving sustainability in construction projects is to consider and include environmental issues at a stage very before the design. According to Cooks and de Wil, environmental assessment is most efficient during the identification and preparation stages of a proposed project (Cooks & Wil, 2002). Setting boundaries is another important point while conducting the life cycle assessment, but, it is still a matter of challenge (Moroz & Lissel).

The other limitation with building assessment methods is that some of them do not include the financial aspect in the assessment frameworks, which is important for affecting the process; a project might be environmentally friendly but very expensive to build. The financial aspect must also be included when assessing environmental concerns. Lack of awareness about the topic is another issue, both, in developed and developing countries. A survey shows that, a quarter of the architects and half of the building contractors do not know about sustainability in construction sector; this survey carried out in 1998 in the Netherlands. Landman in the U.S. stating that lack of education and training about sustainable designs and construction was one of the essential barriers for sustainable practices. On the other hand, the UK put this point as one of its objectives to raise awareness about sustainable construction; but the efforts are still not enough (Sourani & Sohail).

Regionality is another weak point for most of the buildings` environmental assessment methods; they have been developed locally and cannot handle the process on a regional or global scale. Some do not have global functionality and are unable to encompass variations in the regional and global stages. However, some of the variations are complex to define; a set of pre-designed environmental criteria could be prepared for worldwide use without further adjustments; for instance, using a geographically adapted database (Ding, 2007). Recently, some of the databases have been improved, and efforts are underway to develop them. Even though they are still unable to comprehensively compute all environmental impacts of buildings. Some of these databases are TEAM in France, Umberto in Germany, and USLCI data in the United States (Khasreen *et al.,* 2009).

Mohamad Kaniz Khasreen *et al.;* discussed the weaknesses and limitations of the method, adding that “applying LCA in the building sector has become a distinct working area within LCA practices. This is not only due to the complexity of buildings but also because of the following factors, which combine to make this sector unique in comparison to other complex products. First, buildings have long lifetimes, often more than 50 years, and it is difficult to predict the whole life-cycle from cradle-to-grave. Second, during its lifespan, the building may undergo many changes in its form and function, which can be significant or even more significant than the original product. The ease with which changes can be made and the opportunity to minimize the environmental effects are partly functions of the original design. Third, many of the environmental impacts of buildings occur during its use. Proper design and material selection are critical to minimize in-use environmental loads. Fourth, there are many stakeholders in the building industry. The designer, who makes the decisions about the final building or its required performance, does not produce the components, nor does he or she build the building. Traditionally, each building is unique and is designed as such. There is very little standardization in whole building design, so new choices have to be made for each specific situation. In his research, Bastos Stuart A. Batterman Fausto Freire pointing out that there are dependencies between building design, energy consumption, greenhouse gas emissions and climate changes, demographic characteristics, geography, and cultural issues; means that results of same buildings could be different accordingly.

Experts trying to have an environmental assessment method to cross the borders and work globally, they designed to consider regional variations in the evaluation process, one of them are GBS (Green Building Challenge). The other one is GBTool it was developed to consider the evaluation of the areas either ignored or poorly addressed by other environmental building assessment methods. These and other weaknesses make the system further complex (Curwell *et al.,* 1999).

Environmental issues are broad, need a comprehensive system to cover and evaluate all factors affecting the building industry in one way or another. From other point of view, there are two criteria for buildings` environmental performance assessment, quantitative criteria, and qualitative criteria. Whereas quantitative criteria concern with annual energy use, water consumption, and greenhouse gas emissions, etc. and qualitative criteria include impacts on ecological values.

Different assessment methods have different ways for evaluation of quantitative criteria. However, environmental issues are mainly qualitative, which cannot be measured and evaluated using market-based approaches within the existing environmental assessment framework. Environmental issues can only be evaluated on a featured specific basis where points are awarded for the presence or absence of desirable features (Ding, 2007).

Calculation complexity is another point mentioned by some experts, thus restricted extensive usage of LCA in the building sector. The methodology also does not assess some sustainability issues like social and economic, land use, water, and site-specific impacts such as biodiversity. Simplification demands are taken into consideration to further simplify the methodology in construction industry (Ding, 2013).

In summary, adequate structural resistance and adaptability for minimization of expected damages and the ability to quickly recover after natural hazards like earthquakes should be incorporated as an essential part of sustainable buildings, in addition to innovation and energy efficiency. Otherwise, the structure will become unusable long before the completion of its designed life resulting in loss of capital, raw materials, and energy used for construction in addition to other indirect losses such as fatalities, injuries, and downtime. Therefore, comprehensive sustainability assessment techniques are necessary

to properly incorporate structural response against future hazards that the structure may experience.

1.4 Thesis Structure

Chapter 2 discusses about sustainability in construction industry and explaining the overall situation of life cycle assessment LCA of reinforced concrete buildings; going to life cycle structural performance assessment explorations. It further focuses on sustainability in the construction industry in Turkey and reviewing the importance of the topic in higher education sector. The chapter ends with a look to the main construction materials and their environmental impacts.

Chapter 3 starts with an introduction to the main principles of structural analysis of buildings. Later, the relevant information about considered models is presented along with their geometries, section, materials, and detailing. The chapter ends with brief discussion about base shear, lateral forces, and time history analysis.

Chapter 4 concentrates on the results of designing, outcomes of SAP2000 and Athena. This chapter contains number of diagrams, tables, and figures which explaining the outcomes of designing and environmental impacts of both frames. The chapter ends with comparison of the environmental impacts of the models.

Chapter 5 includes the discussion, summary and conclusion, and limitations and recommendations.

CHAPTER 2

SUSTAINABILITY IN CONSTRUCTION INDUSTRY

2.1 Life Cycle Environmental Impact Assessment (LCEIA)

LCEIA is an integrated approach, providing quantifiable investigation and evaluation of the environmental impacts of a product, process, or service related to the whole life cycle. International Organization for Standardization (ISO) is behind this approach; all calculations and evaluations are based on this concept. Similar to LCCA, LCEIA considers the whole life-cycle of a product, process, or system encompassing the extraction and processing of raw materials, manufacturing, transportation and distribution, use, reuse, maintenance, recycling, and final disposal (Hossain, 2013). It is estimated that the global energy demand will increase by up to 71% between 2003 and 2030 (Atmaca, 2016).

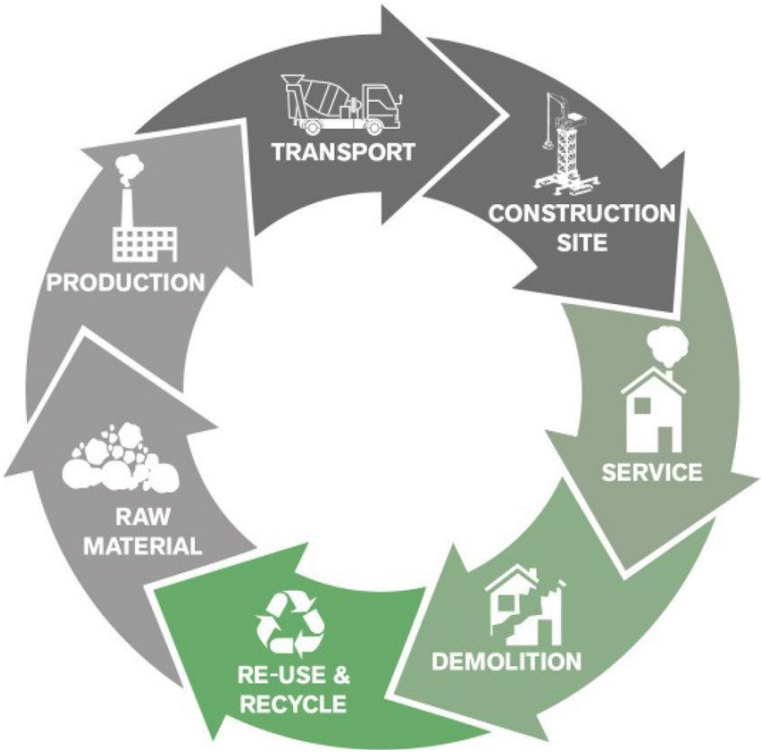


Figure 2.1: Desired Life Cycle of Construction Materials (Attila Puskas, 2015)

Because of its integrated framework for impact assessment and data quality, LCEIA has become one of the widely used methodologies. Four different environmental impact assessment indicators selected by researchers to be considered for both environmental and energy impacts; they are Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and human toxicity (Hossain, 2013).

The whole life cycle was divided into three phases; the construction phase, operation phase, and demolition phase. The occupational or operational phase was the dominant phase, with 83% of total impact, and good correlations were observed between environmental and energy impact (Hossain, 2013). A completely new concept proposed by Schlanbusch, R.D. *et al.,* suggested that to minimize operational stage emissions, efforts shall be focused on shifting the operational phase to the materials production phase (Schlanbusch, *et al.,* 2016). Since the environmental impacts of the operational phase are significant than the manufacturing and construction phases, to decrease the impacts, it was recommended by researchers to focus on using environmentally efficient materials in the operational phase. Using more materials, heavier equipment, and a higher number of vehicles followed in greater emissions of NO_2, SO_2, CO_2, CO, and hydrocarbon in the construction phase of RC buildings. Steel frames, on the other hand, consisted more of volatile organic compounds (VOC) and heavy metals like (Cr, Ni, Mn) because of more paintings and welding of steel elements (Hossain, 2013).

It has been accounted that approximately 1% of buildings in Europe have been built based on sustainable principles. Some countries in Europe providing financial and fiscal incentives for construction companies to work based on sustainable principles and save more energy while constructing new buildings, encouraging them to use renewable resources (Margherita Pero *et al.,* 2017). Studies reveal that the building sector has the potential to cut the emission of GHG by up to 80% and 30% in new buildings and existing buildings, respectively. Overall, those materials made by men are more harmful to the environment than those natural. The reason is that man-made materials need more energy during their extraction, production, and other processes in different stages. It is expected that all products will become sustainable if natural materials with low embodied energy are involved (Ding, 2013).

Scientific Applications International Corporation (SAIC) defines the LCA as it is an assessing technique, to assess the environmental aspect, and potential impacts resulted from products, processes and services (SAIC 2006). To specifically address the point, LCA needs to include a special function; here it is called with the name of Life Cycle Structural Performance Assessment (LCSPA).

2.2 Life Cycle Structural Performance Assessment

Life cycle structural performance assessment (LCSPA) is a methodology of evaluating the structural responses of buildings that come after all forces occurring during the service life of the building. LCSPA aims at evaluating the probable structural damages from the structural response indicators; it also considers the uncertainty during hazard, structural performance, and the damage that could be experienced by the structure (Hossain, 2013).

Since there are uncertainties in structural responses, probable damages, and ground motions, it seems logical to deal with these terms in a probabilistic manner with the help of performance-based earthquake engineering (PBEE) methodology. In the mid-90s, two massive earthquakes took place in Northridge (1994) and Kobe (1995); even the buildings were designed according to the norms and accepted codes of designing, these events caused destruction and fatalities after on the mindset of the researchers, and structural designers turned into a new approach of structural designing, and eventually led steps to several publications and pioneered new design approach; then, Performance-based Earthquake Engineering (PBEE) formulated as the first outcome of the researches (Hossain, 2013).

The performance-based earthquake engineering (PBEE) concept first developed in Pacific Earthquake Engineering (PEER). The methodology is based on certain and explicit ways for determination of performance measures; thus, all stakeholders will get a brighter concept about economic, social, and environmental aspects in a probabilistic manner; considers uncertainties about earthquake ground motions, building responses, different intensities, damages, and losses (Günay & Mosalam).

PBEE is an assessment methodology assessing the structural performance of buildings subjected to seismic loads. In this methodology, the different

performance objectives are achieved when they are subjected to different kinds of seismic hazard levels by adopting different design, construction, and maintenance practices. Performance-based design is a different approach than that of traditional design codes, which only looks onward to fulfill life safety purposes. The first introduction of performance-based design can be traced back to the early twentieth century (Hossain, 2013). An opinion about traditional and performance-based structural design is that traditional design principles mostly focusing on preventive measures of structural and non-structural elements of buildings from different states of damages in different earthquake intensities, while performance-based structural design encompasses other sides as well like downtime, humans lose, monetary, and environmental issues. Another important point to be mention is that the designers do not consider the opinions of experts; rather, they are relying on rigorous probabilities (Günay & Mosalam).

PBEE was dealing with deterministic values; this was the main limitation of this methodology; uncertainties in earthquake intensities, ground motions, and structural responses to earthquake waves, damage, and repair costs were not considered. To address all these uncertainties accurately, the methodology should be developed; therefore, the Pacific Earthquake Engineering Research (PEER) center has developed the PEER PBEE methodology, a probabilistic and comprehensive systematic-level performance methodology. Then the PEER methodology requires successful completion of four analysis stages: hazard, structural, damage, and loss analysis (Hossain, 2013). PEER-PBEE combines all related probabilities in a simple process (Günay & Mosalam).

2.3 Life Cycle Assessment of Reinforced Concrete Buildings

The main part of this work is focusing on sustainability assessment of RC buildings, especially those located in earthquake-prone areas; in such cases, the sustainability components mostly trying to address the structural performance of the buildings under future earthquakes.

Materials used in the construction of buildings are mostly considered because of their performance characteristics, cost, and aesthetics. Their environmental properties are less considered (Ding). Reinforced concrete is a versatile building material; it has the ability to attract many benefits in forms of economic,

durability, resistance, adaptability, thermal insulation, and recycling. Reinforced concrete sustainability highly depends on the properties of materials in the mixture. The strategies which are mainly needed while studying sustainability in the construction sector may include the energy reduction, increasing level of energy efficiency, reducing losses, increasing recycling properties, increasing the reuse of materials, and increasing the whole life cycle of buildings (Ricardo & Arriagada, 2019).

In recent years, LCA gained popularity among related institutions as an important tool for assessing the performance of different aspects of buildings, such as; assessing the performance of products, services, and energy use, environmental performance of product, process, or whole system from cradle-to-grave. The process starting from extracting and manufacturing of raw materials, ending with disposal of the materials to earth (Hossain, 2013). Initially, LCA has widely been used for product comparison in Europe and the United States; currently, this application has been extended to other broader aspects; covered governmental policies, strategic planning, and product design (Ding). Umberto Vitiello *et al*., in the research about LCA of seismic retrofit strategies describing two different approaches, through which LCA could be applied in building sector; one is bottom-up, which studying building materials and, the other is a top-down approach, which the entire building and construction processes are studying (Vitiello *et al.,* 2016).

The scope of LCA has evolved into a broader context, now it is not only dealing with environmental and ecological issues, but it is also a systematic approach for assessing all effects of actions, deformations and interventions in all aspects; use, maintenance, repair, retrofit, aging effects on structural performance over the total or rest of its service life (Hossain, 2013).

2.4 Sustainability in the Construction Industry of Turkey

Buildings particularly tall buildings are an architectural phenomenon. They have been considered as symbolic power by host communities. On the other hand, buildings will be built due to their economic benefits, especially, in dense urban and populated areas. These buildings consume an enormous amount of natural

resources and releasing significant GHGs to the atmosphere during their whole life time (Moon, 2011).

The green building sector is in its emerging stage in Turkey compared to other regional countries. However, rapid developments have been made recently in the field. Turkey`s big cities witnessed unprecedented forward steps. Studies show that, around 98% of completed or partially completed residential buildings` frames are reinforced concrete in big cities of Turkey such as Istanbul (Apay, 2011). LEED and BREEAM are active and issuing certificates to the qualified buildings in Turkey (Ulubeyle, S. et al., 2018). Yet, Turkey does not have an effective method for environmental impacts evaluation for the existing or new buildings (Centiner & Ceylan, 2013).

Turkey, like many other countries in the world, has not yet been able to possess its own assessment method like LEED and BREEAM to certify green buildings inside Turkey. Efforts by the Turkish Green Building Council (ÇEDBİK) are undertaken to establish such a framework suitable for the country. Some buildings received LEED certificates (Yılmaz & Bakış, 2015). At the same time, there is a center for sustainable production, research, and design with the name of SÜRATAM; the center is the coordinator of the EPD-Turkey certification system for ISO 14025 Environmental Product Declarations (EPDs). The center is also issuing certificates for buildings inside Turkey as LEED is doing in the U.S. EPD-Turkey is also compliant with the European EN 15804 standard and addresses the need that arises for the products that target this market (www.suratam.org).

On the other hand, Turkey has started works on sustainability, signed the Kyoto protocol in 2009. The protocol is focusing on decreasing greenhouse gas emissions and fighting global warming and climate change, the protocol is signed by 160 countries (Gultekin *et al.* 2018). The importance of sustainability has recently been recognized in concerned Turkish institutions (Arsalan, 2017). They have newly established the “Energy Performance in Building Regulation” in 2009. Since then, attention to the structure industry increased, followed by adding specific regulations to increase energy efficiency, automation of building systems, renewable energy, and using daylight. The Turkish government has also published Climate Change Action Plan in 2011 for a period of 2011-2023; big milestones were specified to be achieved through this action plan such as; isolation of at least 1 million buildings, increasing usage of renewable energy,

and reducing energy consumption in buildings. It was also part of this action plan to give identity documents to all buildings till 2017. Moreover, Energy Efficiency Strategic Document 2010–2023 targeted a 20% reduction in energy consumption in all buildings in Turkey and to change at least one fourth of construction stock to renewable construction by 2023 (Yılmaz and Adım 2015).

There are several governmental and non-governmental sides involved with sustainability studies in Turkey. The government issued Climate Change Action Plan in 2011; the issue is also under focus by the Energy Efficiency Strategic Document, besides these governmental efforts, non-governmental organizations also showed their supports for sustainability. A report of sustainability in construction sector was prepared by the Turkish Industry and Business Association (TÜSİAD), insisting on sustainability and usage of less energy consumption and mitigation of CO_2 emissions; it is also part of the report that, Turkey will become a technology-centered and Association of Turkish Building Material Producer (İMSAD) (Yılmaz & Bakış, 2015).

It is reported that over 7 million houses are needed until 2023 (Yılmaz & Bakış 2015). Turkey also joined many international institutions concerned with sustainability and green buildings. In 2004, Turkey got the membership of UFCCC (Kara, 2012). It also joined the Kyoto protocol in 2009, through which Turkey will work on the reduction of CO_2 and GHG emissions. The other step was the submission of intended nationally determined contribution (INDC) to the European Union in 2015. Based on this submission, Turkey will work on cutting 246 million tons of CO_2eq emissions to the atmosphere by 2030 (Rende, Ercan & Hilmioğlu, 2019).

Adem Atmaca studied LCA and cost analysis of a residential building in Turkey; he described the overall energy consumption by different sectors, as shown in the figure below:

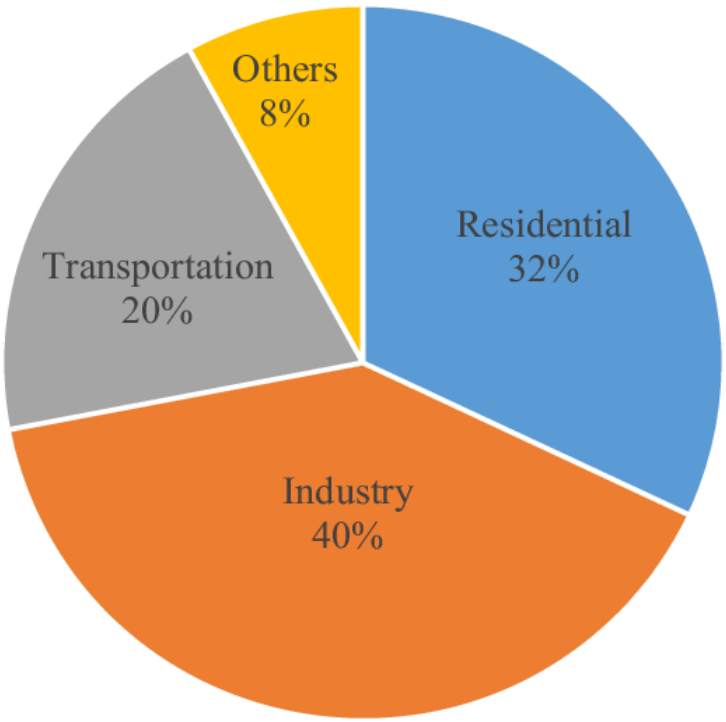


Figure 2.2: Energy consumption by different sector in Turkey (A. A, 2016)

2.5 Sustainability in the Higher Education Sector

F.Topak, O.B Tokdemir, M.K. Pekericli, and A.M. Tanyer studied sustainability from other perspectives; they wanted to know that to which extent the Turkish Higher Education System paying attention to the issue of sustainability in the construction sector; 10 research universities and their curriculum analyzed within this study. Among those 10 research universities, only three recognized as eligible to lead the graduate studies in sustainable construction, no record of Thesis has been witnessed within five other universities. Two universities are counted qualified, they can deal with the aforementioned topic with international standards; they are ITU and METU. As the result of study, the authors stating that sustainability in the construction sector is not seen as an important part of the higher education system; especially, in the departments of architecture and civil engineering (Topak *et al.,* 2019).

Figure 2.3 illustrates the number of graduates conducted studies in research universities in Turkey.

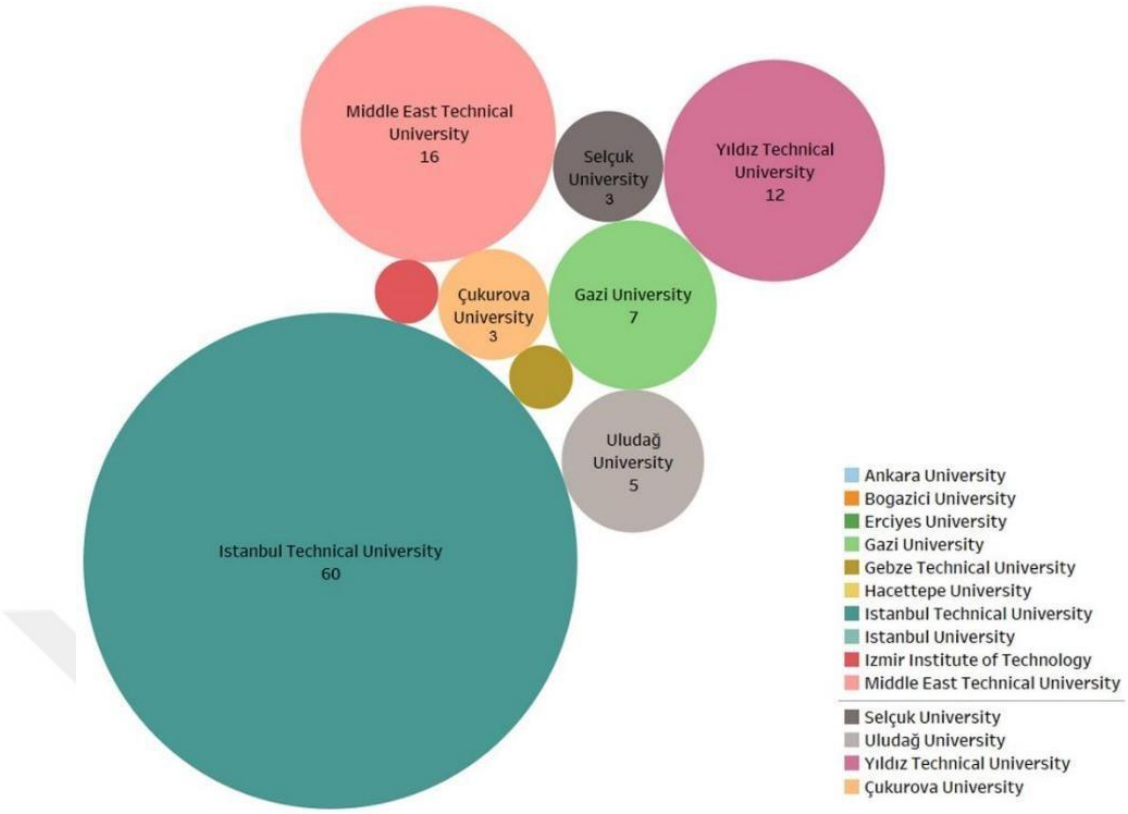


Figure 2.3: Number of conducted graduate studies in research universities in Tureky (Topak *et al.,* 2019)

It is also reported that the Turkish government has been encouraging and supporting the application of energy efficiency investments in any sector. The government offers different kinds of incentives as a supportive step they include; VAT and tariff exemption, tax reduction, employer's national insurance contribution support, interest support, and land allotment (Yildiz, 2017).

2.6 Life Cycle Assessment and Building Materials

Technological development in the last two centuries caused considerable drawdown of raw materials, especially those non-renewable natural materials, and the harmful emissions to air increased significantly (Švajlenka *et al.,* 2018). The construction industry is one of the biggest consumers of natural resources; at the same time, it is one of the largest polluters of our environment. In its annual Emissions Gap 2019 report, the United Nations Environment Program also alarmingly showing the influence of materials on the global warming issue. According to the report, in 2015, the production of materials released 11

$GtCO_2eq$ GHGs to the atmosphere; this amount is much higher than that of 5 $GtCO_2eq$ in 1995. Construction of buildings and infrastructures in 2015 and material supply caused $7GtCO_2eq$ of GHG emissions; $4GtCO_2eq$ is associated only with materials used in construction. With this increment, the total global emissions increased from 15 to 23 percent. The role of developing countries is estimated to be about 70% in construction-related emissions in 2015 (UNEP, 2019).

Materials like steel, cement, lime, plaster, and other construction materials have the largest contribution. A study of a residential building in Scotland shows that concrete is responsible for almost 65% of total energy consumption and environmental impacts (Asif *et al.,* 2007). To be assured of having a good environment for ourselves and future generations, the improvement of buildings performance is an essential and accountable step. By improving the efficiency of supplements, energy, alternative materials, and reducing demand for materials could be effective steps forward to mitigate GHG emissions (UNEP, 2019a).

Recent studies show that concrete and steel have a remarkable part in greenhouse gas emissions. The buildings and construction sector are responsible for utilizing 40% of natural resources, including 12% of freshwater and an enormous contributor to CO_2 and other greenhouse gas emissions (Ochsendorf, 2005). In the US, the construction sector is the third-largest industry in terms of contribution to GHG emissions (Ding, Li, *et al.,* 2010). According to the studies, the construction sector depletes 40% of natural materials, 40% of primary energy consumption, 15% of the world`s freshwater, creates 25% wastes globally, and finally, emits 40-50% of GHG (Ding). In the construction phase of buildings, floors are dominating the consumption of materials, thus have a major role in embodied energy and CO_2 emissions (Atmaca, 2016).

More importantly, GHG emissions can be decreased by proper structural design strategies. It is reported that most of the Steel and RC structures are 20-30% overdesigned (UNEP, 2019). The intensity level of embodied energy in natural materials is considerably lower than those of man-made, which could bring significant changes in the final energy consumption rates. The world will have sustainable products to some extent if they enter low embodied energy natural materials into the sector (Ding). The emission of greenhouse gases is a crucial and global concern; all engineers should acknowledge the seriousness of the

issue, the part structural materials playing in global warming, greenhouse gases, and other relevant issues.

Researches are underway to address the problems with materials` selection. The main purpose of these researches is to find a proper and universally accepted definition for sustainable building materials. However, most of these studies couldn`t get satisfactory results. To identify the environmental impacts throughout their lifetime, the European Commission released the Integrated Product Policy (IPP) in 2003. This (IPP) paves the way and led to the Environmental Product Development (EPD) declarations; it was a wise step let to its recognition by USGBC LEED and further encouragement by the European Union. On the other hand, the reuse of materials is another important point; efforts are needed to find out ways and techniques to consider reusing of materials either as parts or as a whole. A study on reused building materials shows that, reusing materials would cause about 55% of lower environmental impacts in comparison to new (Ding).

The selection of sustainable construction materials is one of the most challenging tasks by far from the industry. Improving material databases and their environmental profile will ease this task (Ding). Turkey does not have an embodied energy database for building materials, using databases from other countries, causing errors in the final results, and hard to receive accurate outcomes (Atmaca, 2016).

In many countries, including Turkey, structural engineering depends on two structural materials, steel, and concrete. These materials require a tremendous amount of energy to produce; globally, they are responsible for a very high level of carbon emissions; in the coming paragraphs, this study will go further and deeper into how these materials affecting our environment.

2.7 Building Materials

2.7.1 Concrete

Throughout history, and when civilization started, concrete has been counted as a remarkable construction material. Concrete had been used as essential construction material during the Roman era, when they were building Pantheon unreinforced dome, survived for more than 2000 years, the same for

cementitious material as they play noticeable performance in reinforced and pre-stressed concrete throughout history.

Concrete is a mixture of coarse aggregates, fine aggregates, water, cement, and admixtures, some of which can be replaced by other recycled concretes. If we consider the energy consumption during concrete production and its inherent properties in use, concrete is the more sustainable material.

Apart from other discussions, concrete as one of the most used construction materials has a very successful history that could also be justified as the only man-made material. Data reveals that the amount of concrete used for construction purposes exceeds 21-31 billion tons annually (ISO/TC71, Business Plan, Concrete Reinforcement Concrete, and Pre-Stressed Concrete 2005); approximately 2 metric tons per person per year. Concrete, the second-largest volume material utilized by humans after water is virtually irreplaceable for innumerable large infrastructure developments from the point of view of economy and ecology (Senot Sangadi/procedia Engineering, 2017).

Abrahao Bernardo Rohden studied design strategies for increasing the sustainability of reinforced concrete adding that, “concrete is one of the most important building materials in the world and is the second most commonly used product on the planet after water (Rohden *et al.,* 2018). Gursel *et al.;* studied life cycle assessment of concrete in Singapore; stated that, concrete could continue as a key construction material because of its features and other acceptable characteristics including, low cost, transportation, fire resistance, and durability. They also mentioned that the total embodied energy releasing to the atmosphere from concrete and steel during construction works makes around 60 – 67%. In buildings, reinforced concrete counts for 73 - 75% CO_2eq emission (Gursel & Ostertag, 2016).

With all details discussed above, concrete has a lot to offer too; therefore, it is deeply rooted in the daily life, using construction materials responsibly is one of the challenges the world has today. To mitigate its environmental impacts, the concrete industry along with other relevant authorities putting their efforts side by side to collaborate and search ways to improve its performance. European countries are among first responders to such sustainability issues (Brundtland, 1987).

The overall construction industry, particularly the concrete industry, is massively involved in today`s environmental concerns. The role it has is tremendous and cannot be miscalculated. Therefore, experts are focusing to get to sustainability goals and find ways and approaches for mitigation of concrete`s environmental harmful impacts. Besides other vital issues, this is an achievement that the concrete sector in many developed countries accepted some terms to improve durability, safety, and health aspects of their products. A study on the ready mixed concrete industry in Turkey shows that, Turkey was the sixth country among all European countries by producing 21 million m3 ready mixed concrete in 2000 (Kazaz *et al.,* 2004). This product is now much higher; the Turkish Ready Mixed Concrete Organization (TRMCO) statistics show that RMC production in 2018 was 100.000.000 m3. Same like in almost many other countries, concrete has been the most used structural material; it represents nearly 10% of the total cost of typical building projects. The study also found that among developed countries, the U.S, Japan, and South Korea are the world`s largest producers (Kazaz *et al.,* 2004).

Recent studies in this regard show that developing countries are now among high producers of ready-mix and normal concrete.

2.7.2 Cement

Cement is playing the most important role in concrete production; it makes up to 12% of the entire mixture of concrete. Cement has a complex production process; it includes a high amount of raw materials with different kinds of fuels for these processes (Cankaya *et al.,* 2019). 27 different types of cement are available in the market, classified into different classes with different qualifications; cement production is the key source of CO_2 emission. It is accounted for the emissions of nearly 8% of global CO_2. On the other hand, cement production is responsible for about 7% of all industrial fuel consumption and for more than 25% of total CO_2 emissions to the air (Hilmioğlu *et al.,* 2019). Cankaya, S. *et al.,* studied life cycle assessment of cement production in Turkey; found that 5-7% of total anthropogenic CO_2 and 3% GHG emissions are from cement production on the global level (Cankaya *et al.,* 2019).

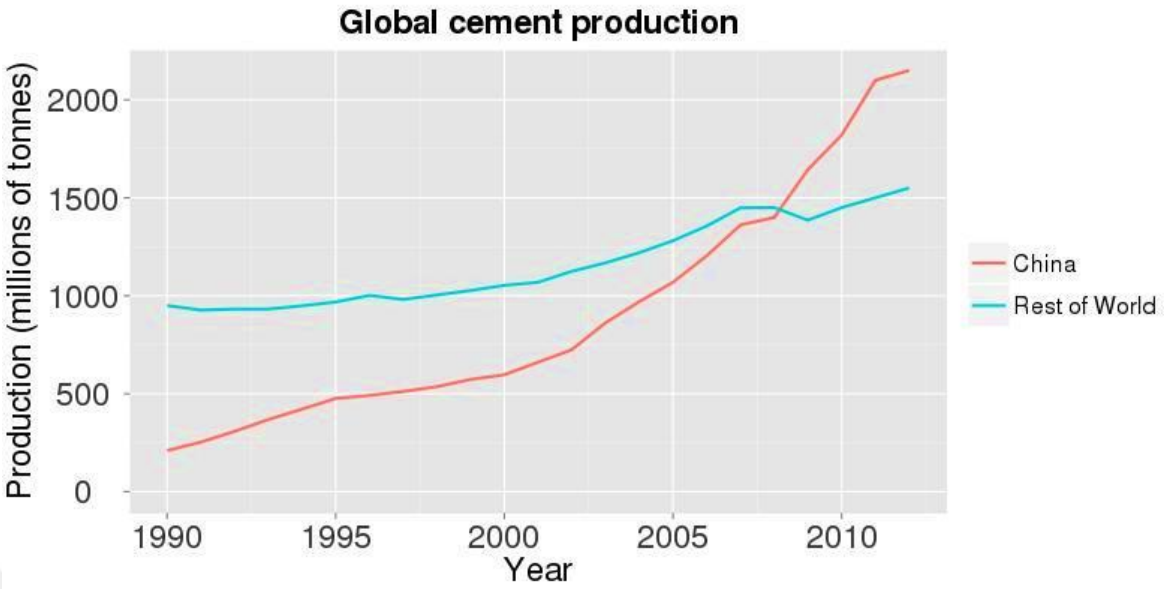


Figure 2.4: Cement Production in the World (Robert Wilson, 2014)

Cement production has grown rapidly in recent years across the globe, especially after World War II, with current levels of global production equivalent to more than half a ton per person per year. Cement production globally has increased more than 30-fold since 1950 and almost 4-fold since 1990, with much more rapid growth than global fossil energy production in the last two decades. According to the reports about cement production from 28 European countries; which say that around 270 million tons of cement producing annually; China currently has the first position, producing more than 56.5% of the world`s cement while India is in the second position with 6.8% cement production (Cement Annual Production in the World and Cement Manufactures` Association CMA 2009-2010). The kiln in which cement production is processing heated up to 2000 ºC. After fossil fuels and land-use change, cement is the third-largest source for the emission of carbon dioxide gas. The main part of the gas exit from cement kilns are CO_2, NOx, and NO_2; these gases also contain a small number of other particles like chlorides, dust, fluorides, carbon monoxide, etc. CO_2 emissions are both raw material-related and energy-related; raw material-related CO_2 emissions are responsible for nearly 60% of the total. Energy-related CO_2 emissions are belonging to two direct and indirect causes; fuels and electricity, respectively.

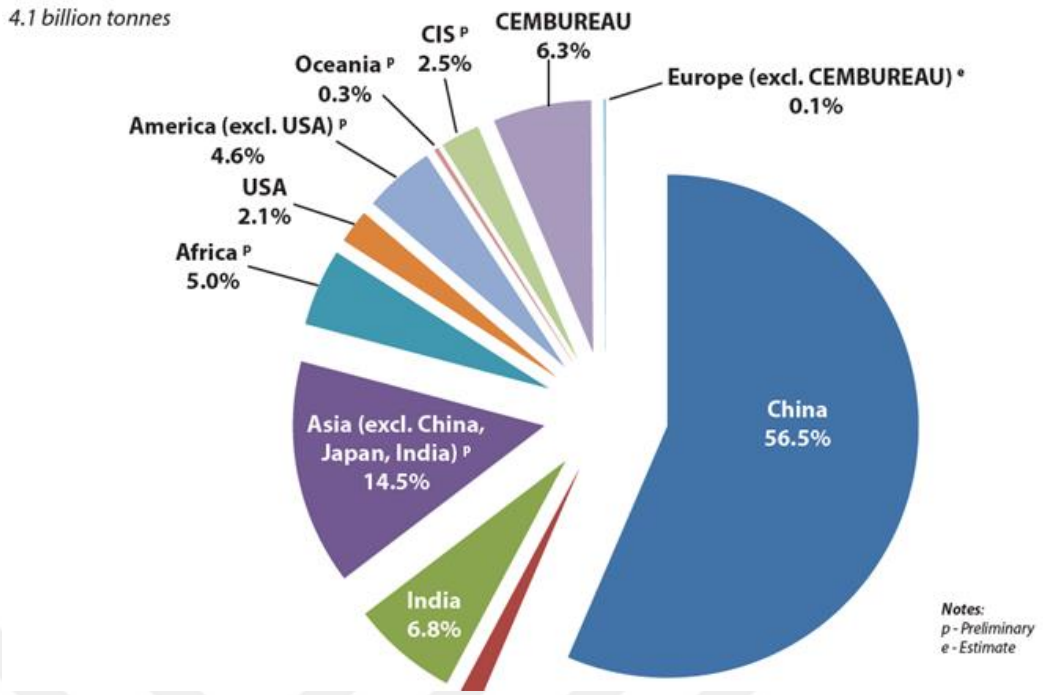


Figure 2.5: World Cement Production 2017 (CEMBERAEU)

Table 2.1: World Cement Production including Turkey from 2001 - 2015 (Rende *et al.,* 2019)

Country	2001	2010	2011	2012	2013	2014	2015
China	661.0	1,881.9	2,063.2	2,137.0	2,359.0	2,438.0	2,350
India	102.9	220.0	270.0	239.0	272.0	280.0	270.0
EU	225.6	192.1	191.6	170.5	157.5	165.8p	172.0
USA	88.9	65.2	68.6	74.0	77.2	83.2	83.4
Brazil	39.4	59.1	63.0	68.0	71.9	72.0	73.0
Turkey	30.0	62.7	63.4	63.8	70.8	72.6	72.8
Russian Federation	28.7	50.4	56.1	53.0	55.6	68.4	69.0
Japan	79.5	56.6	56.4	59.3	61.7	61.9	59.5
Rep. of Korea	52.0	47.4	48.2	46.9	47.3	47.0	49.1
Saudi Arabia	20.0	42.5	48.0	43.0	48.0	51.8	54.0
Indonesia	31.1	39.5	45.2	53.5	52.0	54.2	54.4
Mexico	33.2	34.5	35.4	36.8	37.0	39.4	40.0
Germany	32.1	29.9	33.5	32.4	31.9	32.5	32.0
Italy	39.8	34.4	33.1	26.2	23.1	21.4	20.8
France	19.1	18.0	19.4	18.0	17.5	16.4	15.6
Canada	12.1	12.4	12.0	12.5	12.1	12.8	12.5

*Note: p: predicted.

Turkey has started production of cement in early 1911, the data from TCMA shows that there are now 54 integrated and 18 grinding cement plants in Turkey. This number could increase more as demand for cement is growing inside Turkey. The rapid increase of cement production in Turkey is obvious, it stands

in the 6th position after China, India, EU, US, and Brazil; Turkey is now the largest producer of cement among European countries, with 153.8 $MtCO_2eq$ emissions caused by cement in 1990 while this amount computed as 383.4 $MtCO_2eq$ in 2015 (Rende *et al.,* 2019). USGS in 2017 listed Turkey as the fourth-largest producer of cement in the world. TCMA reports show that cement production has increased by 46% in the past decade (Cankaya *et al.,* 2019).

Table 2.2: The Projection of Cement Production and Corresponding CO_2 Emissions in Turkey, 2017–2023 (Rende *et al.,* 2019)

Million tons (Mt)	2017	2018	2019	2020	2021	2022	2023
Cement production	83.5	86.1	88.6	91.3	94.1	96.8	99.8
Cement sales	66.1	68.1	70.1	72.2	74.4	76.6	78.9
CO_2 emission	66.0	68.0	70.0	72.1	74.3	76.5	78.8

The cement production industry witnessed a remarkable technological development in the past 50 years. Technological changes reduce the amount of energy needed for cement production in industries. Therefore, the amount of energy emission declined significantly; each ton of cement production requires 60-130 Kg of fuel/oil, which depends on the type of cement and requires 110kWh electricity. At the same time, using fuels with fewer environmental impacts as alternatives increased in the last two decades.

2.7.3 Steel

Like other structural materials, steel is also one of those widely used materials; it is hard to imagine a building without steel. Reinforced concrete is a composite of concrete and steel bars, in which concrete works as a compression part of the structural member while steel bars provide tensile strength to the member. Steel reinforcement plays a key role as they ensure the ductility of the structures and strengthen it against lateral loads, like earthquakes. Steel bars have different kinds, using for various purposes.

Concrete is mostly using for its compressive strength; the steel reinforcement is using to take over the tension appearing in the cross-sections of concrete elements, having about 100 times higher tensile strength than the concrete, but with a very similar thermal expansion coefficient. Steel is a 100% recyclable material; using recycled reinforced steel will reduce around 20% of the carbon emissions. As a construction material, steel receives high marks for the

recyclability aspect. It is a fully recyclable structural material; in 2013, nearly 85% of all construction steel scraps recycled. This rate was 97.5% between 2004 and 2008 (Wang *et al.,* 2013).

Steel production is highly dependent on coal; it is accounted that 0.44 Mt of coal is needed to produce 1 million tons of steel (Plaza *et al.,* 2019). Other studies reveal huge environmental impacts cause by steel production during its lifetime, from extracting, processing, producing, use to maintenance stages. Global efforts toward sustainability make governmental and non-governmental steel producers to increase their efforts for energy efficiency in steel production to mitigate CO_2 and GHG emissions (Ates, 2015).

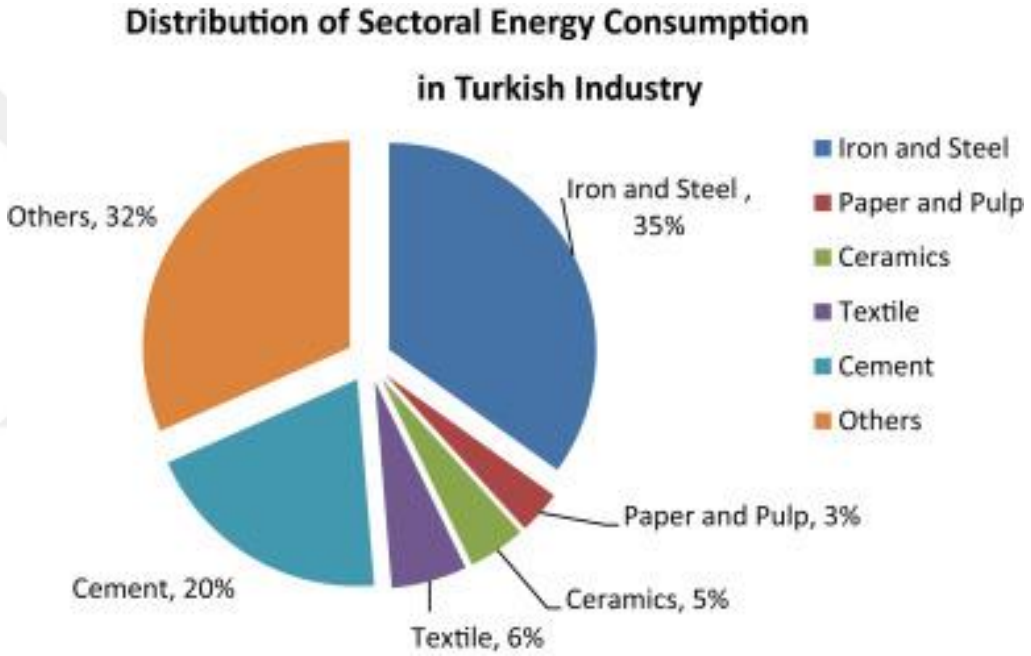


Figure 2.6: Steel and Iron Role in Energy Consumption in Turkey (Ates, 2015).

The steel and Iron industry are considered one of the largest consumers of energy in Turkey. Coal is mainly using for steel production in Turkey; thus, the industry is responsible for roughly 35% of energy consumption and releasing considerable amounts of CO_2 and GHG emissions into the air. Turkey is in the eleventh row with the largest capacity of steel production, 29.4 million tons of steel produced in 2010, demands are still high for steel inside the country because the construction industry is growing, and there is still a high demand to import part of the needed steel every year. Researchers predicted that the capacity of the steel industry could grow further in the coming years (Ates, 2015).

On the governmental level, Turkey increased its attention to energy efficiency in steel production to reduce CO_2 and GHG emissions. Studies in this regard point out many methods on how steel industries inside Turkey can use the strategies to mitigate GHG emissions (Ates, 2015).

When someone wants to compare different types of structures from the material perspective, and when accurate terms and conditions take into consideration, the concrete buildings are holistic. The design life for concrete buildings varies; it is set to be from 50-200 years. Conducted studies reveal that some 80-90% of the energy consumption belongs to the “in use” phase of a building; it means that, industries should to draw more attention to this period of life of a building and focus more on how to mitigate the related energy consumption along with its other environmental impacts. Lack of energy efficiency in buildings costs Europe an estimated 270 bn Euro every year.

CHAPTER 3

STRUCTURAL MODELING

3.1 Equation of Motion

To know structural dynamics from theoretical and mathematical perspectives, understanding earthquake engineering factors and parameters are vital. The important parameters are written in the following equations.

$$M\ddot{u} + C\dot{u} + Ku = -M\ddot{u}t \quad (3.1)$$

$$\ddot{u}_t = \ddot{u}_r + \ddot{u}_g \quad (3.2)$$

The equation (3.1) is the equation of motion and the (3.2) is the equation is for calculation of structural displacements, acceleration, force and period.

The terms mentioned above are standing for,

m = mass of the structure

c = damping coefficient

k = stiffness

$\ddot{u}_t$ = total acceleration

$\ddot{u}_r$ = relative acceleration or structural acceleration

$\ddot{u}_g$ = ground motion acceleration

$\dot{u}$ = relative velocity

u = relative displacement

3.2 Motion Parameters

The coming paragraphs briefly explaining motion related parameters such as ground motion, stiffness, damping, and natural frequency.

3.2.1 Ground Motion

Earthquakes and other man-made incidents that causing motion of the ground is called ground motion. It is used for analyzing the responses of structures during ground shakings. Major earthquakes have been recorded and can be found in several official record institutions like PEER (Pacific Earthquake Engineering Research Centre) and are available for the structural designers. The records include Acceleration ($\ddot{u}_g$), Velocity ($\dot{u}_g$), and Displacement (u_g).

3.2.2 Stiffness

Stiffness is another motion parameter which is illustrated by (K); it is the qualification of a structural member or whole structure that resists the deformation, in other words, stiffness is the ratio between the base shear and the deformation at any point. Stiffness of a structure or structural member depends on many factors like materials, height of the structure, loading type and size, and joints connections. Stiffness resisting the earthquakes loads, thus, dissipating the loads causing damage to the structural and non-structural members.

3.2.3 Damping

The third parameter of motion is damping, earthquake energy is dissipated by damping systems, it helps with the reduction in the amplitude of vibration and assisting the structure or structural members to overcome the external forces. In case of performing an elastic or linear analysis, it is normal to consider 5% inherent damping ratio. The damping also helps the system to decrease the period of motion. The accepted term in all buildings is that energy dissipation is

inherent in all buildings with different ratio. As mentioned earlier, damping mostly depends on the amplitude of vibration and the size of damage.

Damping ratio (β) is calculating with the following equation:

$$\beta = \frac{c}{2\sqrt{km}} \qquad (3.3)$$

Where,

c= damping coefficient

k= stiffness

m= mass

3.2.4 Natural Frequency and Period

Frequency and period are two different terms; natural frequency (ω) is complete cycles of an object in a second while period (T) is the time which is needed for the completion of one cycle. Understanding of these two terms for structural engineers is very important. Knowing the nature of period is the main object in the analyzing of seismically resisted structures, it helps to understand the safety of a building while bearing seismic loads. Longer periods causing lesser accelerations and less inter-story drifts; it means the building will not experience severe damages.

$$\omega = \sqrt{k/m} \qquad (3.4)$$

$$T = 2\pi/\omega \qquad (3.5)$$

3.2.5 Base Shear

Base shear (V_B) is the expected seismic forces at the base of a building along the principle directions. It can be also explained in terms of maximum structure displacement with respect to the base. The base shear governs by the following equation:

$$V = Cs * W \qquad (3.6)$$

Where,

V = base Shear

Cs = the seismic response coefficient

W = the effective seismic weight of the building

The seismic response coefficient can be governed with the following equation:

$$C_S = S_{D1} * I / R \qquad (3.7)$$

Where,

S_{D1} = design spectral response acceleration parameter at a 1-s period

I = Importance factor

R = response modification factor

The American Society of Civil Engineering (ASCE-7-10) recommends values for response modification factor (R) as follows:

Table 3.1: The Response Modification Factor (R)

Types of Force Resisting Buildings	**Response Modification Factor (R)**
Steel Ondinary Concentric Brace Frames	3.23
Steel Special Concentric Brace Frames	6
Steel Ordinary Moment Frames	*NP
Steel Special Moment Frames	8
Concrete Special Moment Frames	8
Intermediate Concrete Moment Frames	5
Concrete Ordinary Moment Frames	3

*NP Not Permitted

3.3 Static Design

Static design procedure considers the process on constant velocity. The other related factors such as displacement and velocity are also calculated based on constant velocity. Three distinct displacements are noticed; design displacement (D_D), total displacement (D_T), and total maximum displacement (D_{TM}). Static design gives clear idea about main characteristics of design.

3.4 Dynamic Design

Unlike static design procedure, dynamic design depends on factors others than the static, when the soil class is *E* or *F*, located in close distance with seismic fault line, and the period at maximum displacement (T_M) is larger than 3 seconds. Dynamic design focuses on ground motions and the mutual behavior of earthquakes and the buildings.

3.4.1 Response Spectrum Analysis (RSA)

RSA is the plot of the peak values of a response quantity; this response could be acceleration, velocity, and/or displacement of a system. This is an extremely useful concept in earthquake engineering, design, and in applying the seismological knowledge of strong earthquake to the design of a structure. The concept first introduced by Hogu Benioff in 1934 and extended by M. A. Biot for earthquake engineering usage. In the design stage, the purpose of response spectrum is to design a building with elastic response to earthquake ground motions. The acceleration spectrum mainly relies on soil class.

3.5 Earthquake

3.5.1 Service Level Earthquake (SLE)

It is the lowest level considering for designing structures. In this analysis, no damage is expected from structures but there might be some displacements and damages in non-structural elements. 50% probability of exceed in 30 years while the probability of return is around 43-year.

3.5.2 Design Basis Earthquake (DBE)

Design basis earthquake may cause some sort of fixable damages and some human injuries; the exceeded probability is 10% in 50 years and return period of such earthquakes are counted to be 475-year. The following equations are used during design basis earthquakes:

$$S_{DS} = \frac{2}{3} Fa * Sa \qquad (3.8)$$

$$S_{D1} = \frac{2}{3} Fv * S_1 \qquad (3.9)$$

The F_a and F_V are site coefficients.

3.5.3 Maximum Capable Earthquake (MCE)

The MCE is the level of earthquake in which 2% exceeded probability is expected in 50 years and the return period is 2475-year. Maximum capable earthquake analysis of structures is considered in the final design stage to consider the protection of both lives, structural and non-structural damages. MCE may cause loss of lives and non-fixable structural damages.

$$S_M = \frac{2}{3} S_D \qquad (3.10)$$

3.5.4 Earthquake in Turkey

As mentioned in the earlier paragraphs, nearly 98% of new or completed residential building frames are reinforced concrete in Turkey. One can claim that concrete is the most used construction material of buildings (Apay, 2011). Turkey is located in a hard-seismic-prone belt of earthquakes. This location witnessed severe and deadliest earthquakes throughout its history. Istanbul remained the center of many civilizations for many eras; earthquakes have been recorded in one or another way. Such clear background about earthquakes gives researchers a brighter and open idea to scientifically discuss the relevant topics. Based on what they have, will allow them to easily understand the overall seismic situations to some good extents.

Almost after every earthquake, engineers from related fields carry out researches and conduct studies to find out the main causes of the failures emerging during an earthquake. Looking at the seismic map of Turkey, around 80% of the country is counted as earthquake-prone (Hasan *et al.,* 2003). A study that talks about earthquakes in the Marmara region of Turkey estimate that 70% of the earthquakes will be with Mw7+ intensity in the coming 30 years. The study also found from historical records that earthquakes with intensities higher than 7+ will reoccur after a period of 300 years (Erdik *et al.,* 2004).

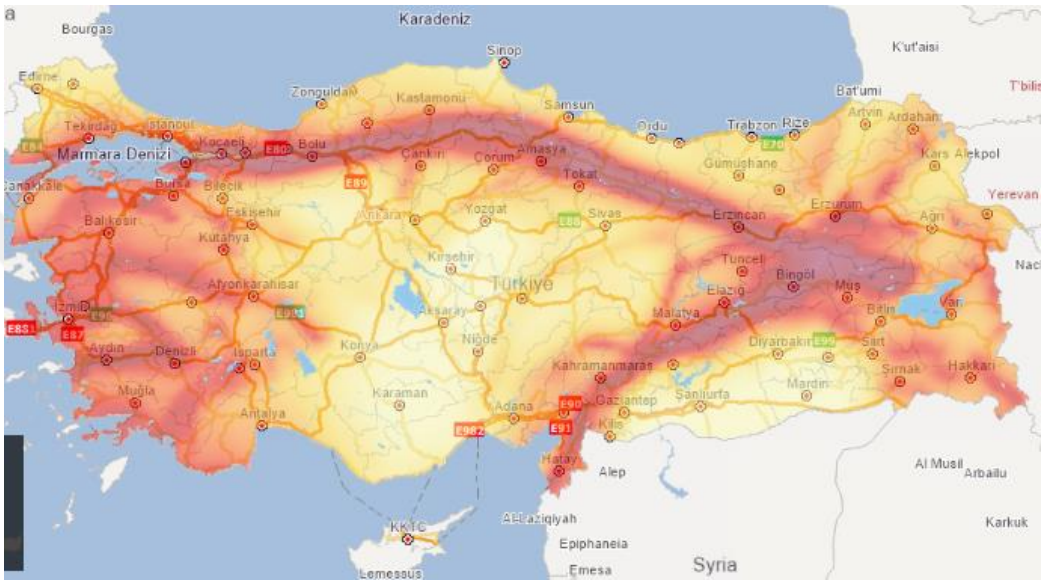


Figure 3.2: Turkey Seismic Map - TDTH Website.

Only in the last century, more than 12 earthquakes with +7 magnitudes took the lives of thousands of people; thousands of buildings damaged and caused billions of dollar losses to private and public properties. Most of the populated and industrial areas in Turkey are under high threat of big earthquakes. Kocaeli earthquake in 1999 with a magnitude of 7.4 can be a recent example. Kocaeli earthquake resulted in the loss of more than 20000 people, caused billions of dollars, and devastated the lives of millions across the country, directly or indirectly (Arslan & Korkmaz, 2006).

Even Turkey develops its earthquake and design codes from time to time; the first code was established in 1940 after 1939 Erzincan 7.9 magnitude earthquakes. The coming earthquakes forced the engineers to develop the code, several developing steps taken in 1968, 1975, and 1998 (TEC-1998).

The evaluation studies of 2003 Bingol and 1999 Kocaeli`s earthquakes revealed some important points. To clearly point out the weak points, studies focused on different levels, observed different aspects such as foundation failures, weak joints, strong beam and weak column, corrosions, detailing problems, curing problems, material quality problems. Both earthquakes caused damage to hundreds of buildings, some partially damaged, and some collapsed totally. Newly constructed school buildings were also damaged after the 2003 Bingol earthquake; the failures have been noticed after these inspections, poor concrete quality, reinforcement, and detailing problems, curing, site mixed concrete, and ignoring the code requirements were main failure factors (Hasan *et al.,* 2003).

When looking to the back and evaluating losses after each earthquake, one can easily realize that the human loss and structural damages after every earthquake in Turkey are higher and, at the same time, severe when considering the same magnitude of the earthquake in other regional countries. Neglecting earthquake codes in the design stage, pre-design geotechnical site studies missing proper inspection during design, and in construction stages relaying under these failures.

3.6 Environmental Impact Estimation

To truly compare the environmental impacts of used materials in a system, materials` quantities shall be calculated. In the second step, the embodied energy and GHG emissions caused by the system(s) separately calculating for during their whole lifetime. To compare the environmental impacts, two or more systems are needed. The systems are then examined and compared based on the utilized materials, concrete, steel, etc. The LCA assessment methodology considered to assess the environmental impacts of the considered systems for the “Cradle-to-Grave” boundary conditions. In this study, only the skeleton of both frames and their environmental impacts considered. In the same time, the environmental impacts come from transportation during lifetime also included in this assessment. Transportation is involved almost in all stages through the life cycle of a building; from material extraction to the site, during materials` processing, production, construction, and even during demolition and recycling of a structural facility. Many factors affect the amount of embodied energy, greenhouse gas emissions and overall environmental impacts while using

transportation, including the distance from extraction site to the construction site, type and size of the vehicle.

Data has an essential role while comparing two different system designs. The quantities obtained and calculated from the maps and cross-sections of frames` members. The models designed and considered for this study are simple structural systems; this simplicity allows us to easily get the reality of the overall concept. From a structural point of view, buildings resisting the lateral loads are mostly related to their flexibility. In such a scenario, the main goal here as mentioned earlier is to know that, how, and to which extent different kinds of construction materials affect our environment.

Selecting assessment boundaries is also a vital task while assessing the environmental impacts of construction activities and materials in LCA methodology. Different boundaries can be considered in the life cycle assessment methodology; the options largely depend on the expectation of a study. The boundaries can be cradle-to-gate, cradle-to-site, and cradle-to-demolition or cradle-to-grave. In this study, the boundary of cradle-to-grave has been considered. This boundary condition considers the assessment of materials throughout their whole lifetime, starting from the very first step of extraction of raw materials, ending with the demolition and reuse of structural materials. All stages in this between included in the study.

3.6.1 Athena Impact Estimator for Buildings

Athena is the only building impact estimator software in North America that is available free for the users. It has the ability to evaluate whole buildings and assemblies based on internationally recognized standards of LCA methodology. Through this software, engineers can easily assess and compare the environmental impacts of different types of buildings, such as industrial, commercial, residential, and institutional. The software is designed easy to use and capable of assessing data from Cradle-to-Grave stages of the life cycle with details and reliable data.

As mentioned before, the software is designed for North America, especially the United States and Canada; names of specific cities considered and can be found in this software. For those areas which cannot be found in the list, the software

prefers to use ‘USA’ (United States-Average); therefore, current study will also consider this option for evaluations.

The ‘Athena Impact Estimator for Building’ software is used for analyzing the environmental impacts of studied frames. The following items will be determined after the calculation processes: Global Warming Potential (GWP), Acidification Potential (AP), Ozone Depletion Potential (ODP), Eutrophication Potential (EP), and Fossil Fuel Consumption (FP). Besides the aforementioned items, transportation impacts are also included in the assessment.

As the construction site is already chosen, the site specifications, loads, probable coming earthquakes are also known taken from ACI-318 codes and Turkish earthquake hazard map website, structural members and their classifications are defined, types of materials needed for structural members are specified, and all cross sections and dimensions are distinguished. The needed data for analyzing has been collected. Athena Impact Estimator needs essential structural members’ dimensions, cross sections details, and types of materials that have been used in the designing stage.

To easily compare the results, the same members of both frames considered for evaluation. Foundations of both frames have the same cross-sections and contain the same volume of materials.

3.6.2 Impact Assessments

After collecting the data from maps, structural design papers, and site, for analyzing the environmental impacts, all needed data entered with their own specifications into the Athena software. Software evaluates different environmental aspects; it also compares the environmental impacts of both frames, allows users to choose the desired one from the list. The outcomes of the Athena Software will be explained with details in chapter 4.

3.7 Models` Information

There are several options for having lateral force-resisting frame, such as braced-frame system, shear wall system, and moment resisting frame. Each has

its own function; every has advantages and disadvantages. A building requires to have at least one of the above systems. Study then recognizes the suitable system to be considered for a structure. Applied loads, dimensions, and height of the building are important factors while considering type of the system, they show independent and different reaction to the applied loads, provide stiffness to the building in the different levels. The moment resisting frames are less stiff than others but suitable from economic and environmental perspectives, they are advised for low-height buildings.

In this part, through a model study, the sustainability assessment of two separate frames, a reinforced concrete frame, and a steel frame have been evaluated. The considered area for the frames will allow us to comfortably compare the environmental impacts of the frames, the life cycle of the frames considered to be 50 years.

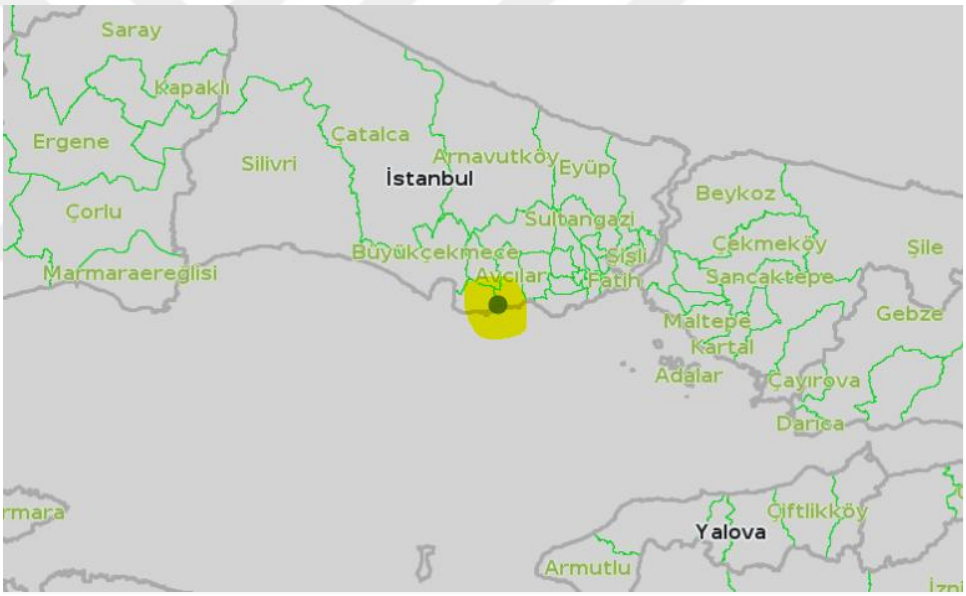


Figure 3.2: Construction Site in the Map

Frames considered in a specific seismic prone area in Istanbul, Turkey at the coordinate 40.977831° and 28.687682°; the site is located at the western side of Beylikdüzü in Istanbul. With 10% the probability of being exceeded in 50 years or 475-year return period.

Table 3.2: Seismic Coefficients

Site Class	S_S	S_1	S_{DS}	S_{D1}	PGA	PGV
B	1.323	0.355	0.882	0.2367	0.533	32.559

Where,

S_s: spectral response acceleration parameter at short periods, 2.0 Sec.
S_1: damped, spectral response acceleration parameter at a period of 1 Sec.
S_{DS}: the design spectral response acceleration parameter at short periods.
S_{D1}: the design spectral response acceleration parameter at a 1-s period.
PGA: peak ground acceleration.
PGV: peak ground velocity.

A hypothetical two separate moment-resisting structural frames` system considered for the design; they are a single long span, 17.8m wide and 7.4m high industrial frames. Both frames are designed with the help of CSI designing software SAP2000, considered as industrial buildings under same site conditions, same loads combinations; they have designed to safely resist all applied loads. The loads considered here are dead loads, live loads, wind loads, and seismic loads. The combination for designing process has been considered base on the American designing code requirements. The structure response modification factor selected based on IBC recommendations; for special moment resisting frames R=8, for both frames. Because we assumed both frames to be moment resisting, as the table 12.2-1 of American Society of Civil Engineering ASCE 7-10 also recommend same terms.

Main structural and non-structural details of the frames presented in table 3.3:

Tabel 3.3: Structural and Non-structural Fuetures of RC Frame.

Frame Fuetures	Description
Location	Yakuplu Merkez, Beylikdüzü, İstanbul - Turkey
Shape	Long Single Span Frame
Span	17.8 m
Height	7.4 m
Foundation	Simple Column Foundation
Materials	Reinforced Concrete and Steel

3.7.1 Concrete Frame

The geographic and geometric details of frames are mentioned above in the table 3.3. Site information taken from the Turkish Earthquake Hazard Website and the design process proceeded based on ACI 318-08 and International

Building Codes (IBC2009) with the help of SAP2000. Site information is taken from the TDTH (Earthquake Hazard Map of Turkey) website.

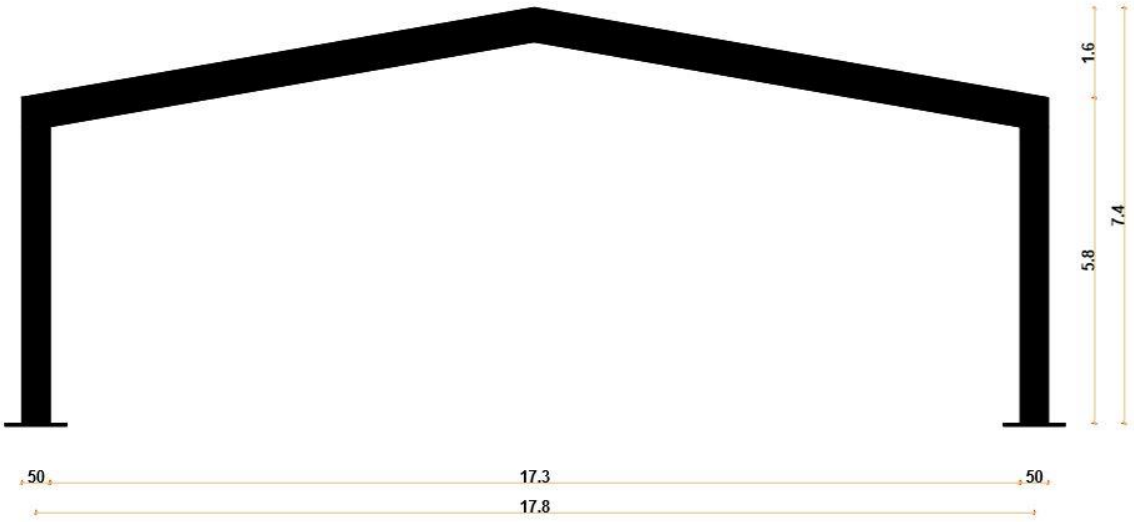


Figure 3.3: Reinforced Concrete Frame

The frame is composed of reinforced concrete with compressive strength of (28 *MPa*), mass per unit volume is (2400 Kg/m^3), and Poisson ratio is (0.2). The longitudinal reinforcement has 32mm diameter, mass per unit volume of the reinforcement is (7850 Kg/m^3) with (250000 *MPa*) modulus of elasticity.

Tabel 3.4: Structural Element Essential Properties

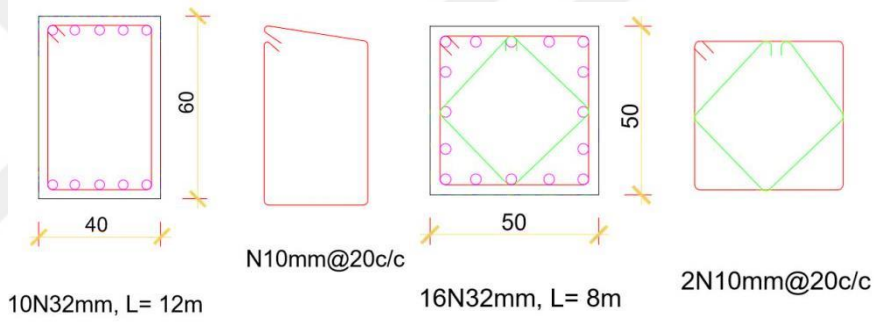
Section Property	Dimension (m)	Cross-section Area (m^2)	Length (m)	Moment of Inertia x-axis (m^4)	Moment of Inertia y-axis (m^4)	Weight (KN)
Column	0.5 x 0.5	0.25	5.8	0.0052	0.0052	68.3
Beam	0.4 x 0.6	0.24	9.09	0.0072	0.0032	102.8

The effective seismic weight of the frame includes full dead loads and a 25% of live loads based on ASCE-7-10 requirements. The frame is assigned to a gravity of dead loads of 2 KN/m^2, live loads of 2 KN/m^2, snow loads of 2 KN/m^2, lateral wind and earthquake loads. The over-strength factor, deflection amplification factor, and response modification factor are 3, 5.5, and 8, respectively. The assumption was that wind load will also be governed by earthquake loads. As

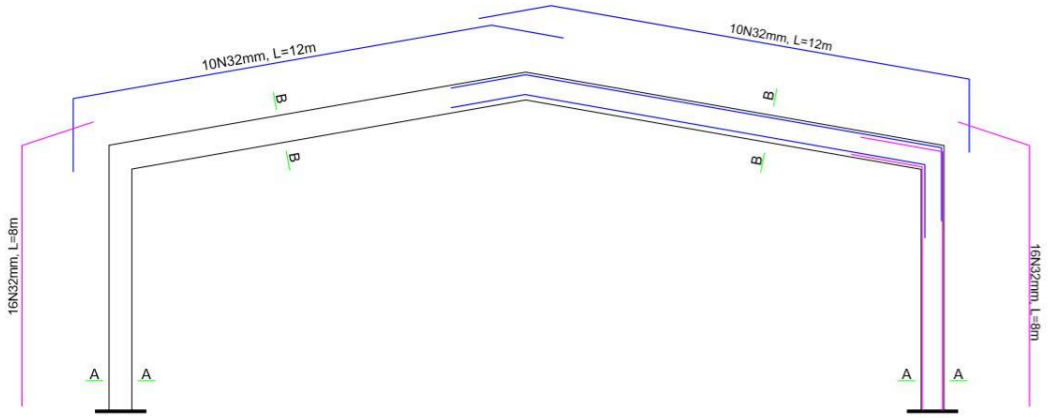
the frame considered in a seismic area, load combinations for both frames are as follows:

Dead Loads,
1.2 Dead Loads + 1.4 Live Loads
Dead Loads + 0.75 EQ
Dead Loads + 0.84 Wind1 Loads + 0.75 Live Loads
Dead Loads + 0.84 Wind2 Loads + 0.75 Live Loads
Dead Loads + 0.75 Snow Loads + 0.75 Live Loads
Dead Loads + 0.75 Live Loads + 0.75 Snow Loads + 0.525 E

The detailing considered for columns and beams are illustrated in the figures below:



(a) (b)



(c)

Figure 3.4: Detailing of Beam (a), Column (b), and Frame (c)

Columns are with square cross sections, have the dimension of (50x50) cm and beam cross-sections considered rectangular with (60x40) cm. Totally, 16 longitudinal bars with 32mm diameter each considered as reinforcement for the columns, (*16N32mm*), length of each bar from foundation including 50d overlaps is 8m (*L=8m*). The longitudinal bars in beam are also 32mm in diameter, each (*10N32mm*), length of each longitudinal bar including 50d overlaps is 12m (*L=12m*). The longitudinal reinforcement in cross-section of the column is 121cm^2 and 87cm^2 for the beam. To accurately strengthen the beam and columns against shear forces *N10mm* stirrup at 20cm considered (*2N10mmØ20*). *N10mm* ties at 20cm, two in every round considered for the columns (*2N10mm@20 c/c*).

The span of the frame is 17.8 m, deflection of the frame controlled; the code says that it shall be in the range of$(\frac{l}{480})$, where *l* represents the net span of the frame. In our case, the deflection is in an acceptable range$(\frac{l}{480} = 3.7cm)$.

3.7.2 Equivalent Lateral Force Analysis (ELF)

This is a method used for obtaining the base shear of a structure when coming under earthquake loads. The value of base shear guaranteeing the structure behavior to withstand properly against earthquake shakes. Recalling the seismic base shear equation,

$$V = Cs * W \qquad (3.11)$$

Where,

Cs = the seismic response coefficient

W = the effective seismic weight of the building

The seismic response coefficient (Cs) can be achieved with the help of the equation (3.12) which is:

$$C_S = S_{D1} * I / R \qquad (3.12)$$

Where,

S_{D1} = design spectral response acceleration parameter at a 1-s period

I = importance factor

R = response modification factor

Also, it is possible to get C_S value from the fundamental period T_a with the help of the following equation; as per ASCE recommendations, Table 12.8.-7:

$$T_a = C_t\,(h)^x \qquad (3.13)$$

Where,

C_t = ASCE table 12.8-2 recommends 0.016 for concrete moment resisting frames and 0.028 for steel moment resisting frames.

h = height of the building

x = ASCE table 12.8-2 recommends 0.9 for concrete frames and 0.8 for steel frames.

$$Ta = 0.016\ (7.4)^{0.9}$$

$$Ta = 0.0969\ sec$$

For the seismic response coefficient Cs;

The S_{Ds} value given for this study is S_{Ds} = 0.7938, the importance factor (I = 1) and the response modification factor (R = 8); then,

$$Cs = 0.7938 * 1 / 8$$

$$Cs = 0.099$$

In this study, the effective seismic weight of the concrete frame including 25% of live loads is W= 172.1 KN, So,

$$V = 0.099 * 172.\ 1$$

$$V = 17.04\ KN$$

3.7.3 Vertical distribution of Seismic Force

As per ASCE-16, table 12.8-3 recommendations; (Fx) is bassically an inertial force at a level which is resulted from the multiplication of acceleration at level x to the mass at that level. The lateral seismic force (Fx) induced at any level can be governed by the following equation:

$$Fx = C_{vx} * V \qquad (3.14)$$

Where,

V = total design lateral force or (shear) at the base of the building

C_{vx} = vertical distribution factor which can be governed by the following equation:

$$C_{vx} = \frac{w_x \, h_x^{\,k}}{\sum_{i=1}^{n} w_i \, h^k{}_i} \qquad (3.15)$$

Where,

W_i, W_x = portion of the total effective seismic weight of the structure (W) located or assigned to level *i* or *x*

h_i, h_x = height from the base to the level *i* or *x*

K = an exponent related to the structure period; the codes requirements are as follow:

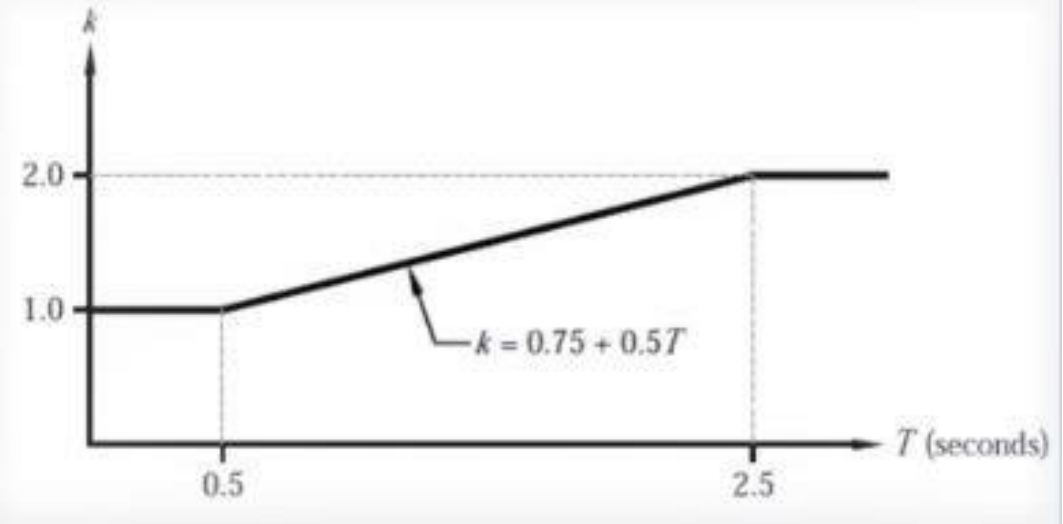


Figure 3.5: Variation of K according to the structure period

- For structures with the structural period equal to 0.5 or less, K=1
- For structures with the structural period equal to 2.5 or more, K=2
- For structures with the structural period between (0.5 - 2.5), K= 1-2

The distribution of the forces are largely related to the first mode shape of the structure not higher shapes.

In the case of this study, the vertical distribution of the force;

$$V = 17.04 \text{ KN}$$

$$Cs = 0.099$$

$$R = 8$$

$$I = 1$$

$$T = 0.0969$$

Seismic base shear is,

$$V = Cs * W$$

$$V = 0.099 * 172.1$$

$$V = 17.04 \text{ KN}$$

As the $T_a = 0.0969$ and less than 0.5, the vertical distribution component k = 1;

So the vertical distribution factor is:

$$C_{vx} = 1$$

And, the lateral force (Fx);

$$Fx = 17.04 \text{ KN}$$

It is important to mention that, if structures are irregular their design processes need to be proceeded with dynamic design procedure.

The overturning moment of reinforced concrete frame is calculated (OTM = 126.096 KN*m).

3.7.4 Lateral Drift

The ASCE-7 (Table12.8.6) defines the drift as the difference between the displacements of up and down floors. In other simple words, drift is the displacement of one floor with respect to other floor after applying lateral loads; while displacement of a floor is the displacement of a floor with respect of the base of the building.

Story drift of structures located in seismic regions and have plan irregularities can be governed with the following equation:

$$\delta x = \frac{Cd * \delta xe}{Ie} \qquad (3.16)$$

Where,

δ_x = deflection at level x

C_d = deflection amplification factor

δ_{xe} = deflection at the level determined by elastic analysis Ie

I_e = Importace factor

ASCE and NEHRP recommend deflection amplification factor (C_d=5.5) for special moment resisting frames, for ordinary moment concrete and steel frames this value is 2.5 and 3, respectively.

The story drift shall be less than the allowable story drift as expressed in the ASCE table 12.12-1. The allowable drift for frame is coming under 0.020hx conditions.

h_x = is the height of the story from base of the building.

3.7.5 Time History Analysis

Most of the current design strategies are based on prescriptive procedures, in this procedure, after checking and satisifying a number of requirements then the building is considered to be safe because it fulfills the safety requirements against collaps. Performance based design method introduced to performe the

design process based on some probabalities in seismic regions. This method is more reliable and in the same time time-consuming, accurate for estimating non-linear structural responses of buildings. The main purpose of this method is to predict the probable hazards affecting safety of a structure, thus, the designers consider those hazards and improving the safety level accordingly.

Through time history analysis hazards predictions can be easily performed. Applying ground motion records of a specific area is an easy method to assume that the building may subjected to a set of ground excitations from this kind. To assure the safety, a scale factor is needed while dealing with natural records. The highest scales are selected from the records and S_A (T_1, *5%)* is added to them.

Through time history analysis the peak ground acceleration, velocity, and displacement can be achieved (Nikos *et al.,* 2013). Based on ASCE 7-05/7-10 recommendations, ground motions from a site shall be selected with enough details such as magnitude, sources, site conditions, and fault distance. Earthquakes with magnitude of lower than 6.5 can cause damage to non-structural members and probaby could cause collapse new structures. The earthquakes with magnitude of higher than 6.5 generate strong motions with long duration and affect a big region. The earthquakes with high ground accelerations causing damages to the structures, the intensity of the motion mostly depend on the distance of structure from the fault. There are different types of faults such as near fault in 10 Km distance, far fault which is located in distance more than 10 Km. The structures located near to the fault line is more likely to damage during earthquakes.

Most of the designs practice with the help of linear methodology using the elastic level, such as equivalent linear static procedure, linear time history analysis, and modal response spectrum methodology. The reduction factor of R is used to get the enelastic response, in this method the elastic loads are divided by R; thus, the system will show ductility and overstrength. If the number of records are between 3 and 6, the maximum responses are taken for calculations. In case the numbers of records are 7 or more than 7, then the average is considered for calculation (Nikos *et al.,* 2013).

Site and ground conditions also affecting the response of structures to earthquake shakes. Soil is classified to different classes, from A to F. Class A

represents hard rocks and class F is reffered to clay. Hard rocks response with high frequency and short period to earthquakes while soft soil transmit low frequency and long period. Below are some of the ground accelerations and displacements of three different earthquakes recorded in Kobe of Japan1995, El Centro Imperial Valley1940, and Friuli in Italy-1976; the relavent information about mentioned earthquakes are listed in the table and figures below:

Table 3.5: Considered Three Different Earthquakes

No.	Name of Earthquake	Year	Magnitude, M	Component
1	Kobe of Japan1995	1995	6.9	0
2	El Centro Imperial-Valley	1940	6.95	180
3	Friuli, Italy-1976	1976	6.5	0

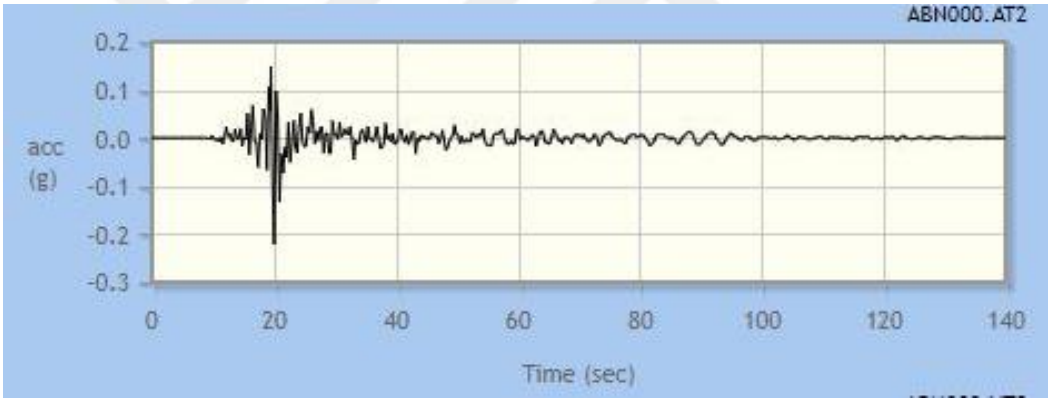


Figure 3.6: Kobe-Japan1995 Earthquake Ground Acceleration in Horizontal-1

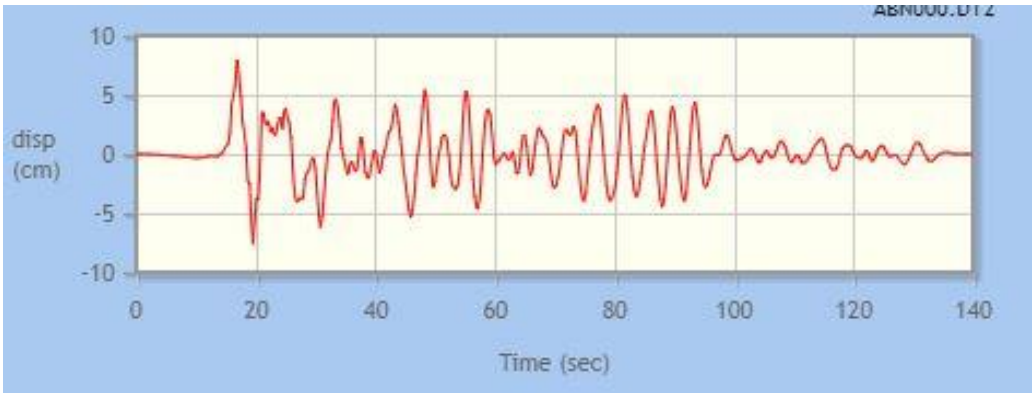


Figure 3.7: Kobe-Japan1995 Earthquake Ground Displacement in Horizontal-1

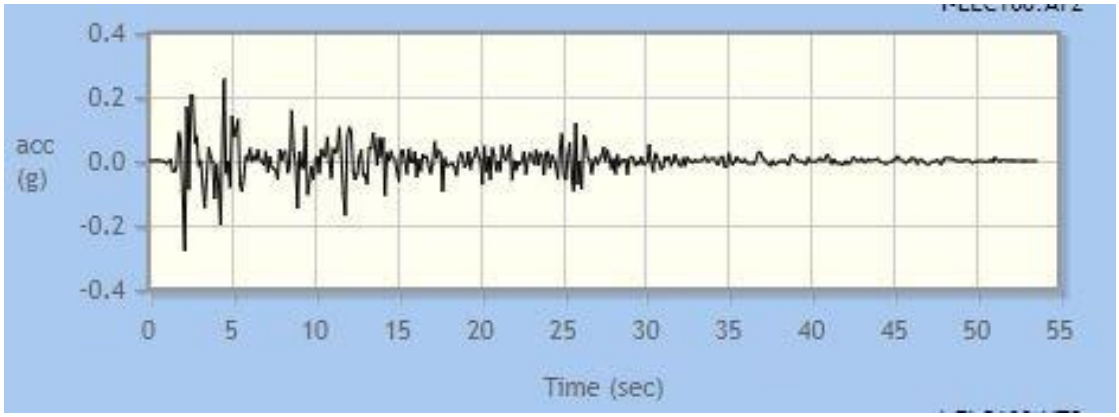


Figure 3.8: El Centro1940 Earthquake Ground Acceleration in Horizontal-1

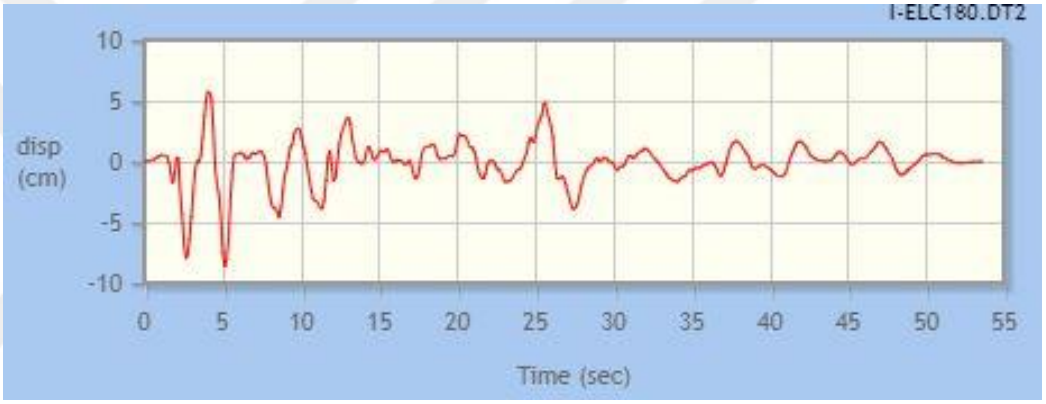


Figure 3.9: El Centro1940 Earthquake Ground Displacement in Horizontal-1

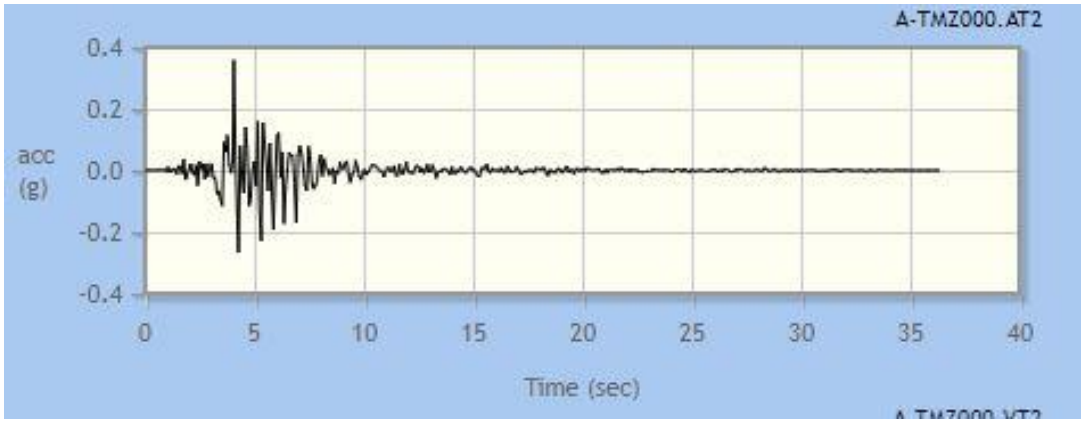


Figure 3.9: Friuli, Italy-1976 Earthquake Ground Acceleration Horizontal-1

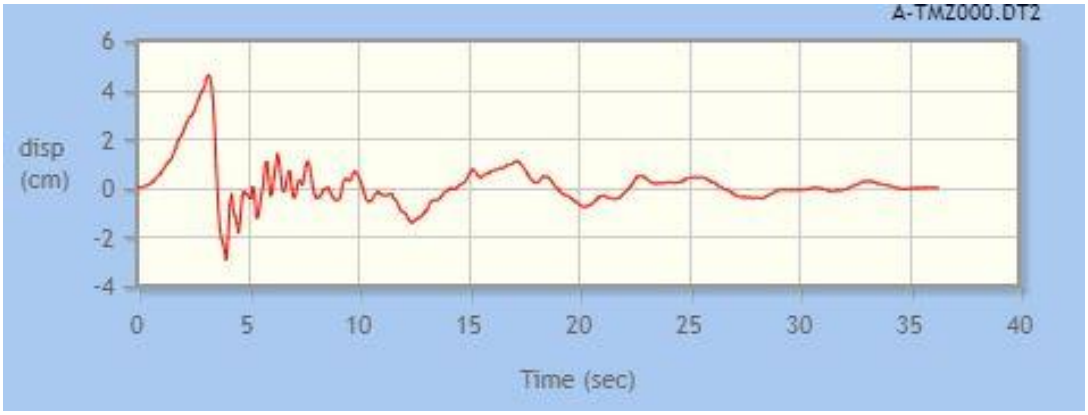


Figure 3.10: Friuli, Italy-1976 Earthquake Ground Displacement H-1

There are different ways for scaling the ground motions, experts have not been agreed on one scaling approach. As mentioned before, the widely used one is the 5%-damped acceleration matching approach with fundamental period of S_A $(T_1, 5\%)$ with site spectrum at 1 sec.

The site spectrum curve for the parameters mentioned in table 3.1 is shown in the figure below:

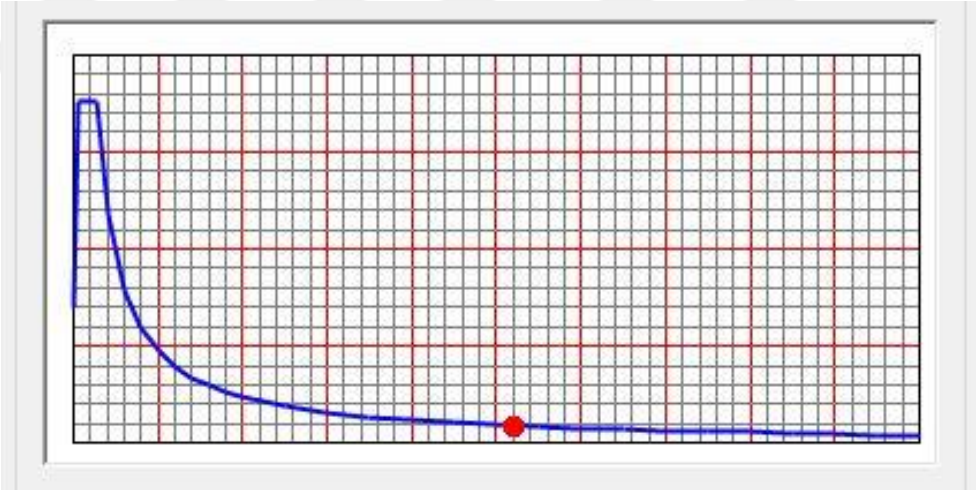


Figure 3.11: Site Response Spectrum Curve

3.7.6 Steel Frame

Steel frame has the same span and height as the RC frame with different column and beam cross-sections. As mentioned before, site conditions, loads

combinations, applied forces and geomery has been considered same as for the concrete frame.

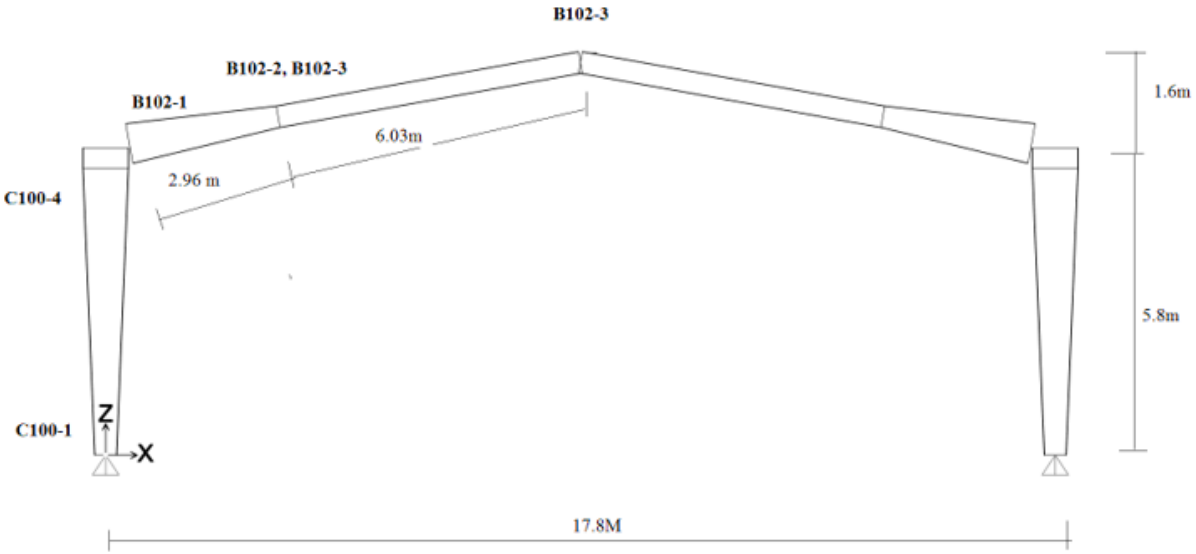


Figure 3.12: Steel Frame

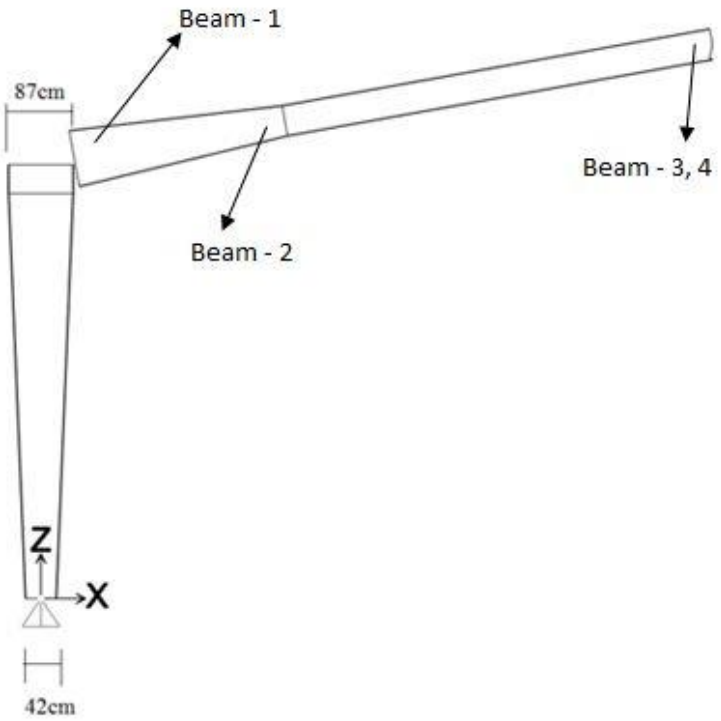


Figure 3.13: Illustration of tapered sectional dimensions

The details about the frame`s materials illustrated in the table 3.6:

Table 3.6: Materials Specifications

f_y	f_{ye}	f_u	f_{ue}	A	E	υ
$24*10^6$	$26*10^6$	$37*10^6$	$4*10^7$	1.170E-05	2100000	0.3

Where,

A: Coefficient of thermal expansion

f_y: Maximum yeild stress

f_u: Minimum tensile stress

f_{ye}: Expected yeild stress

f_{ue}: Expected tensile stress

E: Modulus of elasticity

υ: Poisson ratio

The specifications of the nonprasmatic steel columns are written below in the tables 3.7 and 3.8:

Table 3.7: Sizes of the Steel Column at the Top

Top				
Outside height (t_3) cm	Top flange width (t_2) cm	Top flange thickness (tf) cm	Bottom flange width (t_w) cm	Bottom flange thickness (tf_b) cm
87	25	1.0	25	1.0

Table 3.8: Sizes of the Steel Column at the Bottom

Bottom				
Outside height (t_3) cm	Top flange width (t_2) cm	Top flange thickness (tf) cm	Bottom flange width (t_w) cm	Bottom flange thickness (tf_b) cm
42	25	1.0	25	1.0

Non-prismatic beam sections details are written in the tables 3.9, 3.10, and 3.11 for beam No.1, 2, and 3 respectively:

Table 3.9: Beam 1-2

Beam – 1-2					
Outside height	Top flange width	Top flange thickness	Web thickness	Bottom flange width	Bottom flange thickness
76.6	25	0.8	0.6	25	0.8

Table 3.10: Beam 2-2

Beam – 2-2					
Outside height	Top flange width	Top flange thickness	Web thickness	Bottom flange width	Bottom flange thickness
41.6	25	0.6	0.6	25	0.8

Table 3.11: Beam 2-3

Beam –2-3					
Outside height	Top flange width	Top flange thickness	Web thickness	Bottom flange width	Bottom flange thickness
41.6	25	0.8	0.6	25	0.8

The frame is composed of steel with compressive stress of ($24*10^4$ *MPa*), weight per unit volume is (7850 Kg/m^3), mass per unit volume is (800 Kg/m^3), and Poisson ratio is (0.2).

Tabel 3.12: Structural Element Essential Properties

Section Property	Dimension (m)	Cross-section Area (m^2)	Length (m)	Moment of Inertia x-axis (m^4)	Moment of Inertia y-axis (m^4)
Column	0.42 base	0.0082	5.8	0.000252	0.000026
Column	0.87 top	0.0118	5.8	0.00133	0.000026
Beam 1-2	-	0.0085	9.09	0.000785	0.000021
Beam 2-2	-	0.0064	9.09	0.00019	0.000021
Beam 2-3	-	0.0064	9.09	0.00019	0.000021

While the seismic response coefficient is (Cs = 0.099), the seismic effective weight of the steel frame including 25% of live loads is (W = 158 KN); the base shear calculated for steel frame is V = 15.64 KN.

For the vertical distribution forces (Fx),

$$T_a = 0.079$$

K = 1 because T_a = 0.079<0.5, then C_{vx} = 1; details have been provided in RC frame section.

So,

$$F(x) = C_{vx} * V$$

$$F(x) = 15.64 \text{ KN}$$

The overturning moment of the steel frame is calculated as (OTM= 115.7 KN*m).

3.7.6 Pushover Analysis

In recent years, the performance-based design method is emerging in structural engineering field. The method is still under research; the academics are working on its further improvement. The design processes are slowly changing path from linear to nonlinear design procedures; the outcomes affect thoughts about classic seismic design methods. The Euro Code-8 introduces four methods in total for seismic analysis which are mainly used for buildings and bridges; Linear Static Analysis, Linear Modal Analysis, Nonlinear Pushover Analysis, and Nonlinear Time History Analysis. In structural designing, two main factors are considered, in other words, the design procedure is accomplished based on, a) Displacement and b) Forces.

The simplest method which is able to demonstrate the nonlinear behavior of a structural system is introduced under the name of Pushover Analysis. Through pushover analysis, the strength capacity of a structure beyond its elastic capacity can be estimated. The pushover analysis can be used for the existing structures as well while assessing the need for retrofitting and deficiencies. The method can also predict the weak points by emerging “hinges” in the structure (Rahul Leslie 2013; Buildings Design, DRIQ Board, Kerala PWD, Trivandru).

The pushover analysis is used for the following purposes:

- To understand the over-strength ratio values.
- To estimate the expected formation of mechanisms in the system and damage distribution.
- To assess the structural performance of existence buildings.
- The pushover analysis is an alternative to the linear seismic designing.

In pushover analysis loads intensity is applying in one direction in a time and can be carryout both in 2D and 3D models. The gravity and lateral loads are monotonically applying to the level from which we can get enough points, base shear, and roof displacement. These points help us accurately plot the pushover curve (Rahul Leslie 2013; Buildings Design, DRIQ Board, Kerala PWD, Trivandru).

The governing issue in pushover analysis is the base shear vs roof displacement. There are three well-known pushover approaches:

- Equivalent linearization approach or (Capacity Spectrum Method).
- Displacement modification factor which is called (Displacement Coefficient Method).
- Nonlinear response history analysis (NLRHA) of the equivalent SDF system.

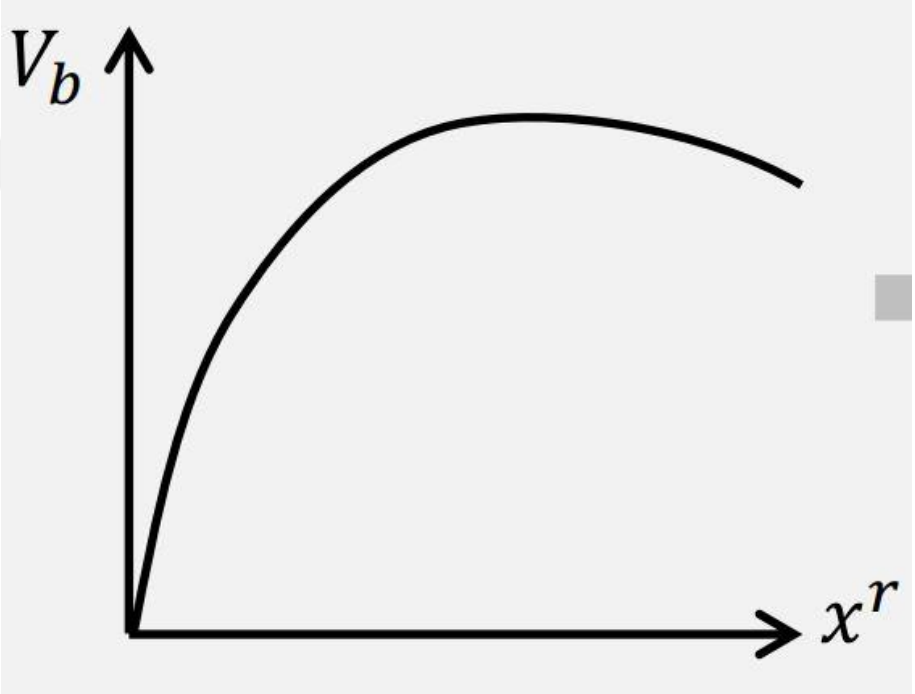


Figure 3.14: Pushover Curve (NUST-2020)

The capacity of a structure is represented by the pushover curve; with the help of Capacity Spectrum Method (CSM), the performance point or target displacement can easily be achieved. This method is based on equivalent linearization approach, in CSM, the nonlinear force deformation behavior of a MDF system is converted into an equivalent SDF system. In this method, the

base shear which is located in Y axis is converted into spectral acceleration and the roof displacement is converted to spectral displacement in X axis. This way the associated factors such spectral acceleration and spectral displacement can be achieved. The newly achieved curve is in the format of Acceleration Displacement Response Spectrum (ADRS). Conversion equations of pushover curve into capacity curve are as follows:

$$S_A = \frac{Vb}{W/Cm} \qquad (3.17)$$

$$S_D = \frac{T2}{4\pi 2} S_A \qquad (3.18)$$

The performance point can then be achieved by conversion of site response spectrum into ADRS format. Therefore, plotting both, the capacity curve and the demand or response spectrum curve in the same coordinates; their intersection point is “Performance Point” which is also called the target displacement.

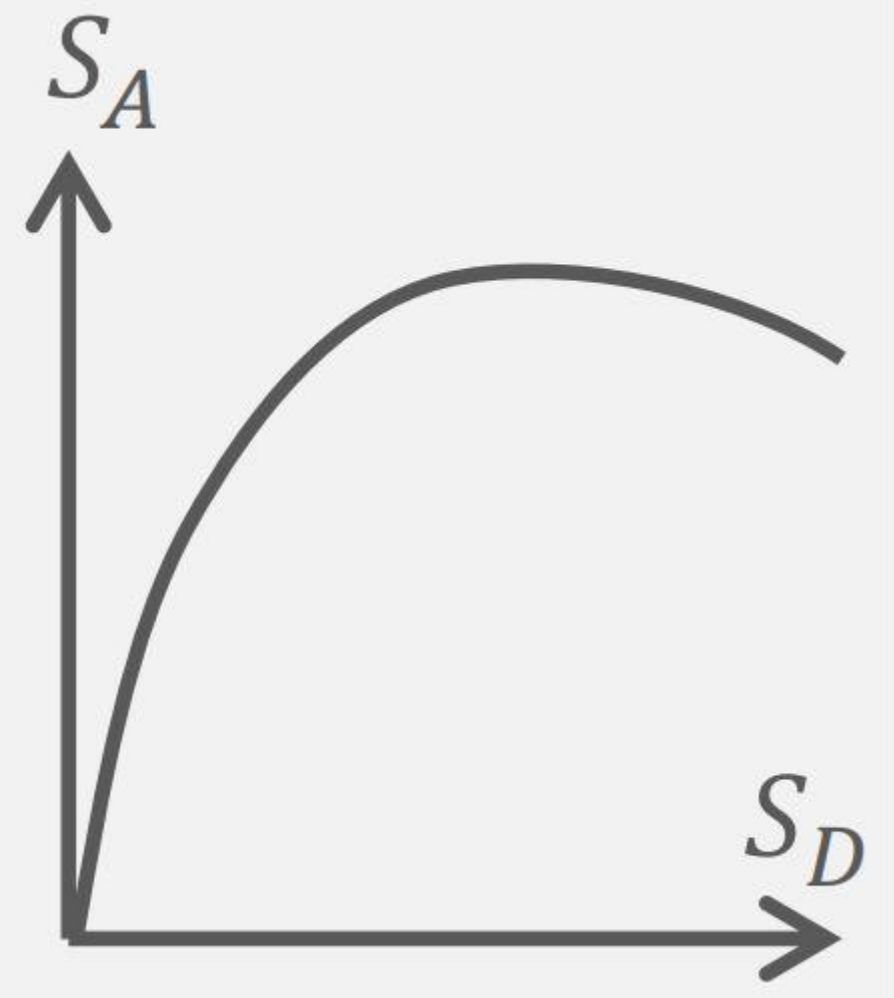


Figure 3.15: Capacity Spectrum Curve (NUST-2020)

It is worth mentioning to add that the demand spectrum is not simply the response spectrum but the reduced form of it. The reduction is basically due to the increment of the damping ratio and elongation of time period.

The FEMA-365 is working based on Displacement Coefficient Method (DCM), while ATC-40 is using the Capacity Spectrum Method (CSM). In ATC-40 method, the analysis continues until the Performance Point is reached. To easily get the performance point, the real MDF system is assumed as SDF system and considering the nonlinear curve to a simple idealized linear curve. The pushover curve could be made of hundreds of points while the idealized pushover curve could be made of 3, 4 or 5 points (Najam & Warnitchai, 2020).

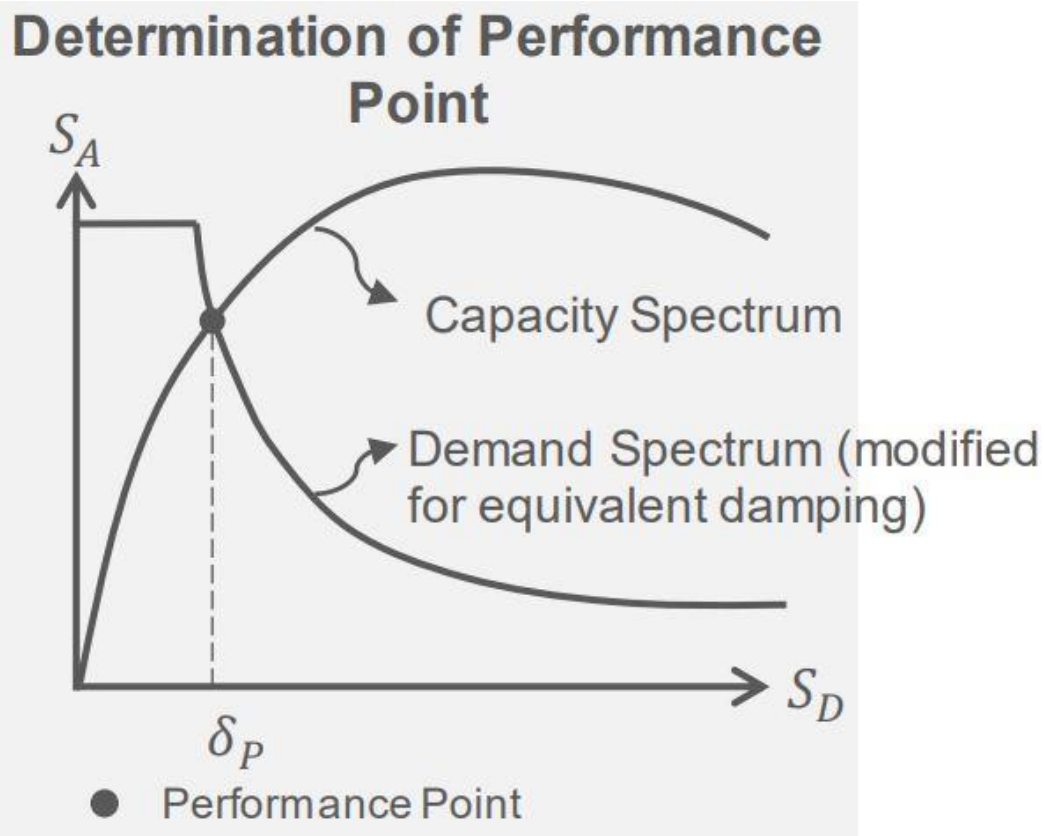


Figure 3.16: Determination of Performance Point (NUST-2020)

Emerging of hinges in structural members are important indicators in pushover analysis. The hinges are points in a structure where cracks start, with further loadings the cracked points experiencing yielding so they demonstrate flexural displacement when reach ultimate strength. The hinges are expected in both ends of structural members. Hinges are classified into three types flexural, shear, and axial hinges (Najam & Warnitchai, 2020).

In pushover analysis, gravity loads and lateral loads are used. In gravity loads, all dead loads and some portion of live loads are included. Lateral loads loading pattern can be selected as uniform (rectangular), based on considered codes requirements, first mode shape (assuming that the building will deform in the first mode shape only), and combination of modes. For low rise buildings, the first mode shape is more likely effective and can be used (Najam & Warnitchai, 2020).

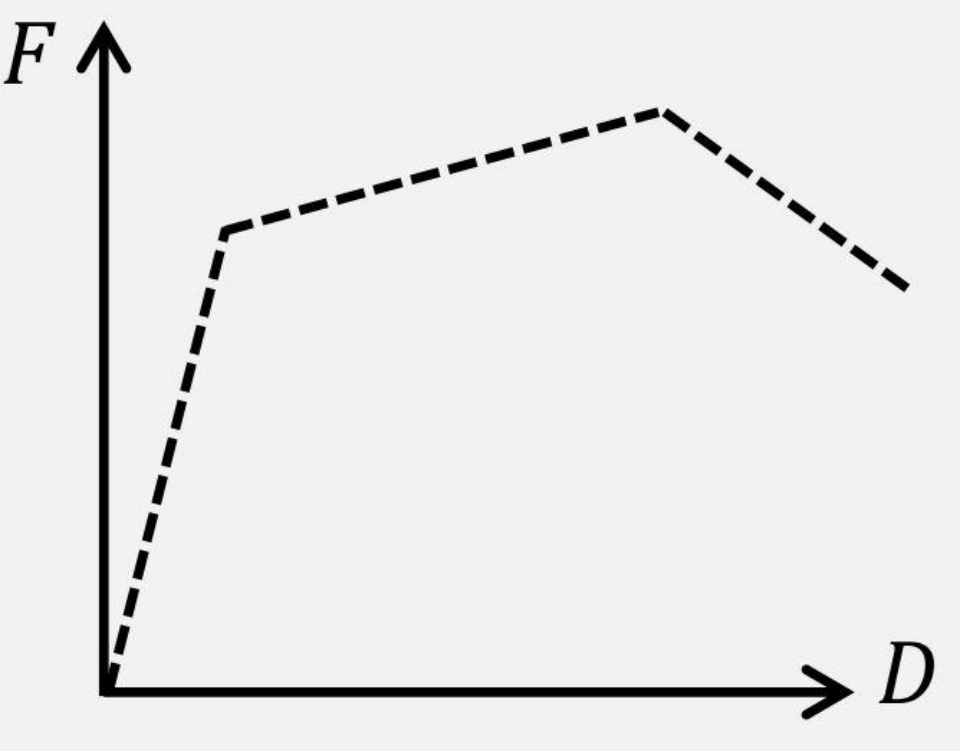


Figure 3.17: Capacity Spectrum Curve (NUST-2020)

According to ASCE/SEI-41, three distinct levels of performance definitions have been classified for buildings under “Structural Performance Levels” and two distinct intermediate levels under “Structural Performance Range”. The three performance levels are Immediate Occupancy (IC), Life Safety (LS), and Collapse Prevention (CP). The intermediate ranges are Damage Control Range and Limited Safety Range. Such definitions aim to alert the users or put them in light of when they have to consider rehabilitation of a structure.

The Turkish Earthquake Code TEC-2007 classified performance definitions into two major classes; “Ductile” and “Brittle”. The ductile members have Minimum Damage Limits (MN), Safety Limits (SL), and Collapse Limits (CL). The brittle members, in TEC-2007 code are not allowed to exceed the (MN) limits, which show the start of plastic behavior (Dilsiz, 2013).

CHAPTER 4

RESULTS

4.1 Concrete Frame

Time history analysis (THA) and pushover analysis for both frames have been performed with the help of SAP2000; in THA, three different earthquakes have been selected from PEER Ground Motion Database of Pacific Earthquake Engineering Research Center. To accurately represent considered site seismicity conditions, magnitudes of the earthquakes selected with different big values. Concrete frame experienced different structural terms after applying loads. The displacements only considered in the X axis because the frame is a single span and single bay structural system.

Figure below shows the deformed shape of the frame after applying the lateral loads.

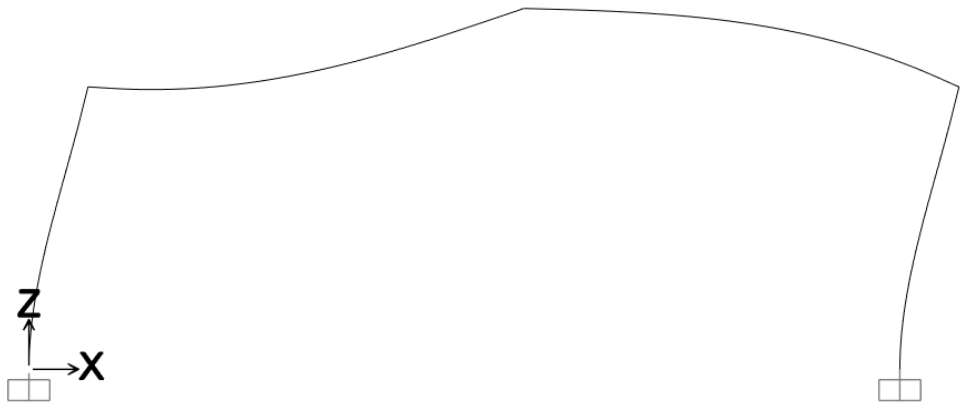


Figure 4.1: Lateral Drift of the Frame

Below are some of the diagrams resulted from different applied loads.

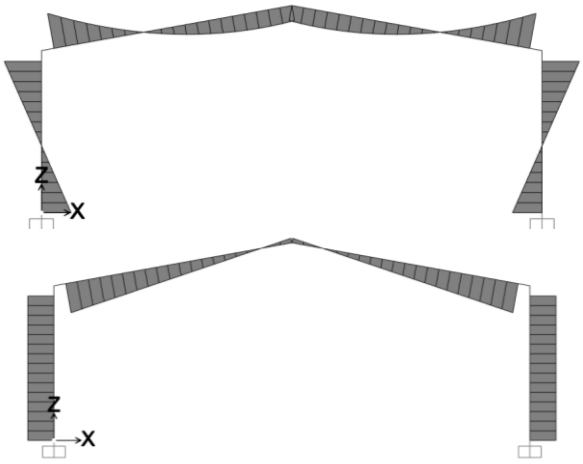


Figure 4.2: Dead Loads Maximum Moment and Shear Diagrams

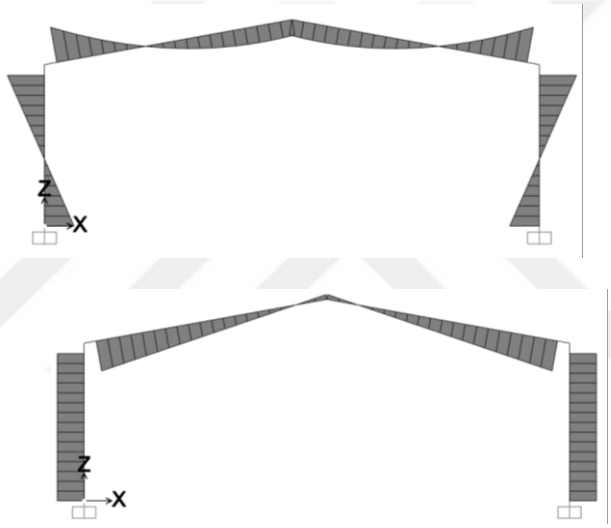


Figure 4.3: Live Loads Maximum Moment and Shear Diagrams

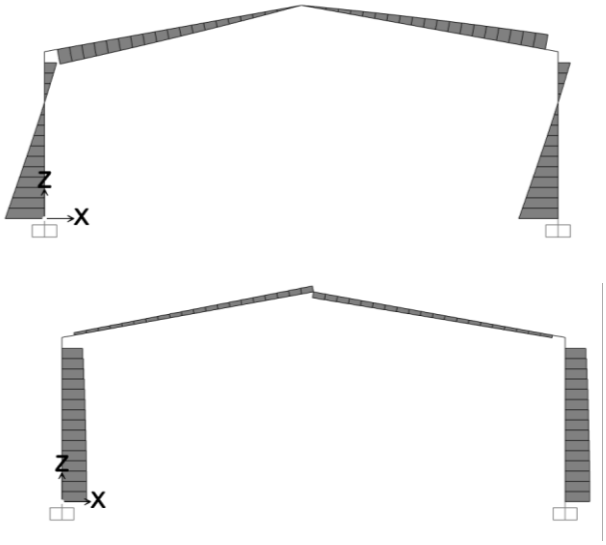


Figure 4.4: Earthquake Loads Maximum Moment and Shear Diagrams

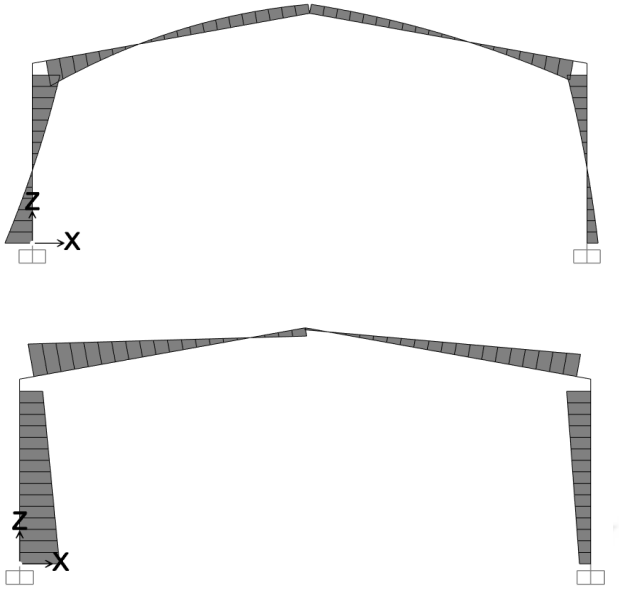


Figure 4.5: Wind Loads Maximum Moment and Shear Diagrams

4.2 Steel Frame

The lateral drift of the frame causing by wind loads is 0.196cm at the rafter level and 0.39cm at the top point of the frame; lateral drift due to earthquake loads is 1.213cm both in rafter and top levels of the frame. The values from Time History Analysis show that, the maximum displacement from Kobe-Japan earthquake records is U1= 0.098cm. Based on ASCE (Table 12.12-1), the allowable drift of systems considered in this study should be less than 2% of the height of the story. Drifts resulted in this study are based on code requirements and are in the range of the allowable drift.

Generally, steel frames have more flexible system than concrete and the joints considered for frames are different from each other, thus, resulted with slightly bigger drift values.

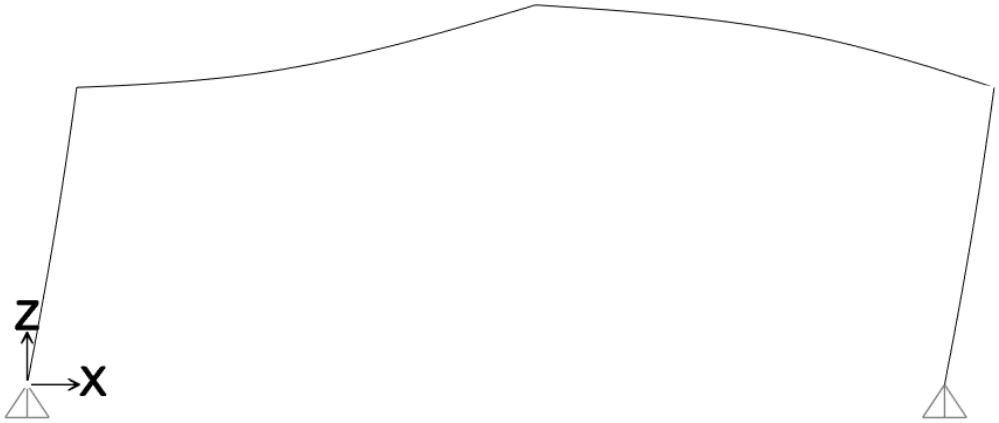


Figure 4.6: Lateral Drift of the Steel Frame

The figures and tables in the coming pages illustrate the moment and shear forces diagrams after applying different loads.

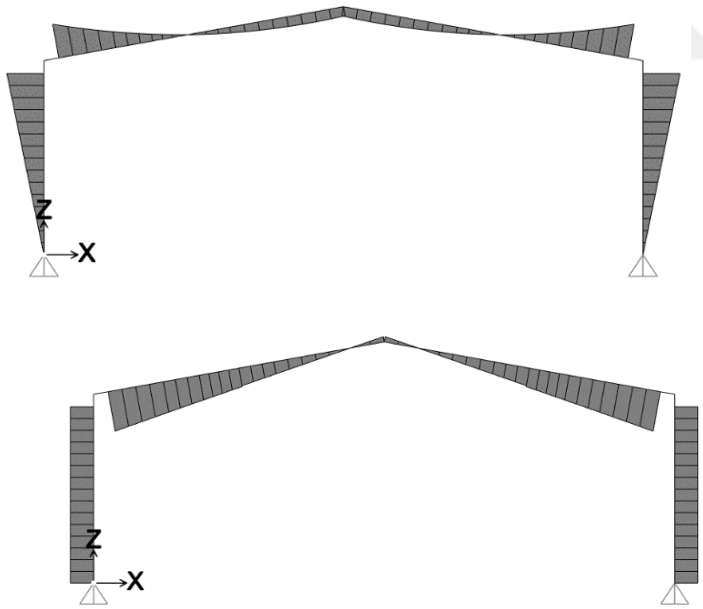


Figure 4.7: Dead loads Maximum Moment and Shear Diagrams

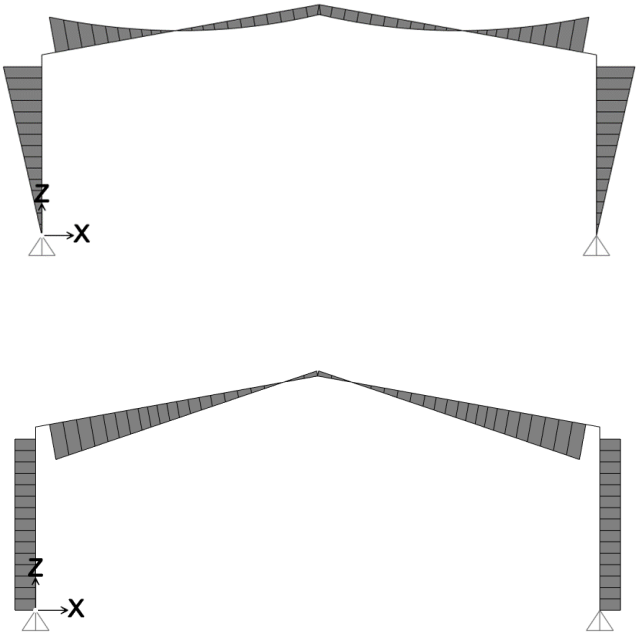


Figure 4.8: Live loads Maximum Moment and Shear Diagrams

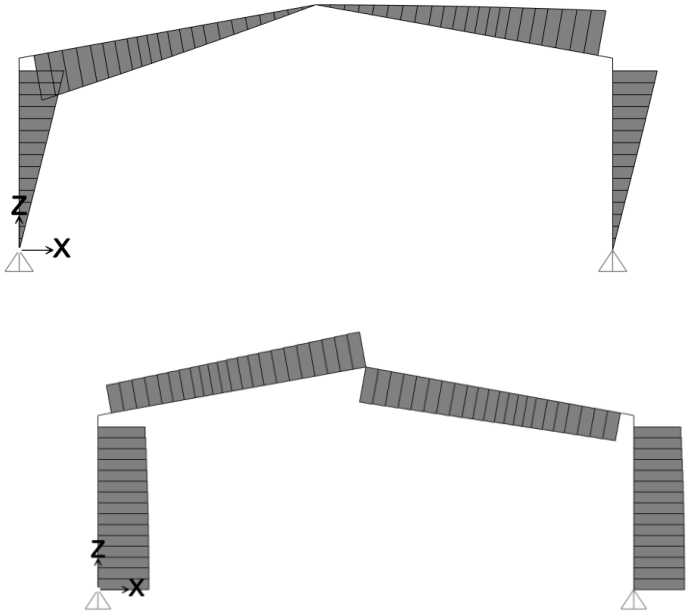


Figure 4.9: Earthquake loads Maximum Moment and Shear Diagrams

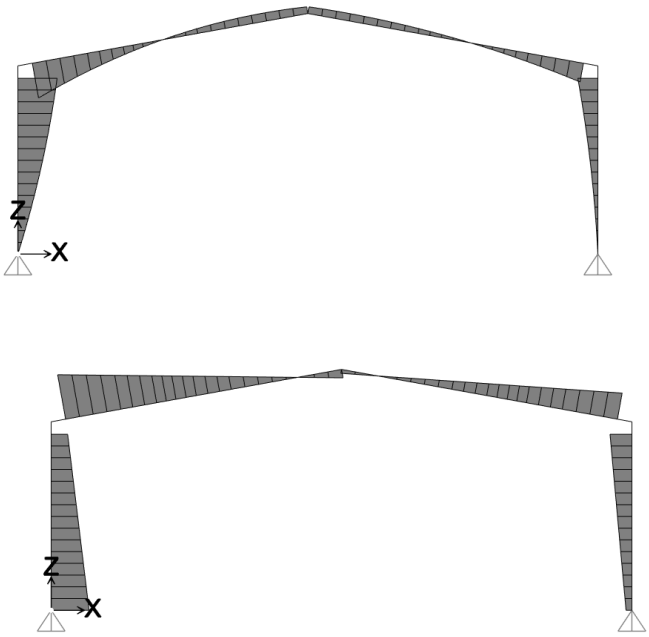


Figure 4.10: Wind loads Maximum Moment and Shear Diagrams

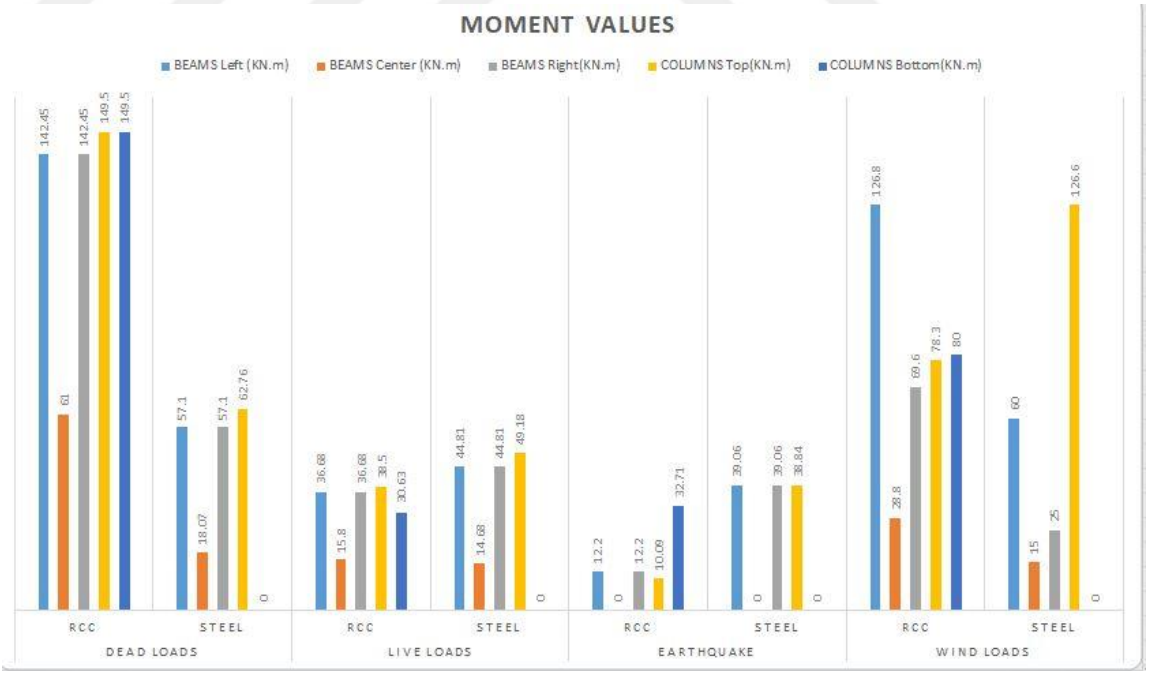


Figure 4.11: Moment Values` Differences in RC and Steel Frames

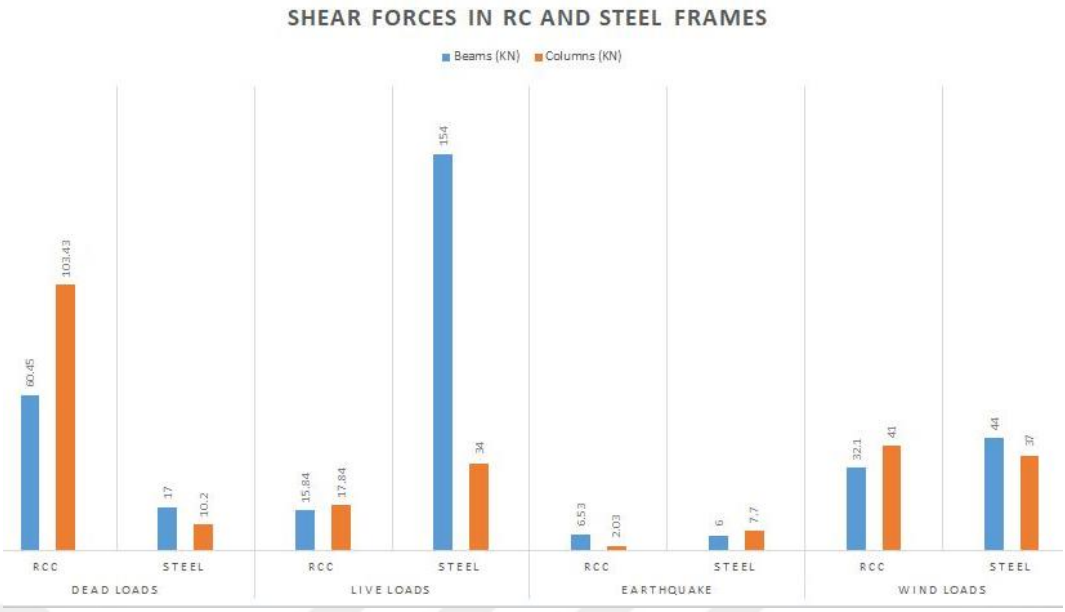


Figure 4.12: Shear Force Values` Differences in RC and Steel Frames

The figures below illustrate the absolute acceleration and absolute displacement of RC frame after performing the time history analysing of considered three earthquake records.

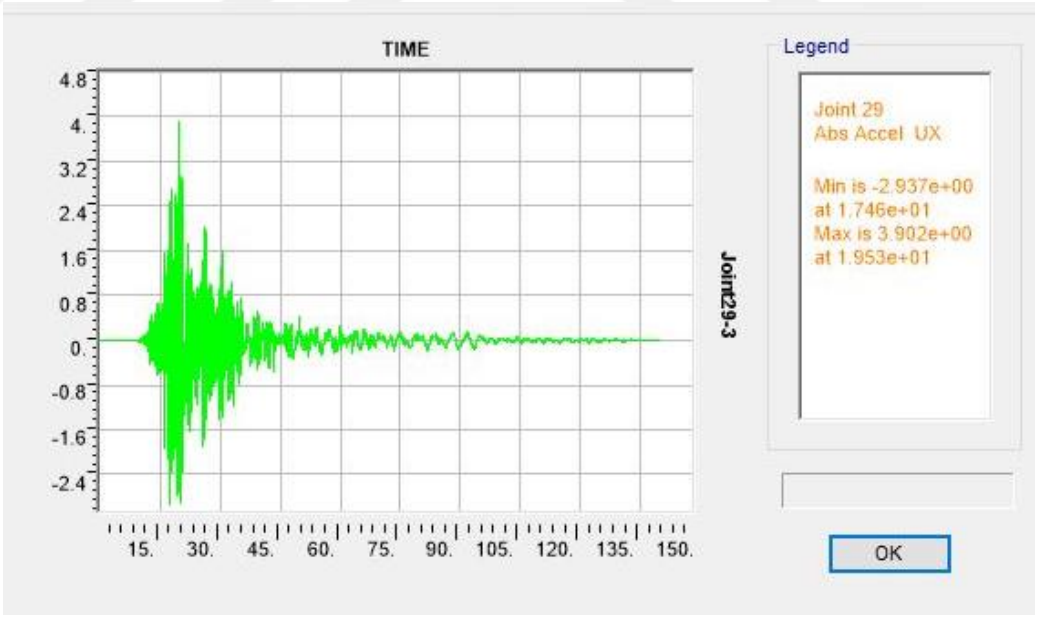


Figure 4.13: Kobe of Japan1995 Earthquake Abs. Acceleration Graph

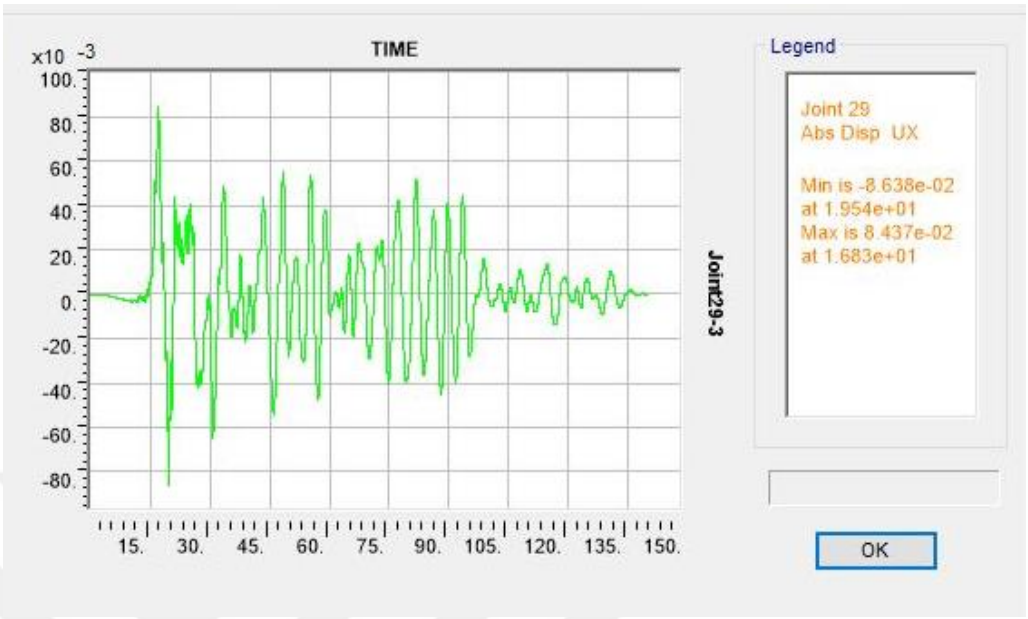


Figure 4.14: Kobe of Japan1995 Earthquake Abs. Displacement Graph

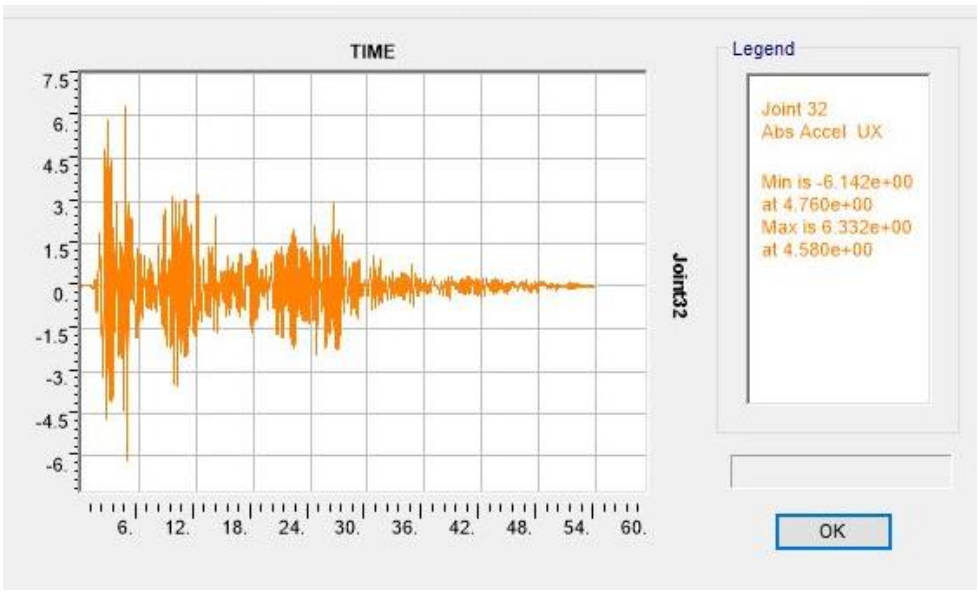


Figure 4.15: El Centro Imperial-1940 Earthquake Abs. Acceleration Graph

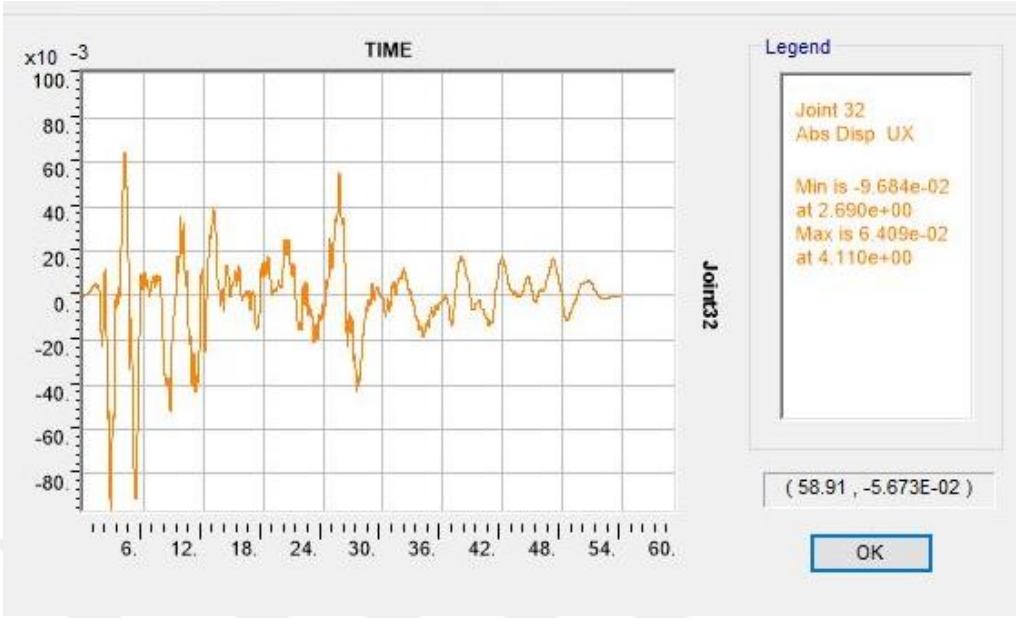


Figure 4.16: El Centro Imperial-1940 Earthquake Abs. Displacement Graph

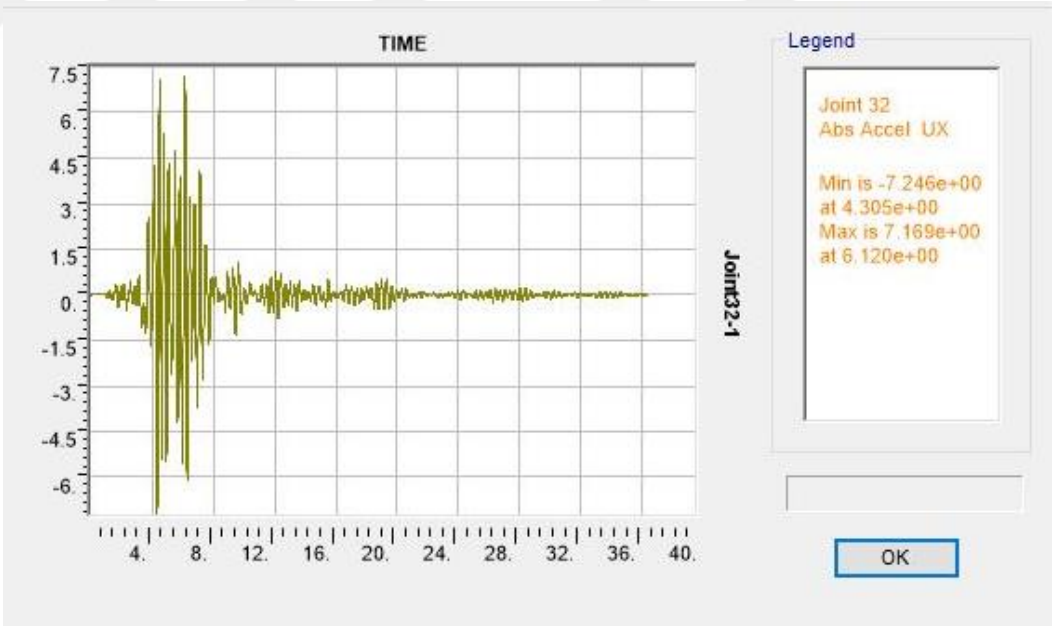


Figure 4.17: Friuli, Italy-1976 Earthquake Abs. Acceleration Graph

Figure 4.18: Friuli, Italy-1976 Earthquake Abs. Displacement Graph

Ground motions from Kobe-Japan1995, El Centro1940, and Friuli of Italy 1976 earthquakes for the steel frame are shown in the following figures:

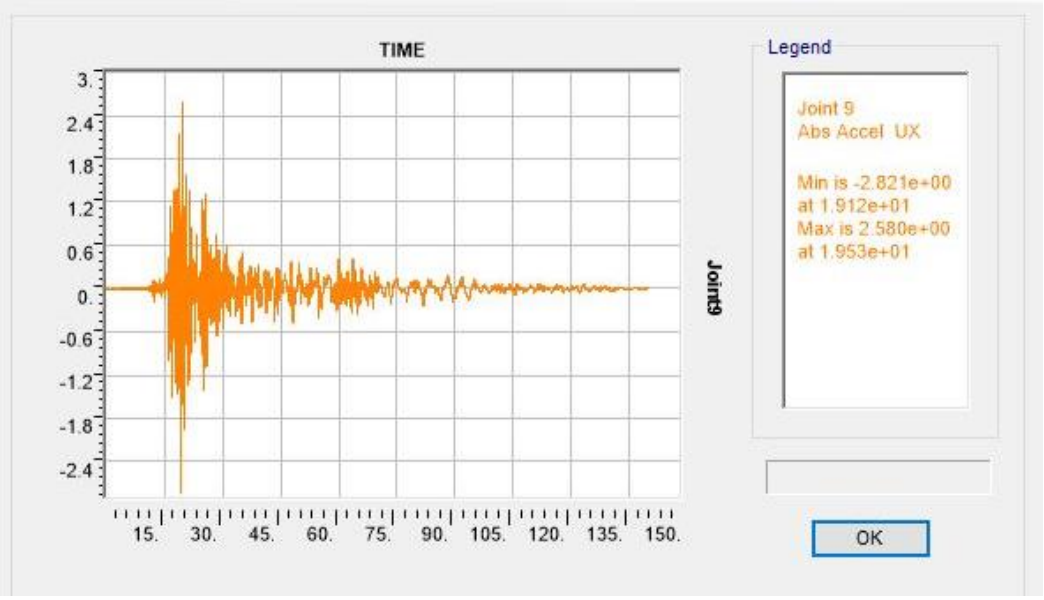


Figure 4.19: Kobe of Japan1995 Earthquake Abs. Acceleration Graph

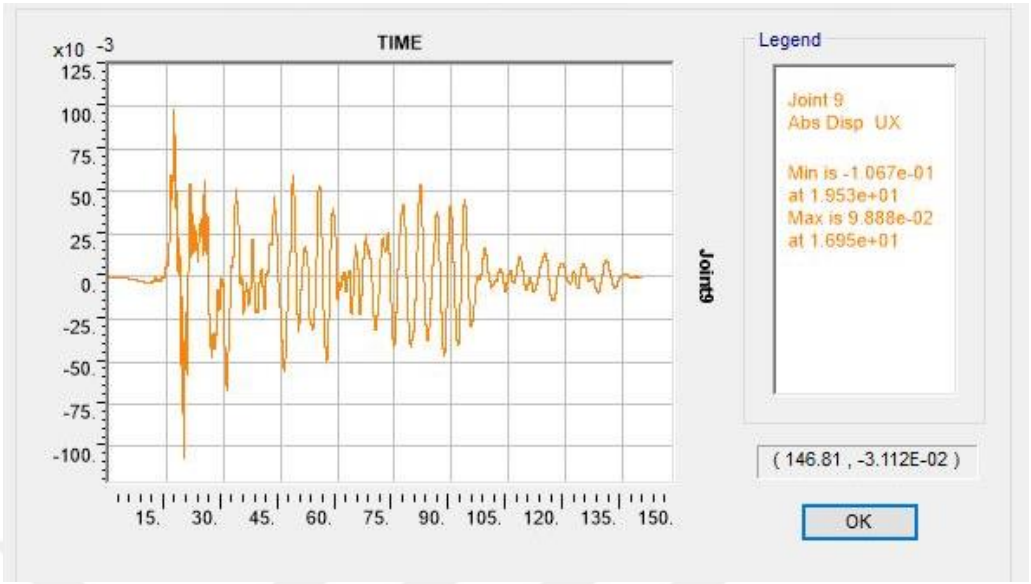


Figure 4.20: Kobe of Japan1995 Earthquake Abs. Displacement Graph

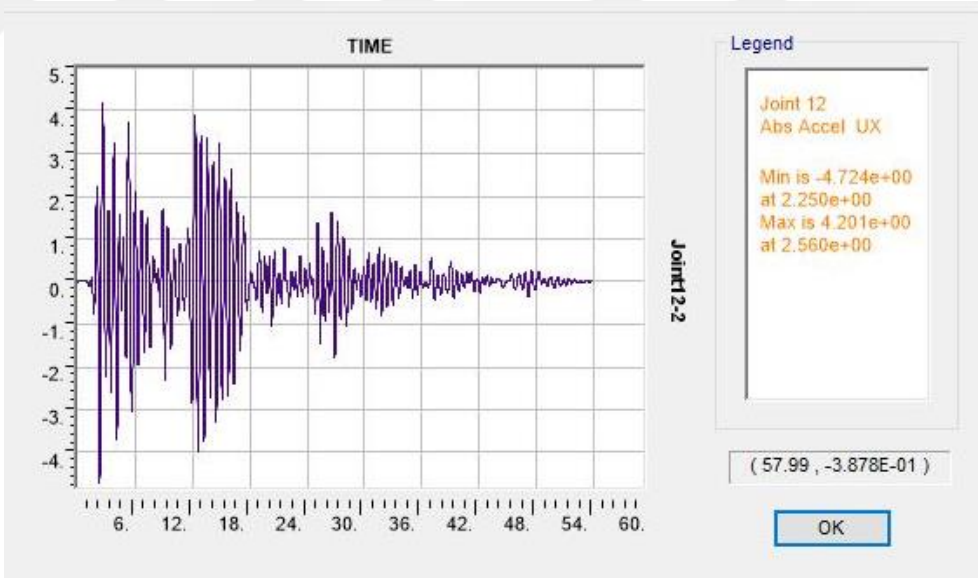


Figure 4.21: El Centro Imperial-1940 Earthquake Abs. Acceleration Graph

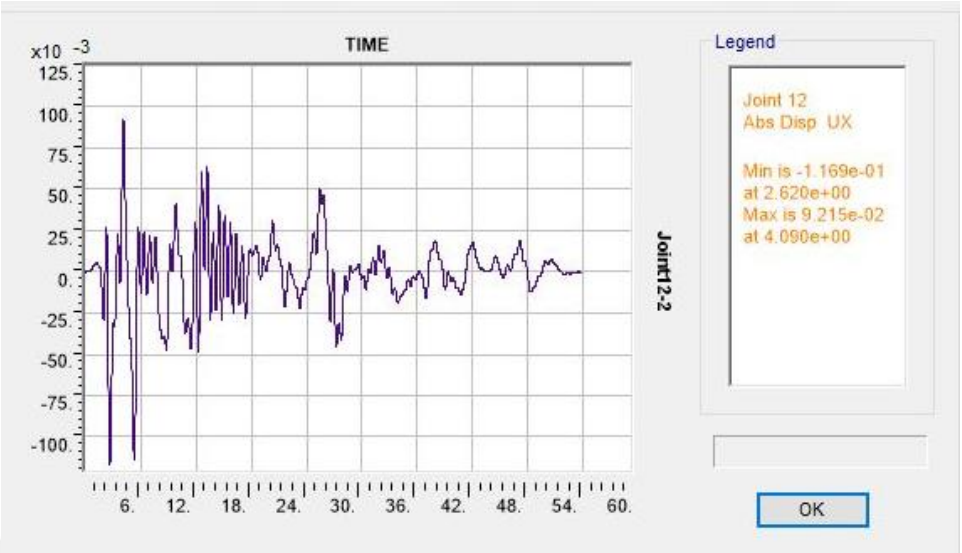


Figure 4.22: El Centro Imperial-1940 Earthquake Abs. Displacement Graph

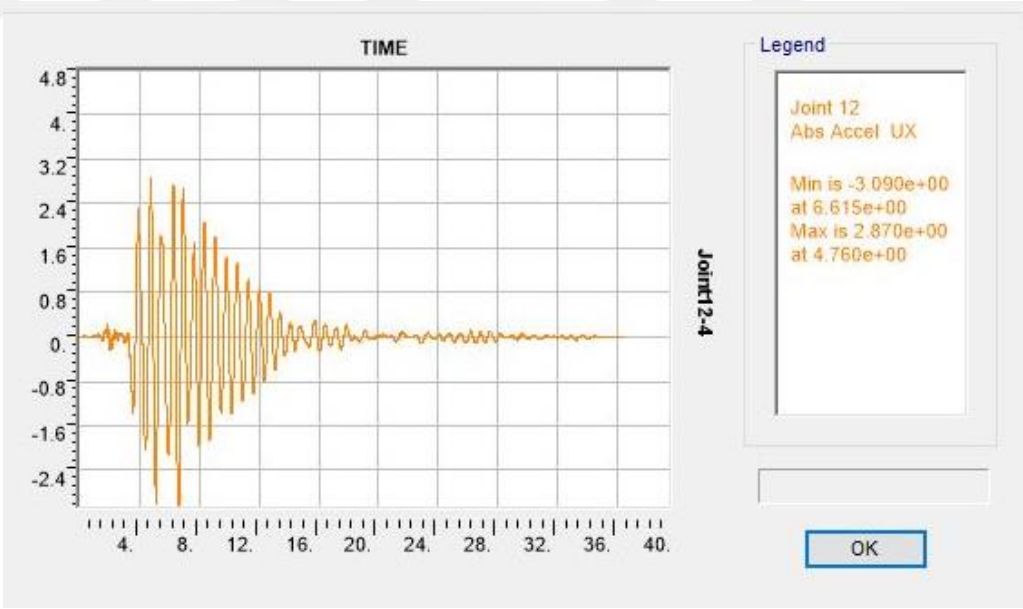


Figure 4.23: Friuli, Italy-1976 Earthquake Abs. Acceleration Graph

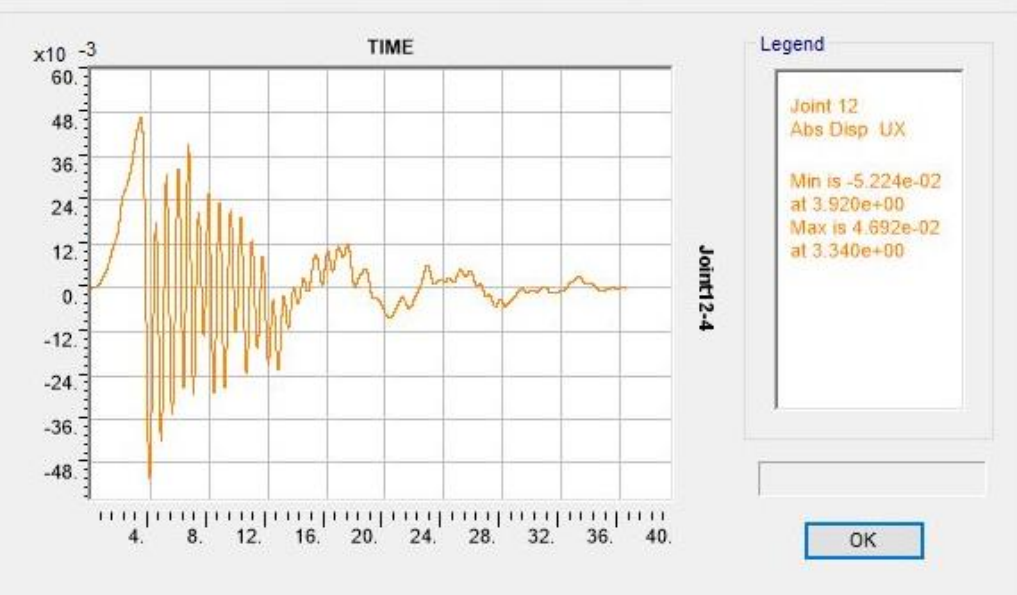


Figure 4.24: Friuli, Italy-1976 Earthquake Abs. Displacement Graph

Tabel 4.1: Maximum Abs. Acceleration and Maximum Abs. Displacement of Frames From Time History Analysis of 3 Different Earthquakes

No.	Earthquake	Maximum Abs. Acceleration		Maximum Abs. Displacement	
		RC Frame	Steel Frame	RC Frame	Steel Frame
1	Kobe Japan1995	3.9	2.58	0.084	0.098
2	El-Centro 1940	6.33	4.201	0.064	0.092
3	Friuli, Italy-1976	7.169	2.87	0.048	0.04

The nonlinear analysis of the frames has been carried out through pushover analysis; the procedure has been explained in section 3.7.6. As seen in the figures; hinge emerges at the lower end of the column, showing Immediate Occupancy (IO) state, in the 2nd step, the hinge in this point is developing to Life Safety (LS) state before going to upper end of the same column, Meanwhile, hinge emerges in the lower end of the other column with Immediate Occupancy (IO) state. In the 3rd step, the hinges are developing in previous points and new hinge emerges at the top end of the first column. The procedure is going this way until the system experiences first failure in steps 5. The process of hinges creation and development is further illustrated in the figures below:

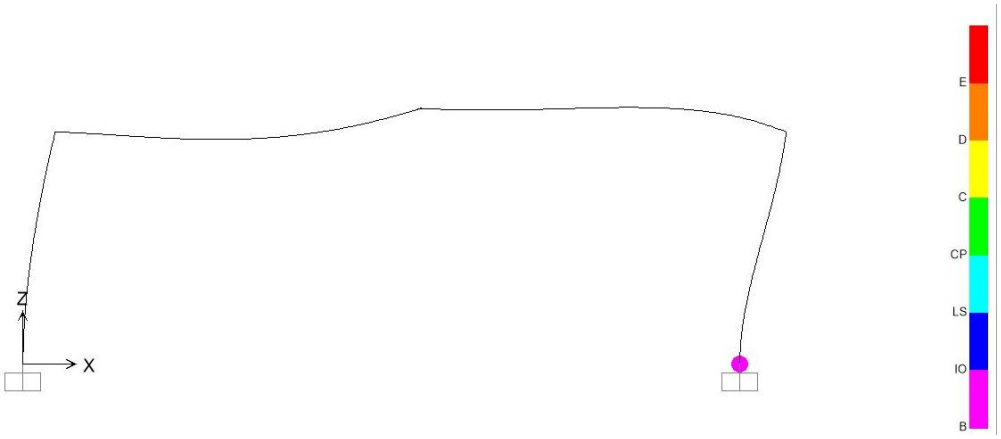


Figure 4.25: Creation of Hinge in RC Frame, Step-1

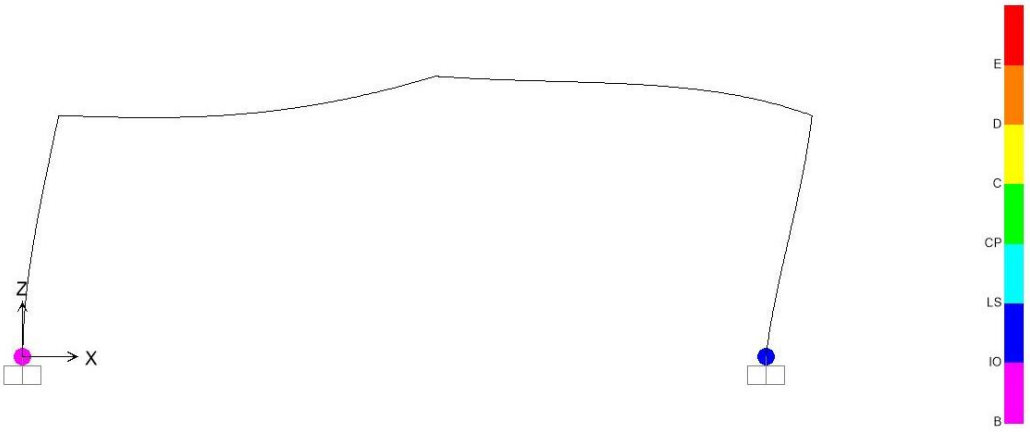


Figure 4.26: Creation of Hinge in RC Frame, Step-2

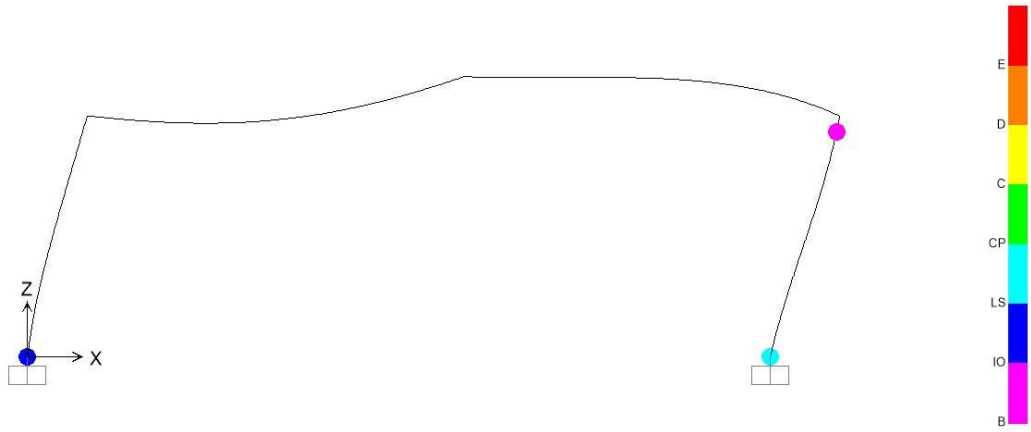


Figure 4.27: Creation of Hinge in RC Frame, Step-3

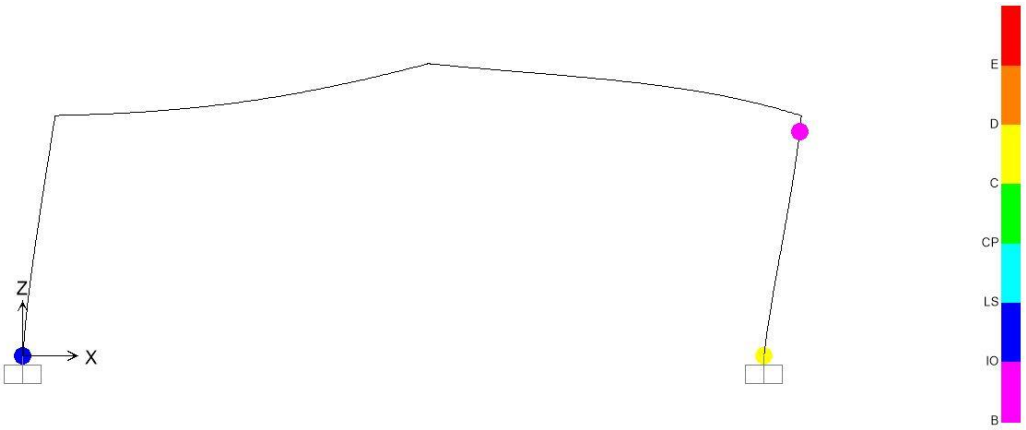


Figure 4.28: Creation of Hinge in RC Frame, Step-4

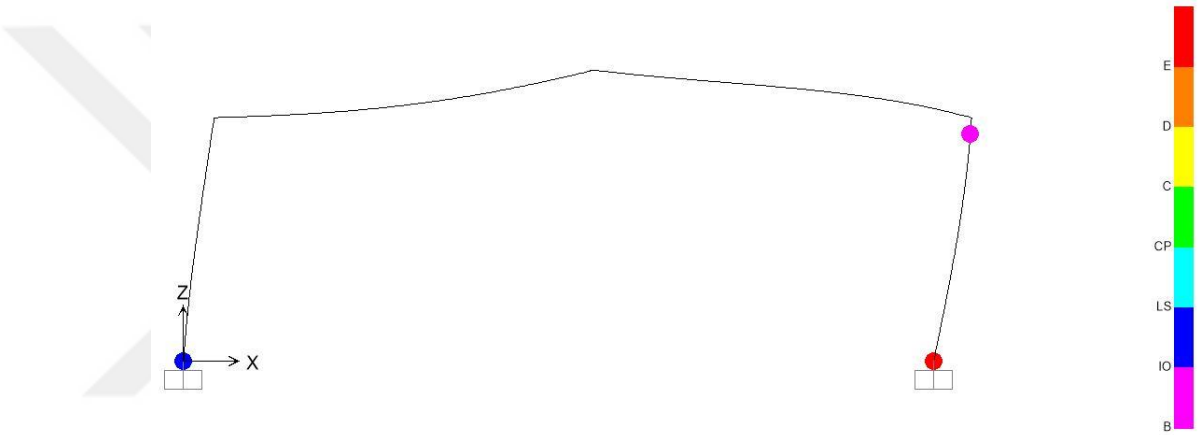


Figure 4.29: Creation of Hinge in RC Frame, Step-5,6

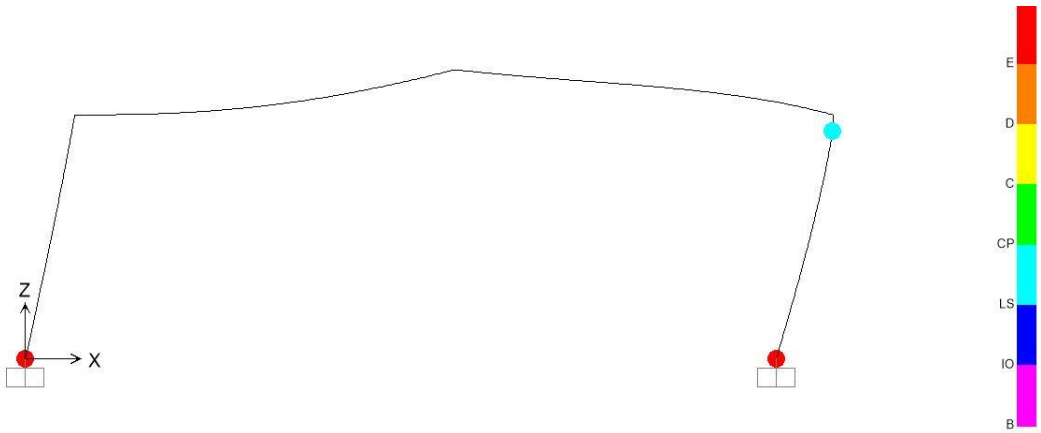


Figure 4.30: Creation of Hinge in RC Frame, Step-8

Below is the pushover curve indicating the base shear vs displacement.

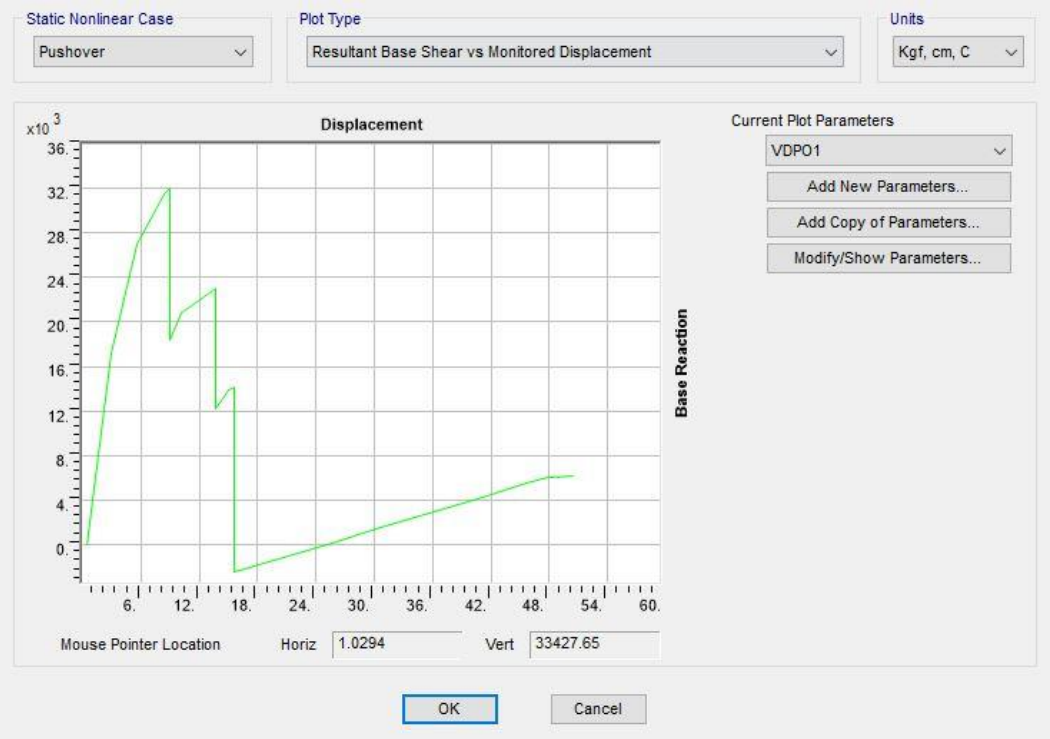


Figure 4.31: Pushover Curve of RC Frame, Base Shear vs Roof Displacement

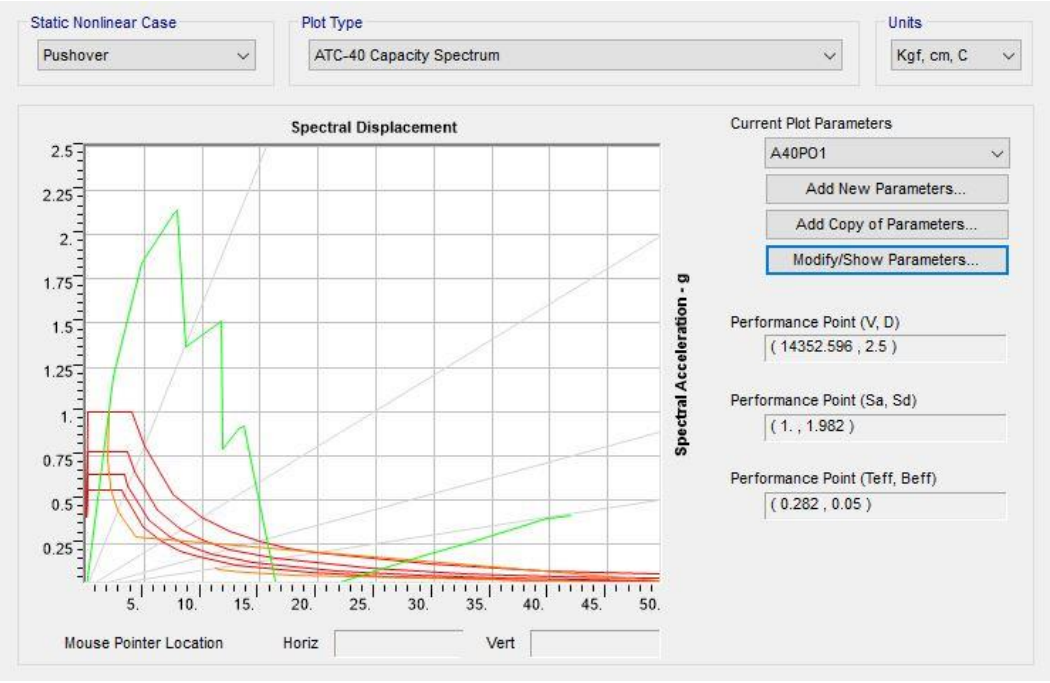


Figure 4.32: Capacity Spectrum of RC Frame

The capacity curve is shown in green color while the demand curve is in yellow. The point where the capacity curve and demand curve intersect each other is called the performance point or target displacement, which represents the global behavior of the system.

While checking the global behavior of the system, the local behavior is also advising to see whether the system experiencing local collapse or not. The performance point of RC frame is at (0.282, 0.05) as shown in the figure above. Looking to the demand capacity table, the period of (0.282, 0.05) is located between 0 and 1th steps. The largest hinge with this period is Immediate Occupancy (IC) state in the 1st step. It means that the system is adequately stable and will not experience local collapse with the considered intensity of earthquake.

Pushover analysis of the steel frame shows different results than that of the RC frame. The outcomes show that, unlike the RC frame, the first hinge in the steel frame emerges in the beam, not in the 1st step, 2nd and 3rd steps, but in 4th step with Immediate Occupancy (IO) state. The hinge develops in this point until it reaches to the Life Safety (LS) state and then the second hinge emerges in the other beam with (IO) state. The steel frame system experiences its first failure in the 8th step and in the beam where the first hinge created.

The figures in the coming pages describe pushover analysis of the steel frame.

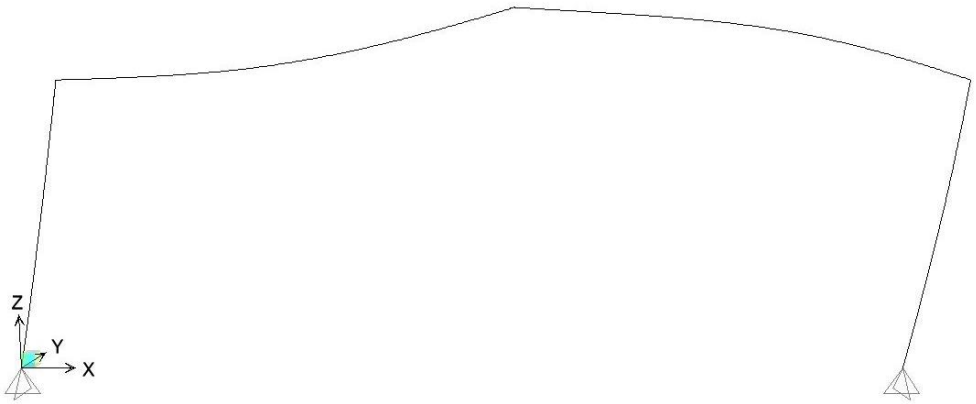


Figure 4.33: No Creation of Hinges in Steel Frame in Steps-1, 2, 3

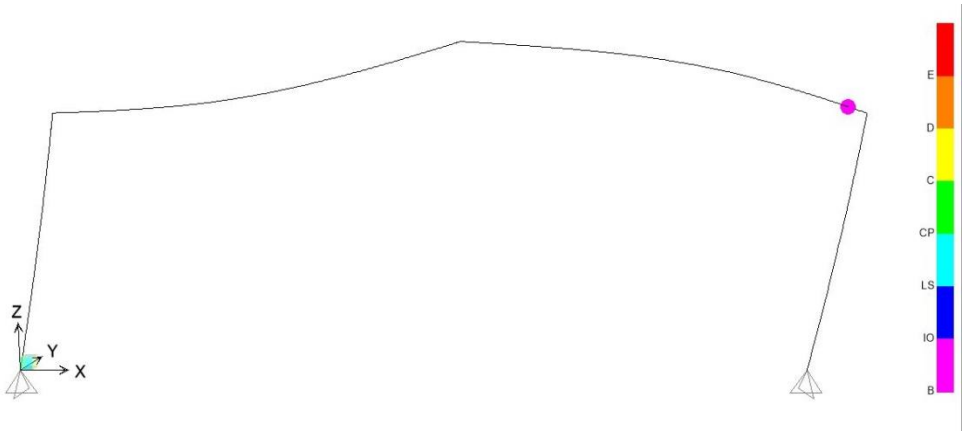


Figure 4.34: Creation of Hinge in Steel Frame, Step-4

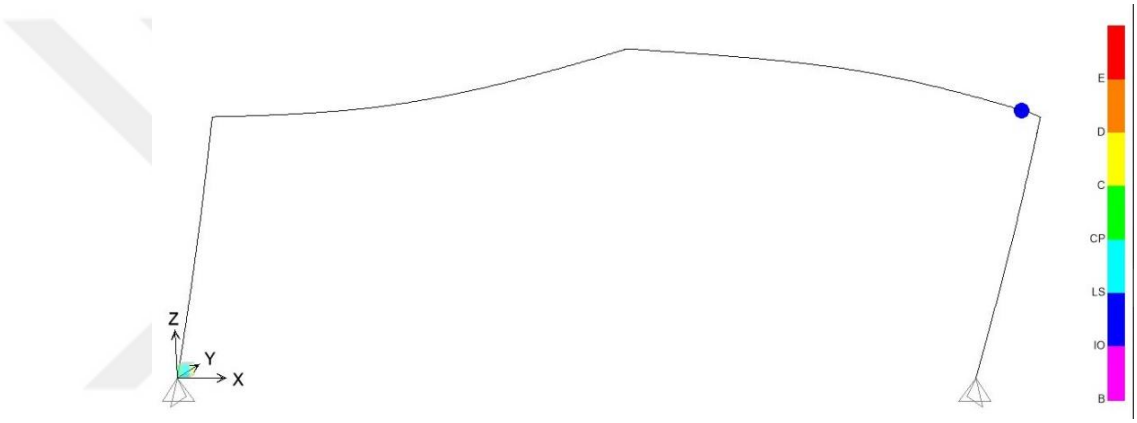


Figure 4.35: Creation of Hinge in Steel Frame, Step-5

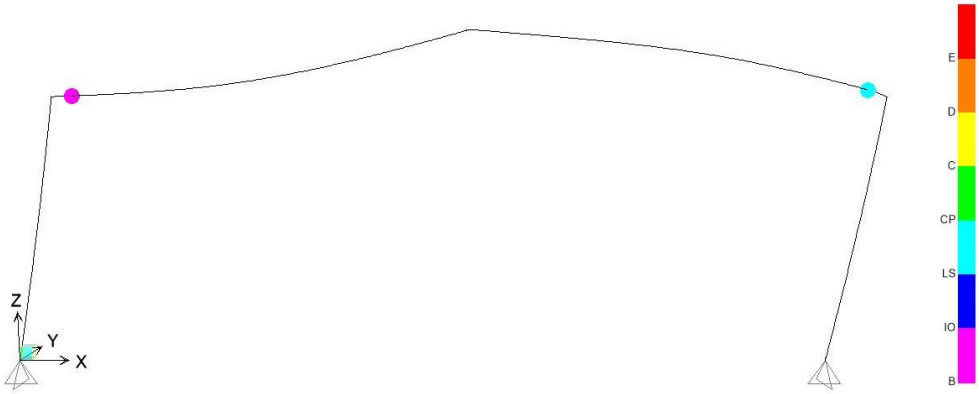


Figure 4.36: Creation of Hinge in Steel Frame, Step-6

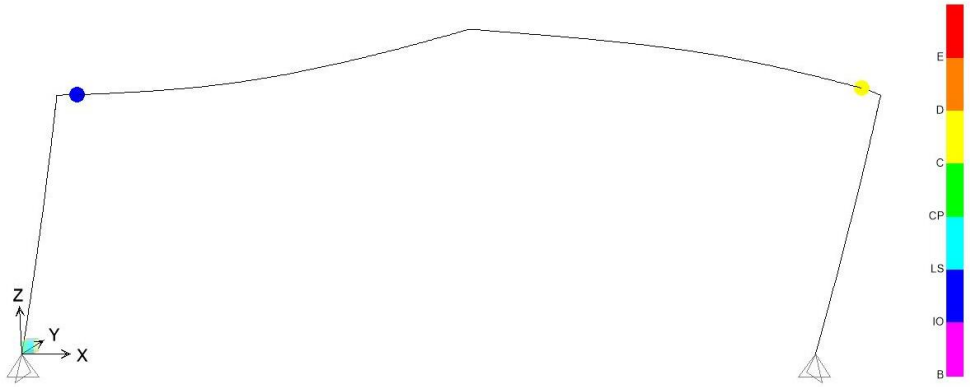


Figure 4.37: Creation of Hinge in Steel Frame, Step-7

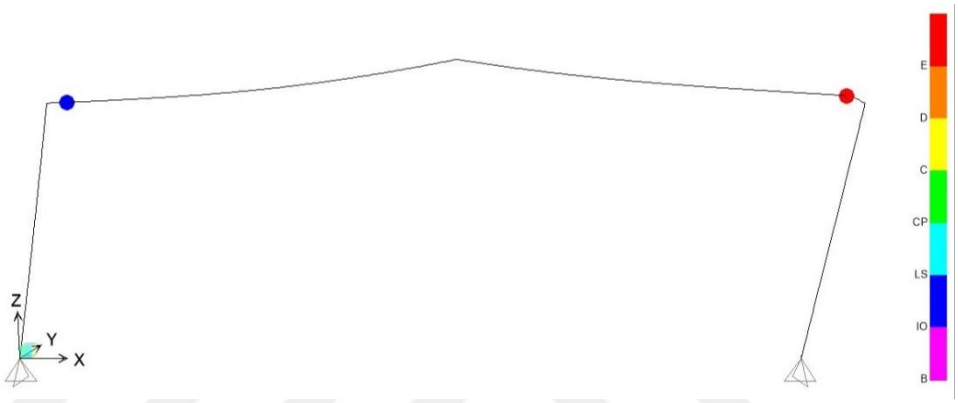


Figure 4.38: Creation of Hinge in Steel Frame, Step-8

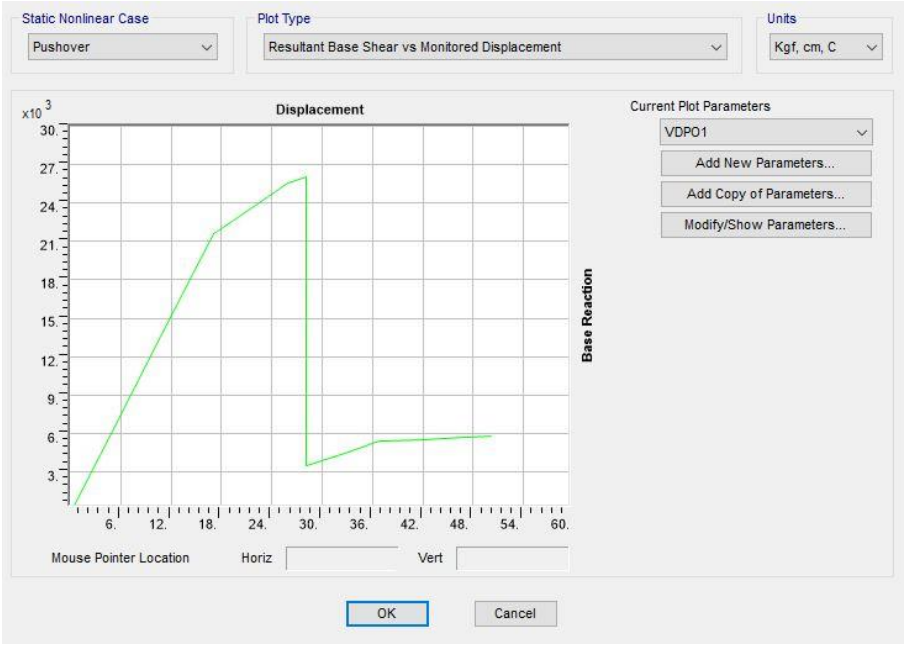


Figure 4.39: Pushover Curve of Steel Frame, Base Shear vs Roof Displacement

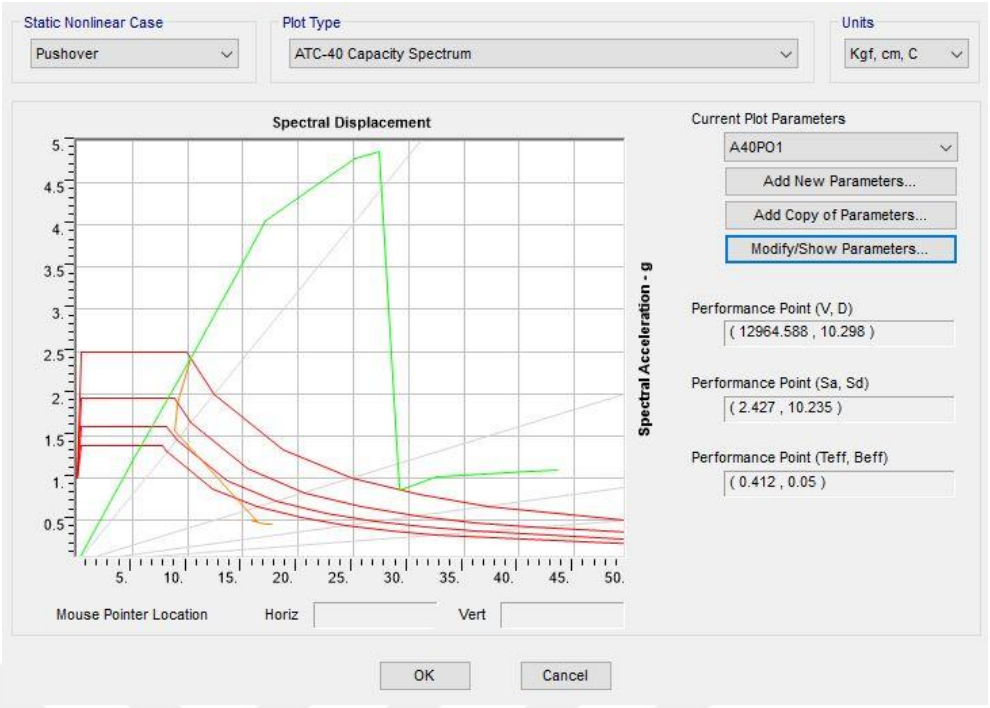


Figure 4.40: Capacity Spectrum of Steel Frame

The pushover curve of the steel frame shows sudden drop of the base shear after first hinge created and reaches other states.

4.3 Environmental Impacts

4.3.1 Concrete Frame Environmental Impact Assessment

As mentioned earlier in the previous chapter, the environmental impact estimator used in this study needs initial materials` quantities and cross sections to properly evaluate their environmental impacts. The figures outline the potential hazardous impacts of consumption of materials and the resulted emissions of GHG to the atmosphere.

The figures and tables in the coming pages describe different impacts and burdens on the environment resulting from concrete frame. The details about Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Fossil Potential (FP) and Ozone Depletion Potential (ODP) can be found.

Table 4.2: Environmental Impact Categories of Concrete Frame

Outputs	Unit	Beams and Columns	Foundation	Total
Global Warming	$kgCO_2eq$	8.75E+03	3.99E+02	**9.15E+03**
Acidification Potential	$kgSO_2eq$	3.86E+01	1.65E+00	**4.02E+01**
Eutrophication Potential	kgNeq	5.67E+00	3.58E-01	**6.03E+00**
Fossil Fuel Potential	MJ	8.17E+04	3.05E+03	**8.48E+04**
Ozone Depletion Potential	kg CFC-11eq	1.00E-04	7.06E-06	**1.08E-04**

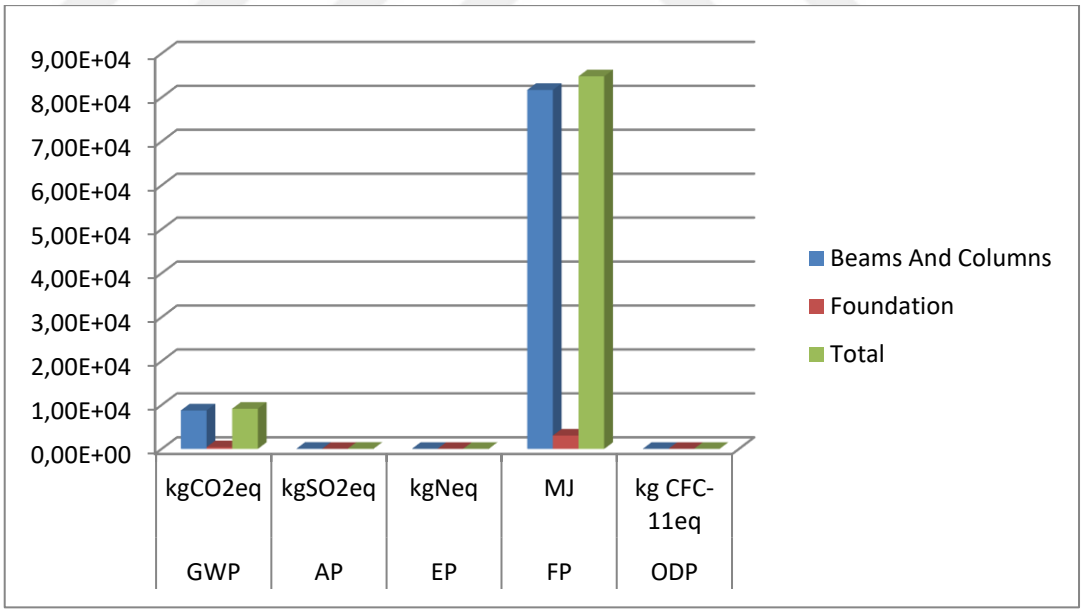


Figure 4.41: Environmental Impact Categories of Concrete Frame

4.3.2 Steel Frame Environmental Impacts

The figures and tables in the coming pages describe different impacts and burdens on the environment resulting from the steel frame. Details about Global

Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Fossil Potential (FP) and Ozone Depletion Potential (ODP) can be found.

Table 4.3: Environmental Impact Categories of Steel Frame

Category	Unit	Beams and Columns	Foundation	Total
Global Warming	$kgCO_2eq$	3.99E+02	2.26E+03	**2.66E+03**
Acidification Potential	$kgSO_2eq$	9.01E+00	1.65E+00	**1.07E+01**
Eutrophication Potential	kgNeq	4.20E-01	3.58E-01	**7.79E-01**
Fossil Fuel Potential	MJ	3.11E+04	3.05E+03	**3.42E+04**
Ozone Depletion Potential	kg CFC-11eq	2.27E-06	7.06E-06	**9.33E-06**

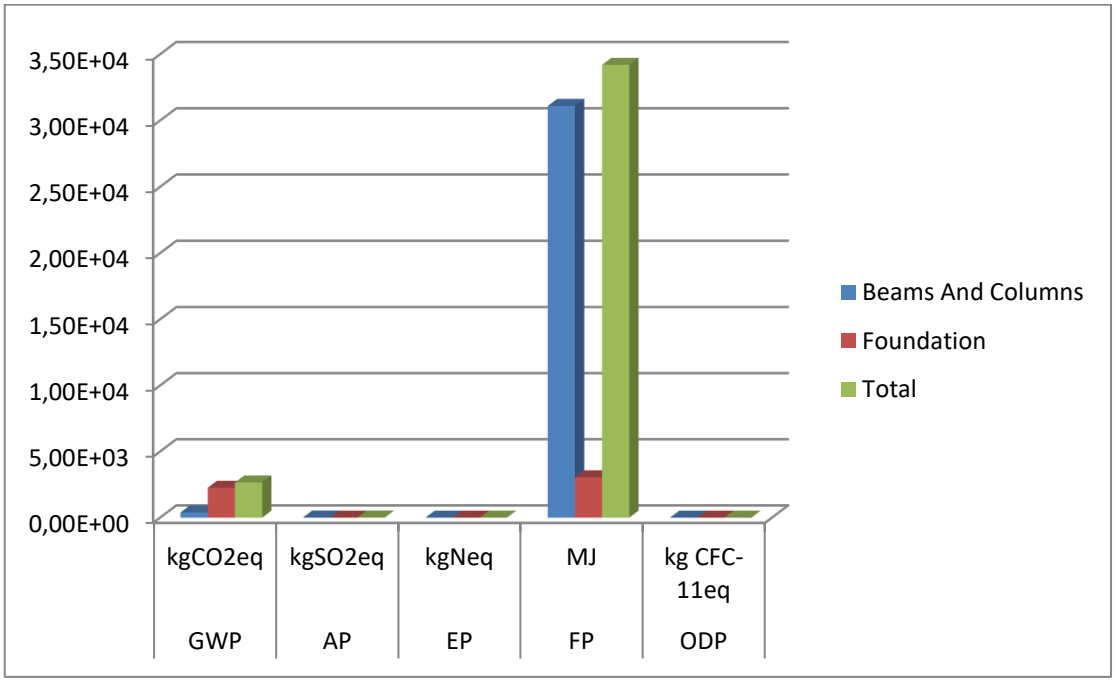


Figure 4.42: Environmental Impact Categories of Steel Frame

4.3.3 Environmental Impacts Comparison of RC and Steel Frames

Athena Impact Estimator has the capability of accommodating multiple comparisons at once; the Impact Estimator allows users to change the design, substitute materials, and make side-by-side comparisons for any one or all of the environmental impact indicators. It gives broad revision opportunity to users to change the needed data at any stage.

The environmental impacts of both frames evaluated separately; in this part, it gives the chance of comparing both systems from different environmental perspectives. Four stages considered in this comparison; product stage, construction stage, use stage, and end of life stage, as illustrated in the figures below:

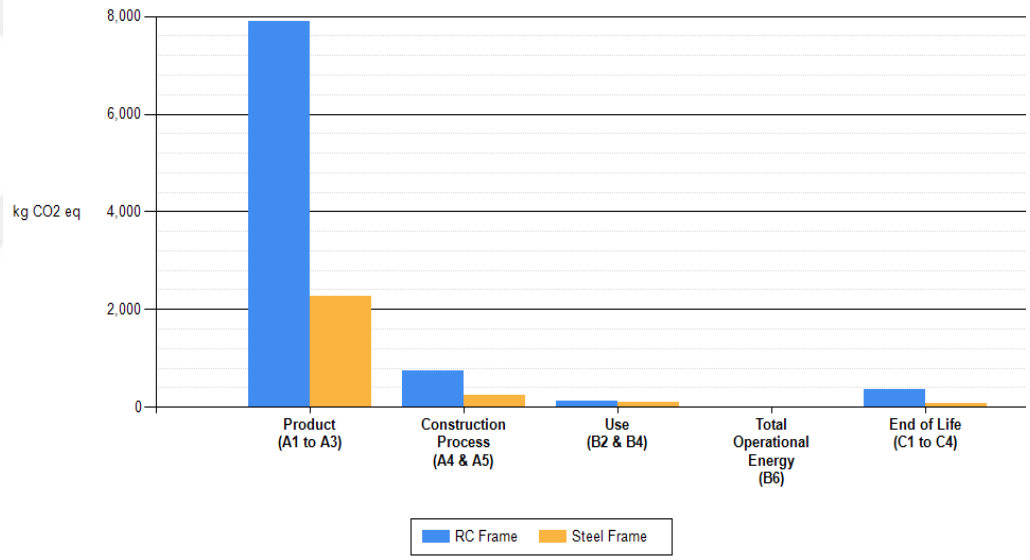


Figure 4.43: Comparison of GWP of RC & Steel Frames In Different LCA Stages

Table 4.4: Comparison of GWP in Different LCA Stages

Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	End of Life (C1 to C4)	Total
RC Frame	$kgCO_2eq$	7.90E+03	7.52E+02	1.31E+02	3.70E+02	**9.15E+03**
Steel Frame	$kgCO_2eq$	2.27E+03	2.32E+02	8.70E+01	6.85E+01	**2.66E+03**
Total	**$kgCO_2eq$**	**1.02E+04**	**9.84E+02**	**2.18E+02**	**4.38E+02**	**1.18E+04**

As seen in the figure and table, the product stage is dominating all other stages with 1.02E+04 total GWP impacts while the use stage has the lowest 2.18E+02 environmental impacts. The RC frame has higher impacts than that of steel in all four stages.

The coming figures and tables compare the primary energy consumption, acidification potential, ozone depletion potential, and eutrophication potential of both frames, respectively. The exact data can also be found in the tables.

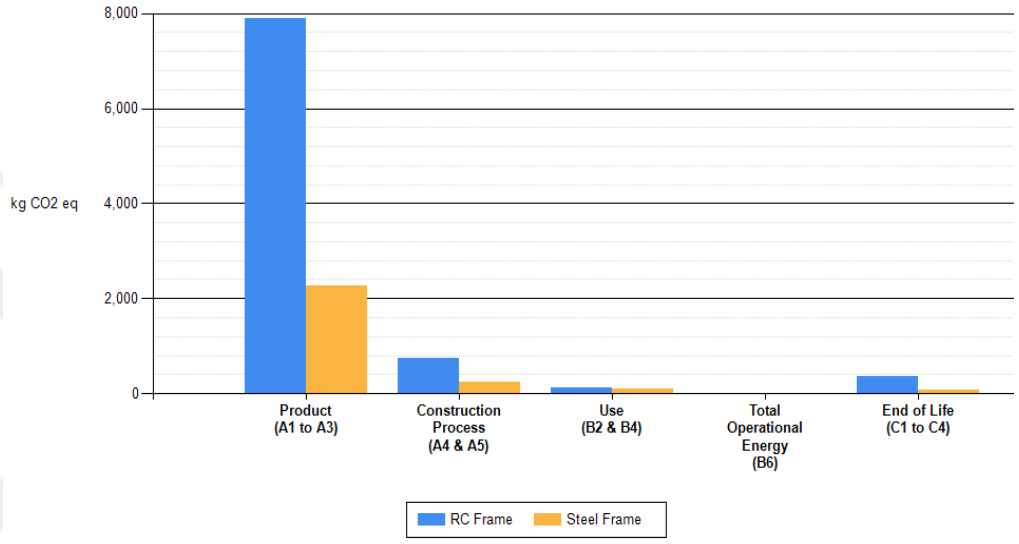


Figure 4.44: Comparison of Primary Energy Consumption in Different Stages

Table 4.5: Comparison of Primary Energy Consumption in Different Stages

Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	End of Life (C1 to C4)	Total
RC Frame	MJ	9.92E+04	9.46E+03	6.74E+03	5.44E+03	**1.21E+05**
Steel Frame	MJ	3.54E+04	3.38E+03	4.49E+03	1.00E+03	**4.43E+04**
Total	**MJ**	**1.35E+05**	**1.28E+04**	**1.12E+04**	**6.45E+03**	**1.65E+05**

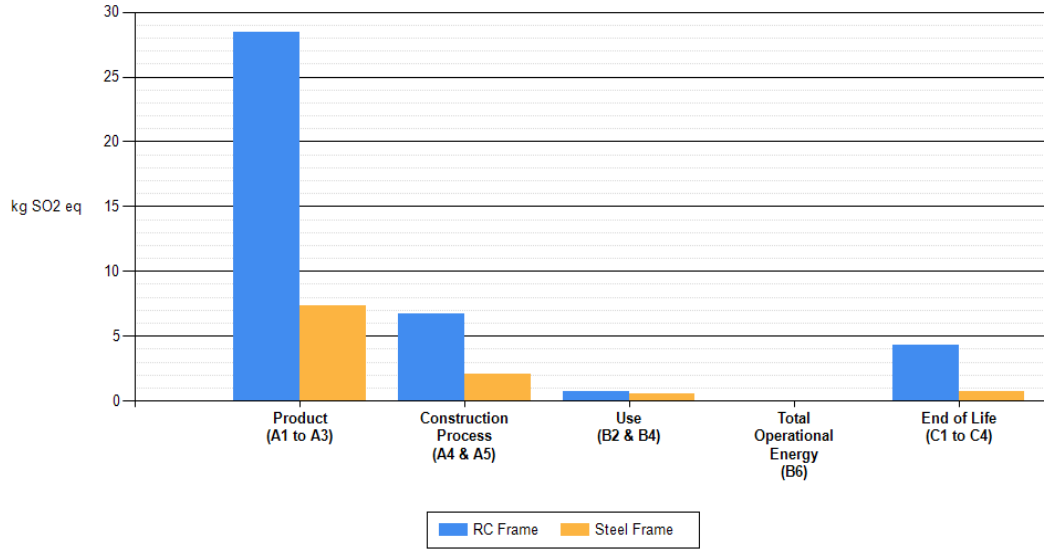


Figure 4.45: Comparison of Acidification Potential in All Stages

Table 4.6: Comparison of Acidification Potential in Different Stages

Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	End of Life (C1 to C4)	Total
RC Frame	$kgSO_2eq$	2.84E+01	6.69E+00	7.59E-01	4.34E+00	**4.02E+01**
Steel Frame	$kgSO_2eq$	7.34E+00	2.08E+00	5.06E-01	7.31E-01	**1.07E+01**
Total	**$kgSO_2eq$**	**3.58E+01**	**8.77E+00**	**1.27E+00**	**5.07E+00**	**5.09E+01**

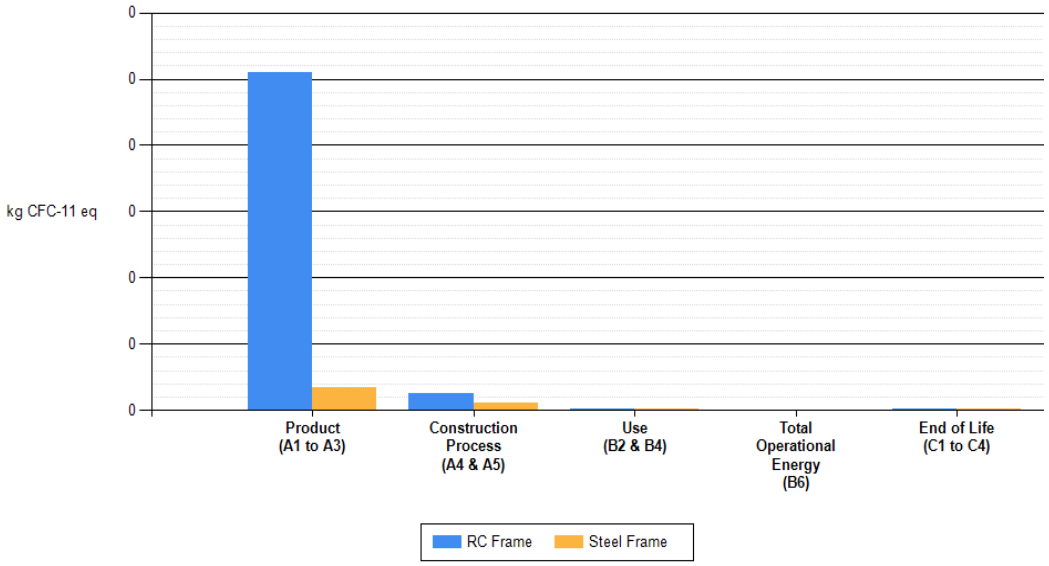


Figure 4.46: Comparison of Ozone Depletion Potential in Different Stages

Table 4.7: Comparison of Ozone Depletion Potential in Different Stages

Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	End of Life (C1 to C4)	Total
RC Frame	kgCFC-11eq	1.02E-04	5.11E-06	4.48E-07	1.53E-08	**1.08E-04**
Steel Frame	kgCFC-11eq	6.83E-06	2.19E-06	2.99E-07	2.90E-09	**9.33E-06**
Total	**kgCFC-11eq**	**1.09E-04**	**7.30E-06**	**7.47E-07**	**1.82E-08**	**1.17E-04**

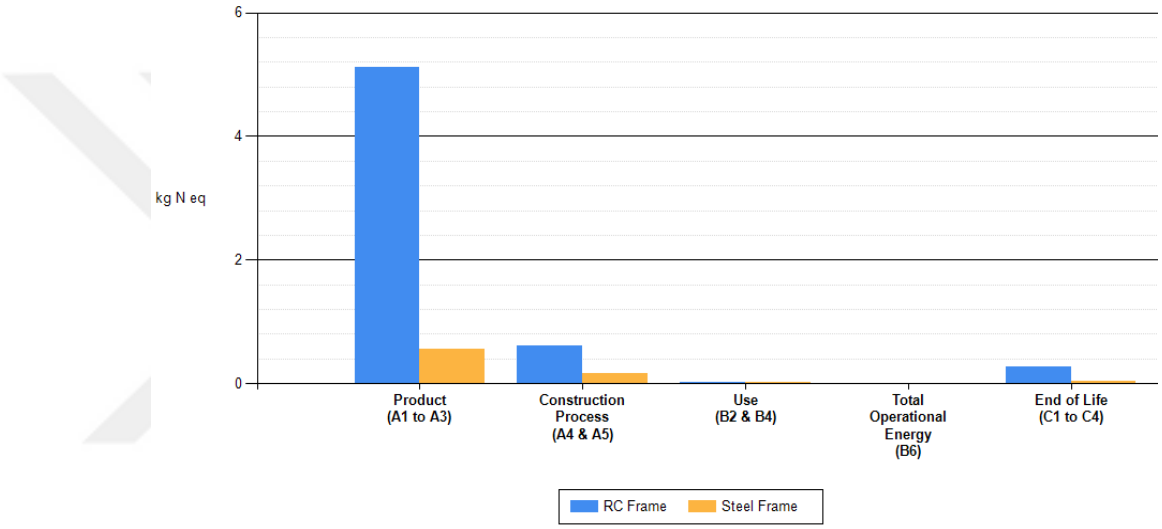


Figure 4.47: Comparison of Eutrophication Potential in different stages

Table 4.8: Comparison of Eutrophication Potential in Different Stages

Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	End of Life (C1 to C4)	Total
RC Frame	kgNeq	5.12E+00	6.07E-01	2.68E-02	2.70E-01	**6.03E+00**
Steel Frame	kgNeq	5.61E-01	1.55E-01	1.79E-02	4.51E-02	**7.79E-01**
Total	**kgNeq**	**5.68E+00**	**7.62E-01**	**4.47E-02**	**3.15E-01**	**6.81E+00**

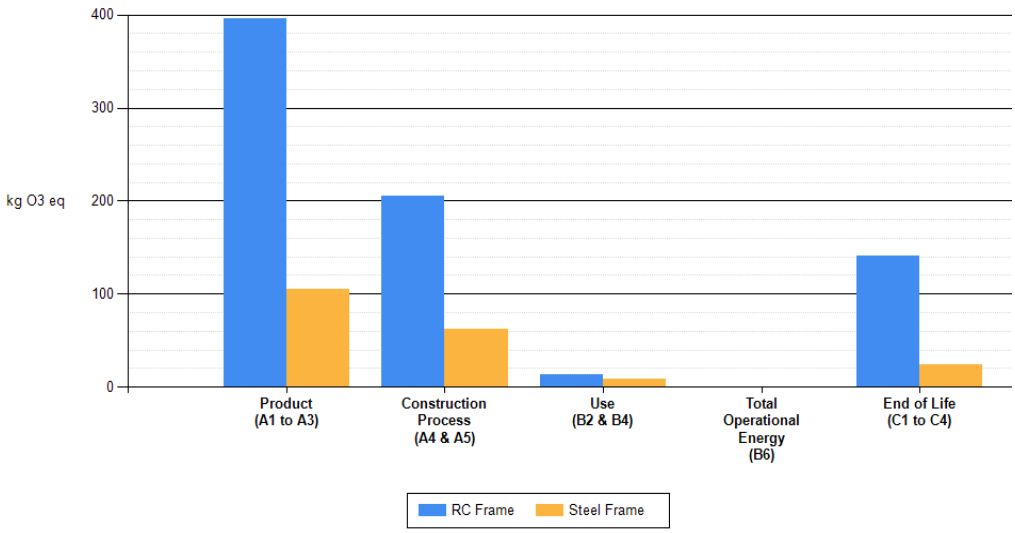


Figure 4.48: Comparison of Smog Potential in Different Stages

Table 4.9: Comparison of Smog Potential in different stages

Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	End of Life (C1 to C4)	Total
RC Frame	kgO_3eq	3.97E+02	2.05E+02	1.35E+01	1.41E+02	**7.56E+02**
Steel Frame	kgO_3eq	1.05E+02	6.23E+01	9.02E+00	2.35E+01	**2.00E+02**
Total	**kgO_3eq**	**5.02E+02**	**2.67E+02**	**2.25E+01**	**1.65E+02**	**9.56E+02**

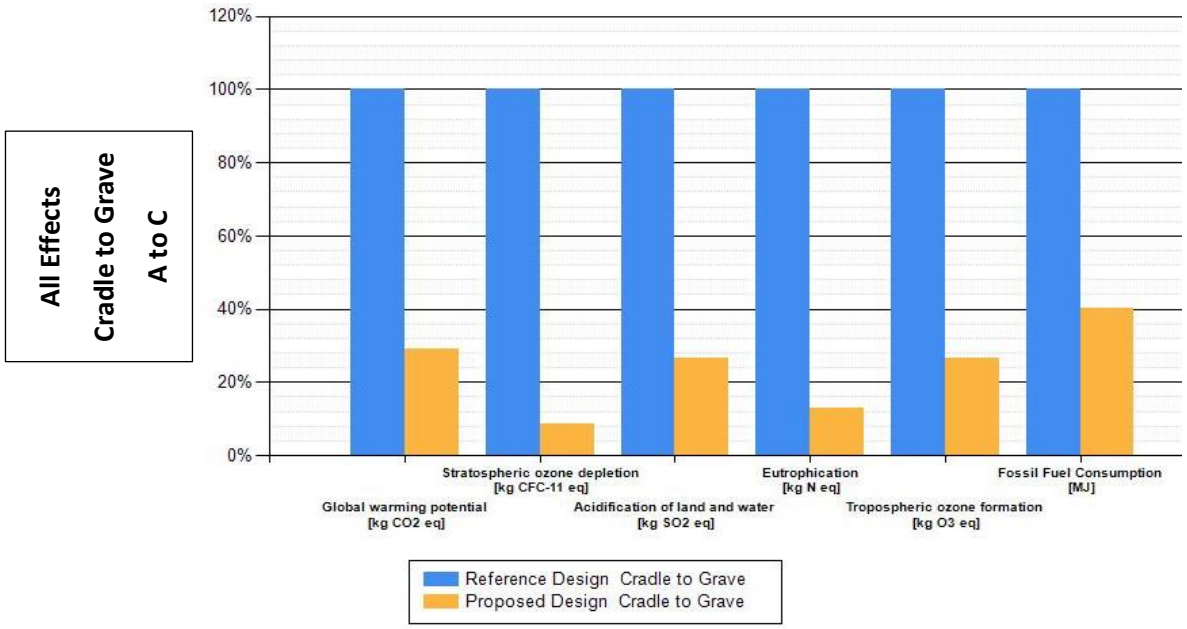


Figure 4.49: LEED LCA Measure Comparison Report Cradle-to-Grave

Table 4.10: LEED Measure Comparison Report Cradle-to-Grave

Summary Measure	Unit	Reference Design Total Effects Cradle to Grave A to C	Proposed Design Total Effects Cradle to Grave A to C	% Difference
Global warming potential	$kgCO_2eq$	9.15E+03	2.66E+03	-70.91%
Stratospheric ozone depletion	kgCFC-11eq	1.08E-04	9.33E-06	-91.32%
Acidification of land and water	$kgSO_2eq$	4.02E+01	1.07E+01	-73.51%
Eutrophication	kgNeq	6.03E+00	7.79E-01	-87.08%
Tropospheric ozone formation	kgO_3eq	7.56E+02	2.00E+02	-73.55%
Depletion of non-renewable energy resources	MJ	1.20E+05	4.42E+04	-63.10%

CHAPTER 5

DISCUSSION, CONCLUSION AND RECOMMENDATIONS

5.1 Discussion

The building and construction industry experienced a noticeable shift in the last few decades. Thoughts shifted about earthquakes, designs, buildings' impacts on human health and the environment. Engineering as a sector developed unbelievably within past two centuries; urbanization, facilities, and income opportunities caused rapid development of the cities. Meanwhile, structures consume a huge amount of natural materials. The first object from constructing a building or any other structure facility is to create a safe and convenient environment for the residents; getting to this stage needs materials; the construction industry is accounted for the big consuming of natural resources. Steps towards sustainable buildings not only require changes in the way of designing, constructing, using, and deconstructing, but also in our lifestyle in a way through which environmental impacts mitigate to the level planet is capable of supporting.

Concrete is a second item on earth after water, used in a big amount by humans. It is hard to imagine construction activities without concrete, as the main item in the construction industry. To decrease the environmental harmful impacts of concrete and other construction processes, experts are looking for alternatives, applicable design new methodologies, using sustainable materials, and experiencing new admixtures in concrete instead of cementitious items that have less environmental impacts.

The lateral drifts causing from earthquake loads are different in both frames; it is 0.293cm in both rafter and top levels of RC frame in X axis while this value increase to 1.213cm in steel frame. The increase in lateral drift is because of the stiffness and ductility frames showing to lateral loads. As steel frame is more

flexible and has more ductility than the RC frame, thus, it has more lateral drift. Base shear is an important factor while designing seismically resistant frames, as site and loading conditions are same for both frames, the base shear is directly associated with the effective seismic weight of structures, the RC frame which has more effective seismic weight than that of the steel frame, resulted in a value bigger than steel frame for the base shear. The weight of the frames, joints, materials, and type of supports affecting the values of moments and shear forces in the structural members. Reinforced concrete frame members are heavier than the steel frame; have stiffer members' joints, thus, different values are received for moment and shear forces. The shapes of the moment and shear diagrams vary because of the member shapes, materials and the supports considered for the frames.

The mathematical values received for base shear of the frames have slight difference with what have been received from SAP2000. The base shear values received through mathematical calculation are 17.04 KN for RC frame and 15.64 KN for steel frame, while these values are 17.24 KN and 14.64 KN for RC and steel frames, respectively. Comparing RC and steel frames` absolute accelerations and absolute displacements, it is obvious that absolute acceleration values for the RC frame are higher than that of steel frame and the displacement values of steel frame is higher than that of RC frame because the two frames showing different reactions to applied loads as shown in figures 4.13-4.24 and table 4.1.

Environmental impacts of specific items of both frames considered in this study, volumes of those items evaluated environmentally. First, the environmental impacts of the reinforced concrete frame assessed; in the second step, the environmental impacts of the steel frame evaluated. In the final step, frames` environmental impacts are compared, and their results illustrated with the help of figures and tables. Global Warming Potential (GWP), Acidification Potential (AP), Ozone Depletion Potential (ODP), Eutrophication Potential (EP), and Fossil Fuel Potential (FP) of reinforced concrete and steel frames evaluated.

Assessment results in all terms, conditions, and stages show that the environmental impacts of the reinforced concrete frame are much higher than that of steel. The GWP of the reinforced frame is 9.15E+03 $kgCO_2eq$, while the GWP of the steel frame is calculated 2.66E+03 $kgCO_2eq$. The figures show a huge difference in the environmental burden when comparing both frames. The

environmental effects in the production stage of both frames are at a higher level than the other stages. At the same time, reinforced concrete in the production stage releases more GHG into the atmosphere than the steel frame in all other stages. In the current case, more materials are needed and used in columns and beams; their burden on the environment is higher than other items. Steel frame releases more GHG during its use stage; because of its constant maintenance necessity in a lifetime.

The LEED assessment results show that; the GWP of reinforced concrete from cradle-to-grave boundary is 9.15E+03 $kgCO_2eq$, while steel GWP is 2.66E+03 $kgCO_2eq$; it means that reinforced concrete has a 70.91% difference with steel; this difference for ODP is 91.32% and for AP 73.51%, respectively.

Environmental impacts resulted from transportation were also considered in all life cycle stages; reinforced concrete frame again has a high hand in environmental burdens. The reinforced concrete frame needs a variety of construction materials in different stages, from different suppliers and different distances; this is the reason behind the high transportation environmental burden listed to the concrete frame.

The social and environmental impacts should be obtained according to the purposes of the building. In seismic prone areas, the social impacts can be presented with safely withstanding of the buildings against earthquakes. Fatality and the time needed for repairing the damaged buildings could be listed in the ground of social impacts of buildings. Yet, less has been done to normalize these terms to understandable and countable measures. Studying the social and economic components of the frames is quite broad area and is not within the scope of this study.

The obtained results from this study are compatible with the literature. It is important to consider other vital issues as well for getting the desired results. Influential if sustainable topics find place in legislation frameworks, there is a need to work on mandatory policies in the concerned government institutions; it will work as a pressure tool. On the other hand, in the emerging steps, financial supports, other needed assistance in the field of technology, and technics play a significant role in profoundly practicing LCA in developing countries; such supports can easily be provided by governments.

5.2 Summary and Conclusion

In this thesis, the environmental burden causing by construction industry discussed, importance of the issue explained through literature review and focused more on buildings environmental impacts located in seismic regions. The life cycle assessment LCA methodology as an integrated assessment approach has been discussed, its workability and limitations reviewed. The thesis further talked about LCA in construction industry, especially, for buildings and other construction materials. It also covered the current situation of sustainability in construction industry in Turkey. In addition, two hypothetical reinforced concrete and steel frames have been modeled with 10% probability of being exceeded in 50 years or 475-year return period. The frames designed in a same seismic region with same code and site specifications in Istanbul-Turkey with the help of SAP2000. Environmental impacts of the frames evaluated and compared through Athena Impact Estimator version 5.4. Thesis works concludes that;

- The overall environmental impacts of seismically strengthened frames noticeably differ in many ways; it highly depends on the type of structure and also more on the types of materials. It has been viewed that buildings using man-made materials highly affecting the environment as they need more processes to get to the stage of use. Concrete and steel are from the list of man-made materials, thus causing huge environmental burden as shown in this study.

- The amount of materials directly affecting all terms of the environment; such as Global Warming Potential GWP, Acidification Potential AP, Eutrophication Potential EP, Fossil Fuel Consumption FFC, and Ozone Depletion Potential ODP. As shown in figures 4.41 and 4.42; tables 4.2 and 4.3; in both frames, where the amount of materials increasing environmental impacts.

- In the case of RC frame, as used materials for structural members are all reinforced concrete, the environmental impacts of beams and columns are higher in all terms, stages, and cases. Since it is made of different types of materials and every one of them processing different procedures to get into the construction circle, such as extraction, production processes, transportation, and construction; therefore, resulting more

environmental impacts. The steel frame on the other hand, is made of almost one material, steel; the number of needed processes is less in comparison with reinforced concrete, therefore, resulting less environmental impacts.

- Again, for the steel frame; foundations considered as reinforced concrete, their contribution in Ozone depletion is much higher than that of steel columns and beams as shown in table 4.3. The contribution of foundations is 7.06E-6 KgCFC-11eq while this amount decreases to 2.27E-6 KgCFC-11eq for columns and beams. Foundations show nearly similar Eutrophication potential with beams and columns as illustrated in table 4.3. The contributions are 3.58E-01 KgNeq and 4.20E-01 KgNeq, respectively.

- While comparing the environmental impacts of the frames in different stages like product, construction, use, and end-of-life, the concrete frame is responsible for higher environmental burden, almost in all stages. Among all above mentioned stages, the product stage has big part in comparison with other stages. Concrete frame contribution to the global warming in product stage is 7.903E+03 $KgCO_2eq$ while this contribution for all other three stages are less than that, as shown in figure 4.43 and table 4.4.

5.3 Limitations and Recommendations

Limitations of current thesis are as follows:

- The reinforced concrete and steel frames considered for this study were the simplest structural systems, the study considered only columns and beams in the evaluation processes. It is possible to consider a residential or commercial building with all architectural detailed drawings, materials, and designing data in such studies. The same processes can be applied.

- Generally, the scientific papers in this regard focusing more on energy efficiency during the operation stage of a building. The structural aspects of buildings are less covered by researchers while discussing sustainability and life cycle assessment issues. Less scientific papers

could be found on this specific topic. Especially, for buildings located in seismic regions.

- Athena Impact Estimator is very simple to use, but, it has less options and is unable to cover other regions except U.S., Canada, and some North American countries. Even the Athena considers transportation environmental impacts but there is no specific calculation space. In the case of materials` database, there are still materials in the database which are not using in other countries. Replacing such materials in the processes affecting the outcomes.

- Recent pandemic and moving restrictions also affected this work to some extent.

It is recommended that future studies related to this subject consider the following points:

- Further development of LCA methodologies are needed to beget better assessment techniques. On the one hand, it will spread and ease the usage of the methodology among the related class of people and on the other hand, the accuracy of the assessment will rise.

- The structural aspect of building has less been studied by the researcher; It is recommended that the construction industry pay more attention to increase its systematic structural research on the topic.
- The educational centers, universities, research centers, and other related institutions should work on increasing the level of awareness about sustainability as a vital issue and focus more on specific group of people who directly involved in any stage of the construction process, such as investors, designers, engineers, and architectures.
- Construction materials should be recycled inside the country, and markets for the recycled construction materials should be established at the national level. The associated governmental frameworks should work on the legislative processes of the subject. There is also need for policies which will act as pressure tools and which will be implemented from the government body.

- Incentives and financial subsidies play an important role, especially in the emerging steps; the governments in close collaborations with the private sector should constitute local rating systems or improve an external system to adjust the local market.
- There is also a need to improve construction activities in all stages from cradle-to-grave by using technological improved devices. On the other hand, it is highly recommended to avoid over-designing of all construction projects.

This study is a step out of an approach that can be further developed. It can also be used in other associated studies as a resource.

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