

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**EFFECTIVENESS OF SEISMIC ISOLATION ON MID-RISE
BUILDINGS**

ÇAĞRI DİKMEN
A THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF SCIENCE
DEPARTMENT OF CIVIL ENGINEERING
EARTHQUAKE AND STRUCTURAL ENGINEERING PROGRAM

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GEBZE

2018

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GEBZE

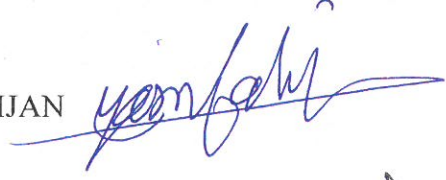
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SUMMARY

In this study, effectiveness of seismic isolation have been investigated on three different mid-rise building. Three buildings of 10, 15 and 20 stories which have the same geometry and framing systems, have been designed according to the requirements of the still draft Turkish Building Seismic Code (2016). Earthquake performances of isolated buildings were determined, using 7 earthquake ground motions scaled to DD-1 & DD-2 earthquake levels corresponding to 2% probability of exceedance in 50 years and 10% probability of exceedance in 50 years, respectively. The performance criterion is that the displacement and strength limits of the isolation units (isolators) are not exceeded by using the lower limit values of isolator system at the DD-1 earthquake level, also superstructure drift and base shear checks are to be done under DD-2 earthquake level with upper bound values of isolator system for targeted-code limited values. Obtained results are compared with commentary.

Key Words: Mid-Rise Building, Seismic Isolation, Nonlinear Dynamic Analysis, Earthquake Performance

ÖZET

Bu çalışmada deprem yalıtımı uygulamalarının üç farklı orta yükseklikteki bina üzerinde etkinliği incelenmiştir. Plan ve taşıyıcı sistem özellikleri hemen hemen aynı olan 10, 15 ve 20 katlı üç bina henüz taslak halde bulunan Türkiye Bina Deprem Yönetmeliği (2016)'nda bulunan şartlara göre deprem yalıtımı tasarımları yapılmıştır. Sırasıyla 50 yılda %2 ve 50 yılda %10 aşılma olasılıklarına tekabül eden DD-1 ve DD-2 deprem seviyelerine göre ölçeklendirilmiş 7 adet deprem kaydı doğrusal olmayan dinamik analizlerde kullanılarak yapılan tasarımların deprem performansları belirlenmiştir. Performans kriterleri, DD-1 deprem seviyesinde izolator sistemlerinin alt sınır değerleri kullanılarak, yalıtım birimlerinin (izolatörlerin) deplasman ve dayanım limitlerinin aşılmaması, DD-2 deprem seviyesinde ise izolatörlerin üst sınır değerleri kullanılarak, üst yapıya etkiyen kuvvet ve kat görelî şekil değıştirmelerinin hedeflenen ve yönetmelikte verilen sınırların altında kalması olarak belirlenmiştir. Elde edilen sonuçlar karşılaştırmalı olarak yorumlanmıştır.

Anahtar Kelimeler: Orta Yükseklikte Bina, Deprem Yalıtımı, Doğrusal Olmayan Dinamik Analiz, Deprem Performansı

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LIST of ABBREVIATIONS and ACRONYMS

<u>Abbreviations</u>	<u>Explanations</u>
<u>and Acronyms</u>	
A	: The total cross sectional area
A_b	: The bonded area of the device
C	: The damping coefficient
c_b	: Damping value of isolation system
C_s	: Design base shear coefficient
c_s	: Damping value of super structure
D	: Displacement
DD-1	: 10% probability of exceedance in 50 year return period.
DD-2	: 2% probability of exceedance in 50 year return period.
$\dot{D}$	: Velocity
$\ddot{D}$	: Acceleration
D_y	: Yield displacement
E_c	: Composite modulus of elasticity
EI	: Bending stiffness
F_D	: Damping force
F_y	: Yield force
FSB	: Flat sliding bearing.
G	: The shear modulus of the elastomer
G'	: Shear storage modulus
G''	: Shear loss modulus
h	: Total height of isolator
I	: Moment of inertia
K	: Bulk modulus
K_1	: Initial stiffness
K_2	: Post yield stiffness
k_b	: Isolation system's stiffness
K_{eff}	: Effective stiffness
K_H	: Horizontal stiffness
k_s	: The stiffness of super structure

K_V	: Vertical stiffness of the isolator
L_i	: Modal Vector
LRB	: Lead Rubber bearing
m	: Lumped mass on the super structure
m_b	: Lumped mass on the isolation layer
M_i	: Modal mass
P	: Axial load on isolator units
P_{crit}	: Critical buckling load
P_E	: Euler buckling mode
P_S	: Shear stiffness per unit length
Q	: Characteristic strength
R	: Radius of the spherical surface
r	: Radius of gyration
S	: Shape factor of isolator
S_D	: Spectral displacement
T	: Period of the structure
t_r	: The total thickness of the rubber
v_b	: Displacement at isolation level
v_g	: The ground displacement
v_s	: Top displacement
W	: Axial load
w	: Frequency
w_b	: Frequency of isolation layer
w_s	: Frequency of super structure
α	: The relative angle between the top and bottom shim plates
β	: Damping ratio
β_b	: Damping ratio of isolation system
β_{eff}	: The effective damping
β_s	: Damping ratio of super structure
γ	: The ratio between mass of super structure to total mass
γ_b	: Shear stress created by bending
δ	: Critical roll-out displacement
ϵ	: Ratio of w_b to w_s

λ_1	: Coupling coefficient. The effect off diagonal component.
λ_2	: Coupling coefficient. The effect off diagonal component.
μ	: The coefficient of friction of the surface
π	: Pi
ρ	: Radius of curvature of elastomeric bearing
Φ_i	: Mode shape
ASCE	: American Society of Civil Engineers
ATC	: Applied Technology Council
EC	: Eurocodes
GTÜ	: Gebze Technical University
IBC	: International Building Code
PTFE	: Polytetrafluoroethylene
TBSC	: Turkish Building Seismic Code
UBC	: Uniform Building Code

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1. INTRODUCTION

Over the last century humankind has grown in population like no other before. Increase in number of people, lead communities to prefer living in more crowded and restricted areas, resulting the invention of mid & high-rise buildings. The more cities include these type of buildings, the more they become susceptible to natural disasters. Earthquake is not an exception. Urban areas with considerable vulnerability and exposure that are closer to fault lines/zones produces great deal of risk in terms of possible life loss and economical cost.

Early remedies came with a trade-off, providing life safety while still leaving with an economical cost. The so-called conventional method, aims to dissipate earthquake energy into structure. Plastic hinges are permitted at preferred locations such as beam ends to damp the energy by displacement dependent hysteretic behavior, whereas ensuring elastic behavior on columns to satisfy overall stability of the structure. Structures designed using conventional method, proven to be safe by preserving precious lives, but there still seemed to be a mile to across in terms of economic goals.

Late 70's and early 80's, came with answers to change the energy dissipation approach of the conventional earthquake resistant design. Structural motion control by passive and active energy dissipation by state-of-the-art devices and software. Passive energy dissipation approaches can be divided into two subsections; seismic isolation and dampers. Seismic isolation aims to dissipate energy at one place and almost no vibration is allowed to the superstructure. Period lengthening using low lateral stiffness elastomeric and frictional devices to reduce vibrations in superstructure and energy dissipation by either lead rubber or friction hysteresis in the duration of motion to create more damping. Whereas dampers are distributed throughout the structure to use the interstory drift and velocity to create additional damping. Yielding hysteretic dampers and friction dampers are good examples for displacement dependent devices, velocity dependent dampers consist of fluid viscoelastic dampers in which damping is created out-of-the-phase with displacement.

In our country passive control devices are recently introduced and has limited use in practice. The Health Ministry of Turkish Republic had decided to seismically

isolate all of the hospitals which has more than hundred patient beds. These decisions lead seismic isolation subject well known in Turkish civil engineering communities. Recent discussions about whether seismic isolation can be preferable for mid to high rise buildings in urbanized areas are generally left without an answer.

1.1. Scope of Work

Seismic isolation of low-rise buildings have been relatively easy, however for mid to high rise buildings it became a challenge to engineers. Emerging difficulties in design applications such as buckling of isolators due to axial loads under large displacements, tensional failures of isolator devices, exceedance of intended base shear on superstructure, limiting of plastic behavior in aimed areas are investigated in this study.

Overall coverage of both latest and last 30 years works have been briefly introduced in Chapter 2. The study continues with Chapter 3 where the theory of seismic isolation of buildings is presented with mechanical properties of isolator types and their design procedures. Chapter 3 also compares code provisions for seismic isolation from American Society of Civil Engineers (ASCE 7-10), Eurocode 8 and Turkish Building Seismic Code 2016 -which is still in draft version during the time this study is written.

Chapter 4 explains the problems in modelling, analysis and design of seismic isolation for mid-rise buildings. A detailed investigation of the subjects in Chapter 4 is realized in a case study on seismic isolation of three mid-rise buildings of 10, 15 & 20-story in Chapter 5.

Lastly the discussion and commentary on outcomes and results are given in Chapter 6.

2. LITERATURE REVIEW

Historically, studies on friction and elastomeric devices for seismic isolation starts around late 70's and early 80's. The early academic studies gathered in Applied Technology Council ATC 17 in 1986, followed by ATC 17-1 in 1993.

These comprehensive studies have created a response in earthquake resistant design codes, namely Universal Building Code UBC-97. Books by James M. Kelly in 1997 and with Farzad Naeim in 1999 given a clear formularization and design procedures for seismic isolation. A rather detailed book on “Mechanics of Rubber Bearings for Seismic and Vibration Isolation” was out on the market in 2011.

Design guidelines also followed this trend, such as Trevor E. Kelly's “Base Isolation of Structures” in 2001. Further guidelines such as 2012 International Building Code IBC Volume 5 on “Examples for Seismically Isolated Buildings and Buildings with Supplemental Damping” are also contributed to the aids for designers.

Fluid viscous dampers that were firstly used in space shuttle programs of NASA, were innovatively began to be used for buildings. Although, the technology is quite expansive, this did not prevent the study understanding the buildings with supplemental in-structure damping by fluid viscous dampers under earthquake loadings. These studies which have been evolving since 70's were mainly from Douglas Taylor and Michael Constantinou.

3. THEORY: SEISMIC ISOLATION

In this part of the study, first of all principles of seismic isolation is explained, secondly the structural dynamics theory of seismically isolated systems are introduced, then mechanical properties for isolation bearings are described with their bilinear modeling techniques. The design procedures and design code provisions are briefly introduced.

3.1. Principles of Seismic Isolation

The main principle of structural or earthquake resistant design is to satisfy the principle;

- Capacity $\geq$ Demand

Conventional design philosophy focuses on the “capacity” side, it has two options;

- In order to maintain elastic behavior, tries to provide more strength which also changes/increases demand.
- Select a capacity lesser than demand and provide ductility at preselected locations. According to this solution damage is accepted and elasto-plastic behavior structural elements are granted.

The aim of seismic isolation is to reduce seismic demand rather than to increase capacity of the structure. To achieve this aim, seismic isolation changes the vibrational characteristics of the structure so that even though the ground is shaking, these vibrations are not reflected to superstructure. Seismic isolation uses the devices which has considerably low lateral stiffness than the superstructure to create a period-shift effect. Period-shift effect reduces the acceleration demand but increases displacement demand. Also these devices (which are briefly explained later) can supply good amount of damping which reduces both the displacement and the

acceleration demand. The linear theory for seismic isolation is explained in Section 3.2 of this thesis.

To implement seismic isolation, structure is separated from ground and isolation devices are deployed. The part over the isolation layer is called as “superstructure” whereas the part lying beneath the superstructure is the “substructure”.

Isolation devices are mainly two types, elastomeric bearings and friction sliding bearings. Elastomeric bearings are made of natural rubber and steel plates, rubber is the main element of lateral rigidity of the bearing whereas steel plates provides the vertical strength. Sliding bearings are constructed by two elements, a PTFE spherical surface and a slider. A more detailed explanation of mechanical properties and behavior for both isolators are provided in Section 3.3 of this thesis. Figures showing these two types are given below.

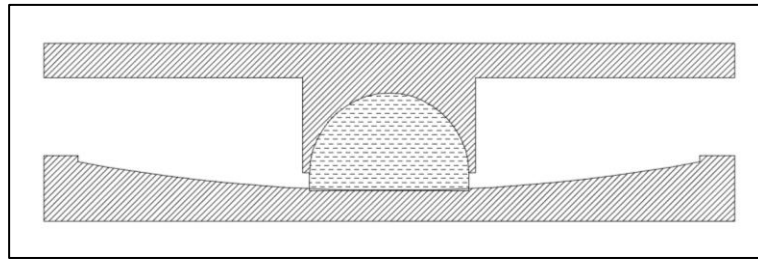


Figure 3.1: Friction pendulum isolator bearing (FPB).

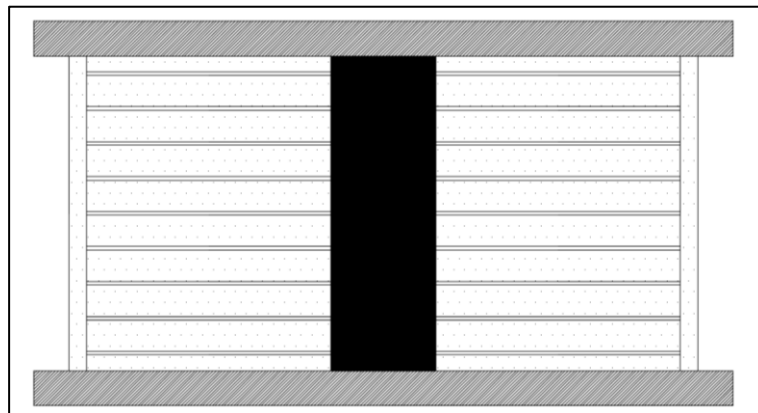


Figure 3.2: Lead rubber bearing (LRB).

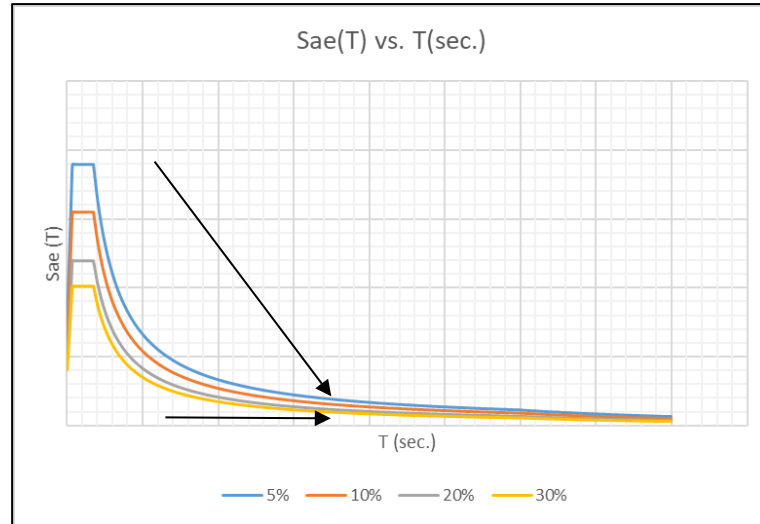


Figure 3.3: Period shift & increased damping effect on spectral acceleration.

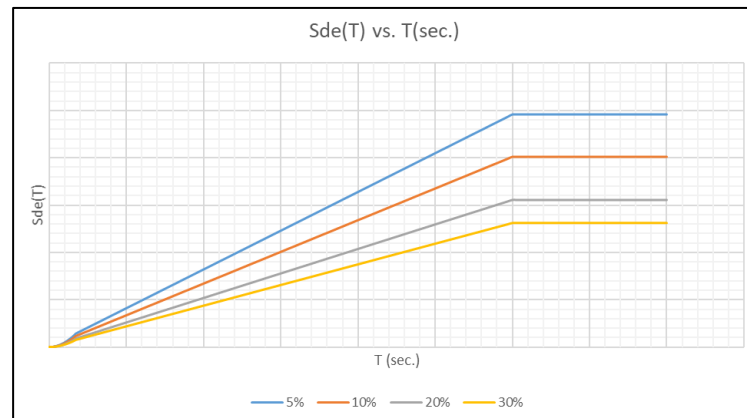


Figure 3.4: Period shift & increased damping effect on spectral displacement.

3.2. Structural Dynamics of Seismic Isolation

The linear theory for single degree of freedom systems were well constructed and understood for a long time. In this section the linear theory of seismic isolation for single-degree-of-freedom systems are briefly discussed and ends with an expansion on the emphasis for seismic isolation of long period structures. James M. Kelly made a very clear and comprehensive explanation of these subjects in his book [Kelly J. M., 1997].

Figure 3.1 shows a seismically isolated single story building with two lumped masses, one on the top m and one on the isolation layer m_b respectively. The stiffness and damping values of superstructure are idealized as k_s and c_s , whereas isolation system properties are denoted by k_b , c_b .

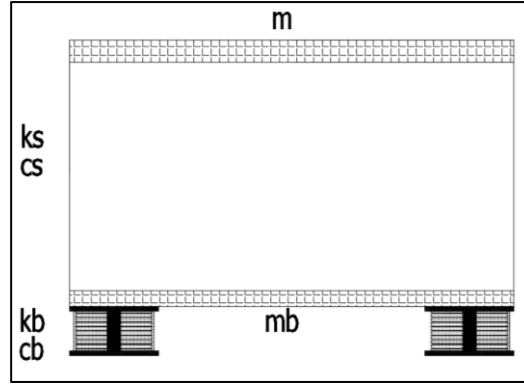


Figure 3.5: Seismically isolated sdf building model.

Furthermore the absolute displacements for m and m_b are represented by u_s and u_b , but if one tries to define relative displacements that would be;

$$v_b = u_b - u_g \quad (3.1)$$

$$v_s = u_s - u_b \quad (3.2)$$

Where the ground displacement is u_g . And the equations of motion for the structure in Figure 3.1 can be constructed as;

$$(m+m_b)\ddot{v}_b + m\ddot{v}_s + c_b\dot{v}_b + k_b v_b = -(m+m_b)\ddot{u}_g \quad (3.3)$$

$$m\ddot{v}_b + m\ddot{v}_s + c_s\dot{v}_s + k_s v_b = -m\ddot{u}_g \quad (3.4)$$

And when these equations are combined in matrix form;

$$\begin{bmatrix} M & m \\ m & m \end{bmatrix} \begin{Bmatrix} v_b'' \\ v_s'' \end{Bmatrix} + \begin{bmatrix} c_b & 0 \\ 0 & c_s \end{bmatrix} \begin{Bmatrix} v_b' \\ v_s' \end{Bmatrix} + \begin{bmatrix} k_b & 0 \\ 0 & k_s \end{bmatrix} \begin{Bmatrix} v_b \\ v_s \end{Bmatrix} = \begin{bmatrix} M & m \\ m & m \end{bmatrix} \begin{Bmatrix} 1 \\ 0 \end{Bmatrix} u_g'' \quad (3.5)$$

Where $M=m+m_b$, and if written in matrix notation;

$$M\ddot{u} + C\dot{u} + Ku = -Mr\ddot{u}_g \quad (3.6)$$

A ratio between mass of superstructure to total mass is defined as γ and equal to;

$$\gamma = \frac{m}{m + m_b} \quad (3.7)$$

And natural frequencies can be written in a way that;

$$w_b^2 = \frac{k_b}{m + m_b} \quad (3.8)$$

$$w_s^2 = \frac{k_s}{m} \quad (3.9)$$

If ε is the ratio of w_b^2 to w_s^2 ;

$$\frac{w_b^2}{w_s^2} = \varepsilon \quad (3.10)$$

When ε is in terms of 10^{-2} , β_b and β_s yield;

$$2w_b\beta_b = \frac{c_b}{m + m_b} \quad (3.11)$$

$$2w_s\beta_s = \frac{c_s}{m} \quad (3.12)$$

So the equations of motion can become;

$$\gamma\ddot{v}_s + \ddot{v}_b + 2w_b\beta_b\dot{v}_b + w_b^2v_b = -\ddot{u}_g \quad (3.13)$$

$$\ddot{v}_s + \ddot{v}_b + 2w_s\beta_s\dot{v}_s + w_s^2v_s = -\ddot{u}_g \quad (3.14)$$

Φ_1 and Φ_2 are the mode shapes of the first and second period respectively.

Thus;

$$\Phi^T = (\Phi_b^i, \Phi_s^i) \quad (3.15)$$

for $i=1,2$ values. With matching frequencies of w_1 and w_2 . The characteristic equation;

$$(1-\gamma)w^4 - (w_s^2 + w_b^2)w^2 + w_b^2 w_s^2 = 0 \quad (3.16)$$

The solutions are;

$$w_1^2 = \frac{1}{2(1-\gamma)} \left\{ w_b^2 + w_s^2 - \left[(w_b^2 - w_s^2)^2 + 4\gamma w_b^2 w_s^2 \right]^{0.5} \right\} \quad (3.17)$$

$$w_2^2 = \frac{1}{2(1-\gamma)} \left\{ w_b^2 + w_s^2 + \left[(w_b^2 - w_s^2)^2 + 4\gamma w_b^2 w_s^2 \right]^{0.5} \right\} \quad (3.18)$$

And to first order in ϵ can be shown as;

$$w_1^2 = w_b^2 (1 - \gamma \epsilon) \quad (3.19)$$

$$w_2^2 = \frac{w_s^2}{1-\gamma} (1 + \gamma \epsilon) \quad (3.20)$$

And the modal amplitudes for each mode;

$$\Phi^{1T} = (1, \epsilon) \quad (3.21)$$

$$\Phi^{2T} = \left\{ 1 - \frac{1}{\gamma} [1 - (1-\gamma)\epsilon] \right\} \quad (3.22)$$

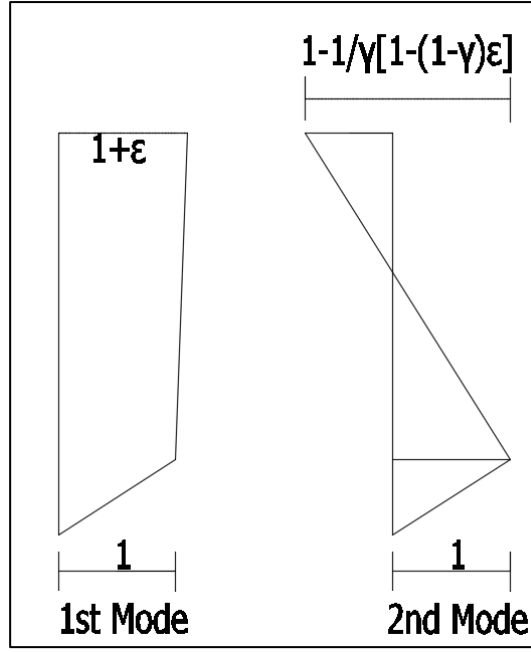


Figure 3.6: Mode shapes for 1st and 2nd modes.

Thus displacements can be obtained from;

$$v_b = q_1 \Phi_b^1 + q_2 \Phi_b^2 \quad (3.23)$$

$$v_b = q_1 \Phi_s^1 + q_2 \Phi_s^2 \quad (3.24)$$

In which q_1, q_2 can be named as time-dependent modal coefficients. If we calculate the modal quantities M_i, L_i ;

$$M_i = \Phi^{iT} M \Phi^i \quad (3.25)$$

$$M_i L_i = \Phi^{iT} M r \quad (3.26)$$

Thus M_1 and M_2 can be written as;

$$M_1 = M(1+2\gamma\epsilon) \quad (3.27)$$

$$M_2 = M \frac{(1-\gamma)[1-2(1-\gamma)\epsilon]}{\gamma} \quad (3.28)$$

And,

$$L_i = 1-\gamma\epsilon \quad (3.29)$$

$$L_2 = \gamma\epsilon \quad (3.30)$$

If the displacement terms in equations (3.1) and (3.2) are replaced with Φ_1 and Φ_2 by their products with q_1 and q_2 , general equations of motion become;

$$\ddot{q}_1 + 2\omega_1\beta_1\dot{q}_1 + \lambda_1\dot{q}_2 + \omega_1^2q_1 = -L_1\ddot{u}_g \quad (3.31)$$

$$\ddot{q}_2 + \lambda_2\dot{q}_1 + 2\omega_2\beta_2\dot{q}_2 + \omega_2^2q_2 = -L_2\ddot{u}_g \quad (3.32)$$

$2\omega_1\beta_1$ and $2\omega_2\beta_2$ are calculated from;

$$M_i 2\omega_i\beta_i = \phi^{iT} \begin{bmatrix} c_b & 0 \\ 0 & c_s \end{bmatrix} \phi^i \quad (3.33)$$

From which can be acquired;

$$2\omega_1\beta_1 = 2\omega_b\beta_b(1-2\gamma\epsilon) \quad (3.34)$$

$$2\omega_2\beta_2 = \frac{1}{1-\gamma}(2\omega_s\beta_s + 2\gamma\omega_b\beta_b) \quad (3.35)$$

In which we get;

$$\beta_1 = \beta_b(1 - \frac{3}{2}\gamma\epsilon) \quad (3.36)$$

$$\beta_2 = \frac{\beta_s + \gamma \beta_2 \epsilon^{1/2}}{(1-\gamma)^{1/2}} \left(1 - \frac{\gamma \epsilon}{2}\right) \quad (3.37)$$

λ_1 and λ_2 express the coupling coefficients. We get these by;

$$\lambda_1 M_1 = \Phi^{iT} \begin{bmatrix} c_b & 0 \\ 0 & c_s \end{bmatrix} \Phi^2 \quad (3.38)$$

Therefore,

$$\lambda_1 M_1 = (1, \epsilon) \begin{bmatrix} c_b & 0 \\ 0 & c_s \end{bmatrix} \begin{pmatrix} 1 \\ -a \end{pmatrix} = c_b - \epsilon \alpha c_s \quad (3.39)$$

$$a = \frac{1}{\gamma} [1 - (1-\gamma)\epsilon] \quad (3.40)$$

If we use the values M_1 and M_2 from equations (3.27) and (3.28) in this calculation we get;

$$\lambda_1 = \frac{2\omega_b \beta_b - \epsilon \{ (1/\gamma) [1 - (1-\gamma)\epsilon] \} 2\omega_s \beta_s m}{M(1+2\gamma\epsilon)} \quad (3.41)$$

Diagonals well as,

$$\lambda_2 = \frac{2\omega_b \beta_b M - \epsilon \{ (1/\gamma) [1 - (1-\gamma)\epsilon] \} 2\omega_s \beta_s m}{[M(1-\gamma)/\gamma] [1 - 2(1-\gamma)\epsilon]} \quad (3.42)$$

Required solution can be obtained for uncoupled equations by neglecting λ_1 and λ_2 which have small effect;

$$\ddot{q}_1 + 2\omega_1 \beta_1 \dot{q}_1 + \omega_1^2 q_1 = -L_2 \ddot{u}_g \quad (3.43)$$

$$\ddot{q}_2 + 2\omega_2 \beta_2 \dot{q}_2 + \omega_2^2 q_2 = -L_2 \ddot{u}_g \quad (3.44)$$

$$|q_1|_{\max} = L_1 S_D(\omega_1, \beta_1) \quad (3.45)$$

$$|q_2|_{\max} = L_2 S_D(\omega_2, \beta_2) \quad (3.46)$$

Where $S_D(\omega, \beta)$ is the displacement response spectrum for the ground motion $\ddot{u}_g(t)$, at frequency ω and damping factor β .

$$|v_s|_{\max} = \left[(\phi_2^1 |q_1|_{\max})^2 + (\phi_2^2 |q_2|_{\max})^2 \right]^{1/2} \quad (3.47)$$

$$|v_b|_{\max} = \left[(\phi_1^1 |q_1|_{\max})^2 + (\phi_1^2 |q_2|_{\max})^2 \right]^{1/2} \quad (3.48)$$

If we apply from equations (3.27), (3.28), (3.47), (3.48), to the above equations;

$$|v_b|_{\max} = \left[(L_1 S_D(\omega_1, \beta_1))^2 + (L_2 S_D(\omega_2, \beta_2))^2 \right]^{1/2} \quad (3.49)$$

$$|v_b|_{\max} = \left\{ (1-\gamma\epsilon)^2 [S_D(\omega_1, \beta_1)]^2 + \gamma^2 \epsilon^2 [S_D(\omega_2, \beta_2)]^2 \right\}^{1/2} \quad (3.50)$$

And;

$$|v_s|_{\max} = \left\{ (\epsilon)^2 (1-\gamma\epsilon)^2 [S_D(\omega_1, \beta_1)]^2 + \gamma^2 \epsilon^2 \frac{1}{\gamma^2} [1-(1-\gamma)\epsilon]^2 [S_D(\omega_2, \beta_2)]^2 \right\}^{1/2} \quad (3.51)$$

$$|v_s|_{\max} = \epsilon \left\{ (1-2\gamma\epsilon)^2 [S_D(\omega_1, \beta_1)]^2 + [1-2(1-\gamma)\epsilon]^2 [S_D(\omega_2, \beta_2)]^2 \right\}^{1/2} \quad (3.52)$$

$$|v_b|_{\max} = (1-\gamma\epsilon) S_D(\omega_1, \beta_1) \quad (3.53)$$

$$|v_s|_{\max} = \epsilon [S_D(\omega_1, \beta_1)^2 + S_D(\omega_2, \beta_2)^2]^{1/2} \quad (3.54)$$

$$C_S = \left| \frac{k_s v_s}{m} \right|_{\max} = \omega_s^2 |v_s|_{\max} \quad (3.55)$$

Becomes;

$$C_S = \omega_s^2 \epsilon [S_D(\omega_1, \beta_1)^2 + S_D(\omega_2, \beta_2)^2]^{1/2} \quad (3.56)$$

$$C_S = [\omega_b^4 S_D(\omega_1, \beta_1)^2 + \epsilon^2 \omega_s^4 S_D(\omega_2, \beta_2)^2]^{1/2} \quad (3.57)$$

$$C_S = [S_A(\omega_1, \beta_1)^2 + \epsilon^2 S_A(\omega_2, \beta_2)^2]^{1/2} \quad (3.58)$$

Because ϵ is so small, second terms in square root equation above can be written as;

$$|v_s|_{\max} = \frac{\epsilon S_V}{\omega_b} = \epsilon S_D(\omega_b, \beta_b) \quad (3.60)$$

$$|v_b|_{\max} = \frac{S_V}{\omega_b} = S_D(\omega_b, \beta_b) \quad (3.61)$$

Base shear coefficient C_S is;

$$C_S = \frac{k_s v_s}{m} = \omega_s^2 v_s \quad (3.62)$$

3.3. Isolator Mechanical Properties & Design Procedures

This section deals with mechanical properties of isolators, bilinear modelling of lateral behavior of isolators and design procedures created for both elastomeric and friction based isolators.

3.3.1. Elastomeric Bearings

Elastomeric bearings constructed in layers of natural rubber and steel plates. The most important property of elastomeric bearing is of course lateral stiffness which is given as;

$$K_H = \frac{GA}{t_r} \quad (3.63)$$

Where G is the shear modulus of the elastomer, A is the total cross section area and t_r is the total thickness of the rubber. The shear strain of the isolator can be found by dividing horizontal displacement to rubber thickness and can be found in the equation below.

$$\gamma = \frac{D}{t_r} \quad (3.64)$$

And vertical stiffness of the elastomeric bearings can be expressed by;

$$K_V = \frac{E_c A}{t_r} \quad (3.65)$$

Where E_c is composite modulus of elasticity and can be obtained from;

$$E_c = 6GS^2 \quad (3.66)$$

Where S is the shear factor and is the ratio of loaded area to force free area. For lead-rubber bearings effective stiffness K_{eff} can be obtained by;

$$K_{eff} = K_2 + \frac{Q}{D} \quad (3.67)$$

Where $D \geq D_y$ and D_y expresses yield displacement and K_2 is post-yield stiffness. ω expresses the natural frequency and it is given by;

$$\omega = \sqrt{\frac{K_{eff}g}{W}} \quad (3.68)$$

$$\omega = \sqrt{\omega_0^2 + \mu \frac{g}{D}} \quad (3.69)$$

Where $\mu = Q/W$, $\omega_0^2 = \sqrt{K_2 g/W}$ And the effective period can be expressed as;

$$T = \frac{2\pi}{\omega} \quad (3.70)$$

$$T = \frac{2\pi}{\sqrt{\omega_0^2 + \mu \frac{g}{D}}} \quad (3.71)$$

If $D \geq D_y$ then the effective damping β_{eff} can be written as;

$$\beta_{\text{eff}} = \frac{4Q(D - D_y)}{2\pi K_{\text{eff}} D^2} \quad (3.72)$$

And D_y the yield displacement is the ratio of yield force to initial stiffness.

$$D_y = \frac{F_y}{K_1} \quad (3.73)$$

Thus,

$$F_y = Q + K_2 D_y \quad (3.74)$$

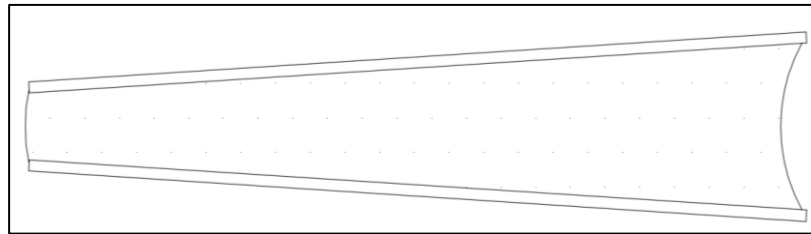


Figure 3.7: Bent shape for single layer.

The bending stiffness of the elastomeric bearings can be obtained by an analogy to beam behavior. In the formula below α represents the relative angle between the top and bottom plates. ρ is the radius of curvature and r is the radius of gyration [Kelly J. M., Konstantinidis D. A. 2011].

$$\frac{1}{\rho} = \frac{\alpha}{r} \quad (3.75)$$

Analogy with given formula below yields;

$$M = \frac{EI}{\rho} \quad (3.76)$$

$$M = (EI)_{\text{eff}} \frac{\alpha}{t} \quad (3.77)$$

For a given radius R above equation becomes;

$$M = \frac{\alpha G \pi R^6}{8t^3} \quad (3.78)$$

And moment of inertia I for circular bearing is;

$$I = \frac{\pi R^4}{4} \quad (3.79)$$

And bending stiffness for circular pad with a central hole is;

$$(EI)_{\text{eff}} = 2GS^2I \frac{(b+a)^2}{b^2 - a^2} \quad (3.80)$$

The shear stress created by bending is;

$$\gamma_b = 6S\epsilon_b \quad (3.81)$$

For large shape factor bearings, compressibility becomes important and approximately expressed as;

$$\frac{1}{E_c} = \frac{1}{E_c} + \frac{1}{K} \quad (3.82)$$

Where $1/E_c'$ is the compression modulus assuming incompressibility and K is the bulk modulus. Rewriting this equation we get;

$$E_c = \frac{E_c' K}{E_c' + K} \quad (3.83)$$

Critical buckling load of the multilayered elastomeric isolators can be obtained by the same Euler buckling approach to the columns. If we assume a total height as h and effective shear area A_s thus, shear stiffness per unit length comes;

$$P_s = G A_s \quad (3.84)$$

Where;

$$A_s = A \frac{h}{t_r} \quad (3.85)$$

The bending stiffness is modified for a single pad as $E I_s$ is;

$$E I_s = \frac{1}{3} E_c I \frac{h}{t_r} \quad (3.86)$$

And horizontal stiffness is;

$$K_H = \frac{G A_s}{h} \quad (3.87)$$

For no lateral displacement situations Euler buckling formula becomes;

$$P_E = \pi^2 \frac{E I_s}{h^2} \quad (3.88)$$

Critical buckling load is the solution of the equation given below;

$$P^2 + PP_S - P_S P_E = 0 \quad (3.89)$$

And the solution to above equation is;

$$P_{crit} = \frac{-P_S + \sqrt{P_S^2 + 4P_S P_E}}{2} \quad (3.90)$$

The influence of vertical load on horizontal stiffness can be expressed as;

$$K_H = \frac{GA_S}{h} \left[1 - \left(\frac{P}{P_{crit}} \right)^2 \right] \quad (3.91)$$

For isolators that are connected to both sub and super structure by shear keys that cannot take tensile forces another form of failure mode called roll-out stability failure may happen. For these types of connections a critical displacement must be calculated.

That is;

$$\delta_{max} = \frac{Pb}{P + K_H h} \quad (3.92)$$

3.3.2. Friction Pendulum Bearings

Unlike elastomeric bearings, friction based bearings depend on friction instead of shear modulus. This may seem advantageous because it is simpler to model the friction pendulum bearings than the elastomeric bearings. The main parameter is the radius of the spherical surface. The resisting force is given in the formula below;

$$F = \frac{W}{R} D + \mu W (\text{sgn } \dot{D}) \quad (3.93)$$

In the formula above, W is the axial load, R is the radius of the spherical surface, μ is the coefficient of friction of the surface and D , $\dot{D}$ are the displacement and the velocity respectively. Horizontal stiffness can be expressed as;

$$K_H = \frac{W}{R} \quad (3.94)$$

Thus, the period of the structure becomes;

$$T = 2\pi \sqrt{\frac{R}{g}} \quad (3.95)$$

Effective stiffness at given displacement is;

$$K_{\text{eff}} = \frac{W}{R} + \frac{\mu W}{D} \quad (3.96)$$

And the effective damping is;

$$\beta_{\text{eff}} = \frac{4\mu WD}{4\pi K_{\text{eff}} D^2} \quad (3.97)$$

Vertical displacement for a horizontal displacement is;

$$\delta_V = R \left[1 - \cos \left(\sin^{-1} \frac{D}{R} \right) \right] \quad (3.98)$$

3.4. Bilinear Modeling of Isolators

Isolator properties mentioned above can be successfully modeled and their behavior is represented by three parameters; K_1 , K_2 and Q . K_1 represents elastic stiffness of the bearing which can be obtained by test results for high damping rubber bearings and a multiple of post yield stiffness for lead rubber bearings and friction pendulum bearings [Kelly J. M., Naeim F., 1999].. Q can be calculated from the

hysteresis loops for high damping rubber bearings, for lead-rubber bearings Q is the yield stress times area of the lead-plug and for friction pendulum devices it is the multiplication of coefficient of friction by axial load carried. The post yield stiffness can be precisely calculated for all three types of bearings.

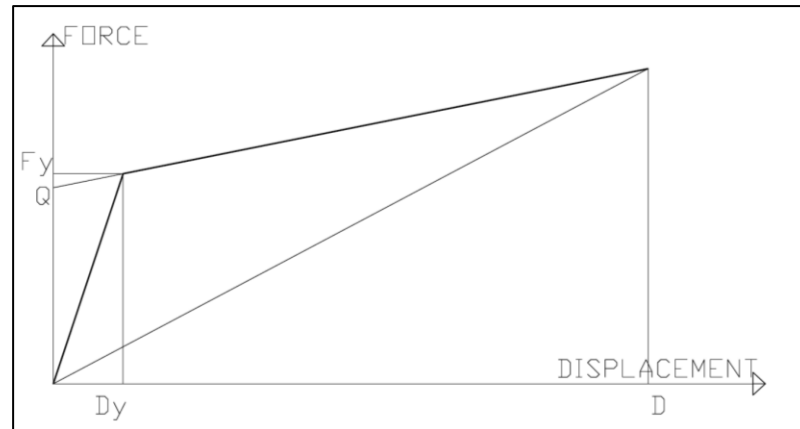


Figure 3.8: Bilinear force displacement relationship for elastomeric isolators.

3.5. Design Procedures

Design procedure for high damping rubber bearing is as follows;

- Determine a cross sectional area from the demands of both vertical loads and lateral loads.
- Determine the required rubber height.
- Check for shear strain and stability under vertical design loads.
- Check for stability and roll-out under earthquake loads.
- Design procedure for lead-rubber bearings are quite similar to high damping rubber bearings and the details can be found below;
- Determine the cross sectional area for the rubber from the demands of both vertical loads and lateral loads.
- Determine the required cross sectional area of the lead core according to desired yield force and displacement.
- Determine the required rubber height.
- Check for shear strain and stability under vertical design loads.
- Check for stability and roll-out under earthquake loads.

- Design procedure for friction pendulum systems can be written as;
- Choose a period such that the earthquake forces massively reduced.
- Calculate the radius of each bearing under vertical force.
- Check for uplift in the bearing under lateral loads.
- Check for the requirement of the restoring force to ensure the re-centering of the structure.

3.6. Design Code Provisions for Seismic Isolation

Since its invention, seismic isolation seems quite attractive to the civil engineers making designs in earthquake hazardous zones. This forced the seismic design codes to include chapters on seismic isolation. Codes like UBC– Uniform Building Code were the first ones to supply this demand.

Here in this part of the thesis, relevant sections from the latest codes in United States [ASCE 7-10, 2010] and Europe [EC8, 1998] with currently draft Turkish Building Seismic Code [TBDY 2017] are briefly collected and compared.

- **Design Spectra:** The design earthquake level spectra for both isolators and super structure from For ASCE 7-10 and TBDY 2017, two different levels of earthquakes were defined, MCE (Maximum Credible Earthquake) 2% probability of exceedance in 50 years (2475 years of return period) and DBE (Design Basis Earthquake) 10% probability of exceedance in 50 years (475 years of return period) to check maximum displacement and maximum shear in isolators respectively. However, in Eurocode 8 both displacement and shear check is done according to DBE (Design Basis Earthquake).
- **Importance Factor:** ASCE 7-10 doesn't implement an importance factor for design unlike Eurocode 8. Draft TBSC 2016 defines the importance factor $I=1$.
- **Design Methods:** Equivalent Lateral Load Method (ELLM), Response Spectrum Analysis (RSA) and Non-linear Time History Analysis (NLTHA) are available as design methods in all three codes.
- **ELFM Basic Conditions:** ELFM is permitted under strict rules such as limiting the height of the building and isolated period, building regularity, site soil conditions and one second period spectral acceleration for all three codes.

- **Vertical Earthquake Component Effects:** All three codes take into account the effects of vertical earthquake component which becomes more important as seismic isolation also affects the vertical structural stiffness.
- **Modeling:** Both ASCE 7-10 and EC 8 permits to 2D analysis model for ELFM, 3D model is compulsory when ELFM is not available. TBDY 2017 makes almost no comment on this issue.
- **Safety Factor on Isolation Capacity:** Design codes tend to increase the design displacements to enhance the safety of isolators. ASCE 7-10 makes an implicit raise in the design displacement for MCE level earthquake whereas EC 8 and TBDY 2017 explicitly multiplies the design displacement by 1.2 and 1.3 respectively.
- **Super Structure Requirements:** All three codes allow low ductility on super structure, $R_{max} = 2$ for ASCE 7-10 and TBDY 2017, $R_{max} = 1.5$ for EC 8. The assumption that total base shear is taken by isolators.
- **Clearance:** All three codes require a clearance distance equal to maximum displacement obtained for MCE level earthquake.
- **Design Review:** Design review is mandatory in ASCE 7-10 and EC 8 but TBDY 2017 doesn't mention.
- **Testing:** In all three codes, the design engineer must be in the testing facilities and also define/control the force-displacement, effective lateral and vertical stiffnesses and effective damping ratio of the isolators.

4. SEISMIC ISOLATION FOR MID-RISE BUILDINGS

Ideas on seismic isolation of long-period mid to high rise buildings are reflected under this section. Firstly, possible problems on the analysis and design of the mentioned structures are discussed with a theoretical basis. Secondly, an existing solution with a different approach to same problem is reintroduced. Possible benefits of combination of these two systems are also acknowledged.

4.1. Problems in Design & Analysis

One of the main assumptions made in design of seismic isolation is rigid structure assumption which reckons that the super structure is so stiff with respect to isolation system, there would be no or rather limited displacements/accelerations to be realized in super structure. Experience shows that this assumption is very well in accordance with the reality. On the other hand, this assumption may not be valid in the practice of seismic isolation of long-period structures in which the super structure has a lack of required stiffness to make rigid structure assumption come true. An example by Kelly [Kelly, 1997] of a structure which has the same period of vibration with its isolated design.

Characteristic equation for the system mentioned above can be written as,

$$(1-\gamma)\omega^4 - 2\omega_0^2\omega^2 + \omega_0^4 = 0 \quad (4.1)$$

In which the assumption is;

$$\omega_0 = \omega_b = \omega_s \quad (4.2)$$

Thus the natural frequencies become;

$$\omega_1^2 = \frac{1-\gamma^{1/2}}{1-\gamma} \omega_0^2 \quad (4.3)$$

$$\omega_2^2 = \frac{1+\gamma^{1/2}}{1-\gamma} \omega_0^2 \quad (4.4)$$

And the mode shapes corresponding to the mentioned modal frequencies are;

$$\phi^{1^T} = (1, \gamma^{1/2}) \quad (4.5)$$

$$\phi^{2^T} = (1, -\gamma^{1/2}) \quad (4.6)$$

Thus the modal mass and modal participation factors for both modes will be equal;

$$L_1 = \frac{1}{2} \quad (4.7)$$

$$L_2 = \frac{1}{2} \quad (4.8)$$

Which would make modal damping ratios result as;

$$\beta_1 = \frac{\beta_b + \beta_2}{2} \left(\frac{1}{1-\gamma^{1/2}} \right)^{1/2} \quad (4.9)$$

$$\beta_2 = \frac{\beta_b + \beta_s}{2} \left(\frac{1}{1+\gamma^{1/2}} \right)^{1/2} \quad (4.10)$$

As Kelly theoretically proved, the benefit of reducing the base shear may seem possible. But, it may not be sufficient to make the decision or show the effectiveness of seismic isolation on long period buildings.

It is quite probable to come across with several more design and analysis challenges. For instance, the wind loads on these large buildings can be larger than the lateral resisting force especially for friction pendulum type isolators. Also, larger structure requires larger displacement demand which would raise the question about availability of sufficient area to accommodate these displacements. Furthermore, the

flexible super structure could also be affected by floor accelerations which are not reflected by the isolation layer. These accelerations could be critical for non-structural components of the building.

The drift limits of elastic behavior are very well under threat as well. There is a good chance of not attaining the desired damping ratio by not achieving the targeted displacement because of the fact that the rigid super structure behavior is not accomplished.

Last but not least, the stability issues of buckling due to high levels of axial force, overturning tendency as a result of high aspect ratio, hard to avoid uplift forces on isolator devices can be easily encountered. Obviously, to overcome these problems are quite challenging, the general approach is usually to stiffen the super structure or reducing the force and displacement demand by additional in structure damping members to the system.

5. CASE STUDY: INVESTIGATION OF EFFECTIVENESS OF SEISMIC ISOLATION ON THREE MID-RISE BUILDINGS OF 10, 15 & 20 STORIES

In this part of the study, three buildings having 10, 15 and 20 stories are generated on the basis of the same plan view. Lateral load resisting system is also the same for columns and beams but shear wall geometries are differently chosen to optimize the building's drift ratio to 1.5% at DBE (DD-2 level earthquakes TBDY 2016, 10% probability of exceedance in 50 years) level earthquakes.

Seismic isolation design according to TBDY 2016 regulations are performed for these three buildings, and to investigate the success and effectiveness of the seismic isolation designs 7 pairs of earthquakes are scaled to DD-1 and DD-2 level design spectrums for non-linear time history analysis.

Performance of sub-structure which is assumed to be only composed by seismic isolator units are to be checked under DD-1 level (maximum credible earthquake, 2% probability of exceedance in 50 years) earthquake ground motions using lower bound properties of isolator units. These checks are namely maximum displacement check and maximum axial load check of isolators.

The super structure performance checks are comprised of maximum base shear occurred, and inter story drifts. These checks are done under DD-2 level earthquake ground motions using upper bound properties of isolator units. Additionally, floor response spectra at top story levels are obtained for comparison using nominal properties of isolator units.

Modeling of the fixed base and isolated structures have been done in ETABS [ETABS, 2000] finite element software. Columns and beams are modelled by using frame elements while shell elements are used to model shear walls. Slabs are not modelled, their behavior is reflected by deploying diaphragm constraints, and however the loading coming from slabs are calculated and implemented on the beams as trapezoidal and triangular distributed loadings. Modeling of isolators are done by using nonlinear link elements, isolator backbone curves are reflected on these elements.

5.1. Seismic Hazard

Turkish Building Seismic Code [TBDY-2017], requires/prefers 2 levels of earthquake hazard level for the design of seismic isolation design. These levels are as pre-mentioned DD-1 (2% probability of exceedance in 50 years, Maximum credible earthquake) and DD-2 (10% probability of exceedance in 50 years, Design basis earthquake) of which the spectral values can be easily obtained for any given coordinates from [Web 1,2017]. The horizontal and vertical spectrum values and graphs are obtained from website and presented below, the website also produces reports for hazard data and attached to the appendices' of this thesis.

Spectral acceleration values and response spectrum graphs of horizontal earthquake effects corresponding to DD-1 and DD-2 Turkish Building Seismic Code is given below.

Table 5.1: Horizontal spectral acceleration values for DD-1 & DD-2 level earthquake spectrums.

	DD-1	DD-2
S_S	1.579	0.905
S_1	0.440	0.250
PGA	0.637	0.371
F_S	1.2	1.2
F_1	1.5	1.5
Soil	ZC	ZC
L_F	>25	>25
γ_F	1	1
S_{DS}	1.895	1.086
S_{D1}	0.660	0.375

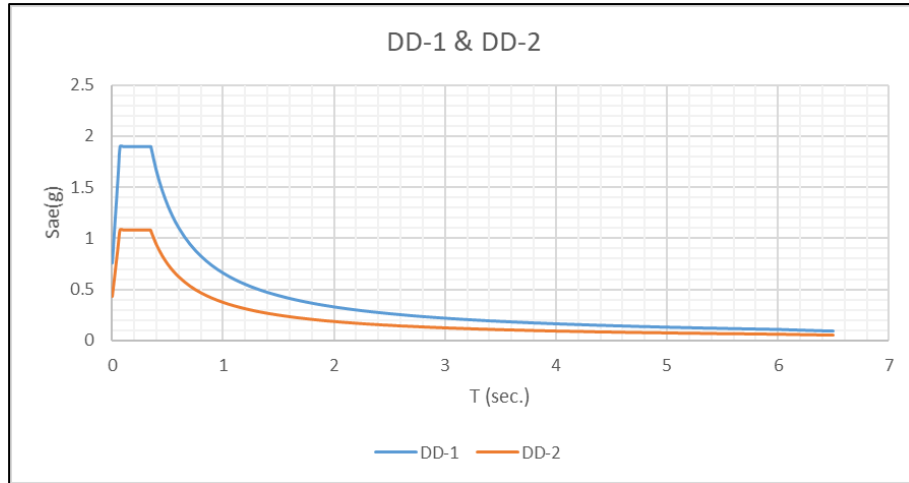


Figure 5.1: Horizontal acceleration response spectrum for DD-1 & DD-2 earthquake levels.

The seismic isolation designs are checked by nonlinear time history analyses, 7 pairs of earthquake ground motions are scaled between 0.5 to 5.0 seconds to both DD-1 and DD-2 response spectra. Summary for seismic input are given in the table below.

Table 5.2: Horizontal seismic input summary scaled to DD-1 & DD-2 response spectrums respectively.

#	Rec. Num.	EQGM	Year	Rec. Time	DD-1 SF	DD-2 SF
1	15	Kern County	1952	54.2	3.20131	1.819
2	731	Loma Prieta	1989	39.95	3.00053	1.705
3	776	Loma Prieta	1989	59.975	1.05018	0.597
4	827	Cape Mendocino	1992	44	2.87763	1.635
5	838	Landers	1992	40	3.38808	1.925
6	1148	Kocaeli	1999	30	4.11074	2.336
7	1163	Kocaeli	1999	106.625	3.97785	2.260

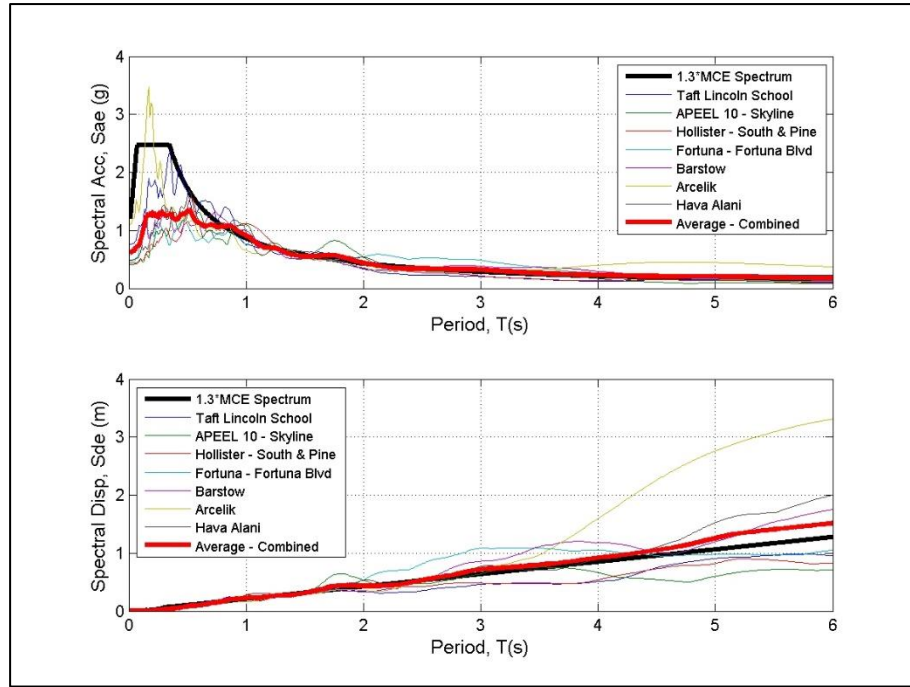


Figure 5.2: Scaled horizontal acceleration response spectra of eqgm's for DD-1 earthquake levels.

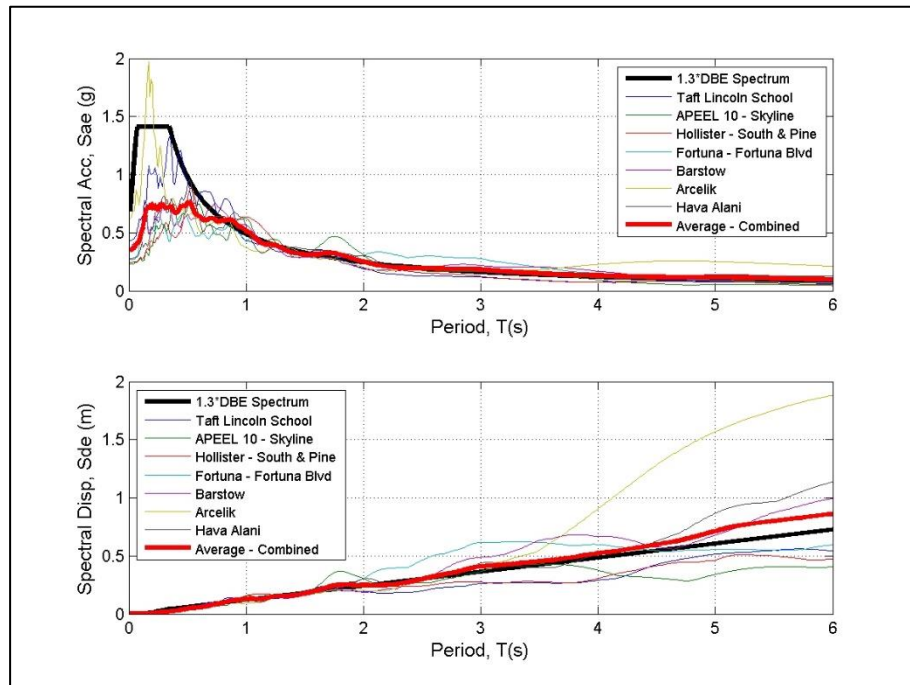


Figure 5.3: Scaled horizontal acceleration response spectra of eqgm's for DD-2 earthquake levels.

Additionally, seismically isolated structures are known to have a tendency to vertical components of earthquake ground motions, especially structures with a vertical period longer than 0.1 seconds. Therefore a scaled vertical ground motion

set is advised to be used. Vertical components of the selected ground motions are scaled between 0.5 to 5.0 seconds to vertical response spectra of both DD-1 & DD-2 earthquake levels

The vertical response spectra is derived from horizontal response spectra is presented in below graph, also matched spectra of selected earthquake ground motions are also given below graphs.

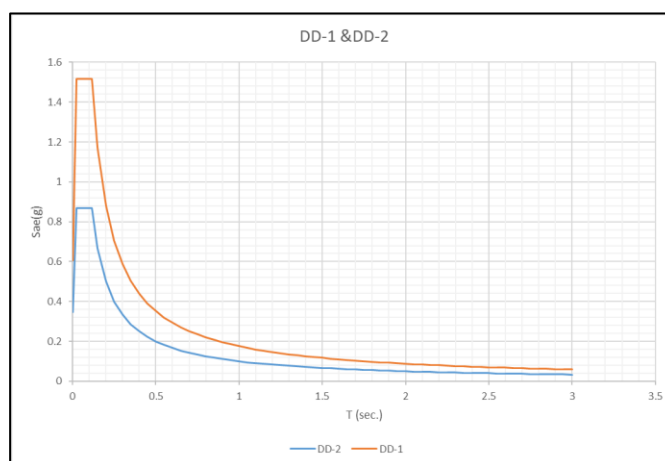


Figure 5.4: Vertical acceleration response spectrum for DD-1 & DD-2 earthquake levels.

Table 5.3: Horizontal spectral acceleration values for DD-1 & DD-2 level earthquake spectrums.

	DD-1	DD-2
$0.8 \cdot S_{DS}$	1.516	0.869
$0.32 \cdot S_{DS}$	0.606	0.348
T_{AD}	0.023	0.023
T_{BD}	0.116	0.115
T_{LD}	3.000	3.000

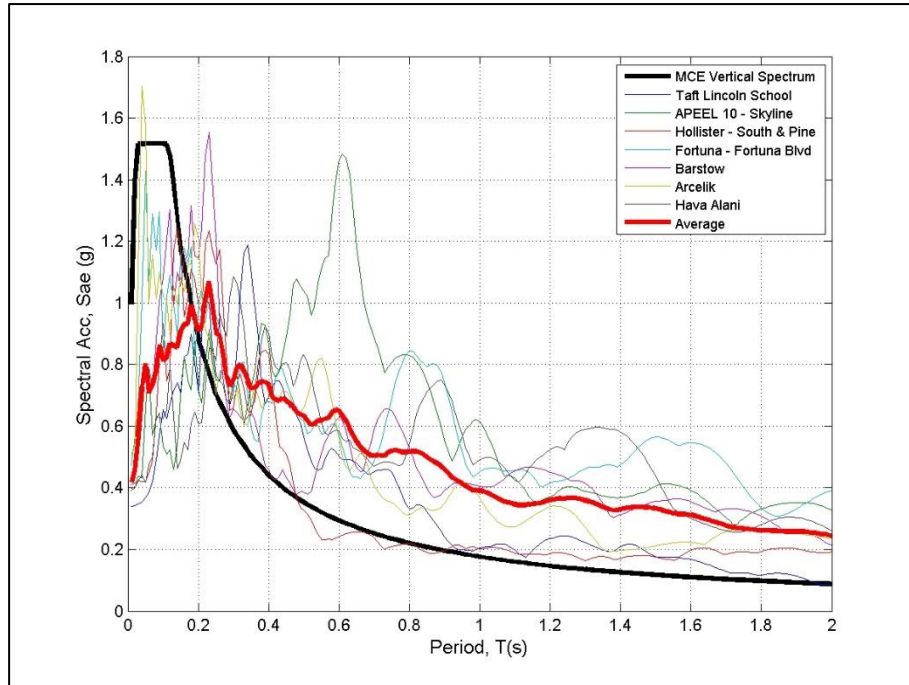


Figure 5.5: Scaled vertical acceleration response spectra of eqgm's for DD-1 earthquake levels.

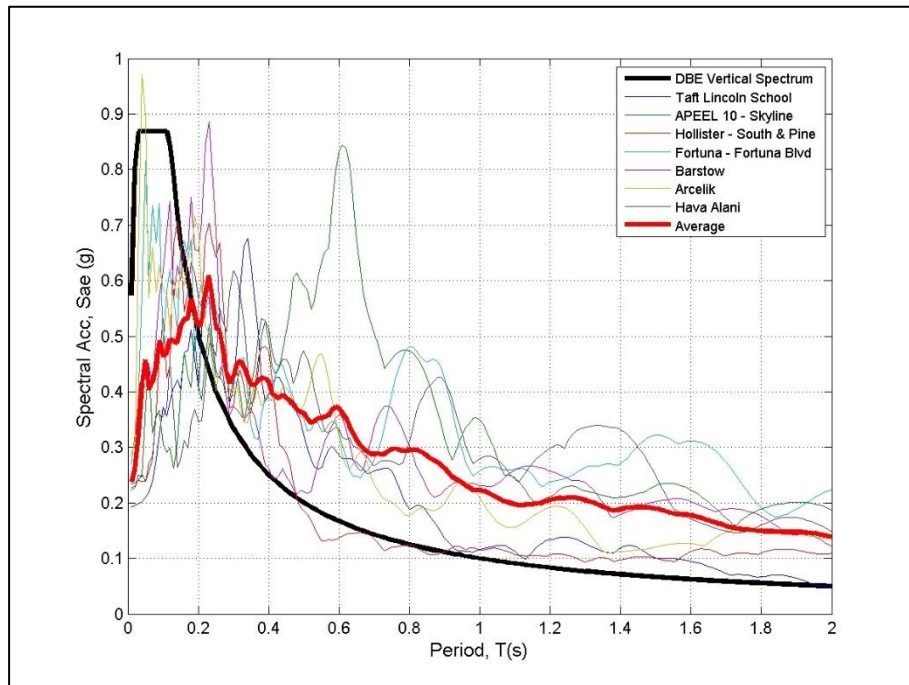


Figure 5.6: Scaled vertical acceleration response spectra of eqgm's for DD-2 earthquake levels.

5.2. Design & Analysis of 10 Story Building

In this section, first material and geometrical properties of 10 story building have been introduced. Secondly the fixed base model is analyzed for scaled earthquake records. Thirdly the seismic isolation design of 10 story building have been conducted and nonlinear time history analyses have been performed, and lastly results obtained from both fixed base and base isolated buildings have been compared.

5.2.1. Properties of the Building

The 10-story reinforced concrete wall frame building is to be seismically isolated and analyzed under pre-mentioned scaled seismic input, before seismic isolation design and analyze results are presented, the building is to be introduced and some properties of fixed base building is going to be given in this section.

The building is 23.3 m by 41.5 m in plan, the story height is taken as 3m making the height of the building 30 meters. The concrete material property is taken as C30 with a modulus of elasticity as 26000 MPa. The building is composed of 5 different types of columns (C1, C2, C3, C4, C5) and 2 types of beams namely “Interior” and “Perimeter”, the shear wall thickness is taken to be 30 cm as well as slab thicknesses are taken as 15 centimeters.

Table 5.4: Geometrical properties of columns and beams.

		b (cm)	h (cm)
Columns	C1	70	70
	C2	30	120
	C3	140	40
	C4	150	40
	C5	160	40
Beams	Interior	40	75
	Perimeter	50	90

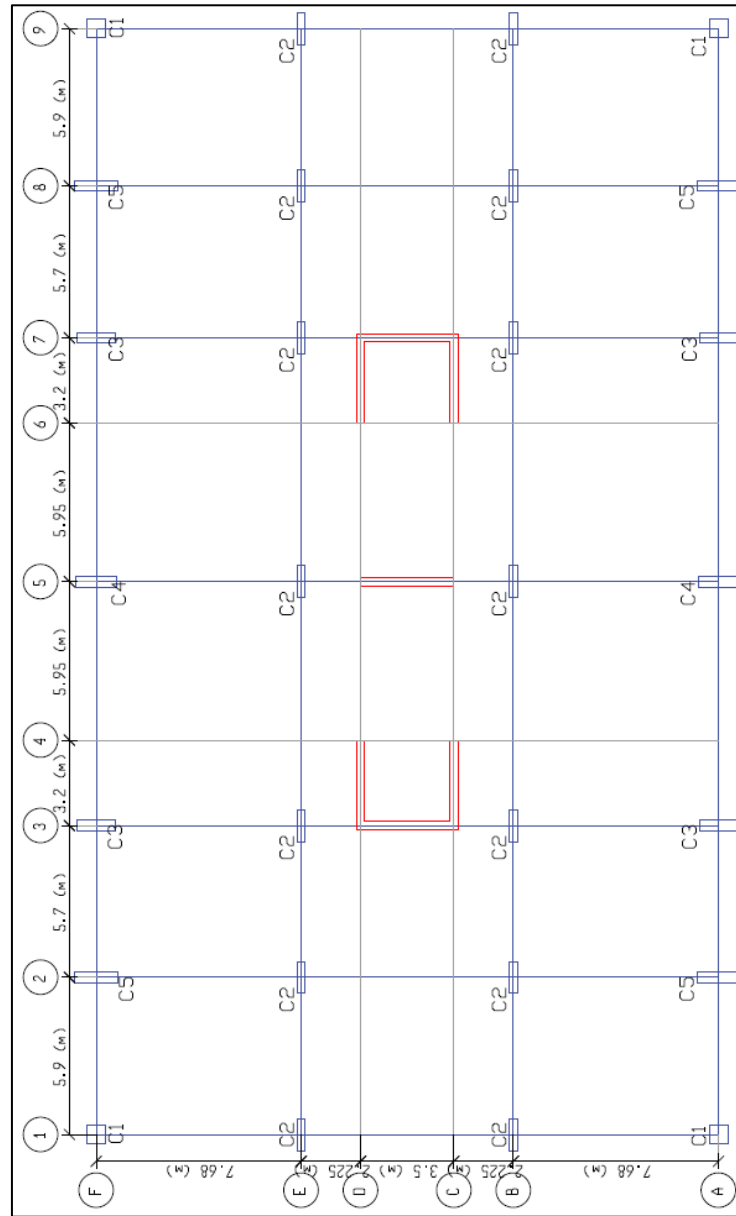


Figure 5.7: Plan view of the 10 story building.

The building is considered as residence thus the loadings on floors are taken as per [TS498, 1984];

- Superimposed Dead Load: 2 kN/m^2
- Live Load: 2.5 kN/m^2

The building is modelled as fixed base, using 3D finite elements and a modal analysis is carried out to obtain dynamical properties of the fixed base building. Cracked section stiffness properties are taken into account as per code requirements.

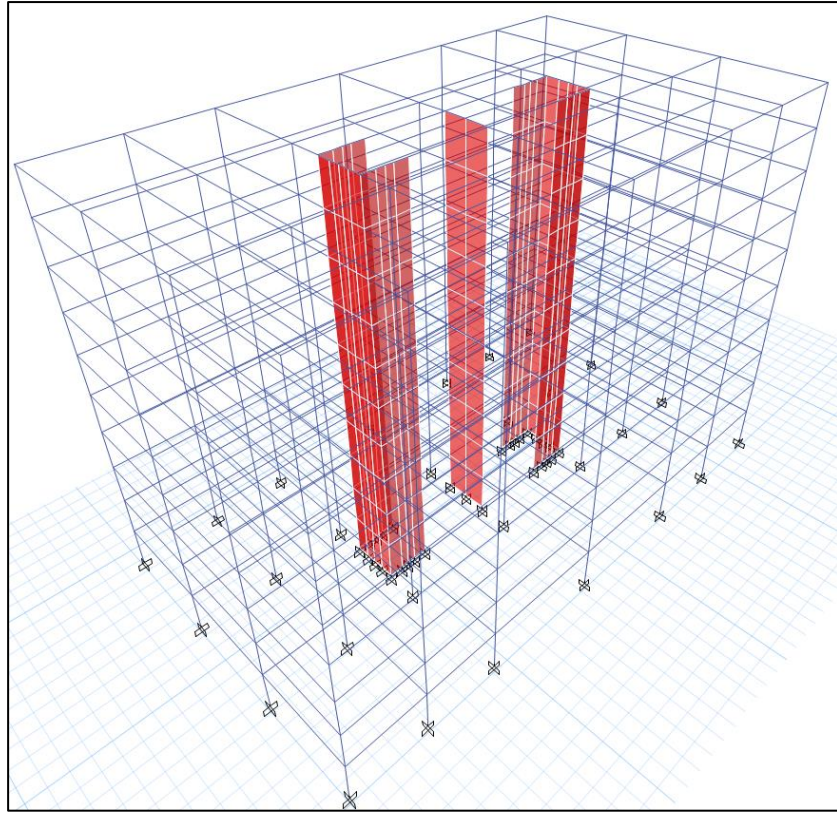


Figure 5.8: 3d finite element modeling view of the fixed base 10 story building.

Table 5.5: Modal periods and corresponding mass ratios for 10 story fixed base building.

Mode	Period	UX	UY	RZ
#	(Sec.)	Unitless	Unitless	Unitless
1	1.225	0.000	0.000	0.748
2	1.208	0.740	0.000	0.000
3	1.166	0.000	0.713	0.000
4	0.357	0.000	0.000	0.134
5	0.344	0.126	0.000	0.000
6	0.307	0.000	0.159	0.000
7	0.178	0.000	0.000	0.053
8	0.162	0.056	0.000	0.000
9	0.142	0.000	0.058	0.000
10	0.111	0.000	0.000	0.027
11	0.095	0.031	0.000	0.000
12	0.086	0.000	0.029	0.000

As it can be seen from the table above, the fixed base building has almost the same natural fundamental period values in both X and Y directions, and the modal participating masses are around 70 to 74 percent of the total mass.

To compare the results with seismically isolated structure, a linear time history analysis, using scaled earthquake records to DD-2 level, has been conducted. As a result story shear forces, drifts and displacements have been obtained with the average of the maximum values. The results are given by table and figure below.

- Story Shear Forces at DD-2 Level

Obtained story shear forces are presented in this section. Mean Maximum base shears for the building is obtained as 25083 kN for X direction and 26050 kN for Y direction.

Table 5.6: Average story shear forces for fixed base building for x and y directions.

	Story Force (kN)	
	X Dir.	Y Dir.
Story10	5287	5765
Story9	9705	10549
Story8	12979	14060
Story7	15586	16607
Story6	17705	18498
Story5	19419	20302
Story4	20900	22589
Story3	22611	24328
Story2	24241	25546
Story1	25083	26050
Base	25083	26050

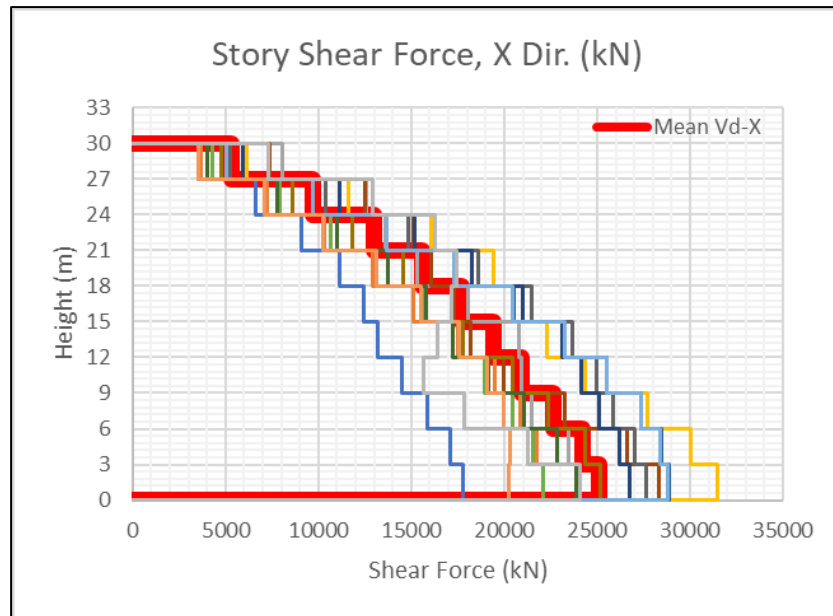


Figure 5.9: Story shear forces x direction.

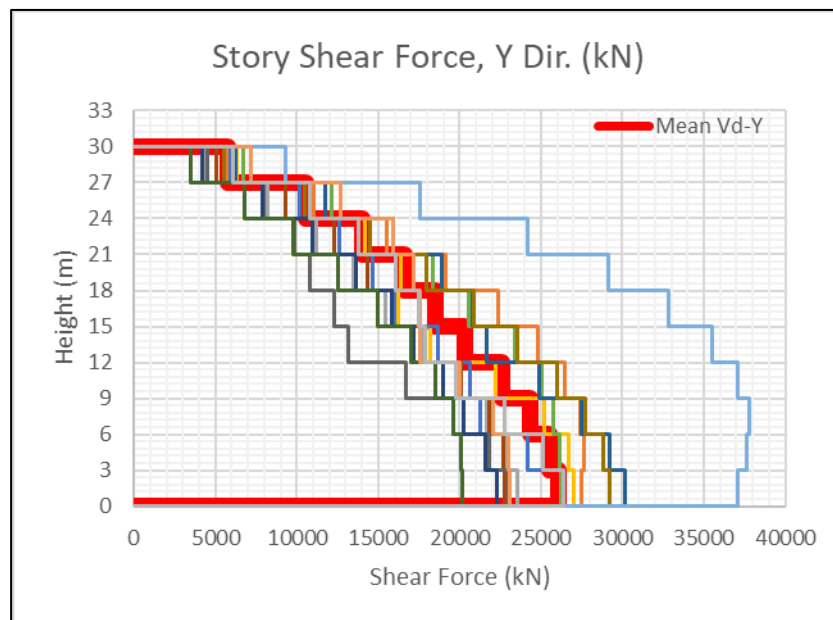


Figure 5.10: Story shear forces y direction.

- Story Displacements at DD-2 Level

Obtained story displacements are presented in this section. Mean Maximum displacements for the building is obtained as 116.9 mm for X direction and 127.8 mm for Y direction.

Table 5.7: Average story displacements for fixed base building for x and y directions.

	Displacement (mm)	
	X Dir.	Y Dir.
Story10	116.9	127.8
Story9	108.4	115.3
Story8	98.5	102.0
Story7	87.2	87.9
Story6	74.3	73.0
Story5	60.1	57.9
Story4	45.3	42.7
Story3	30.3	28.1
Story2	16.4	15.1
Story1	5.2	4.9
Base	0.0	0.0

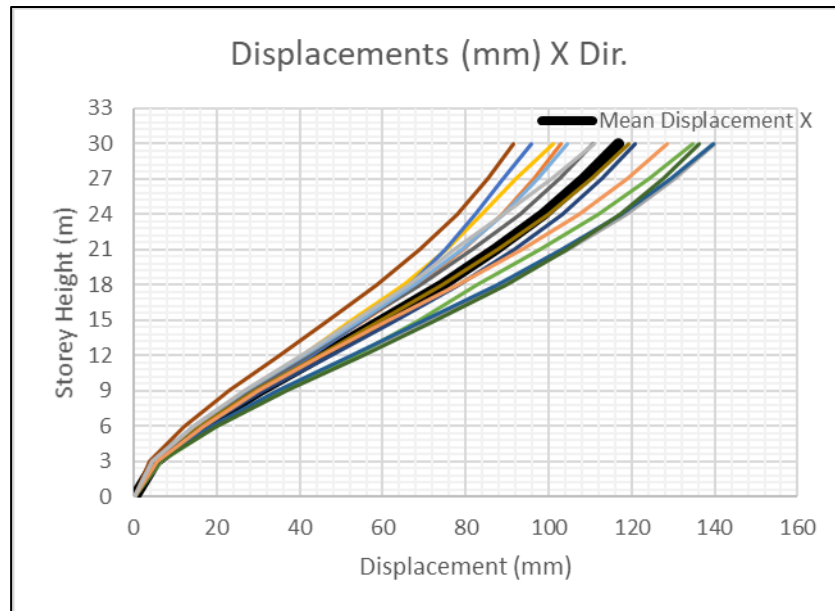


Figure 5.11: Story displacements x direction.

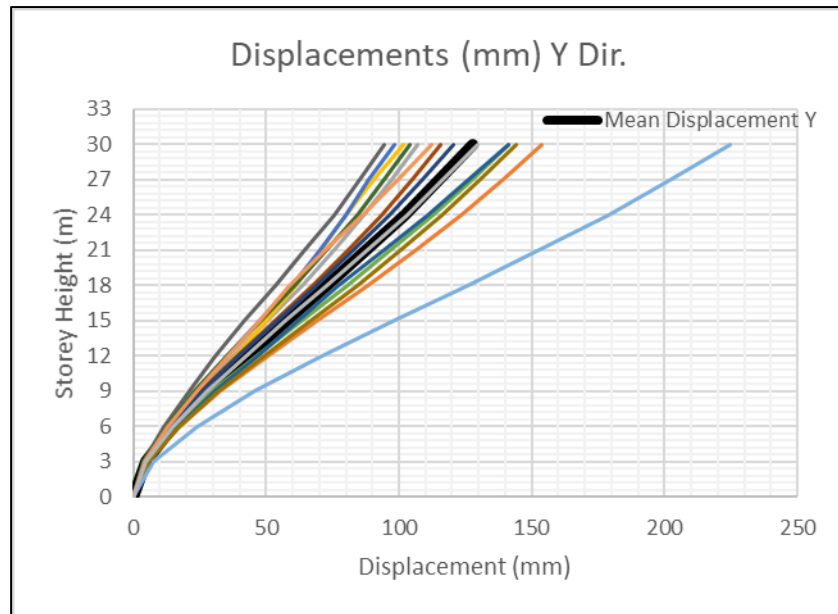


Figure 5.12: Story displacements y direction.

- Story Drifts at DD-2 Level

Obtained story drifts are presented in this section. Mean Maximum drifts for the building is obtained as 0.00516 for X direction and 0.005279 for Y direction. Mean maximum drifts per story is given in the following table and graphs.

Table 5.8: Average story drifts for fixed base building for x and y directions.

	Drift	
	X Dir.	Y Dir.
Story10	0.00296	0.004311
Story9	0.00351	0.004676
Story8	0.00408	0.005005
Story7	0.00458	0.005225
Story6	0.00496	0.005279
Story5	0.00516	0.005179
Story4	0.00512	0.004905
Story3	0.00472	0.004364
Story2	0.00376	0.003392
Story1	0.00177	0.001632
Base	0	0

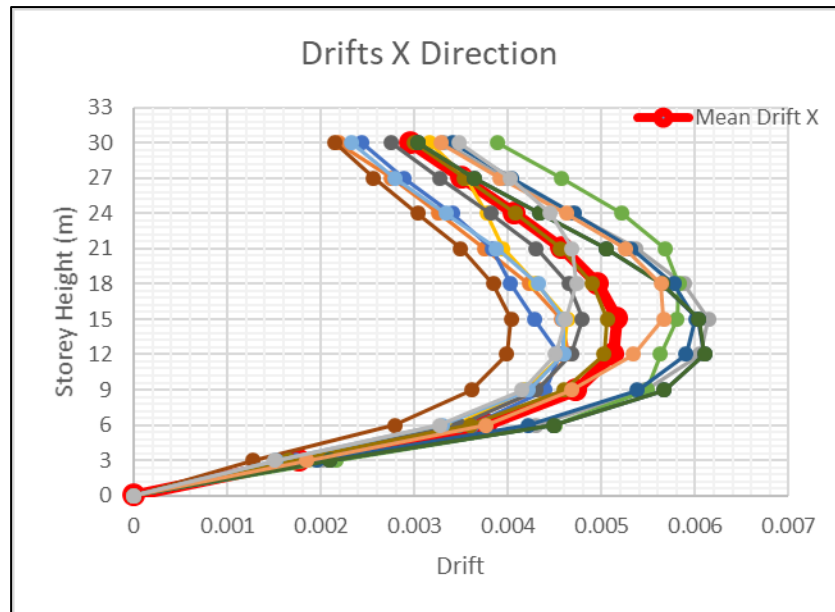


Figure 5.13: Story drifts x direction.

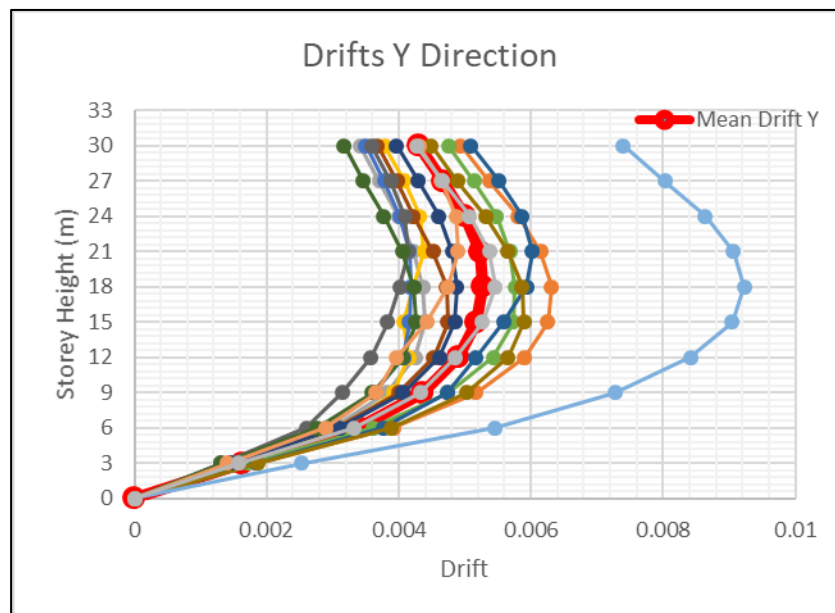


Figure 5.14: Story drifts y direction.

5.2.2. Seismic Isolation Design for 10 Story Building

An effort to seismically isolate the building described above is presented in this part. The general philosophy and the method of seismic isolation with the help of code requirements are done. The strategy followed is using lead rubber bearings under the columns and flat sliding bearings under the shear walls. To separate the sub and the superstructure and to make sure the isolation layer is working as it is intended

to a reinforced concrete slab layer/floor is modelled on the base level, having the same mass and loadings as a normal floor.

Furthermore, for the sake of simplicity, refinement and to get a better understanding of the behavior only one lead rubber bearing and one flat sliding bearing is used in the design. The material and geometrical properties are selected carefully and they are hand in hand with the practice.

The seismic weight of the structure is calculated as 123965 kN, making seismic mass 12636.6 t. Linear design of the isolation system has been made using DD-1 & DD-2 level design spectrums with both horizontal and vertical components. Design level earthquake demands and periods are as follows.

Earthquake demands on the single degree of freedom isolated structure is given in the following table.

Table 5.9: DD-1 & DD-2 earthquake demands on sdof isolated structure.

DD-1	T_M (sec.)	2.503
	D_M (m)	0.322
DD-2	T_D (sec.)	1.958
	D_D (m)	0.117

Modal periods and corresponding mass ratios are calculated and given in the tables below. Note that modal mass ratios for the first and second mode is almost 100 % of the seismic weight.

Table 5.10: Modal periods and corresponding mass ratios for 10 story base isolated building at DD-2 level earthquakes.

Mode	Period	UX	UY	UZ	RZ
#	(Sec.)	Unitless	Unitless	Unitless	Unitless
1	2.129	0	0.9814	0	0
2	2.129	0.9831	0	0	0
3	2.026	0	0	0	0.976
4	0.533	0	0.0186	0	0
5	0.507	0.0169	0	0	0
6	0.48	0	0	0	0.024
7	0.08	0	0	0.8252	0
8	0.072	0	0	0.0413	0
9	0.058	0	0	0.0052	0

Table 5.11: Modal periods and corresponding mass ratios for 10 story base isolated building at DD-1 level earthquakes.

Mode	Period	UX	UY	UZ	RZ
#	(Sec.)	Unitless	Unitless	Unitless	Unitless
1	2.598	0	0.992	0	0
2	2.598	0.9927	0	0	0
3	2.383	0	0	0	0.9879
4	0.557	0	0.008	0	0
5	0.53	0.0073	0	0	0
6	0.506	0	0	0	0.0121
7	0.08	0	0	0.8252	0
8	0.072	0	0	0.0413	0
9	0.058	0	0	0.0052	0

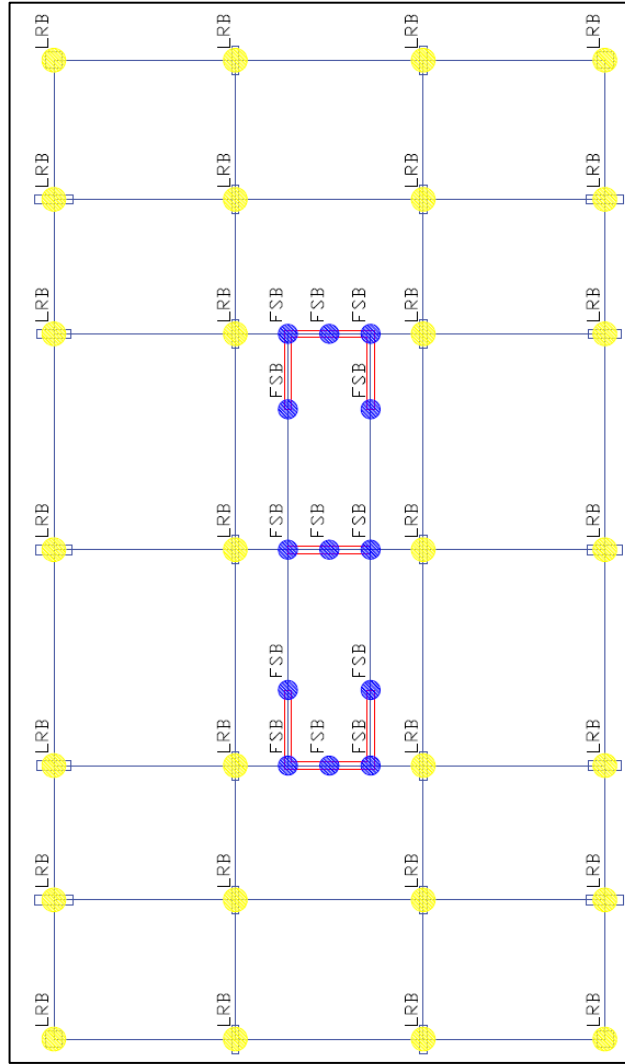


Figure 5.15: Isolation bearings location plan (lrb: lead rubber bearing, fsb: flat sliding bearing).

Number of bearings per bearing types are given in the following table.

Table 5.12: Isolator bearing types and quantities used in design.

Bearing Type	Nos #
Lead Rubber Bearing	28
Flat Sliding Bearing	13
Total	41

- Lead Rubber Bearing Design (LRB)

The design of lead rubber bearing is briefly summarized here, the stiffness and strength values represent the nominal bearing properties. Code requirement upper and lower bound properties for lead rubber bearing is derived from the nominal bearing properties.

The design of lead rubber bearing has been conducted according to the methods prescribed in draft Turkish Building Seismic Code'16, the design axial forces and chosen properties with nominal bearing properties are presented in the tables below.

Table 5.13: Design axial forces for lead rubber bearing.

P_{K1} (kN)	8520	Comb. 14.1 - $1.4G+1.6Q$
P_{K2} (kN)	10780	Comb.14.2 - $1.2G+Q+-E_d$
P_{K3} (kN)	8820	Comb. 14.3 - $0.9G+-E_d$

Table 5.14: Geometrical, material and stiffness properties of lead rubber bearing.

D_0 (mm)	1000	Total Diameter of Bearing
B (mm)	990	Dia. of Rubber Btwn. Shims
B_L (mm)	200	Diameter of Lead Plug
T_r (mm)	244	Total Elastomeric Height
S	34	First Shape Factor
G_v (MPa)	0.6	Shear Modulus of Rubber
T_{yp} (MPa)	1.0	Yield Stress of Lead
k_1 (kN/m)	23603	Nominal Initial Stiffness
k_2 (kN/m)	1816	Post Yield Stiffness
k_{eff} (kN/m)	2593	Effective Stiffness
F_q (kN)	250	Approx. Yield Strength
F (kN)	835	Ultimate Strength
d_y (m)	0.011	Yield Displacement
d_M (m)	0.322	Displacement Demand
ξ	18.46%	Damping Ratio
k_v (kN/m)	4081679	Axial Stiffness

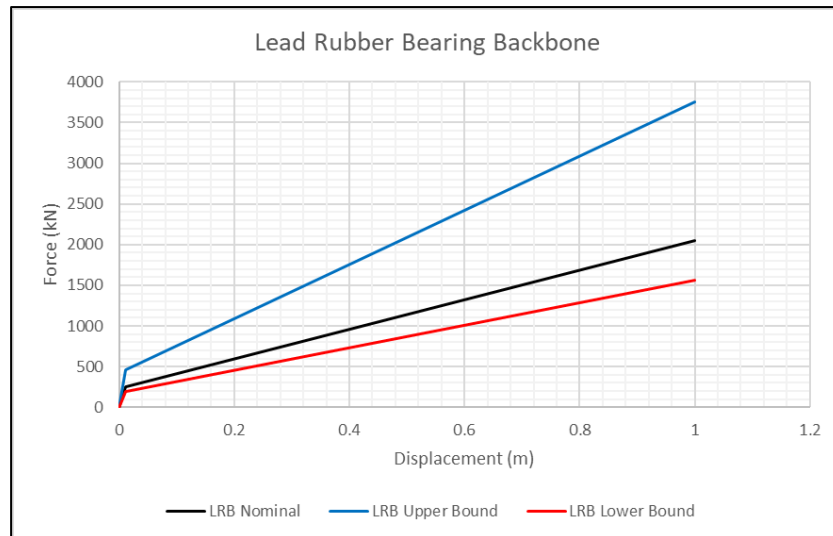


Figure 5.16: Lead rubber bearing backbone with corresponding upper & lower bound properties.

- Flat Sliding Bearing Design (FSB)

The flat sliding bearing is a friction pendulum bearing with an infinite radius, which means that two flat plates with a very low coefficient of friction. This bearing is made of PTFE (Polytetrafluoroethylene), but with being flat (infinite radius) the post yielding stiffness is “0”. The design of flat sliding bearing is summarized below.

Table 5.15: Design axial forces for flat sliding bearing.

P_1 (kN)	3780	Comb. 14.1 - $1.4G+1.6Q$
P_2 (kN)	17530	Comb. 14.2 - $1.2G+Q+-E_d$

Table 5.16: Geometrical, material and stiffness properties of flat sliding bearing.

D_0 (mm)	800	Diameter of Bearing
t_{plate} (mm)	2	Thickness
E (MPa)	400000	PTFE Modulus of Elasticity
k_1 (kN/m)	174374	Nominal Initial Stiffness
k_2 (kN/m)	0	Post Yield Stiffness
k_{eff} (kN/m)	542	Effective Stiffness
F_q (kN)	174	Approx. Yield Strength
F (kN)	174	Ultimate Strength
d_y (m)	0.001	Yield Displacement
d_M (m)	0.322	Displacement Demand
ξ	63.5%	Damping Ratio
k_v (kN/m)	1E+11	Axial Stiffness

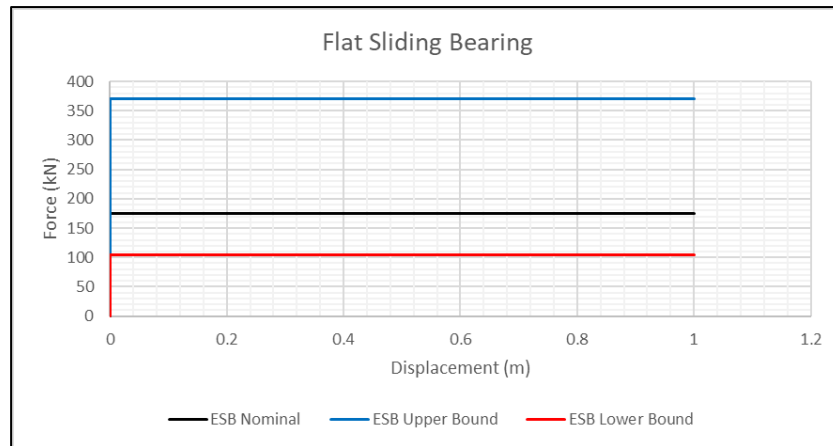


Figure 5.17: Flat sliding bearing backbone with corresponding upper & lower bound properties.

- Composite System Properties

Construction of composite system is done by taken into account of contribution of both lead rubber bearings and flat sliding bearings together. Behavior of the composite system consisting of 28 LRB's and 13 FSB's is presented below.

Table 5.17: Bearing summary for construction of composite system.

Bearing Summary			
Type	LRB	FSB	Total
#Nos	28	13	41
k_1	23603	174374	
k_2	1816	0	
k_{eff}	2593	542	
F_q	250	174	
F	835	174	
d_y	0.011	0.001	
d_M	0.322	0.322	
ξ	18.5%	63.5%	

Following composite system properties can be computed as;

Table 5.18: Composite system stiffness properties.

Composite System		
K_1	660886	kN/m
K_2	50837	kN/m
K_{eff}	79641.8	kN/m
d_y	0.015	m
F_Q	10048	kN
D_M	0.322	m
F_u	25645	kN
β	22.43%	
W	123965	kN
m	12637	tons
T_m	2.503	sec.

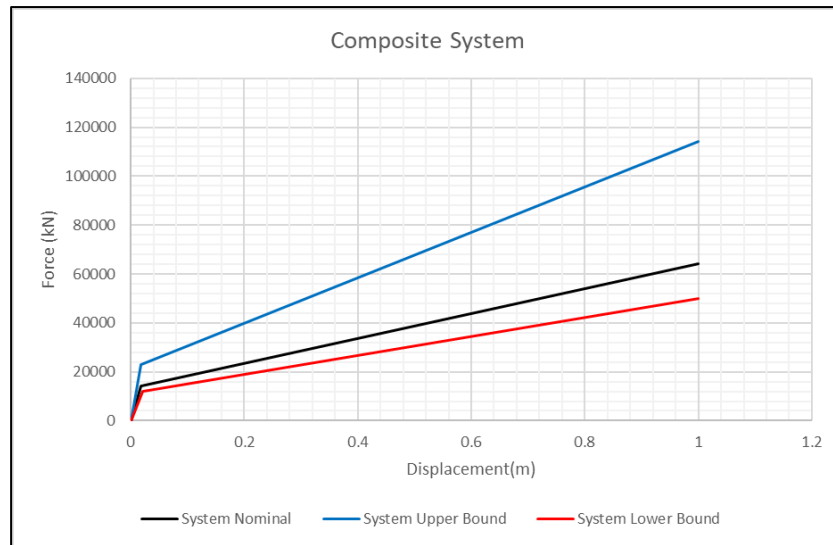


Figure 5.18: Composite system backbone with corresponding upper & lower bound properties.

5.2.3. Analysis and Results

The isolators are modelled as link elements and added to 3D finite element model of 10 story structure. Analysis of isolated structure have been conducted with scaled earthquake records. Total 7 pairs, and using each pair on both x & y directions, in total 14 time history analysis have been performed for every design level. Result tables and graphs are produced on the basis of average of maximums for every structural response that is taken into account. The criteria of assessment is for both sub and superstructure and summarized below;

- Base shear not exceeding 10% of the seismic weight at DD-2 level ground motions (Superstructure),
- Story drifts not exceeding $0.005h_i$ at DD-2 level ground motions (Superstructure),
- Displacement of isolation devices, so that the shear strain of the isolation device is less than 200% at DD-1 level ground motions (Substructure),
- Isolator compressive/tensile performance for DD-1 level earthquake (Substructure).

5.2.3.1. Superstructure Results

Superstructure results are given in this section, displaying shear forces, displacements and drifts on both perpendicular directions.

- Story Shear Forces at DD-2 Level

Obtained story shear forces are presented in this section. Mean Maximum base shears for the building is obtained as 32335 kN for X direction and 32221 kN for Y direction.

Table 5.19: Average story shear forces for base isolated building for x and y directions.

	Story Force (kN)	
	X Dir.	Y Dir.
Story10	3032	3018
Story9	6290	6262
Story8	9548	9506
Story7	12806	12749
Story6	16064	15993
Story5	19323	19237
Story4	22581	22480
Story3	25839	25724
Story2	29097	28967
Story1	32355	32211
Base	32355	32211

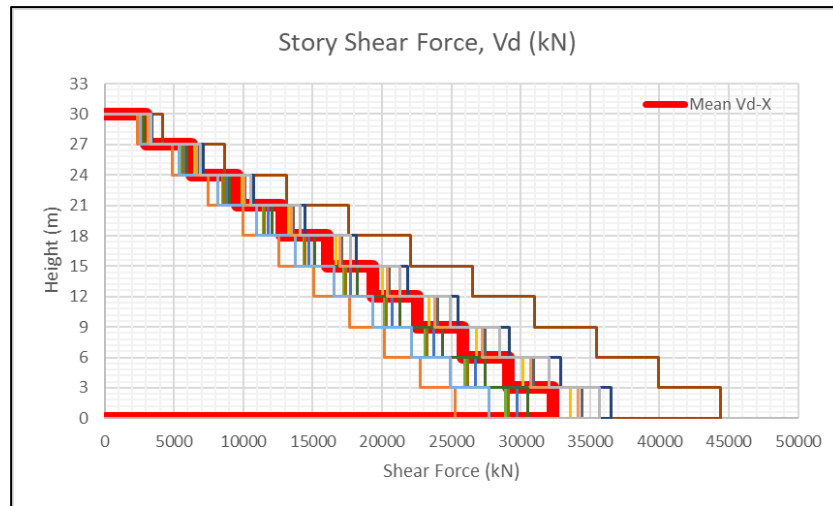


Figure 5.19: Story shear forces x direction.

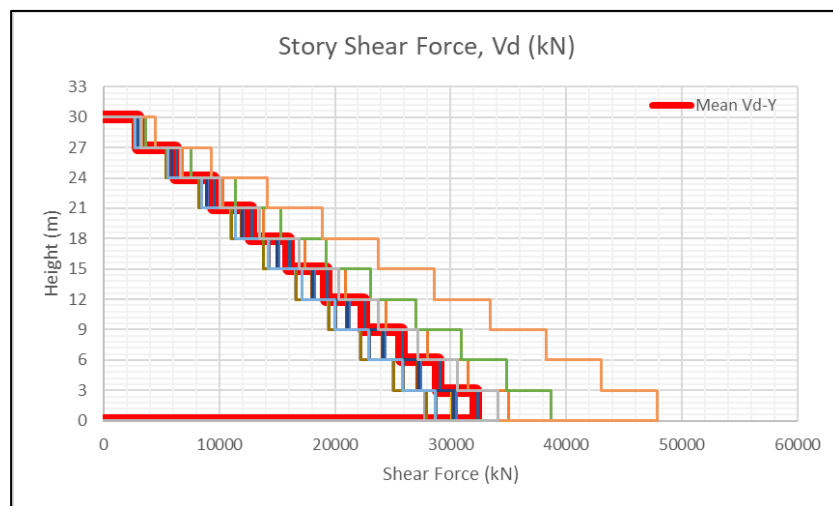


Figure 5.20: Story shear forces x direction.

- Story Displacements at DD-2 Level

Obtained story displacements are presented in this section. Mean Maximum displacements for the building is obtained as 62.3mm for X direction and 69.3mm for Y direction.

Table 5.20: Average story displacements for base isolated building for x and y directions.

	Displacement (mm)	
	X Dir.	Y Dir.
Story10	62.3	69.3
Story9	58.1	62.4
Story8	53.0	55.1
Story7	46.8	47.2
Story6	39.7	39.1
Story5	32.1	30.9
Story4	24.1	23.0
Story3	16.3	15.4
Story2	9.1	8.8
Story1	3.3	3.3
Base	0.0	0.0

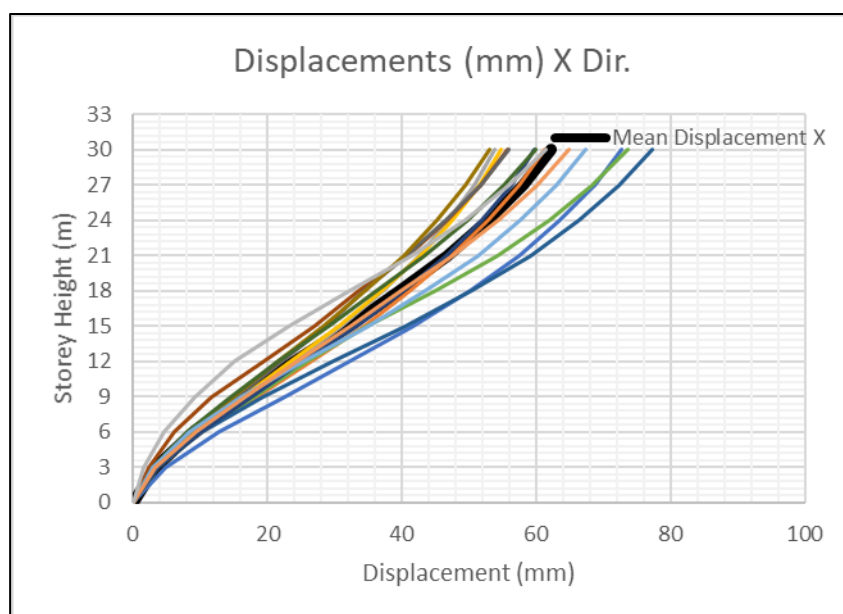


Figure 5.21: Story displacements x direction.

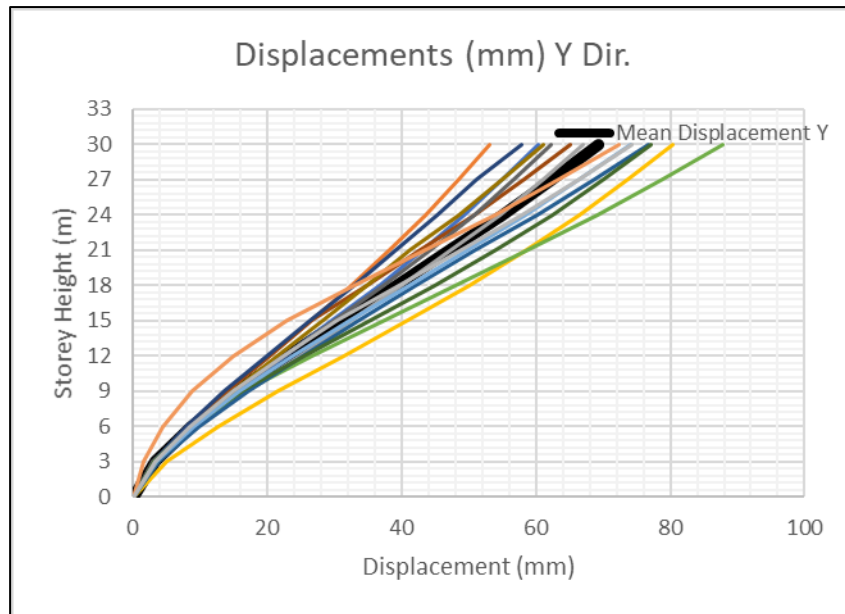


Figure 5.22: Story displacements y direction.

- Story Drifts at DD-2 Level

Obtained story drifts are presented in this section. Mean Maximum drifts for the building is obtained as 0.00407 for X direction and 0.003896 for Y direction.

Table 5.21: Average drifts for base isolated building for x and y directions.

	Drift	
	X Dir.	Y Dir.
Story10	0.00168	0.002691
Story9	0.00203	0.002928
Story8	0.00248	0.00321
Story7	0.00298	0.003496
Story6	0.00345	0.00374
Story5	0.00385	0.003893
Story4	0.00407	0.003896
Story3	0.00399	0.003673
Story2	0.00342	0.003127
Story1	0.00201	0.002026
Base	0	0

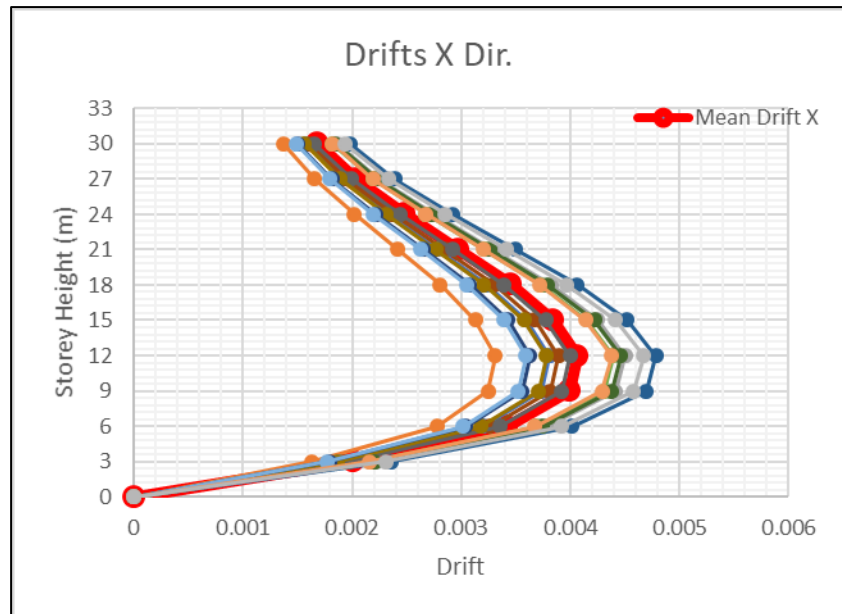


Figure 5.23: Story drifts x direction.

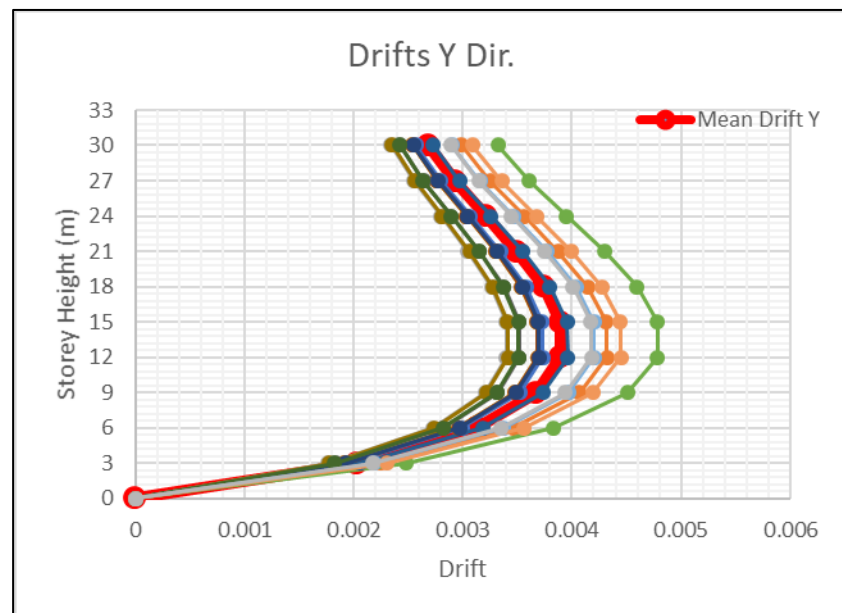


Figure 5.24: Story drifts y direction.

5.2.3.2. Substructure Results

Substructure results are given in this section, displaying mean and maximum displacements at isolation level and maximum shear and axial forces, for isolators.

- Maximum Displacements at DD-1 Level

This section yields maximum displacements and mean of the maximum displacement. Maximum displacement is obtained as 777 mm for 1148-A record, and shown in the following graph.

Table 5.22: Maximum displacements for base isolated building for x and y directions.

Record		Maximum SRSS Disp. (mm)
731	A	297
731	B	289
1148	A	777
1148	B	754
838	A	253
838	B	241
1163	A	296
1163	B	307
827	A	490
827	B	503
776	A	294
776	B	301
15	A	222
15	B	224
Average of Maximums		375

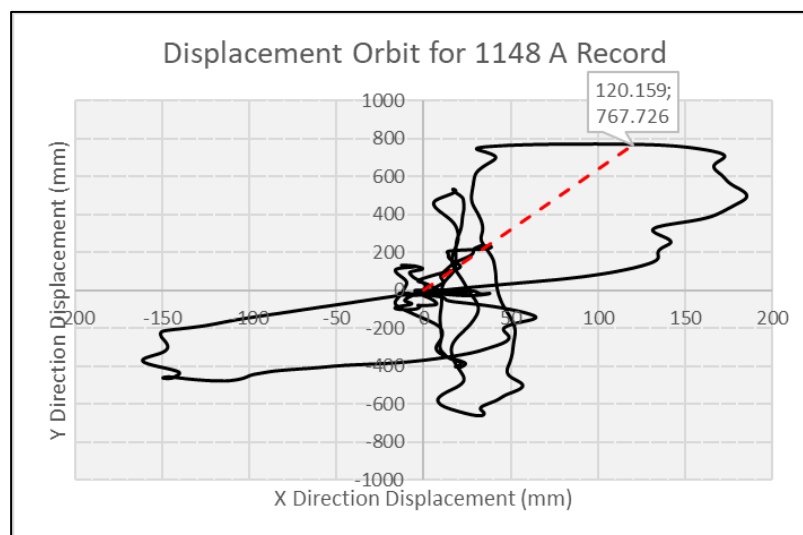


Figure 5.25: Displacement orbit for 1148-A record.

- Maximum Bearing Axial Forces at DD-1 Level

In this section, maximum axial loads (compression, tension) for isolator bearings are presented. Axial loads are very crucial especially for lead rubber bearings. Mean of the maximum compressive axial load for lead rubber bearing is obtained as 9469.6 kN while 642.9 kN of tensional force is obtained.

Table 5.23: Maximum lrb compressive forces.

Lead Rubber Bearing Axial Forces - Compression		
Record		Maximum Axial Force (kN)
731	A	-9517.4
	B	-8752.0
1148	A	-13716.7
	B	-9068.8
838	A	-8780.3
	B	-8400.8
1163	A	-8364.3
	B	-9017.5
827	A	-11728.4
	B	-9959.7
776	A	-7796.9
	B	-10541.7
15	A	-8555.5
	B	-8374.7
Average of Max.		-9469.6

Table 5.24: Maximum lrb tensile forces.

Lead Rubber Bearing Axial Forces - Tension		
Record		Maximum Axial Force (kN)
731	A	-
	B	-
1148	A	642.9
	B	-
838	A	-
	B	-
1163	A	-
	B	-
827	A	-
	B	-
776	A	-
	B	-
15	A	-
	B	-
Average of Max.		642.9

Mean of the maximum flat sliding bearing force is obtained as 15930.9 kN.

Table 5.25: Maximum fsb compressive forces.

Flat Sliding Bearing Axial Forces		
Record		Maximum Axial Force (kN)
731	A	-17636.9
	B	-14367.4
1148	A	-23636.0
	B	-17429.3
838	A	-14802.3
	B	-14054.2
1163	A	-13916.7
	B	-15921.6
827	A	-16940.4
	B	-15754.5
776	A	-13120.0
	B	-17598.5
15	A	-14739.2
	B	-13116.0
Average of Max.		-15930.9

Maximum axial force vs. axial deformation hysteresis for a lead rubber bearing is given below for the 1148-A record.

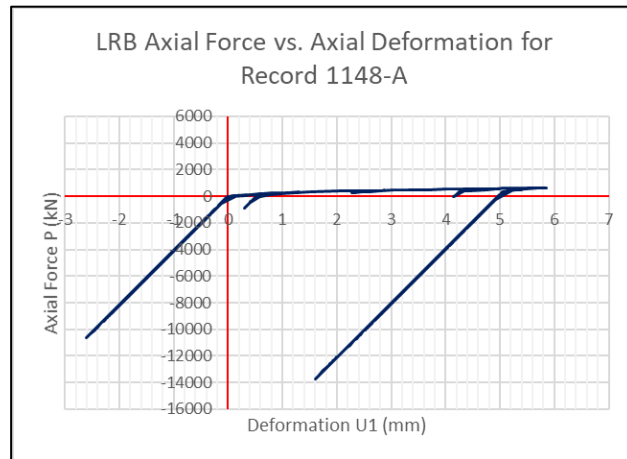


Figure 5.26: Lrb axial force vs. axial deformation hysteresis graph for 1148-A record.

Nonlinear shear behavior vs. lateral displacement for the lead rubber bearing is given in the following two graphs for both orthogonal directions.

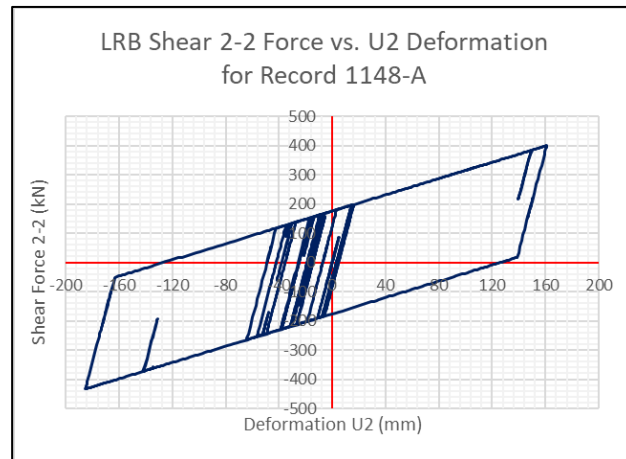


Figure 5.27: Lrb shear 2-2 force vs. u2 deformation hysteresis graph for 1148-A record.

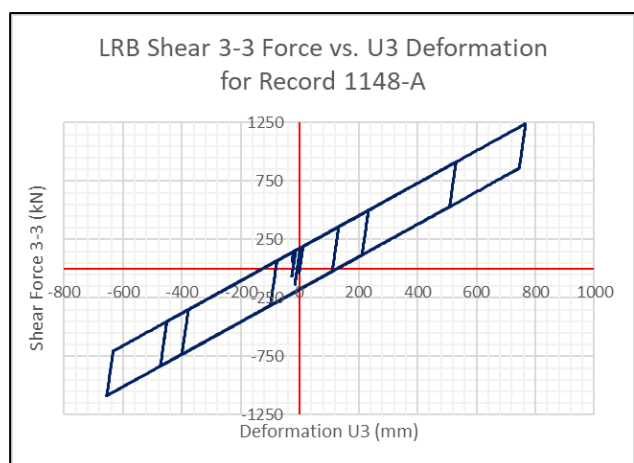


Figure 5.28: Lrb shear 3-3 force vs. u3 deformation hysteresis graph for 1148-A record.

Flat sliding bearing axial force vs. axial deformation results are given in the below figure. Note that flat sliding bearing has no tensional restraint thus there's no tensional force occurred in the bearing, also axial deformations are quite limited due to high axial stiffness of the flat sliding bearing.

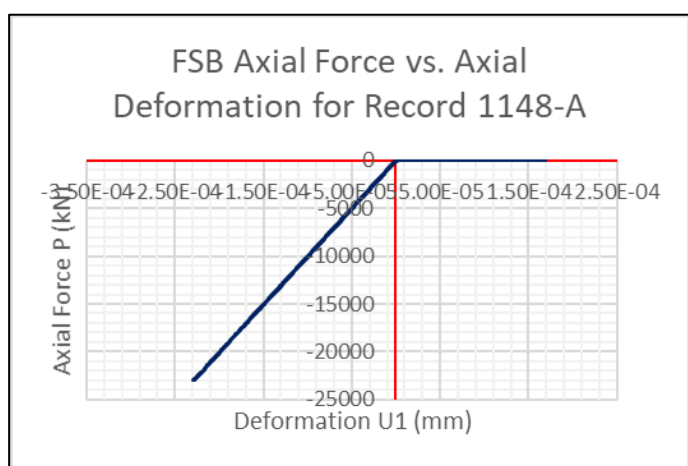


Figure 5.29: Fsb axial force vs. u1 deformation hysteresis graph for 1148-A record.

Lateral behavior results of the flat sliding bearing is given in the following two graphs. Note the difference on the lateral sliding force which is dependent of axial load carried, also it can easily be observed that the result of the rocking behavior on these bearings.

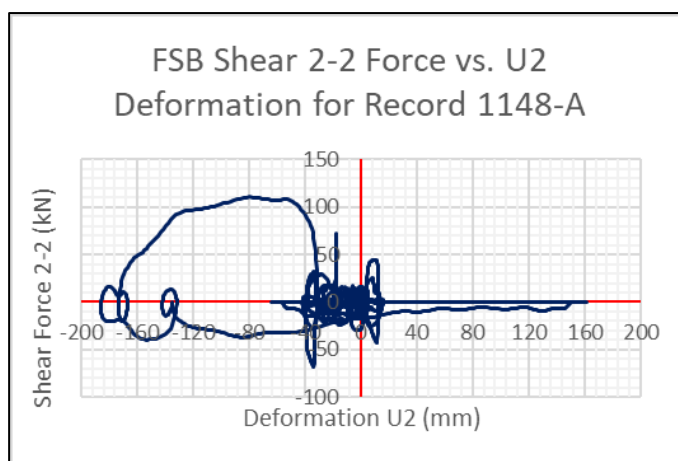


Figure 5.30: Fsb shear 2-2 force vs. u2 deformation hysteresis graph for 1148-A record.

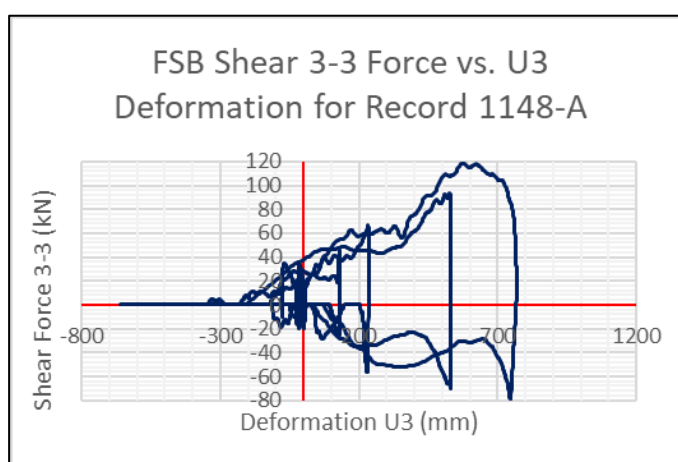


Figure 5.31: Fsb shear 3-3 force vs. u3 deformation hysteresis graph for 1148-A record.

Buckling controls of the lead rubber bearing can be done by calculating critical buckling load for each shear strain level. Below table shows critical buckling load at predefined shear strains and graph yields the axial force vs. shear strain history for the most critical lead rubber bearing with critical buckling load lines.

Table 5.26: Axial force vs. shear strain values corresponding to factor of safety=1.33 and factor of safety=1.00.

γ (%)	$P_{\max}$ (kN)	
	FoS=1.33	FoS=1.00
0	39015	51890
50	31369	41721
100	23909	31799
200	10394	13823

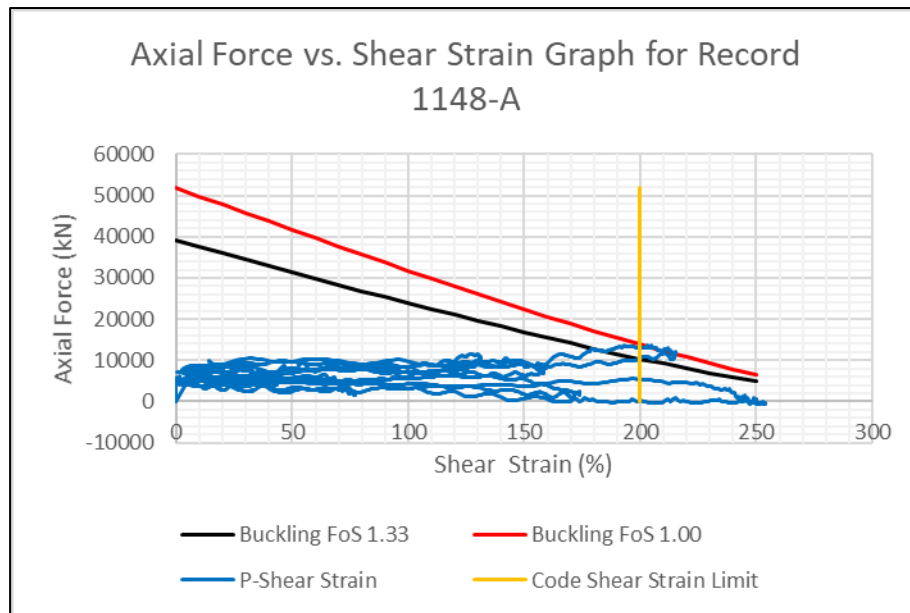


Figure 5.32: Lrb axial vs shear strain results for 1148-A record.

5.2.3.3. Comparison of Isolated and Fixed Base Structure

- Base Shear

The elastic base shear comparison for fixed and isolated structures is presented with following two graphs. It can be seen that for DD-2 level earthquakes the isolated structure was exposed to larger amounts of base shear force with respect to its counterpart and is failed to comply with the target base shear force which is 10% of the seismic weight (~12400 kN), however the base isolation is reduced the upper story shears which can be explained by mitigation of higher mode effects.

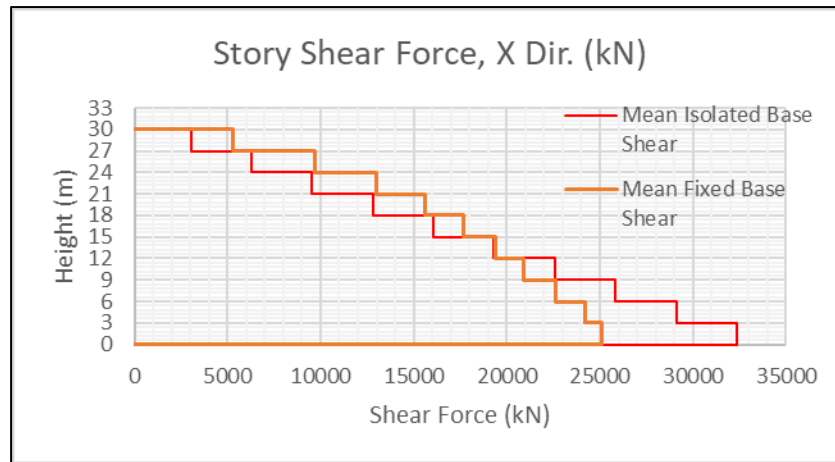


Figure 5.33: Mean isolated vs. fixed base story shear forces x direction.

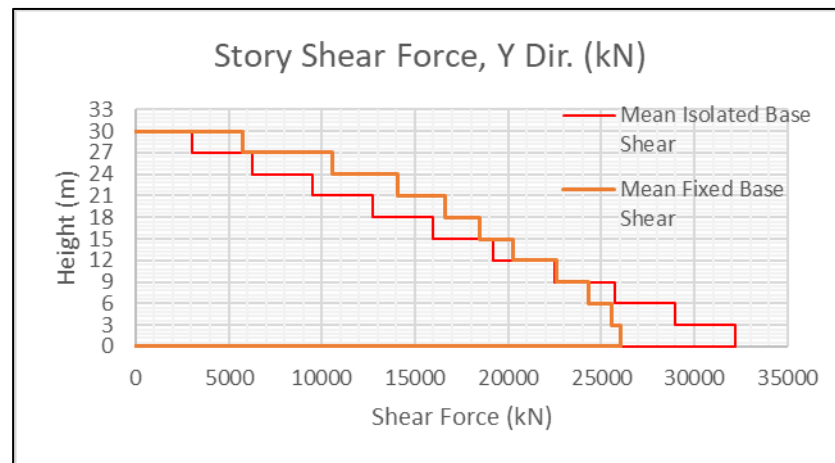


Figure 5.34: Mean isolated vs. fixed base story shear forces y direction.

- Displacement

Base isolated building have almost halved the displacement demand of its fixed base counterpart by reducing the displacement from ~120 mm to ~65 mm. Note the shear behavior of the building throughout the height of the building.

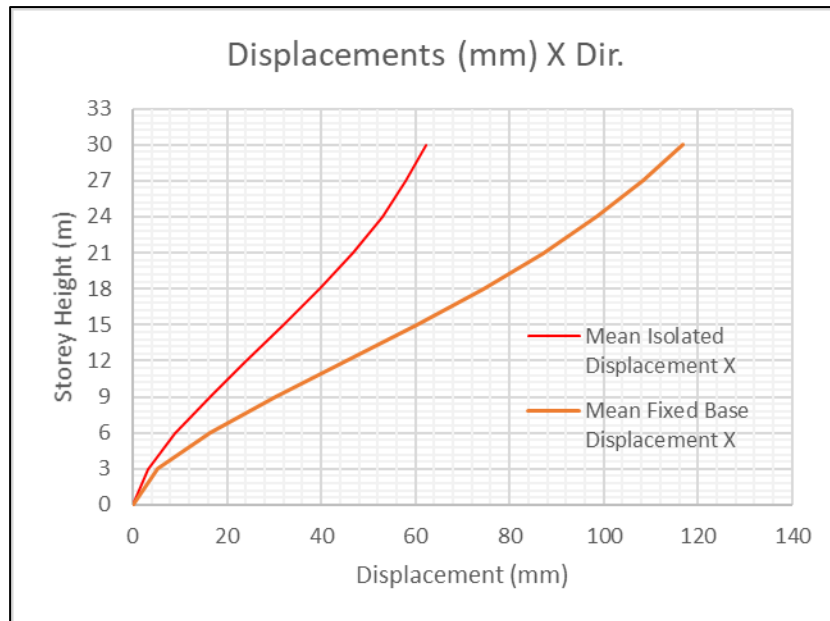


Figure 5.35: Mean isolated vs. fixed base displacements x direction.

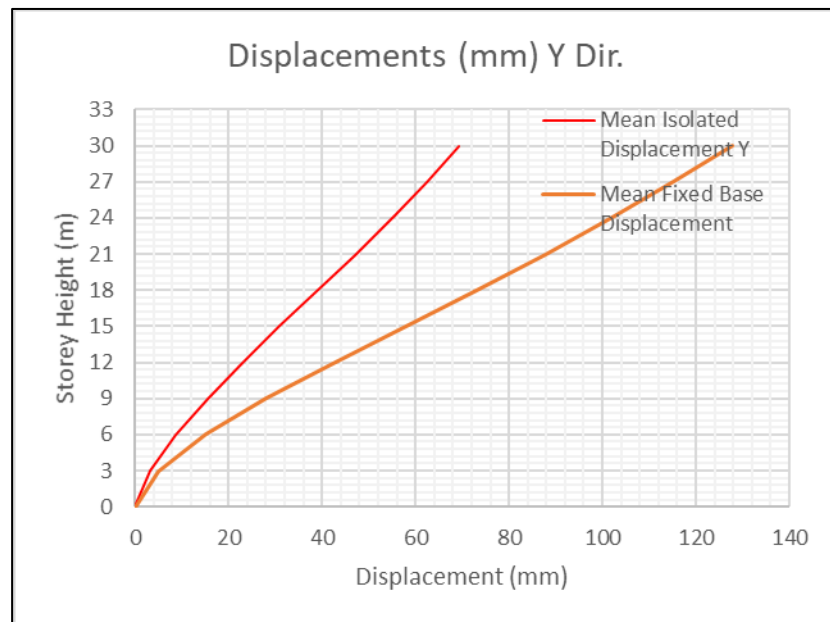


Figure 5.36: Mean isolated vs. fixed base displacements y direction.

- Drift

As well as displacements, drifts are also almost halved. Additionally the structure is complied with the code limitation which is $0.005h_i$. The drifts of first 2-3 stories are almost the same but it is obvious that seismic isolation produced better results for higher stories. This can be explained by the difference between the story shear patterns of fixed base and base isolated building.

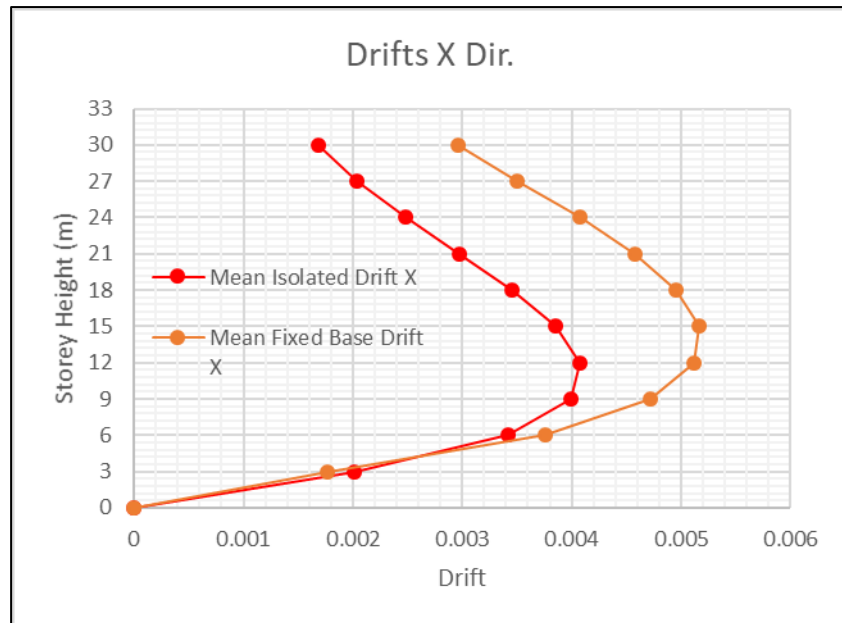


Figure 5.37: Mean isolated vs. fixed base drifts x direction.

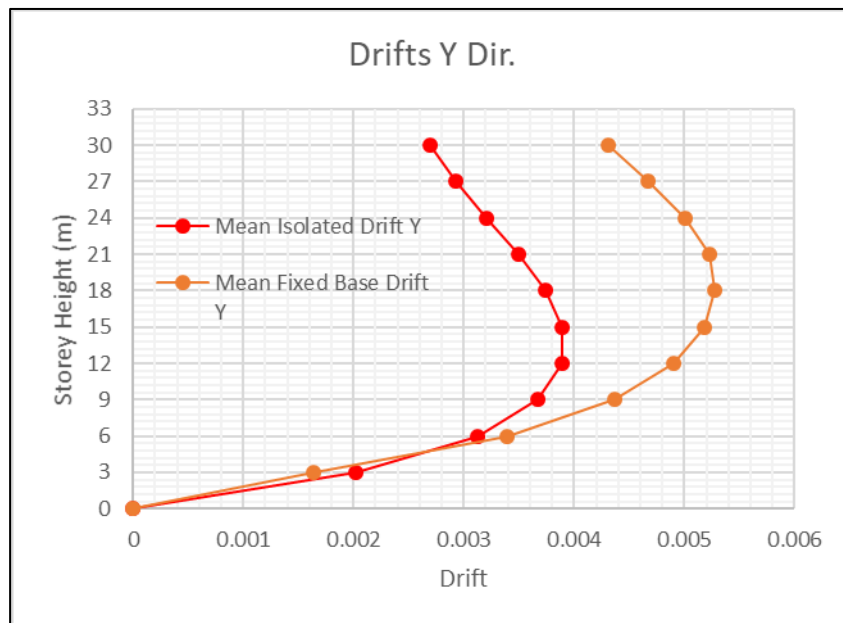


Figure 5.38: Mean isolated vs. fixed base drift y direction.

- Substructure

The average of maximum displacements at isolation level obtained from the nonlinear time history analyses is 0.375 m which is larger than the linear analysis result 0.322m. The average of maximum axial loads for lead rubber bearing isolators have obtained to be 15931 kN which is larger than the linear design force 10780 kN,

obtained from DD-1 level spectral analysis. The reason for this can be the influence of rocking behavior of shear walls to its surrounding columns.

5.3. Design & Analysis of 15 Story Building

In this section, first material and geometrical properties of 15 story building have been introduced. Secondly the fixed base model is analyzed for scaled earthquake records. Thirdly the seismic isolation design of 15 story building have been conducted and nonlinear time history analyses have been performed, and lastly results obtained from both fixed base and base isolated buildings have been compared.

5.3.1. Properties of the Building

The loading values and material properties of 15 story building is the same properties used for 10 story building, but geometrical some geometrical properties have been changed. The building height is inherently increased to 45m and shear wall dimensions are enlarged which can be seen in the figure below.

The building is first modelled as fixed base 3D, and linear response history analyses have been conducted.

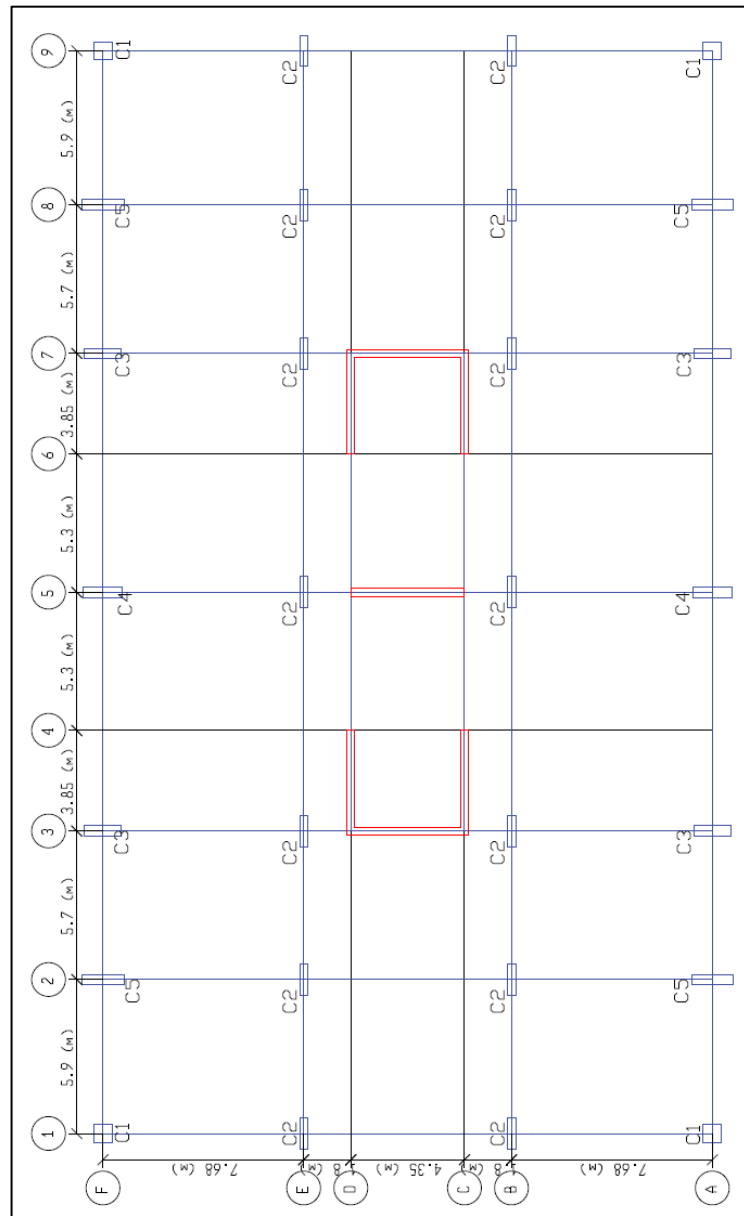


Figure 5.39: Plan view of the 15 story building.

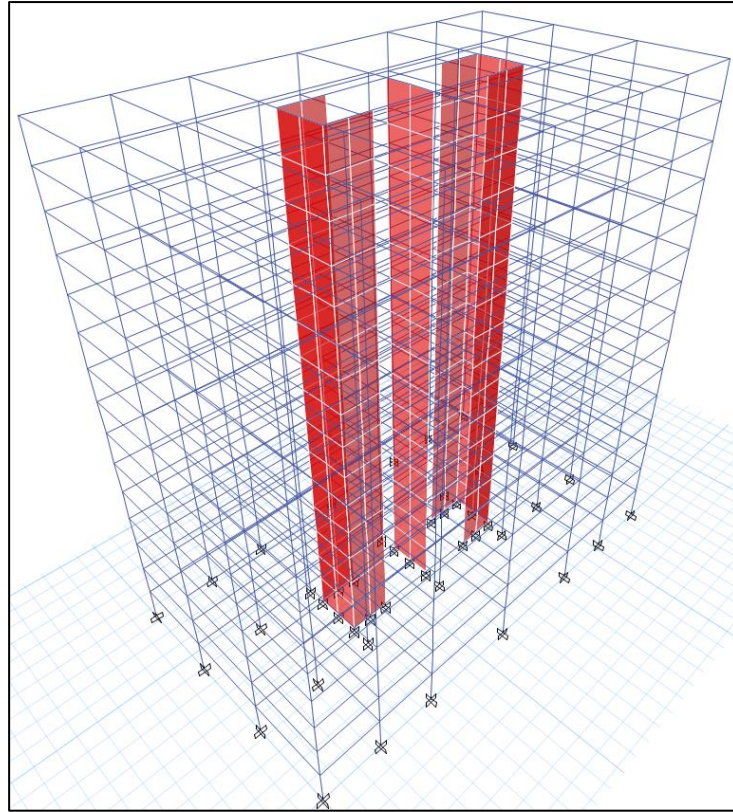


Figure 5.40: 3d finite element modeling of the fixed base 15 story building.

Table 5.27: Modal periods and corresponding mass ratios for 15 story fixed base building.

Mode	Period	UX	UY	RZ
#	(Sec.)	Unitless	Unitless	Unitless
1	1.768	0.000	0.000	0.738
2	1.727	0.739	0.000	0.000
3	1.722	0.000	0.696	0.000
4	0.516	0.000	0.000	0.133
5	0.504	0.120	0.000	0.000
6	0.444	0.000	0.164	0.000
7	0.258	0.000	0.000	0.053
8	0.247	0.052	0.000	0.000
9	0.204	0.000	0.058	0.000
10	0.162	0.000	0.000	0.027
11	0.147	0.030	0.000	0.000
12	0.124	0.000	0.029	0.000

As it can be seen from the table above, the fixed base building has almost the same natural fundamental period values in both X and Y directions, and the modal participating masses are around 74 percent of the total mass.

To compare the results with seismically isolated structure, a linear time history analysis, using scaled earthquake records to DD-2 level, has been conducted. As a result story shear forces, drifts and displacements have been obtained with the average of the maximum values. The results are given by table and figure below.

- Story Shear Forces at DD-2 Level

Obtained story shear forces are presented in this section. Mean Maximum base shears for the building is obtained as 38652 kN for X direction and 39043 kN for Y direction.

Table 5.28: Average story shear forces for fixed base building for x and y directions.

	Story Force (kN)	
	X Dir.	Y Dir.
Story15	6044.49	6269.4
Story14	11173.5	11500.9
Story13	15016	15303.1
Story12	18006	18094.4
Story11	20579.2	20532.3
Story10	22874.1	22703.8
Story9	24793	24729.9
Story8	26534	26645.8
Story7	28105.4	28271.3
Story6	29955.8	30171.8
Story5	32102.5	32403.5
Story4	34045.1	34381
Story3	36100.9	36557.9
Story2	37681.6	38164.5
Story1	38652.6	39043
Base	0	0

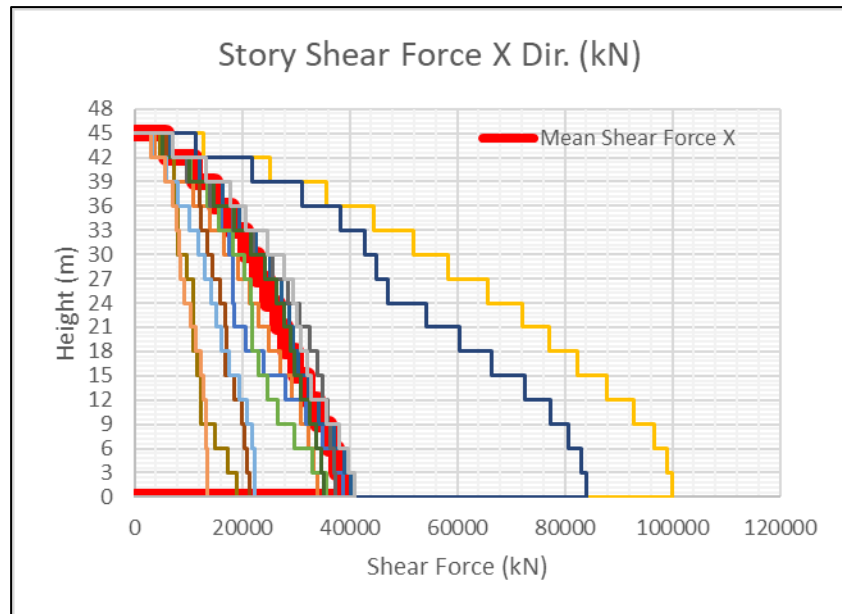


Figure 5.41: Story shear forces x direction.

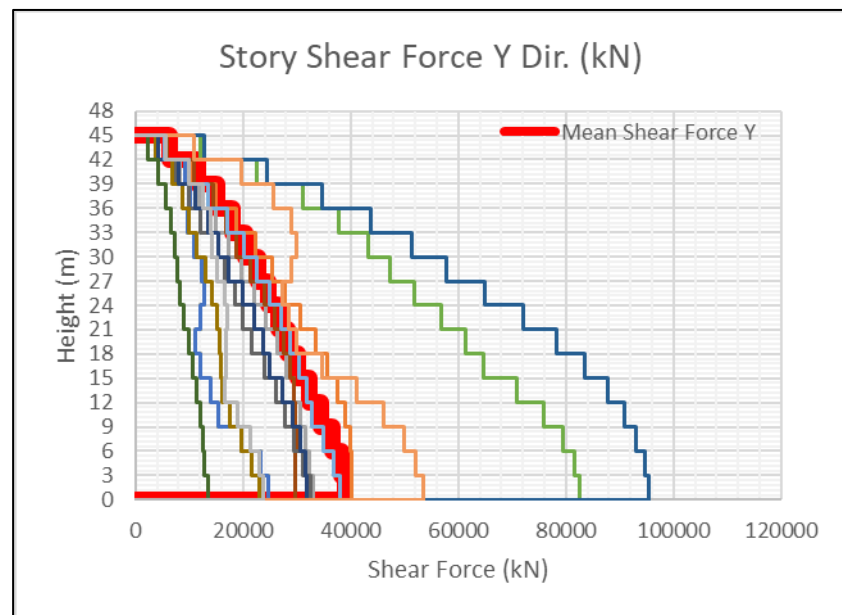


Figure 5.42: Story shear forces y direction.

- Story Displacements at DD-2 Level

Obtained story displacements are presented in this section. Mean Maximum displacements for the building is obtained as 249.7 mm for X direction and 272.2 mm for Y direction.

Table 5.29: Average story displacements for fixed base building for x and y directions.

	Displacement (mm)	
	X Dir.	Y Dir.
Story15	249.7	272.2
Story14	240.0	254.7
Story13	229.0	236.5
Story12	216.4	217.5
Story11	201.8	197.6
Story10	185.4	176.8
Story9	167.5	155.4
Story8	148.3	133.7
Story7	127.6	111.8
Story6	105.9	90.2
Story5	83.6	69.4
Story4	61.2	49.8
Story3	39.9	32.0
Story2	21.0	16.9
Story1	6.6	5.5
Base	0.0	0.0

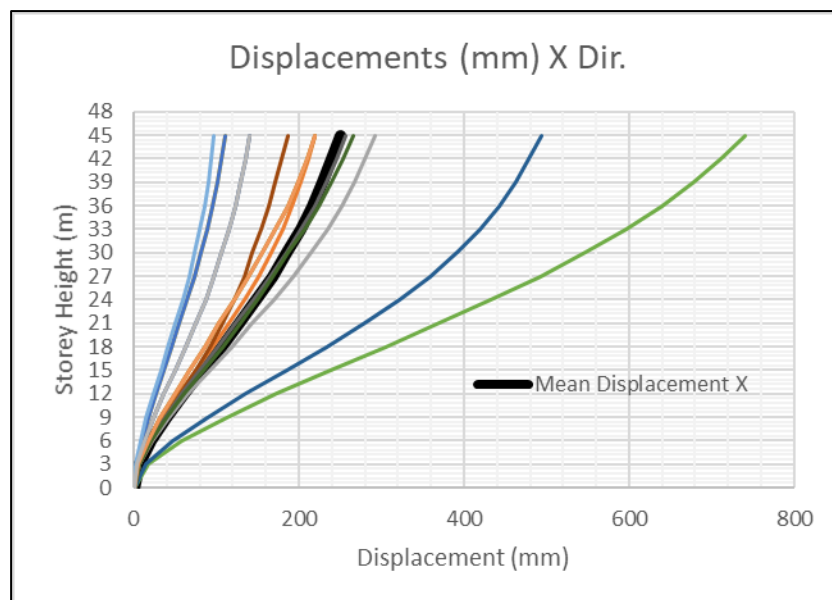


Figure 5.43: Story displacements x direction.

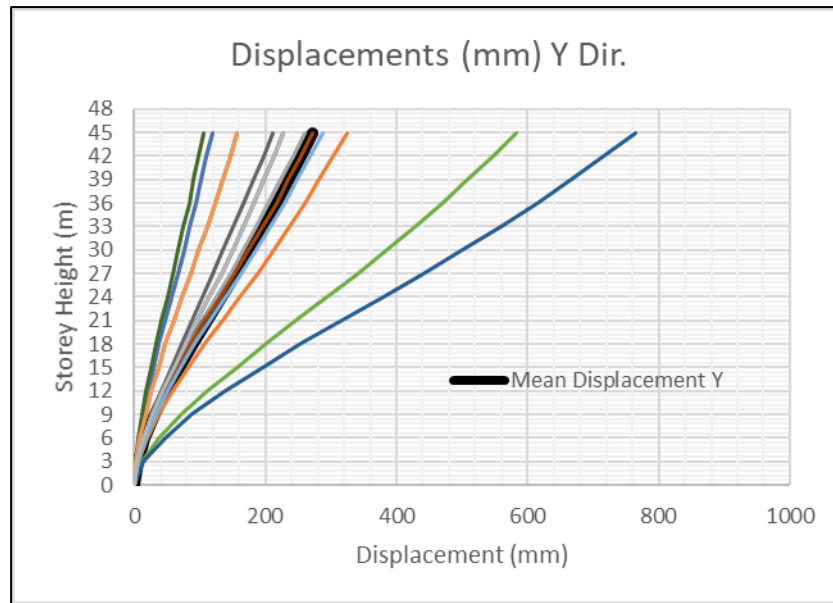


Figure 5.44: Story displacements y direction.

- Story Drifts at DD-2 Level

Obtained story drifts are presented in this section. Mean Maximum drifts for the building is obtained as 0.00775 for X direction and 0.007641 for Y direction. Mean maximum drifts per story is given in the following table and graphs.

Table 5.30: Average story drifts for fixed base building for x and y directions.

	Drift	
	X Dir.	Y Dir.
Story15	0.00388	0.006291
Story14	0.00438	0.006601
Story13	0.00497	0.006893
Story12	0.00559	0.007139
Story11	0.00618	0.007372
Story10	0.00669	0.007556
Story9	0.00708	0.007641
Story8	0.00741	0.007614
Story7	0.00767	0.00749
Story6	0.00775	0.007209
Story5	0.00765	0.00676
Story4	0.00725	0.006111
Story3	0.0064	0.005208
Story2	0.00486	0.00392
Story1	0.00224	0.001887

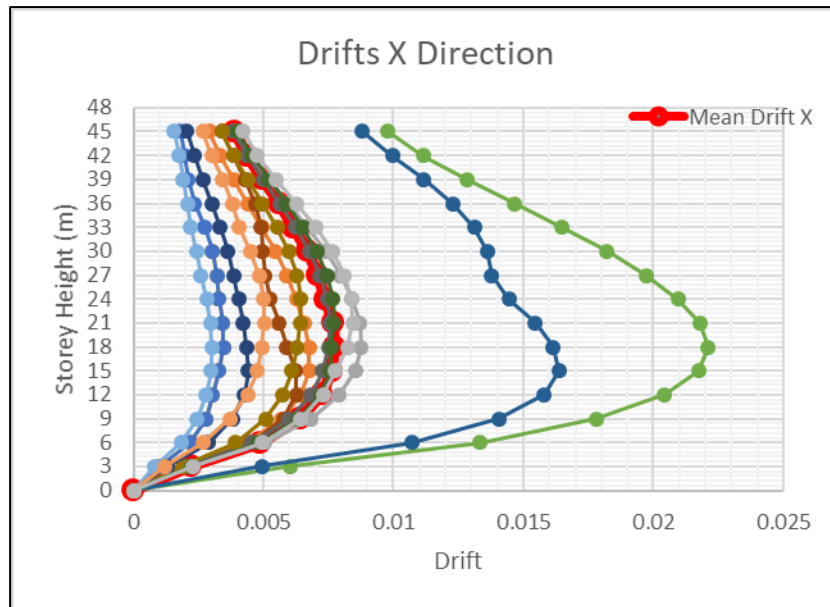


Figure 5.45: Story drifts x direction.

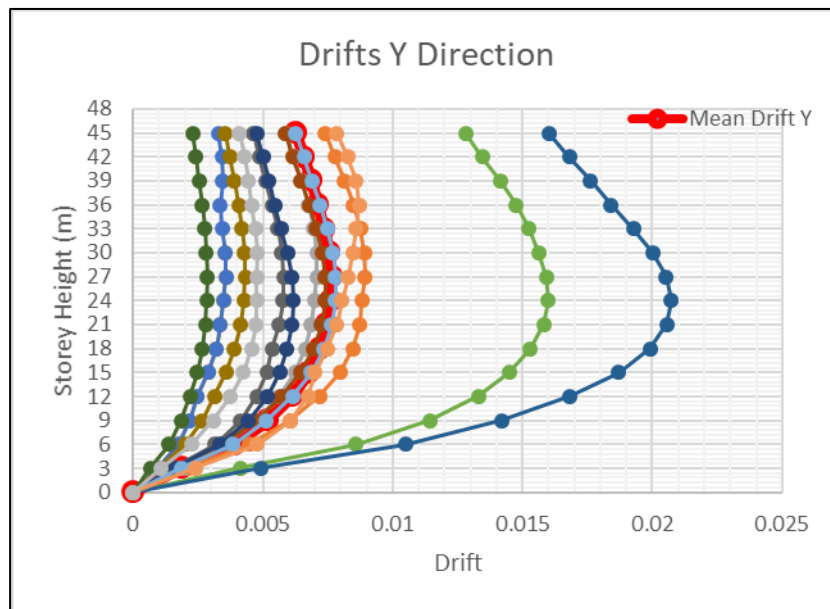


Figure 5.46: Story drifts y direction.

5.3.2. Seismic Isolation Design for 15 Story Building

Seismic isolation design for 15 story building is presented in this part. The general philosophy and the method of seismic isolation with the help of code requirements are done. The strategy followed is using lead rubber bearings under the columns and flat sliding bearings under the shear walls. To separate the sub and the superstructure and to make sure the isolation layer is working as it is intended to a

reinforced concrete slab layer/floor is modelled on the base level, having the same mass and loadings as a normal floor.

Furthermore, for the sake of simplicity, refinement and to get a better understanding of the behavior only one lead rubber bearing and one flat sliding bearing is used in the design. The material and geometrical properties are selected carefully and they are hand in hand with the practice.

The seismic weight of the structure is calculated as 180000 kN, making seismic mass 18349 t. Linear design of the isolation system has been made using DD-1 & DD-2 level design spectrums with both horizontal and vertical components. Design level earthquake demands and periods are as follows.

Earthquake demands on the single degree of freedom isolated structure is given in the following table.

Table 5.31: DD-1 & DD-2 earthquake demands on sdof isolated structure.

DD-1	T _M (sec.)	2.917
	D _M (m)	0.388
DD-2	T _D (sec.)	2.314
	D _D (m)	0.141

Table 5.32: Modal periods and corresponding mass ratios for 15 story base isolated building at DD-2 level earthquakes.

Mode	Period	UX	UY	UZ	RZ
#	(Sec.)	Unitless	Unitless	Unitless	Unitless
1	2.70	0	0.96	0	0
2	2.70	0.97	0	0	0
3	2.58	0	0	0	0.96
4	0.77	0	0.04	0	0
5	0.70	0.03	0	0	0
6	0.67	0	0	0	0.04
7	0.11	0	0	0.80	0
8	0.09	0	0	0.06	0
9	0.07	0	0	0	0

Table 5.33: Modal periods and corresponding mass ratios for 15 story base isolated building at DD-1 level earthquakes.

Mode	Period	UX	UY	UZ	RZ
#	(Sec.)	Unitless	Unitless	Unitless	Unitless
1	3.193	0	0.981	0	0
2	3.19	0.9843	0	0	0
3	2.946	0	0	0	0.9754
4	0.815	0	0.019	0	0
5	0.744	0.0157	0	0	5.08E-07
6	0.715	0	0	0	0.0246
7	0.113	0	0	0.8051	0
8	0.093	0	0	0.0538	0
9	0.072	0	0	0.0024	0

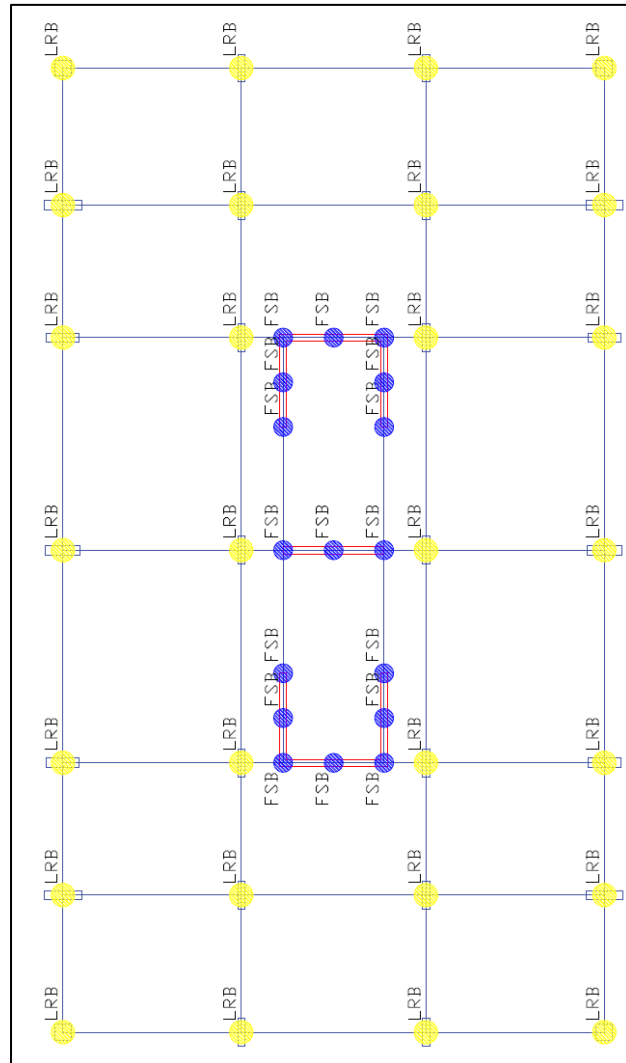


Figure 5.47: Isolation bearings location plan (lrb: lead rubber bearing, fsb: flat sliding bearing).

Number of bearings per bearing types are given in the following table.

Table 5.34: Isolator bearing types and quantities used in design.

Bearing Type	Nos #
Lead Rubber Bearing	28
Flat Sliding Bearing	14
Total	45

- Lead Rubber Bearing Design (LRB)

The design of lead rubber bearing is briefly summarized here, the stiffness and strength values represent the nominal bearing properties. Code requirement upper and lower bound properties for lead rubber bearing is derived from the nominal bearing properties.

The design of lead rubber bearing has been conducted according to the methods prescribed in draft Turkish Building Seismic Code'16, the design axial forces and chosen properties with nominal bearing properties are presented in the tables below.

Table 5.35: Design axial forces for lead rubber bearing.

P_{K1} (kN)	12100	Comb. 14.1 - $1.4G+1.6Q$
P_{K2} (kN)	15800	Comb.14.2 - $1.2G+Q+-E_d$
P_{K3} (kN)	13400	Comb. 14.3 - $0.9G+-E_d$

Table 5.36: Geometrical, material and stiffness properties of lead rubber bearing.

D_0 (mm)	1100	Total Diameter of Bearing
B (mm)	1090	Dia. of Rubber Btwn. Shims
B_L (mm)	215	Diameter of Lead Plug
T_r (mm)	265	Total Elastomeric Height
S	37	First Shape Factor
G_v (MPa)	0.6	Shear Modulus of Rubber
T_{yp} (MPa)	1.0	Yield Stress of Lead
k_1 (kN/m)	26397	Nominal Initial Stiffness
k_2 (kN/m)	2031	Post Yield Stiffness
k_{eff} (kN/m)	2776	Effective Stiffness
F_q (kN)	289	Approx. Yield Strength
F (kN)	1077	Ultimate Strength
d_y (m)	0.011	Yield Displacement
d_M (m)	0.388	Displacement Demand
ξ	16.61%	Damping Ratio
k_v (kN/m)	4846098	Axial Stiffness

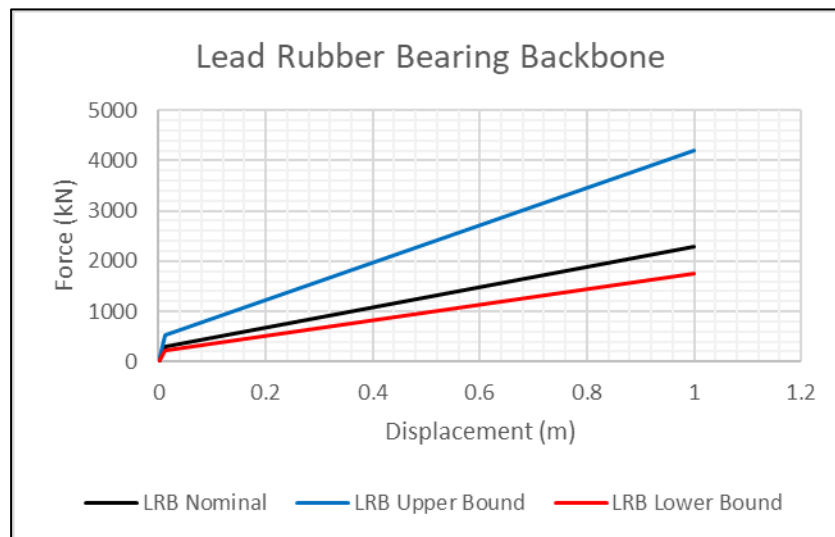


Figure 5.48: Lead rubber bearing backbone with corresponding upper & lower bound properties.

- Flat Sliding Bearing Design (FSB)

The flat sliding bearing is a friction pendulum bearing with an infinite radius, which means that two flat plates with a very low coefficient of friction. This bearing

is made of PTFE (Polytetrafluoroethylene), but with being flat (infinite radius) the post yielding stiffness is “0”. The design of flat sliding bearing is summarized below.

Table 5.37: Design axial forces for flat sliding bearing.

P_1 (kN)	5100	Comb. 14.1 - 1.4G+1.6Q
P_2 (kN)	17000	Comb. 14.2 - 1.2G+Q+-E _d

Table 5.38: Design axial forces for flat sliding bearing.

D_0 (mm)	800	Diameter of Bearing
t_{plate} (mm)	2	Thickness
E (MPa)	400000	PTFE Modulus of Elasticity
k_1 (kN/m)	169102	Nominal Initial Stiffness
k_2 (kN/m)	0	Post Yield Stiffness
k_{eff} (kN/m)	436	Effective Stiffness
F_q (kN)	169	Approx. Yield Strength
F (kN)	169	Ultimate Strength
d_y (m)	0.001	Yield Displacement
d_M (m)	0.388	Displacement Demand
ξ	63.5%	Damping Ratio
k_v (kN/m)	1E+11	Axial Stiffness

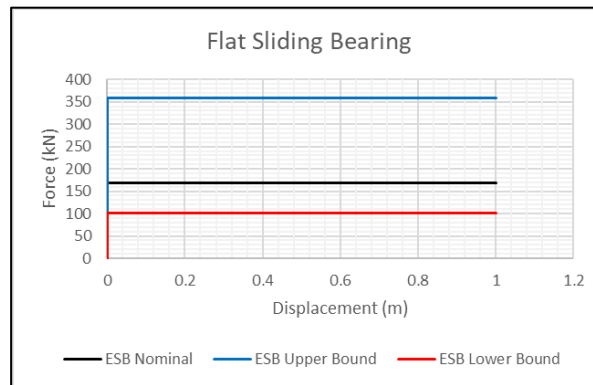


Figure 5.49: Flat sliding bearing backbone with corresponding upper & lower bound properties.

- Composite System Properties

Construction of composite system is done by taken into account of contribution of both lead rubber bearings and flat sliding bearings together. Behavior of the composite system consisting of 28 LRB's and 17 FSB's is presented below.

Table 5.39: Bearing summary for construction of composite system.

Bearing Summary			
Type	LRB	FSB	Total
#Nos	28	17	45
k_1	26397	169102	
k_2	2031	0	
k_{eff}	2776	436	
F_q	289	169	
F	1077	169	
d_y	0.011	0.001	
d_M	0.388	0.388	
ξ	16.6%	63.5%	

Table 5.40: Composite system stiffness properties.

Composite System		
K_1	739120	kN/m
K_2	56855	kN/m
K_{eff}	85138	kN/m
d_y	0.016	m
F_Q	11888	kN
D_M	0.388	m
F_u	33033	kN
β	20.69%	
W	180000	kN
m	18349	tons
T_m	2.917	sec.

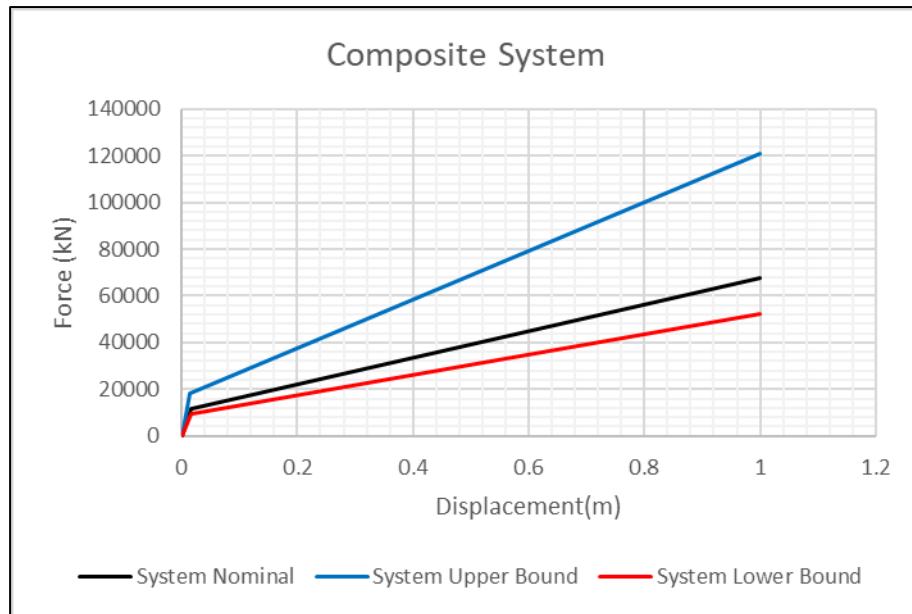


Figure 5.50: Composite system backbone with corresponding upper & lower bound properties.

5.3.3. Analysis and Results

The isolators are modelled as link elements and added to 3D finite element model of 15 story structure. Analysis of isolated structure have been conducted with scaled earthquake records. Total 7 pairs, and using each pair on both x & y directions, in total 14 time history analysis have been performed for every design level. Result tables and graphs are produced on the basis of average of maximums for every structural response that is taken into account. The criteria of assessment is for both sub and superstructure and summarized below;

- Base shear not exceeding 10% of the seismic weight at DD-2 level ground motions (Superstructure),
- Story drifts not exceeding $0.005h_i$ at DD-2 level ground motions (Superstructure),
- Displacement of isolation devices, so that the shear strain of the isolation device is less than 200% at DD-1 level ground motions (Substructure),
- Isolator compressive/tensile performance for DD-1 level earthquake (Substructure).

5.3.3.1. Superstructure Results

Superstructure results are given in this section, displaying shear forces, displacements and drifts on both perpendicular directions.

- Story Shear Forces at DD-2 Level

Obtained story shear forces are presented in this section. Mean Maximum base shears for the building is obtained as 33876 kN for X direction and 35122 kN for Y direction.

Table 5.41: Average story shear forces for base isolated building for x and y directions.

	Storey Force (kN)	
	X Dir.	Y Dir.
Story15	2101	2178
Story14	4370	4531
Story13	6640	6884
Story12	8910	9238
Story11	11179	11591
Story10	13449	13944
Story9	15719	16297
Story8	17988	18650
Story7	20258	21003
Story6	22527	23356
Story5	24797	25709
Story4	27067	28063
Story3	29336	30416
Story2	31606	32769
Story1	33876	35122

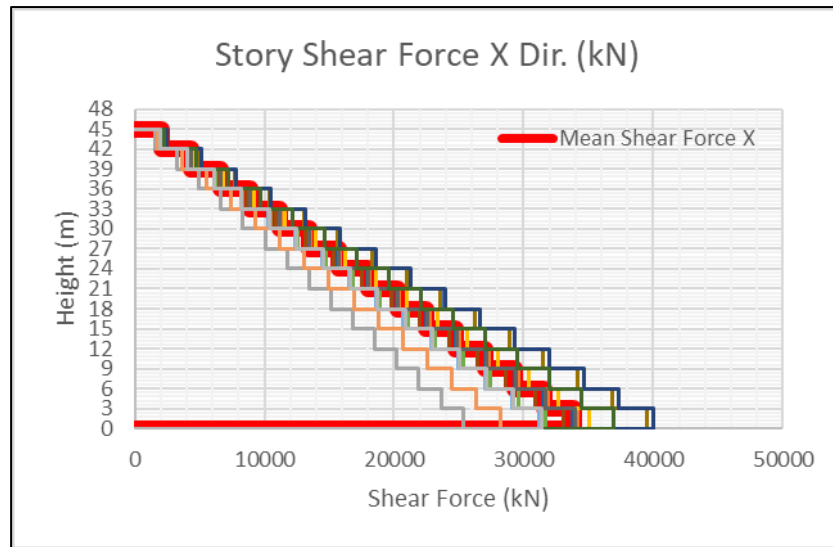


Figure 5.51: Story shear forces x direction.

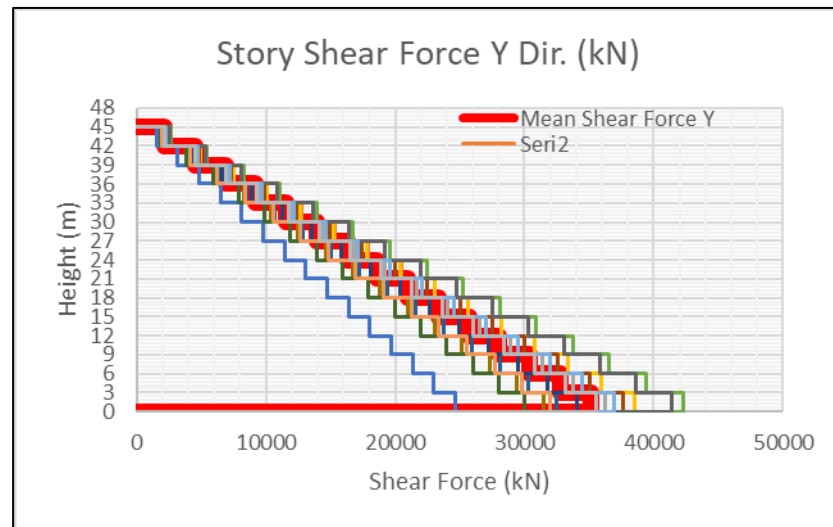


Figure 5.52: Story shear forces y direction.

- Story Displacements at DD-2 Level

Obtained story displacements are presented in this section. Mean Maximum displacements for the building is obtained as 121 mm for X direction and 142 mm for Y direction

Table 5.42: Average story displacements for base isolated building for x and y directions.

	Displacement (mm)	
	X Dir.	Y Dir.
Story15	121	142
Story14	117	133
Story13	112	124
Story12	106	114
Story11	99	103
Story10	91	93
Story9	82	82
Story8	73	70
Story7	62	59
Story6	51	47
Story5	40	36
Story4	29	26
Story3	19	17
Story2	11	9
Story1	4.	3
Base	0	0

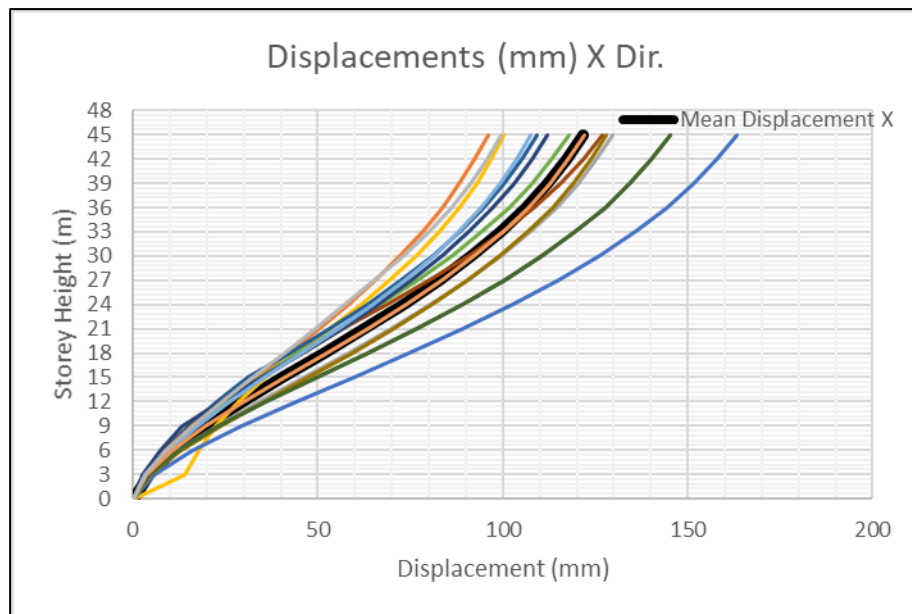


Figure 5.53: Story displacements x direction.

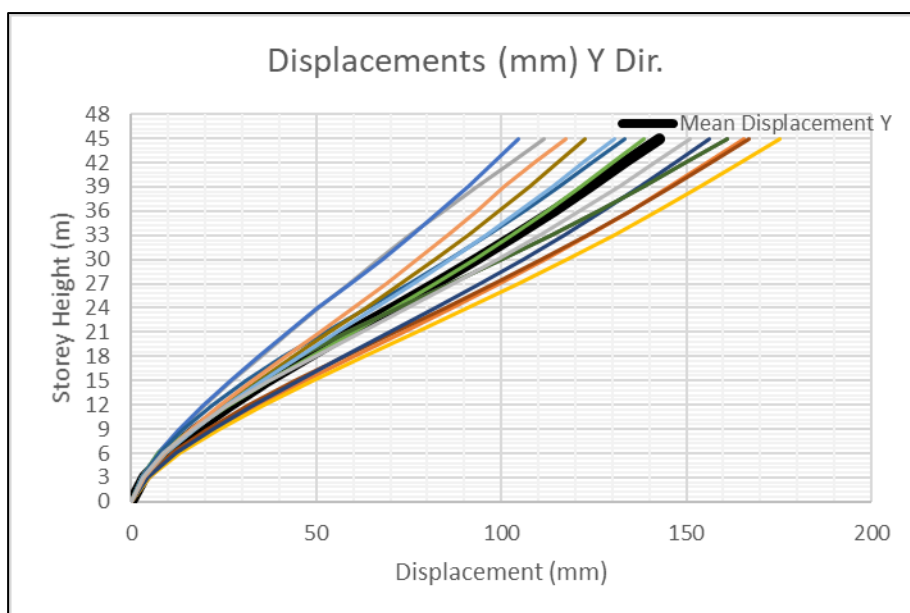


Figure 5.54: Story displacements y direction.

- Story Drifts at DD-2 Level

Obtained story drifts are presented in this section. Mean Maximum displacements for the building is obtained as 0.004446 for X direction and 0.004336 for Y direction

Table 5.43: Average drifts for base isolated building for x and y directions.

	Drift	
	X Dir.	Y Dir.
Story15	0.001777	0.003053
Story14	0.001988	0.003203
Story13	0.002262	0.003383
Story12	0.002584	0.003584
Story11	0.00293	0.00379
Story10	0.003281	0.003985
Story9	0.00362	0.004152
Story8	0.003928	0.004275
Story7	0.004191	0.004336
Story6	0.004381	0.004314
Story5	0.004446	0.004182
Story4	0.004324	0.003904
Story3	0.003921	0.003435
Story2	0.003086	0.002691
Story1	0.001715	0.001632

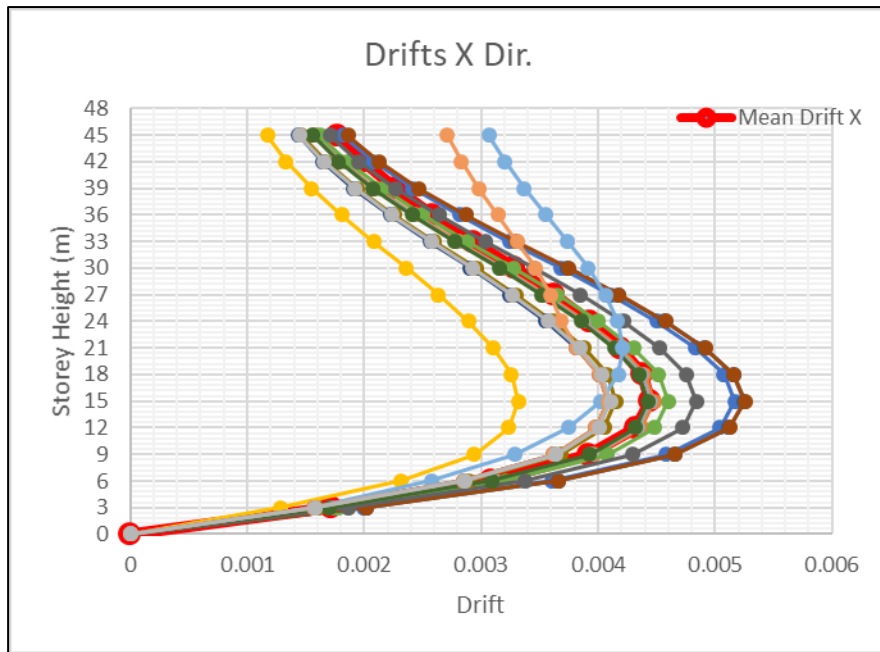


Figure 5.55: Story drifts x direction.

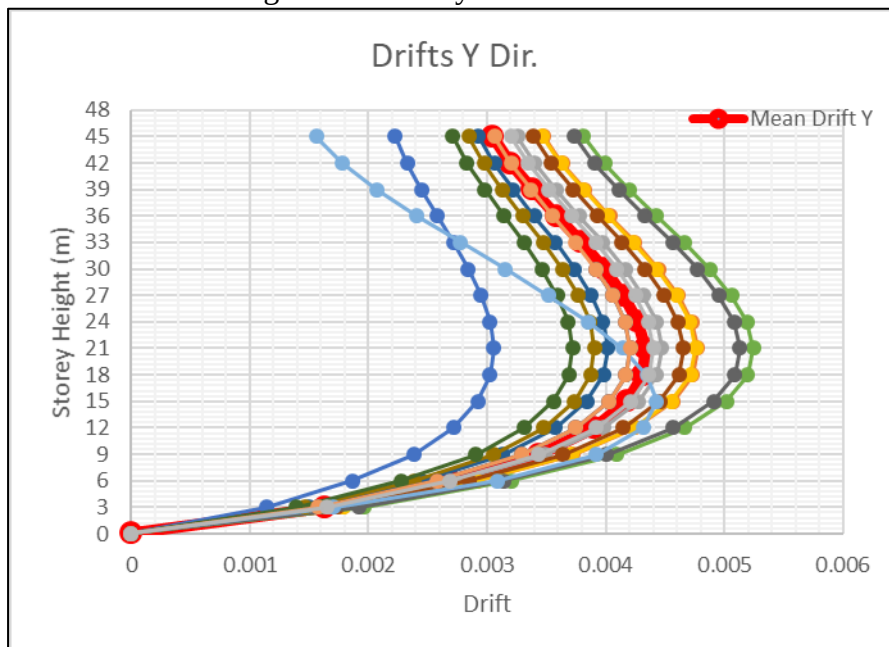


Figure 5.56: Story drifts y direction.

5.3.3.2. Substructure Results

Substructure results are given in this section, displaying mean and maximum displacements at isolation level and maximum shear and axial forces, for isolators.

- Maximum Displacements at DD-1 Level

This section yields maximum displacements and mean of the maximum displacement. Maximum displacement is obtained as 777 mm for 1148-B record, and shown in the following graph.

Table 5.44: Maximum displacements for base isolated building for x and y directions.

Record		Maximum SRSS Disp. (mm)
731	A	308
731	B	320
1148	A	1331
1148	B	1343
838	A	396
838	B	390
1163	A	381
1163	B	366
827	A	539
827	B	536
776	A	354
776	B	355
15	A	254
15	B	253
Average of Max.		509

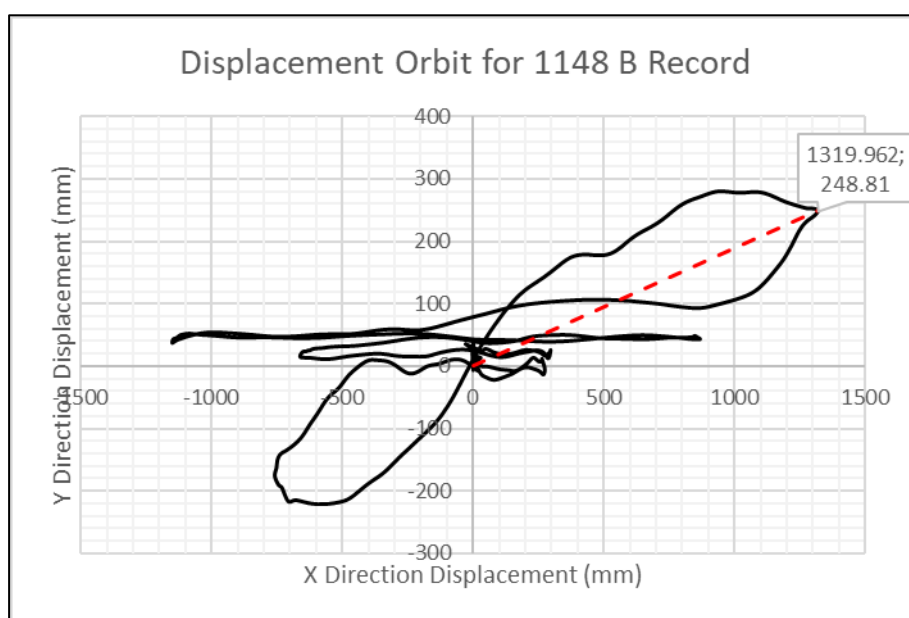


Figure 5.57: Displacement orbit for 1148-B record.

- Maximum Bearing Axial Forces at DD-1 Level

In this section, maximum axial loads (compression, tension) for isolator bearings are presented. Axial loads are very crucial especially for lead rubber bearings. Mean of the maximum compressive axial load for lead rubber bearing is obtained as 13776.6 kN while 722.5 kN of tensional force is obtained.

Table 5.45: Maximum lrb compressive forces.

Lead Rubber Bearing Axial Forces - Compression		
Record		Maximum Axial Force (kN)
731	A	-11765.3
	B	-11939.2
1148	A	-23075.5
	B	-16015.8
838	A	-14006.1
	B	-13746.0
1163	A	-12443.0
	B	-13225.7
827	A	-14066.9
	B	-12953.8
776	A	-11466.1
	B	-13592.5
15	A	-12611.7
	B	-11965.0
Average of Max.		-13776.6

Table 5.46: Maximum lrb tensile forces.

Lead Rubber Bearing Axial Forces - Tension		
Record		Maximum Axial Force (kN)
731	A	-
	B	-
1148	A	487.3
	B	957.8
838	A	-
	B	-
1163	A	-
	B	-
827	A	-
	B	-
776	A	-
	B	-
15	A	-
	B	-
Average of Max.		722.5

Mean of the maximum flat sliding bearing force is obtained as 20039.8 kN.

Table 5.47: Maximum fsb compressive forces.

Flat Sliding Bearing Axial Forces		
Record		Maximum Axial Force (kN)
731	A	-17790.5
	B	-16718.6
1148	A	-36551.2
	B	-32504.1
838	A	-17686.4
	B	-19180.2
1163	A	-20122.4
	B	-20613.6
827	A	-19975.3
	B	-17006.7
776	A	-14277.4
	B	-18695.7
15	A	-14889.0
	B	-14546.7
Average of Max.		-20039.8

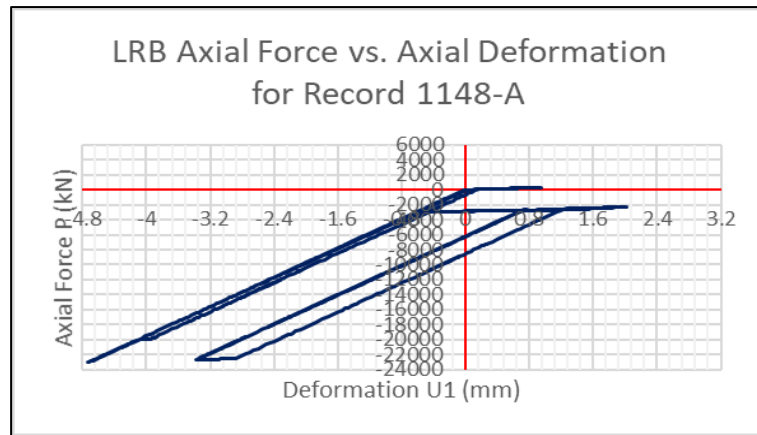


Figure 5.58: Lrb axial force vs. axial deformation hysteresis graph for 1148-A record.

Nonlinear shear behavior vs. lateral displacement for the lead rubber bearing is given in the following two graphs for both orthogonal directions.

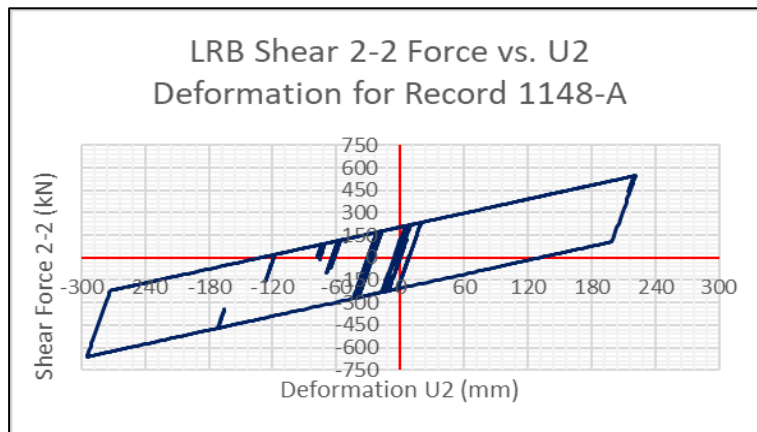


Figure 5.59: Lrb shear 2-2 force vs. u2 deformation hysteresis graph for 1148-A record.

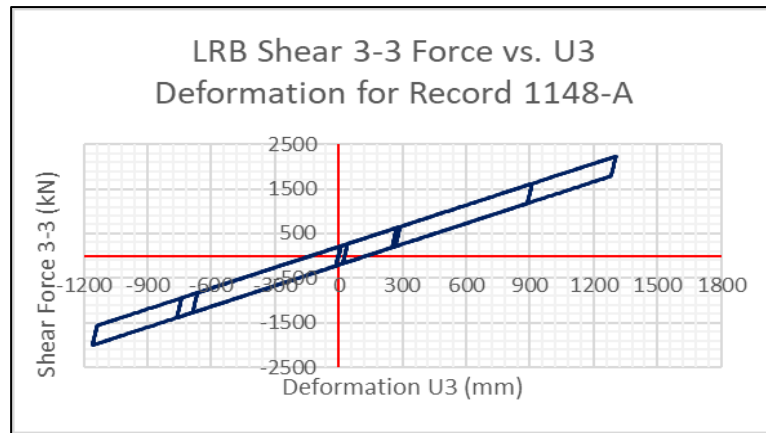


Figure 5.60: Lrb shear 3-3 force vs. u3 deformation hysteresis graph for 1148-A record.

Flat sliding bearing axial force vs. axial deformation results are given in the below figure. Note that flat sliding bearing has no tensional restraint thus there's no tensional force occurred in the bearing, also axial deformations are quite limited due to high axial stiffness of the flat sliding bearing.

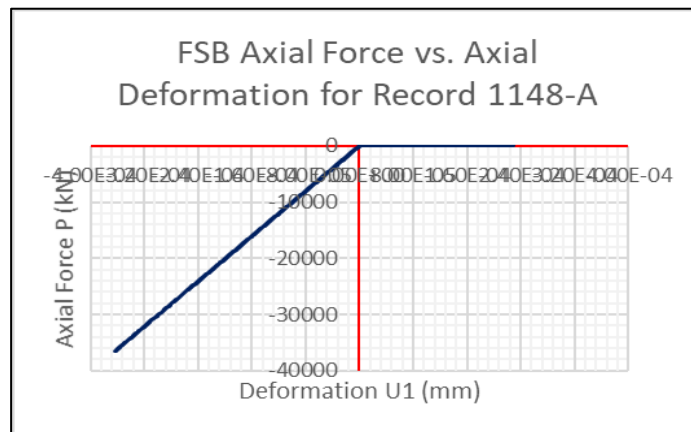


Figure 5.61: Fsb axial force vs. u1 deformation hysteresis graph for 1148-A record.

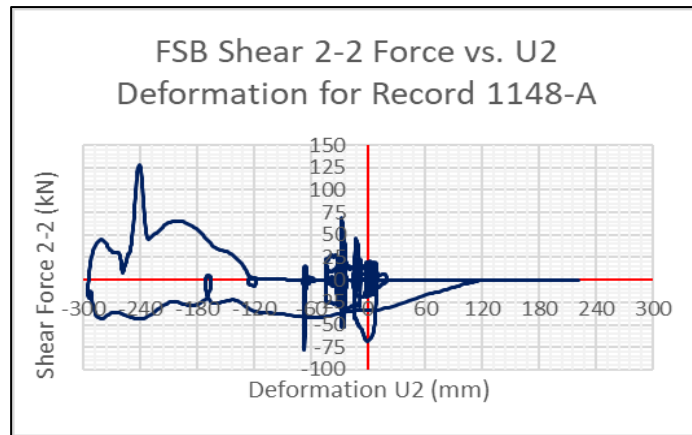


Figure 5.62: Fsb shear 2-2 force vs. u2 deformation hysteresis graph for 1148-A record.

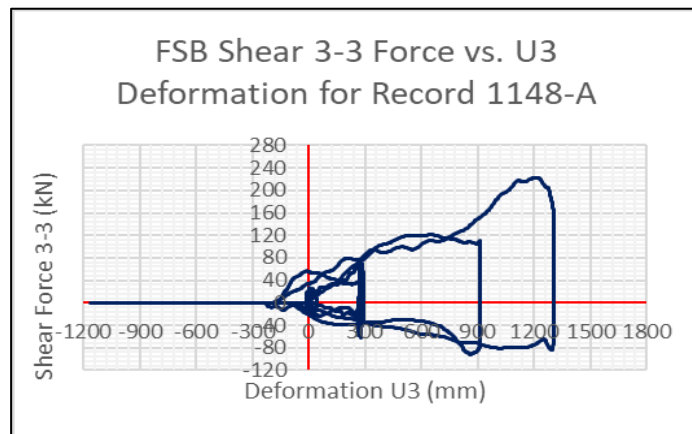


Figure 5.63: Fsb shear 3-3 force vs. u3 deformation hysteresis graph for 1148-A record.

Buckling controls of the lead rubber bearing can be done by calculating critical buckling load for each shear strain level. Below table shows critical buckling load at predefined shear strains and graph yields the axial force vs. shear strain history for the most critical lead rubber bearing with critical buckling load lines.

Table 5.48: Axial force vs. shear strain values corresponding to factor of safety=1.33 and factor of safety=1.00.

	P _{max} (kN)	
γ (%)	FoS=1.33	FoS=1.00
0	53005	70497
50	42736	56839
100	32712	43508
200	14502	19288

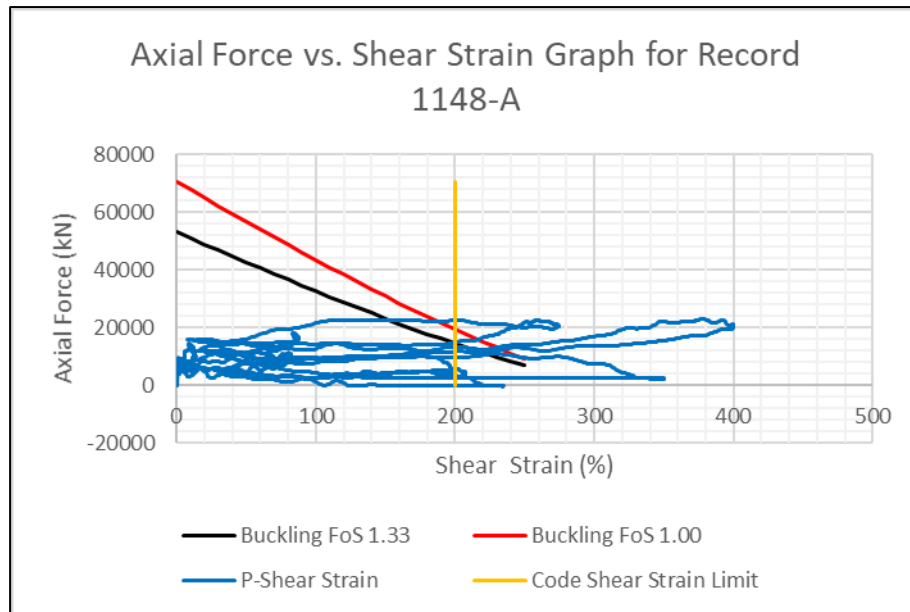


Figure 5.64: Lrb axial vs shear strain results for 1148-A record.

5.3.3.3. Comparison of Isolated and Fixed Base Structure

- Base Shear

The elastic base shear comparison for fixed and isolated structures is presented with following two graphs. It can be seen that for DD-2 level earthquakes the isolated structure was exposed to minor amounts of base shear force with relevance to its counterpart but the isolation system is failed to comply with the target base shear force which is 10% of the seismic weight (~ 18000 kN), the base isolation produced a good pattern for force distribution over the height of the structure.

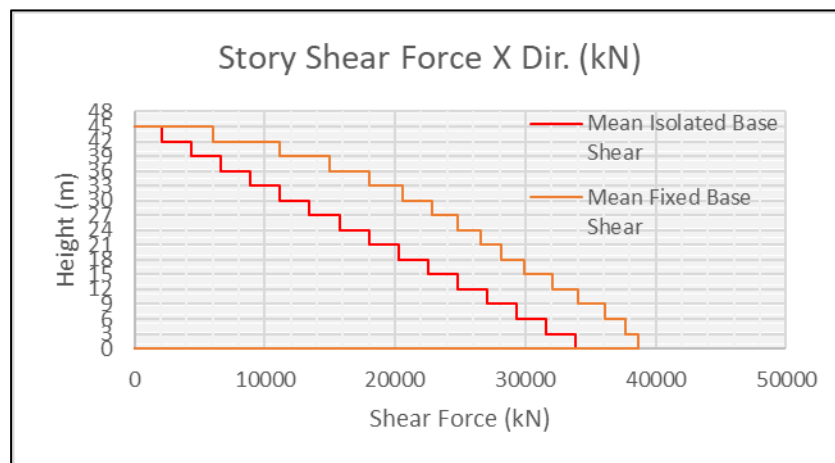


Figure 5.65: Mean isolated vs. fixed base story shear forces x direction.

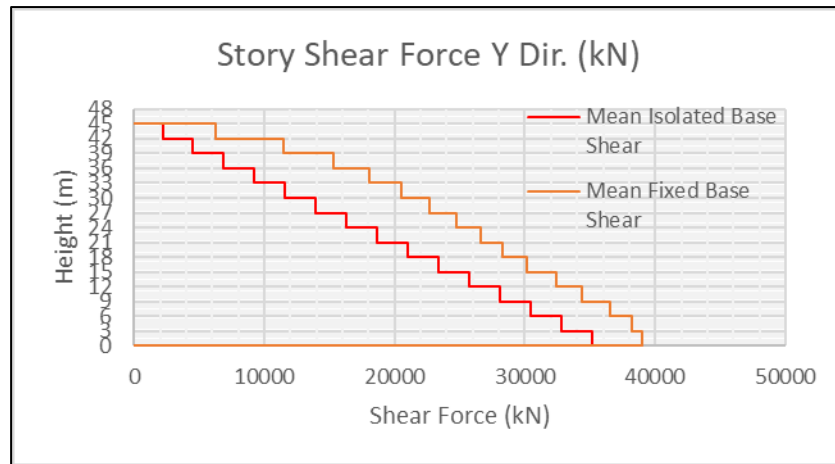


Figure 5.66: Mean isolated vs. fixed base story shear forces y direction.

- Displacement

Base isolated building have almost halved the displacement demand of its fixed base counterpart by reducing the displacement from ~270-250 mm to ~140-120 mm.

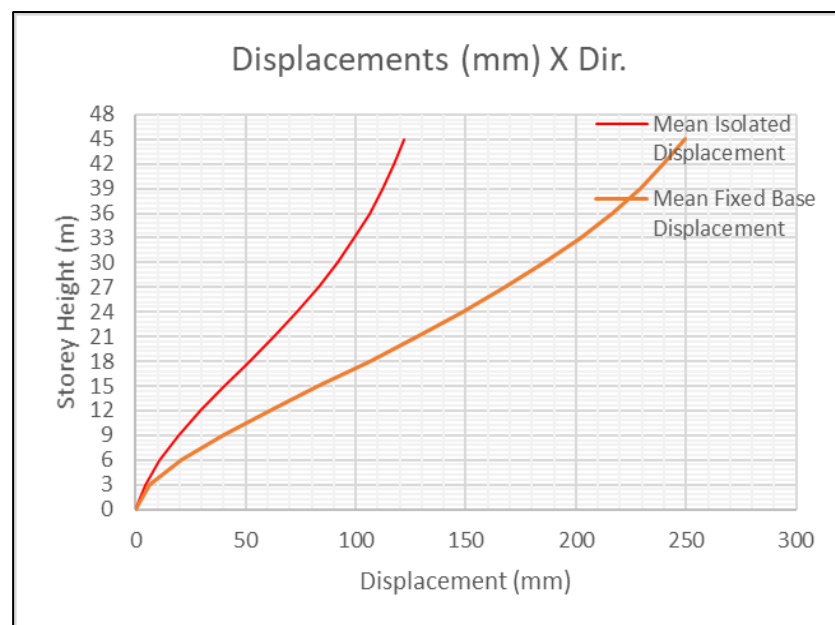


Figure 5.67: Mean isolated vs. fixed base displacements x direction.

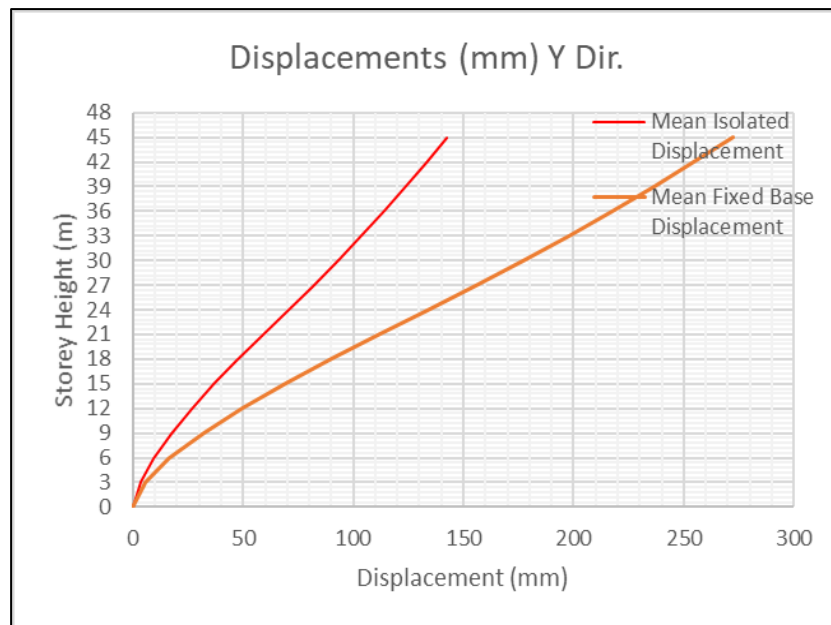


Figure 5.68: Mean isolated vs. fixed base displacements y direction.

- Drift

As well as displacements, drifts are also almost halved. Additionally the structure is complied with the code limitation which is $0.005h_i$. The drifts of first 2 stories are almost the same but it is obvious that seismic isolation produced better results for higher stories.

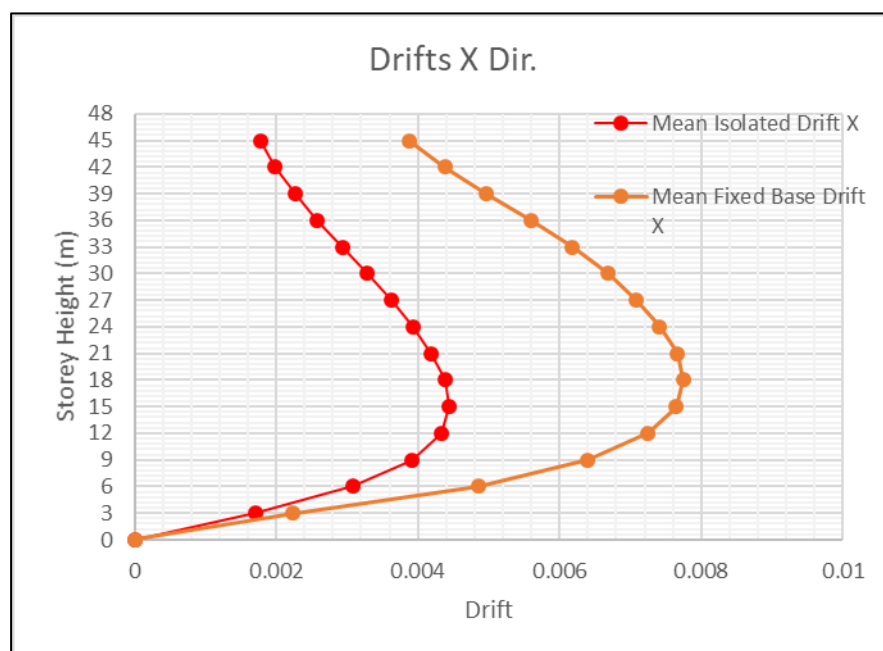


Figure 5.69: Mean isolated vs. fixed base drifts x direction.

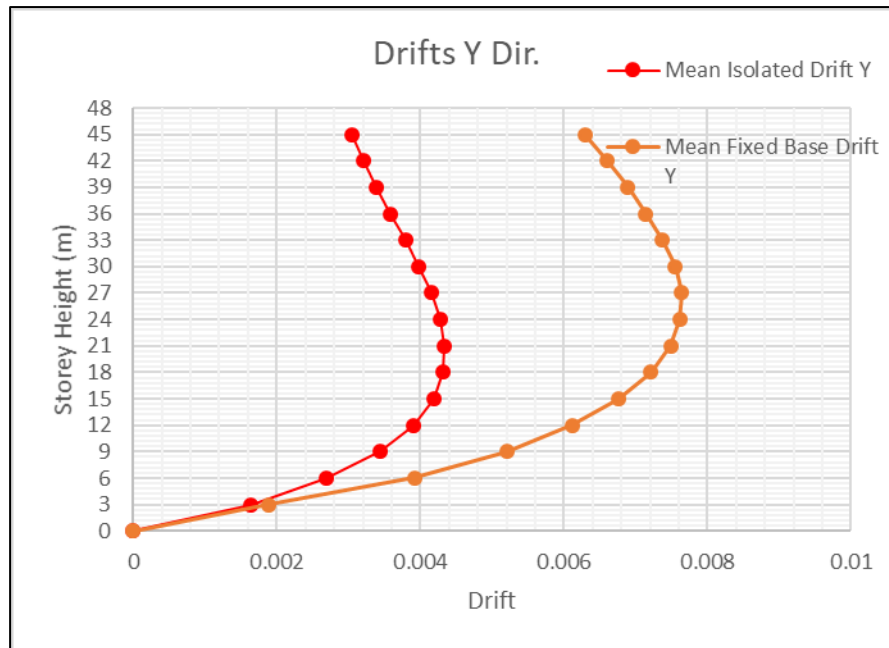


Figure 5.70: Mean isolated vs. fixed base drift y direction.

- Substructure

The average of maximum displacements at isolation level obtained from the nonlinear time history analyses is 0.509 m which is larger than the linear analysis result 0.388m. The average of maximum axial loads for lead rubber bearing isolators have obtained to be 13777 kN which is smaller than the linear design force 15800 kN, obtained from DD-1 level spectral analysis.

5.4. Design & Analysis of 20 Story Building

In this section, first material and geometrical properties of 20 story building have been introduced. Secondly the fixed base model is analyzed for scaled earthquake records. Thirdly the seismic isolation design of 20 story building have been conducted and nonlinear time history analyses have been performed, and lastly results obtained from both fixed base and base isolated buildings have been compared.

5.4.1. Properties of the Building

The loading values of 20 story building is the same properties used for 10 & 15 story buildings, but some geometrical and material properties have been changed. The building height is inherently increased to 60m and shear wall dimensions are enlarged which can be seen in the figure below, also the concrete quality is increased to C35 which has modulus of elasticity of 28100 MPa.

The building is first modelled as fixed base 3D, and linear response history analyses have been conducted.

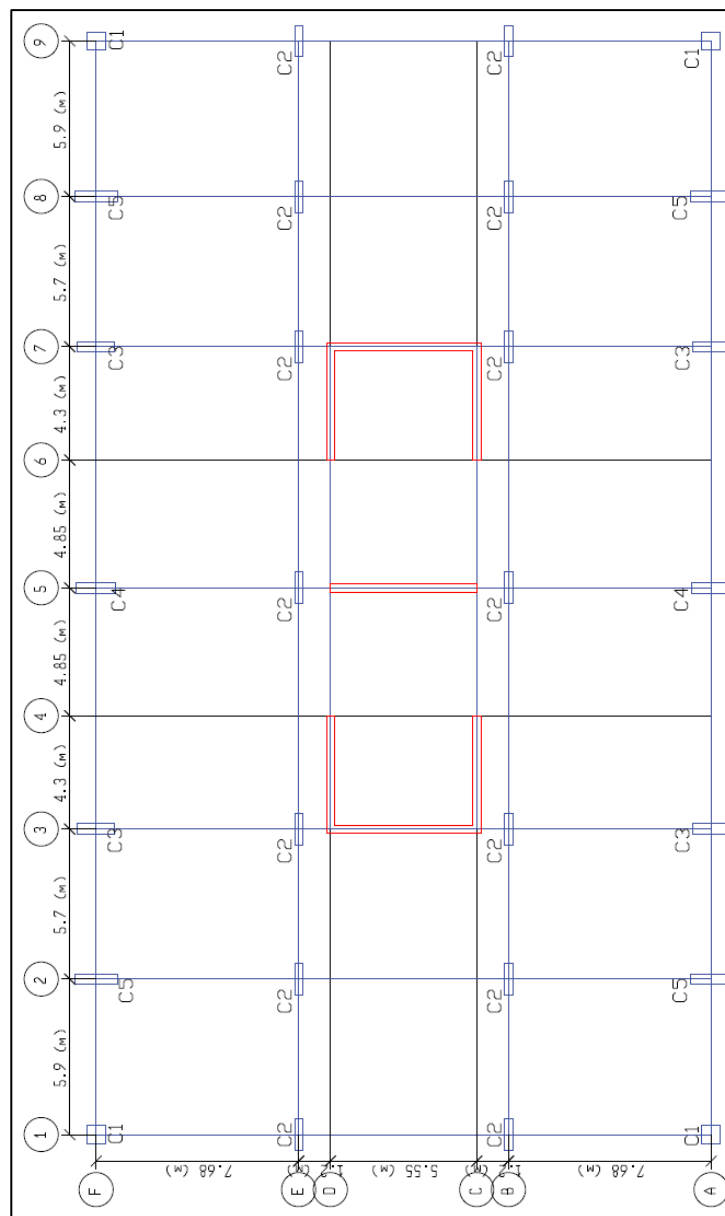


Figure 5.71: Plan view of the 20 story building.

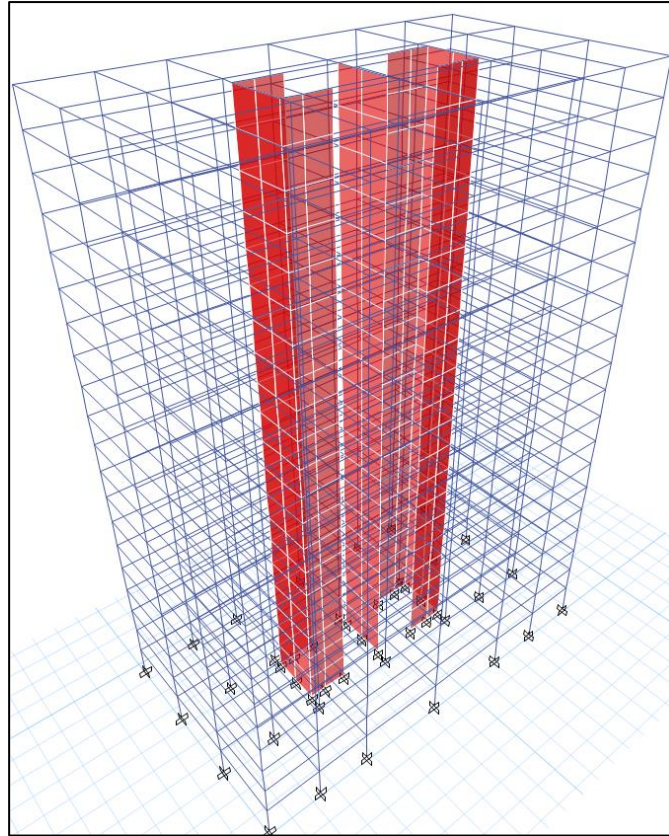


Figure 5.72: 3d finite element modeling of the fixed base 20 story building.

Table 5.49: Modal periods and corresponding mass ratios for 20 story fixed base building.

Mode	Period	UX	UY	RZ
#	(Sec.)	Unitless	Unitless	Unitless
1	2.156	0.000	0.000	0.726
2	2.144	0.000	0.678	0.000
3	2.133	0.738	0.000	0.000
4	0.631	0.117	0.000	0.000
5	0.618	0.000	0.000	0.137
6	0.520	0.000	0.173	0.000
7	0.314	0.050	0.000	0.000
8	0.305	0.000	0.000	0.055
9	0.232	0.000	0.061	0.000
10	0.190	0.000	0.000	0.028
11	0.190	0.029	0.000	0.000
12	0.141	0.000	0.030	0.000

As it can be seen from the table above, the fixed base building has almost the same natural fundamental period values in both X and Y directions, and the modal participating masses are around 74~68 percent of the total mass.

To compare the results with seismically isolated structure, a linear time history analysis, using scaled earthquake records to DD-2 level, has been conducted. As a result story shear forces, drifts and displacements have been obtained with the average of the maximum values. The results are given by table and figure below.

- Story Shear Forces at DD-2 Level

Obtained story shear forces are presented in this section. Mean Maximum base shears for the building is obtained as 33077 kN for X direction and 37494 kN for Y direction.

Table 5.50: Average story shear forces for fixed base building for x and y directions.

	Force (kN)	
	X Dir.	Y Dir.
Story20	4660	4965
Story19	8612	9273
Story18	11472	12482
Story17	13483	14691
Story16	15534	16129
Story15	17350	17437
Story14	18688	18541
Story13	19826	19283
Story12	21028	19710
Story11	22302	20333
Story10	23397	21546
Story9	24352	23350
Story8	25348	25381
Story7	26036	27203
Story6	26845	29146
Story5	28159	31120
Story4	29583	32961
Story3	30867	34797
Story2	32033	36354
Story1	33077	37494

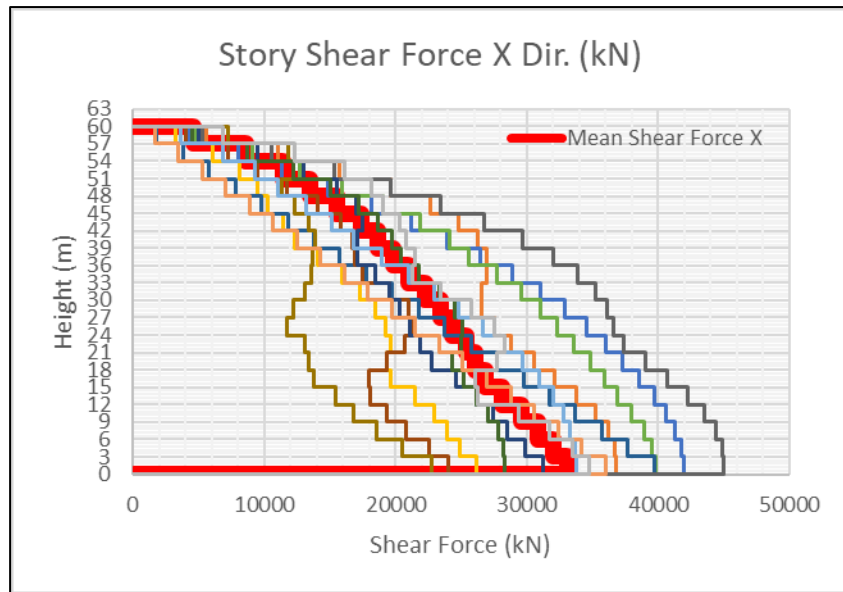


Figure 5.73: Story shear forces x direction.

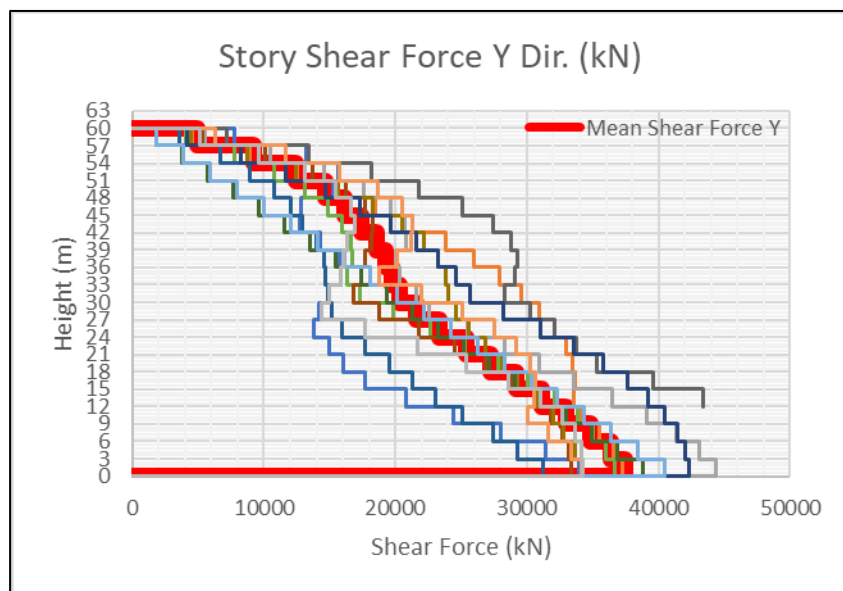


Figure 5.74: Story shear forces y direction.

- Story Displacements at DD-2 Level

Obtained story displacements are presented in this section. Mean Maximum displacements for the building is obtained as 227 mm for X direction and 243 mm for Y direction.

Table 5.51: Average story displacements for fixed base building for x and y directions.

	Displacement (mm)	
	X Dir.	Y Dir.
Story20	227	243
Story19	220	230
Story18	212	217
Story17	204	203
Story16	195	189
Story15	185	175
Story14	175	161
Story13	163	147
Story12	151	133
Story11	137	119
Story10	124	104
Story9	110	90
Story8	95	77
Story7	80	64
Story6	66	51
Story5	51	39
Story4	37	27
Story3	24	18
Story2	12	9
Story1	4	3
Base	0	0

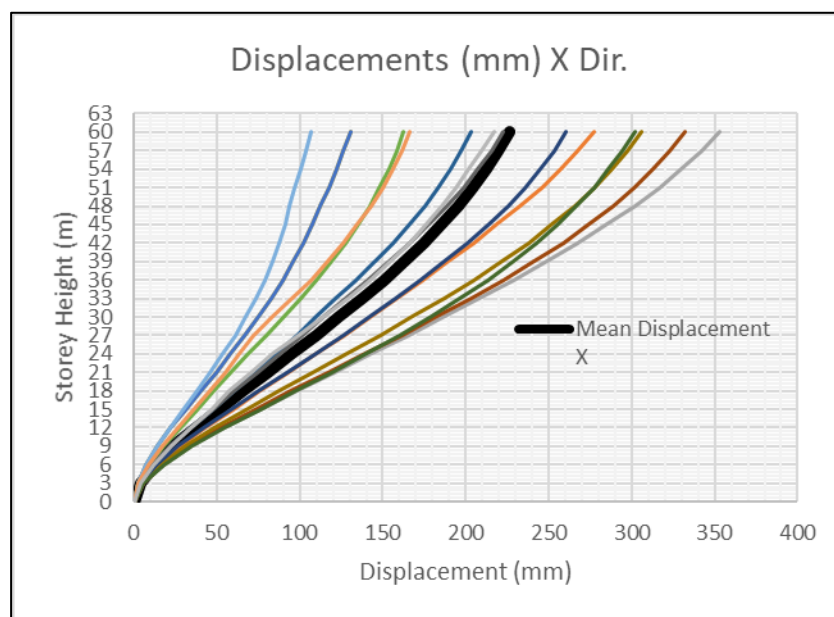


Figure 5.75: Story displacements x direction.

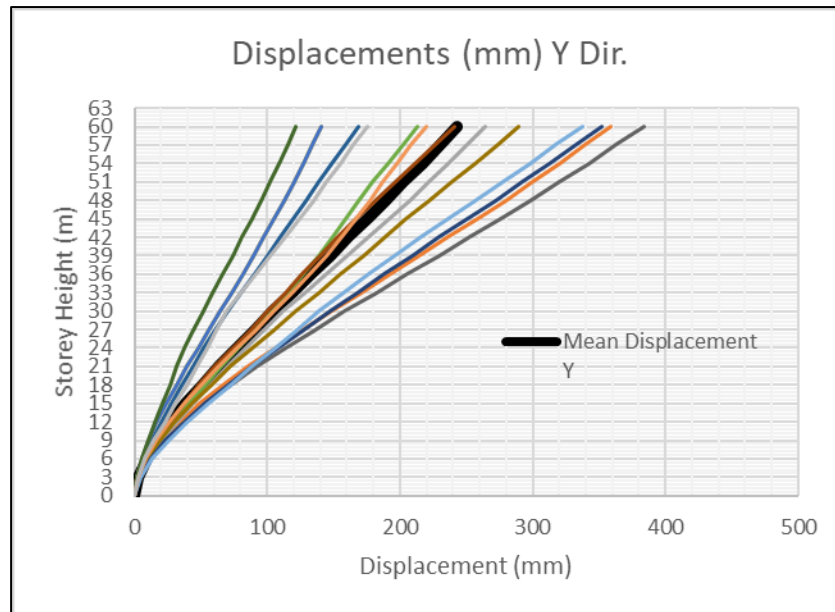


Figure 5.76: Story displacements y direction.

- Story Drifts at DD-2 Level

Obtained story drifts are presented in this section. Mean Maximum drifts for the building is obtained as 0.00513 for X direction and 0.005081 for Y direction. Mean maximum drifts per story is given in the following table and graphs.

Table 5.52: Average story drifts for fixed base building for x and y directions.

	Drift	
	X Dir.	Y Dir.
Story20	0.002615	0.004688
Story19	0.00288	0.004828
Story18	0.003176	0.004947
Story17	0.00349	0.005039
Story16	0.00379	0.0051
Story15	0.00405	0.005139
Story14	0.004276	0.005147
Story13	0.0045	0.005127
Story12	0.00471	0.005081
Story11	0.00489	0.00501
Story10	0.005014	0.004899
Story9	0.00511	0.004753
Story8	0.00513	0.00459
Story7	0.005081	0.004373
Story6	0.004979	0.004096
Story5	0.004768	0.00377
Story4	0.004412	0.003342
Story3	0.003802	0.00278
Story2	0.002837	0.002071
Story1	0.001299	0.001034
Base	0	0

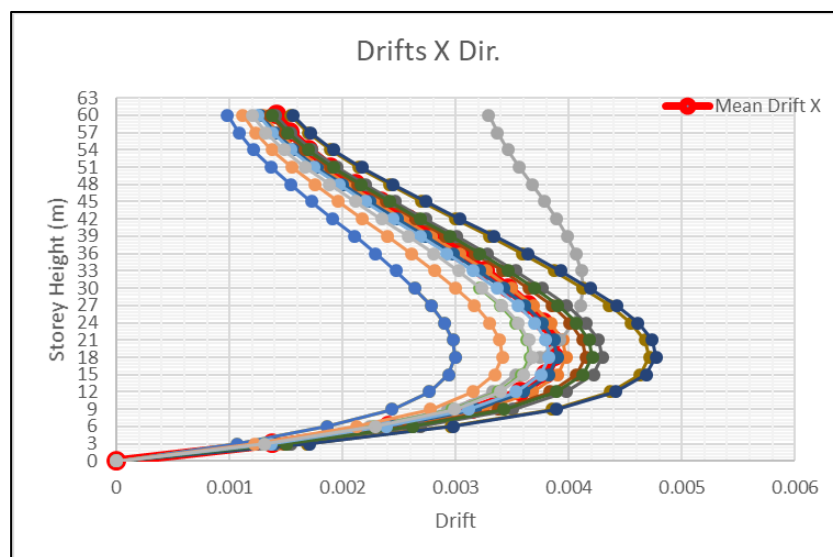


Figure 5.77: Story drifts x direction.

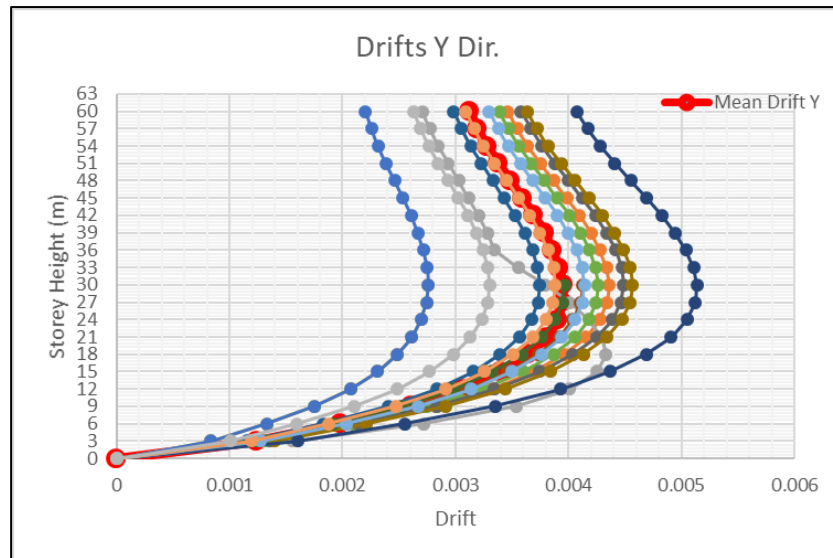


Figure 5.78: Story drifts y direction.

5.4.2. Seismic Isolation Design for 20 Story Building

Seismic isolation design for 20 story building is presented in this part. The general philosophy and the method of seismic isolation with the help of code requirements are done. The strategy followed is using lead rubber bearings under the columns and flat sliding bearings under the shear walls. To separate the sub and the superstructure and to make sure the isolation layer is working as it is intended to a reinforced concrete slab layer/floor is modelled on the base level, having the same mass and loadings as a normal floor.

Furthermore, for the sake of simplicity, refinement and to get a better understanding of the behavior only one lead rubber bearing and one flat sliding bearing is used in the design. The material and geometrical properties are selected carefully and they are hand in hand with the practice.

The seismic weight of the structure is calculated as 240000 kN, making seismic mass 24460 t. Linear design of the isolation system has been made using DD-1 & DD-2 level design spectrums with both horizontal and vertical components. Design level earthquake demands and periods are as follows.

Earthquake demands on the single degree of freedom isolated structure is given in the following table.

Table 5.53: DD-1 & DD-2 earthquake demands on sdof isolated structure.

DD-1	T_M (sec.)	3.300
	D_M (m)	0.437
DD-2	T_D (sec.)	2.615
	D_D (m)	0.158

Modal periods and corresponding mass ratios are calculated and given in the tables below. Note that modal mass ratios for the first and second mode is almost 100 % of the seismic weight.

Table 5.54: Modal periods and corresponding mass ratios for 20 story base isolated building at DD-2 level earthquakes.

Mode	Period	UX	UY	UZ	RZ
#	(Sec.)	Unitless	Unitless	Unitless	Unitless
1	3.126	0	0.952	0	0
2	3.115	0.963	0	0	0
3	2.977	0	0	0	0.952
4	0.918	0	0.048	0	0
5	0.806	0.037	0	0	0
6	0.782	0	0	0	0.048
7	0.133	0	0	0.800	0
8	0.102	0	0	0.054	0
9	0.085	0	0	0.004	0

Table 5.55: Modal periods and corresponding mass ratios for 20 story base isolated building at DD-1 level earthquakes.

Mode	Period	UX	UY	UZ	RZ
#	(Sec.)	Unitless	Unitless	Unitless	Unitless
1	3.662	0	0.976	0	0
2	3.658	0.982	0	0	0
3	3.37	0	0	0	0.972
4	0.988	0	0.024	0	0
5	0.868	0.018	0	0	0
6	0.845	0	0	0	0.028
7	0.133	0	0	0.800	0
8	0.102	0	0	0.054	0
9	0.085	0	0	0.004	0

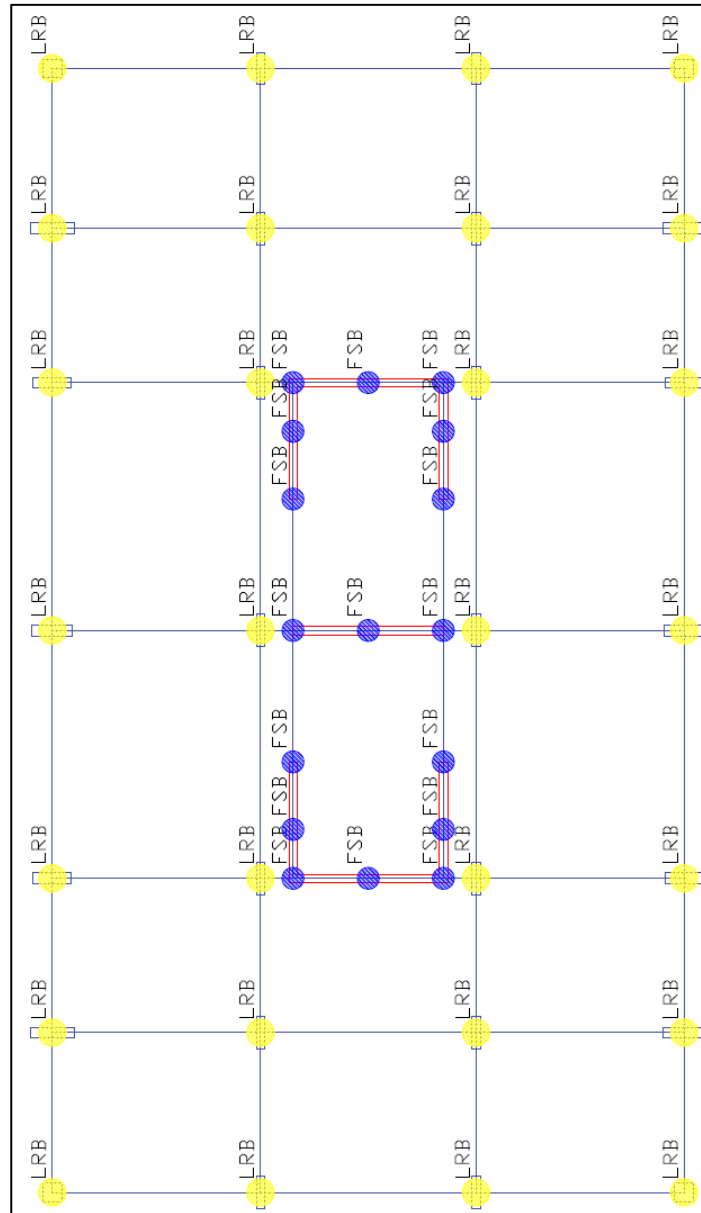


Figure 5.79: Isolation bearings location plan (lrb: lead rubber bearing, fsb: flat sliding bearing).

Table 5.56: Isolator bearing types and quantities used in design.

Bearing Type	Nos #
Lead Rubber Bearing	28
Flat Sliding Bearing	14
Total	45

- Lead Rubber Bearing Design (LRB)

The design of lead rubber bearing is briefly summarized here, the stiffness and strength values represent the nominal bearing properties. Code requirement upper and lower bound properties for lead rubber bearing is derived from the nominal bearing properties.

The design of lead rubber bearing has been conducted according to the methods prescribed in draft Turkish Building Seismic Code'16, the design axial forces and chosen properties with nominal bearing properties are presented in the tables below.

Table 5.57: Design axial forces for lead rubber bearing.

P_{K1} (kN)	15500	Comb. 14.1 - $1.4G+1.6Q$
P_{K2} (kN)	18260	Comb.14.2 - $1.2G+Q+-E_d$
P_{K3} (kN)	15750	Comb. 14.3 - $0.9G+-E_d$

Table 5.58: Geometrical, material and stiffness properties of lead rubber bearing.

D_0 (mm)	1150	Total Diameter of Bearing
B (mm)	1040	Dia. of Rubber Btwn. Shims
B_L (mm)	230	Diameter of Lead Plug
T_r (mm)	279	Total Elastomeric Height
S	39	First Shape Factor
G_v (MPa)	0.6	Shear Modulus of Rubber
T_{yp} (MPa)	1.0	Yield Stress of Lead
k_1 (kN/m)	27374	Nominal Initial Stiffness
k_2 (kN/m)	2106	Post Yield Stiffness
k_{eff} (kN/m)	2863	Effective Stiffness
F_q (kN)	331	Approx. Yield Strength
F (kN)	1077	Ultimate Strength
d_y (m)	0.012	Yield Displacement
d_M (m)	0.437	Displacement Demand
ξ	16.38%	Damping Ratio
k_v (kN/m)	5145802	Axial Stiffness

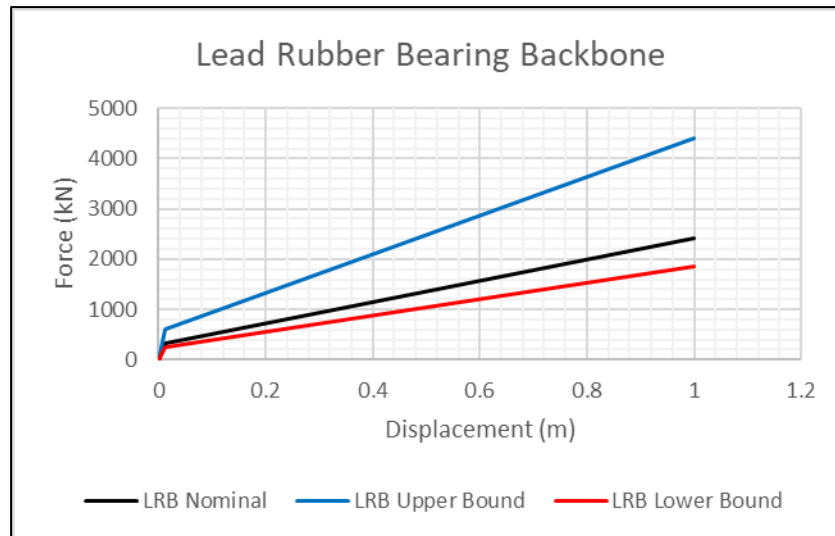


Figure 5.80: Lead rubber bearing backbone with corresponding upper & lower bound properties.

- Flat Sliding Bearing Design (FSB)

The flat sliding bearing is a friction pendulum bearing with an infinite radius, which means that two flat plates with a very low coefficient of friction. This bearing is made of PTFE (Polytetrafluoroethylene), but with being flat (infinite radius) the post yielding stiffness is “0”. The design of flat sliding bearing is summarized below.

Table 5.59: Design axial forces for flat sliding bearing.

P_1 (kN)	8700	Comb. 14.1 - $1.4G+1.6Q$
P_2 (kN)	22000	Comb. 14.2 - $1.2G+Q+-E_d$

Table 5.60: Design axial forces for flat sliding bearing.

D_0 (mm)	800	Diameter of Bearing
t_{plate} (mm)	2	Thickness
E (MPa)	400000	PTFE Modulus of Elasticity
k_1 (kN/m)	218838	Nominal Initial Stiffness
k_2 (kN/m)	0	Post Yield Stiffness
k_{eff} (kN/m)	501	Effective Stiffness
F_q (kN)	219	Approx. Yield Strength
F (kN)	219	Ultimate Strength
d_y (m)	0.001	Yield Displacement
d_M (m)	0.437	Displacement Demand
ξ	63.5%	Damping Ratio
k_v (kN/m)	1E+11	Axial Stiffness

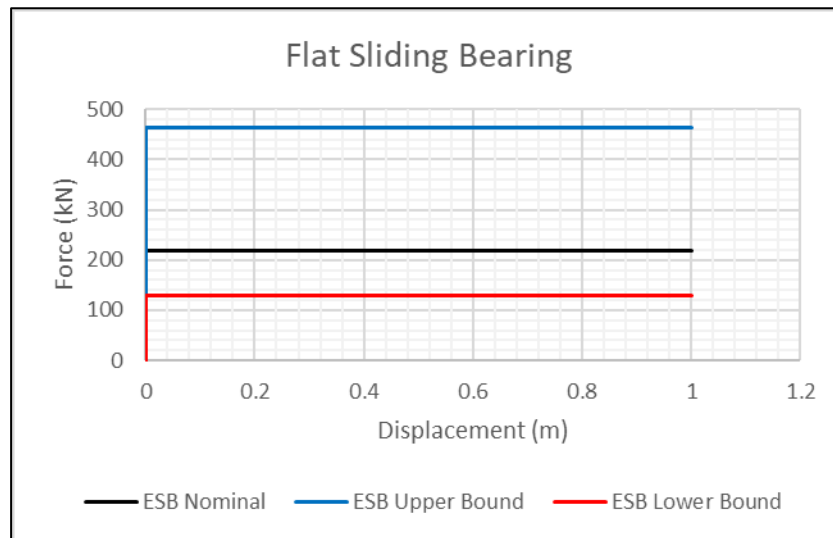


Figure 5.81: Flat sliding bearing backbone with corresponding upper & lower bound properties.

- Composite System Properties

Construction of composite system is done by taken into account of contribution of both lead rubber bearings and flat sliding bearings together. Behavior of the composite system consisting of 28 LRB's and 17 FSB's is presented below.

Table 5.61: Bearing summary for construction of composite system.

Bearing Summary			
Type	LRB	FSB	Total
#Nos	28	17	45
k_1	27374	218838	
k_2	2106	0	
k_{eff}	2863	501	
F_q	331	219	
F	1251	219	
d_y	0.012	0.001	
d_M	0.437	0.437	
ξ	16.4%	63.5%	

Table 5.62: Composite system stiffness properties.

Composite System		
K_1	766479	kN/m
K_2	58960	kN/m
K_{eff}	85138	kN/m
d_y	0.018	m
F_Q	14071	kN
D_M	0.437	m
F_u	38754	kN
β	20.90%	
W	240000	kN
m	24458	tons
T_m	3.300	sec.

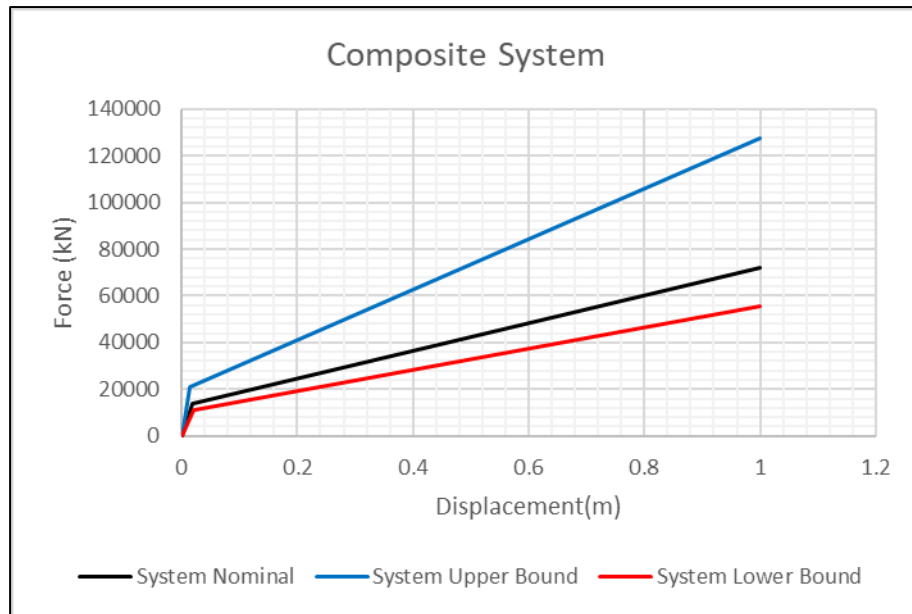


Figure 5.82: Composite system backbone with corresponding upper & lower bound properties.

5.4.3. Analysis and Results

The isolators are modelled as link elements and added to 3D finite element model of 20 story structure. Analysis of isolated structure have been conducted with scaled earthquake records. Total 7 pairs, and using each pair on both x & y directions, in total 14 time history analysis have been performed for every design level. Result tables and graphs are produced on the basis of average of maximums for every structural response that is taken into account. The criteria of assessment is for both sub and superstructure and summarized below;

- Base shear not exceeding 10% of the seismic weight at DD-2 level ground motions (Superstructure),
- Story drifts not exceeding $0.005h_i$ at DD-2 level ground motions (Superstructure),
- Displacement of isolation devices, so that the shear strain of the isolation device is less than 200% at DD-1 level ground motions (Substructure),
- Isolator compressive/tensile performance for DD-1 level earthquake (Substructure).

5.4.3.1. Superstructure Results

Superstructure results are given in this section, displaying shear forces, displacements and drifts on both perpendicular directions.

- Story Shear Forces at DD-2 Level

Obtained story shear forces are presented in this section. Mean Maximum base shears for the building is obtained as 36867.9 kN for X direction and 38840.5 kN for Y direction.

Table 5.63: Average story shear forces for base isolated building for x and y directions.

	Force (kN)	
	X Dir.	Y Dir.
Story20	1703.74	1794.89
Story19	3554.48	3744.66
Story18	5405.23	5694.43
Story17	7255.98	7644.2
Story16	9106.72	9593.97
Story15	10957.5	11543.7
Story14	12808.2	13493.5
Story13	14659	15443.3
Story12	16509.7	17393
Story11	18360.5	19342.8
Story10	20211.2	21292.6
Story9	22061.9	23242.4
Story8	23912.7	25192.1
Story7	25763.4	27141.9
Story6	27614.2	29091.7
Story5	29464.9	31041.4
Story4	31315.7	32991.2
Story3	33166.4	34941
Story2	35017.2	36890.7
Story1	36867.9	38840.5

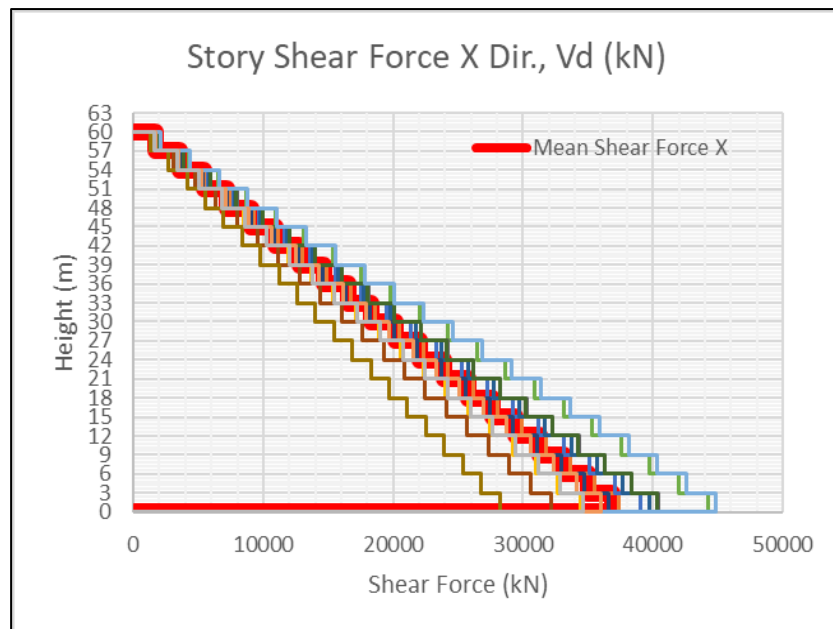


Figure 5.83: Story shear forces x direction.

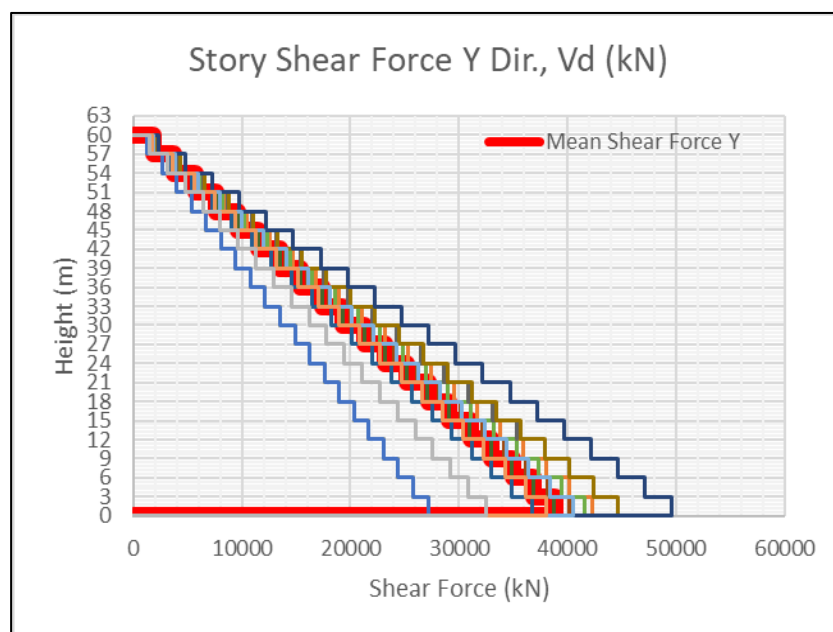


Figure 5.84: Story shear forces y direction.

- Story Displacements at DD-2 Level

Obtained story displacements are presented in this section. Mean Maximum displacements for the building is obtained as 142mm for X direction and 179 mm for Y direction

Table 5.64: Average story displacements for base isolated building for x and y directions.

	Displacement (mm)	
	X Dir.	Y Dir.
Story20	142	179
Story19	138	170
Story18	134	161
Story17	130	151
Story16	125	141
Story15	119	131
Story14	113	121
Story13	106	110
Story12	98	99
Story11	90	88
Story10	81	77
Story9	72	66
Story8	62	56
Story7	52	46
Story6	42	36
Story5	32	27
Story4	23	19
Story3	15	12
Story2	8	7
Story1	3	3
Base	0	0

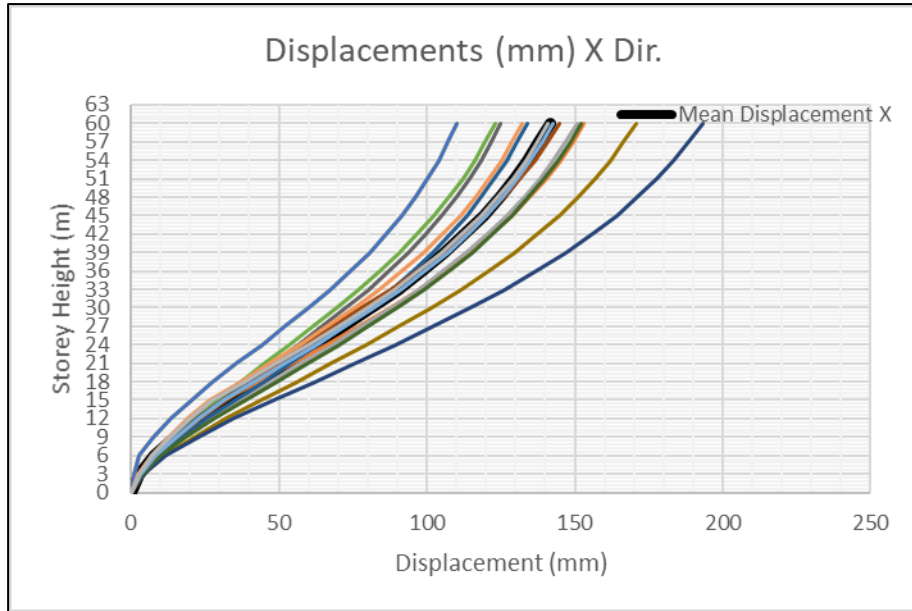


Figure 5.85: Story displacements x direction.

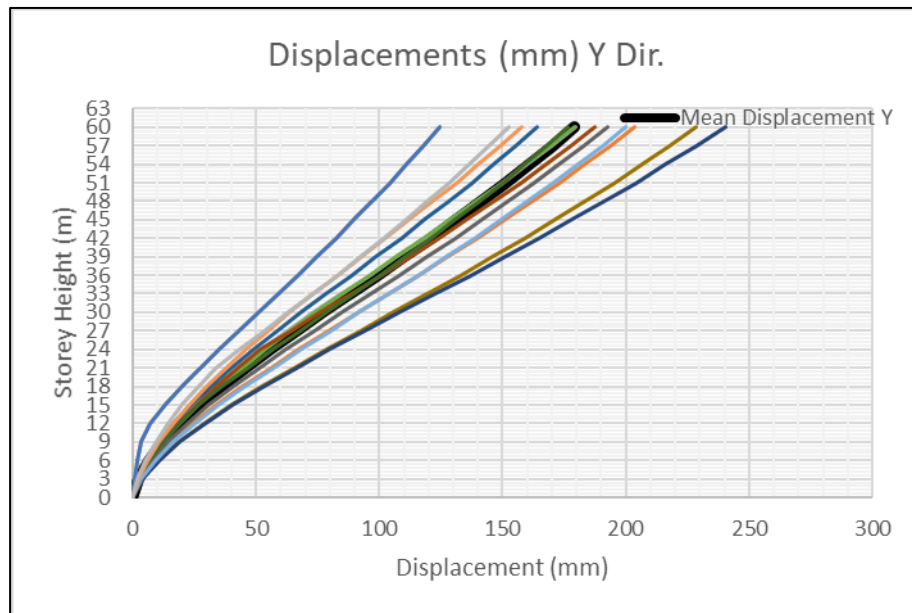


Figure 5.86: Story displacements y direction.

- Story Drifts at DD-2 Level

Obtained story drifts are presented in this section. Mean Maximum displacements for the building is obtained as 0.004446 for X direction and 0.004336 for Y direction

Table 5.65: Average drifts for base isolated building for x and y directions.

	Drift	
	X Dir.	Y Dir.
Story20	0.001417	0.003121
Story19	0.001542	0.003196
Story18	0.001704	0.003281
Story17	0.001899	0.00338
Story16	0.002117	0.003486
Story15	0.002347	0.003592
Story14	0.002583	0.003693
Story13	0.002818	0.003783
Story12	0.003049	0.003855
Story11	0.003268	0.003915
Story10	0.003469	0.00395
Story9	0.003643	0.003948
Story8	0.003781	0.003902
Story7	0.003867	0.003803
Story6	0.00388	0.003639
Story5	0.003796	0.003399
Story4	0.003577	0.003063
Story3	0.003153	0.002609
Story2	0.002415	0.001983
Story1	0.001386	0.00124
Base	0	0

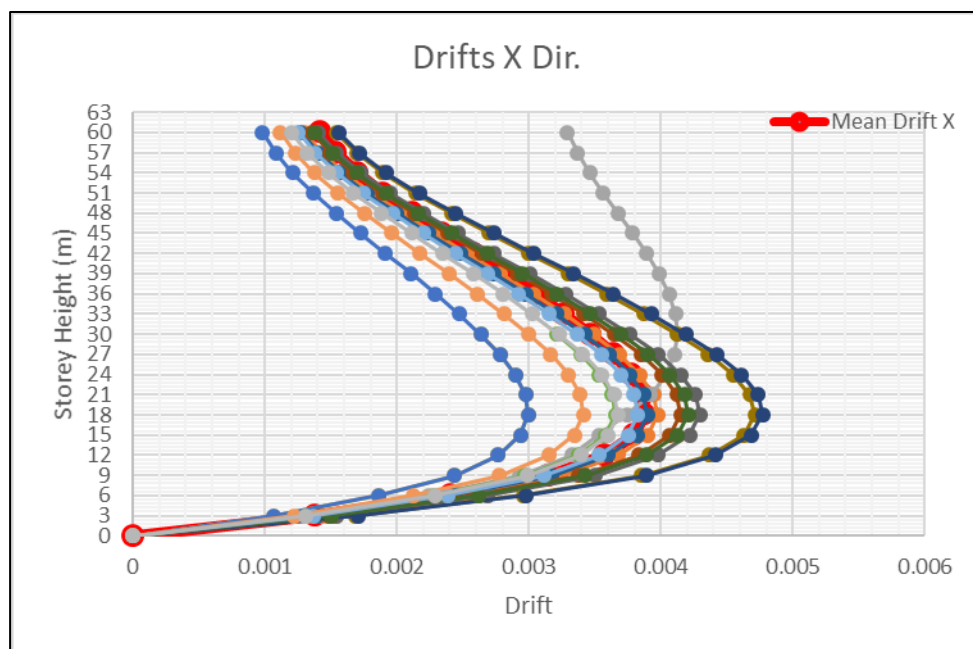


Figure 5.87: Story drifts x direction.

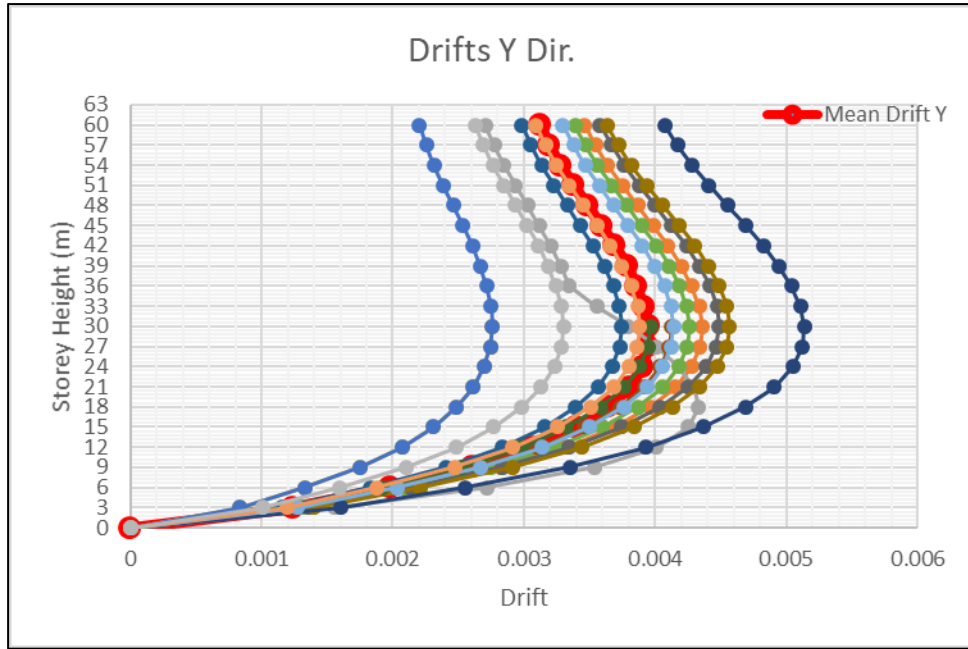


Figure 5.88: Story drifts y direction.

5.4.3.2. Substructure Results

Substructure results are given in this section, displaying mean and maximum displacements at isolation level and maximum shear and axial forces, for isolators.

- Maximum Displacements at DD-1 Level

This section yields maximum displacements and mean of the maximum displacement. Maximum displacement is obtained as 777 mm for 1148-B record, and shown in the following graph.

Table 5.66: Maximum displacements for base isolated building for x and y directions.

Record		Maximum SRSS Disp. (mm)
731	A	251
731	B	318
1148	A	1839
1148	B	1852
838	A	489
838	B	465
1163	A	454
1163	B	477
827	A	548
827	B	572
776	A	362
776	B	334
15	A	224
15	B	223
Average of Max.		601

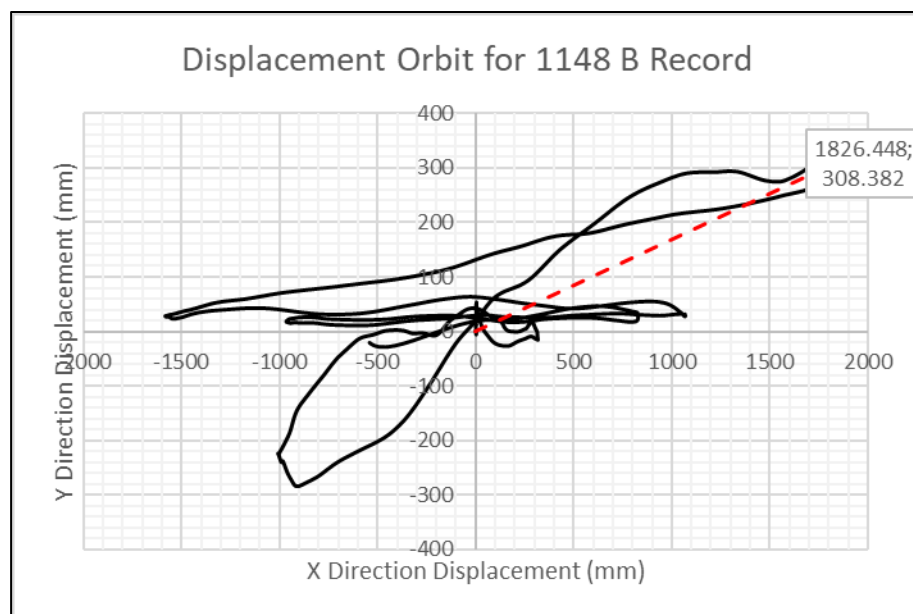


Figure 5.89: Displacement orbit for 1148-b record.

- Maximum Bearing Axial Forces at DD-1 Level

In this section, maximum axial loads (compression, tension) for isolator bearings are presented. Axial loads are very crucial especially for lead rubber

bearings. Mean of the maximum compressive axial load for lead rubber bearing is obtained as 18939.9 kN while 722.5 kN of tensional force is obtained.

Table 5.67: Maximum lrb compressive forces.

Lead Rubber Bearing Axial Forces - Compression		
Record		Maximum Axial Force (kN)
731	A	-15605.1
	B	-15179.5
1148	A	-35596.6
	B	-25237.3
838	A	-18438.5
	B	-18423.8
1163	A	-15209.3
	B	-16423.1
827	A	-19547.0
	B	-17726.1
776	A	-17183.3
	B	-17933.3
15	A	-16538.4
	B	-16117.7
Average of Max.		-18939.9

Table 5.68: Maximum lrb tensile forces.

Lead Rubber Bearing Axial Forces - Tension		
Record		Maximum Axial Force (kN)
731	A	-
	B	-
1148	A	487.3
	B	957.8
838	A	-
	B	-
1163	A	-
	B	-
827	A	-
	B	-
776	A	-
	B	-
15	A	-
	B	-
Average of Max.		722.5

Mean of the maximum flat sliding bearing force is obtained as 25962.9 kN.

Table 5.69: Maximum fsb compressive forces.

Flat Sliding Bearing Axial Forces		
Record		Maximum Axial Force (kN)
731	A	-19090.0
	B	-17117.8
1148	A	-53550.6
	B	-49317.9
838	A	-23760.1
	B	-23586.7
1163	A	-21492.3
	B	-23196.1
827	A	-27413.6
	B	-23379.0
776	A	-18885.0
	B	-25392.3
15	A	-18581.4
	B	-18717.4
Average of Max.		-25962.9

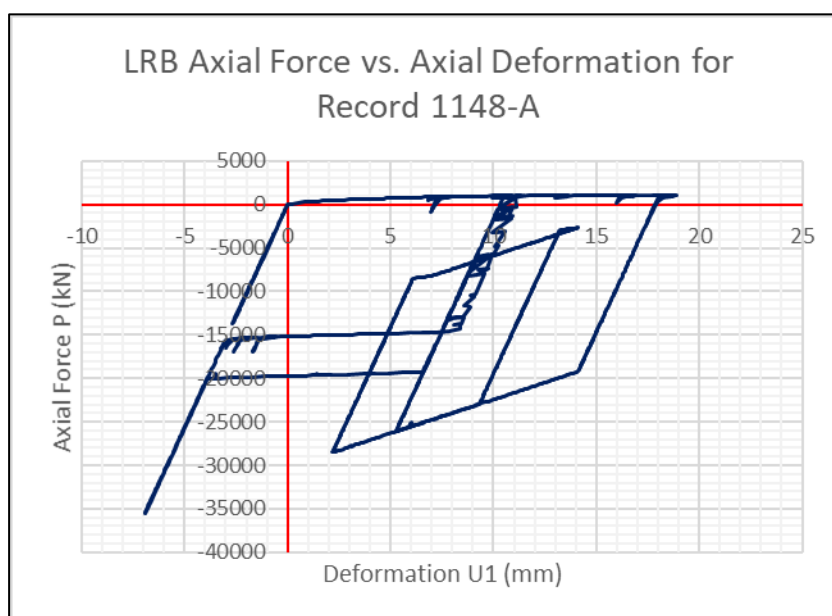


Figure 5.90: Lrb axial force vs. axial deformation hysteresis graph for 1148-A record.

Nonlinear shear behavior vs. lateral displacement for the lead rubber bearing is given in the following two graphs for both orthogonal directions.

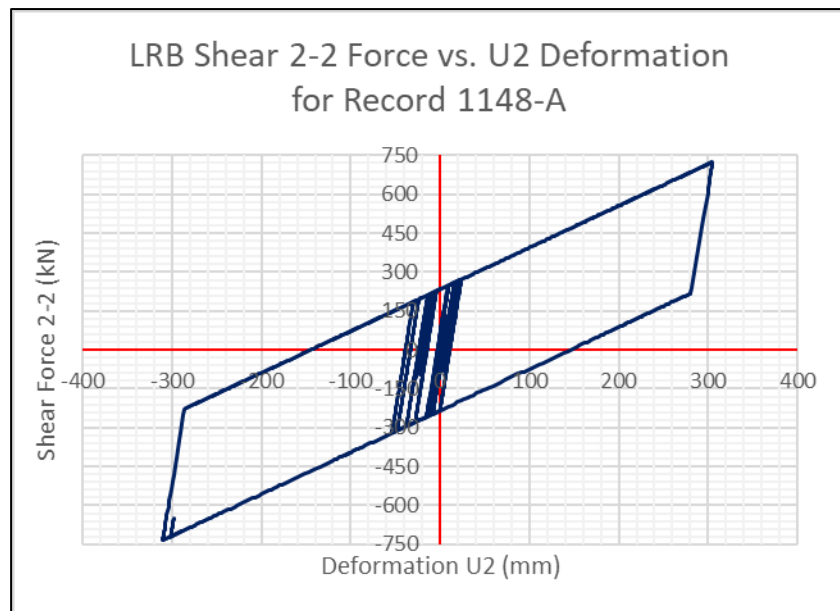


Figure 5.91: Lrb shear 2-2 force vs. u2 deformation hysteresis graph for 1148-A record.

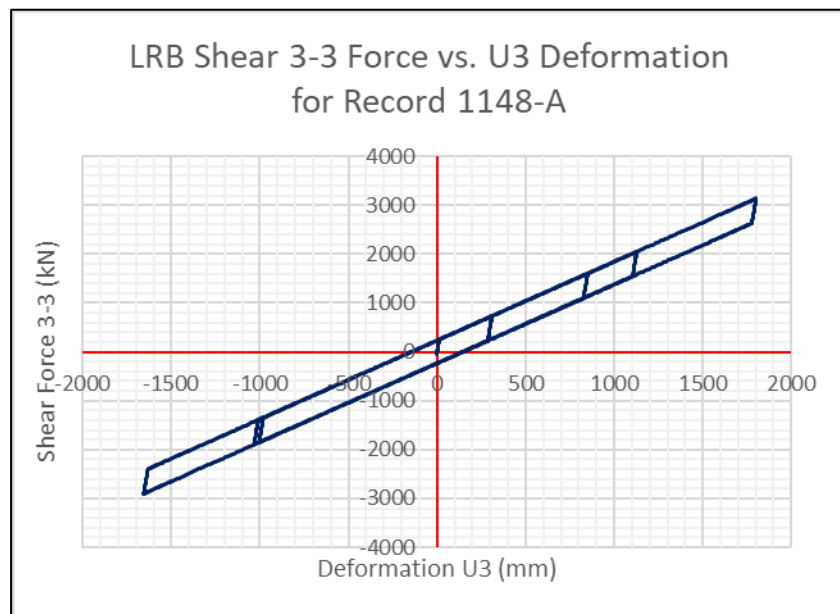


Figure 5.92: Lrb shear 3-3 force vs. u3 deformation hysteresis graph for 1148-A record.

Flat sliding bearing axial force vs. axial deformation results are given in the below figure. Note that flat sliding bearing has no tensional restraint thus there's no tensional force occurred in the bearing, also axial deformations are quite limited due to high axial stiffness of the flat sliding bearing.

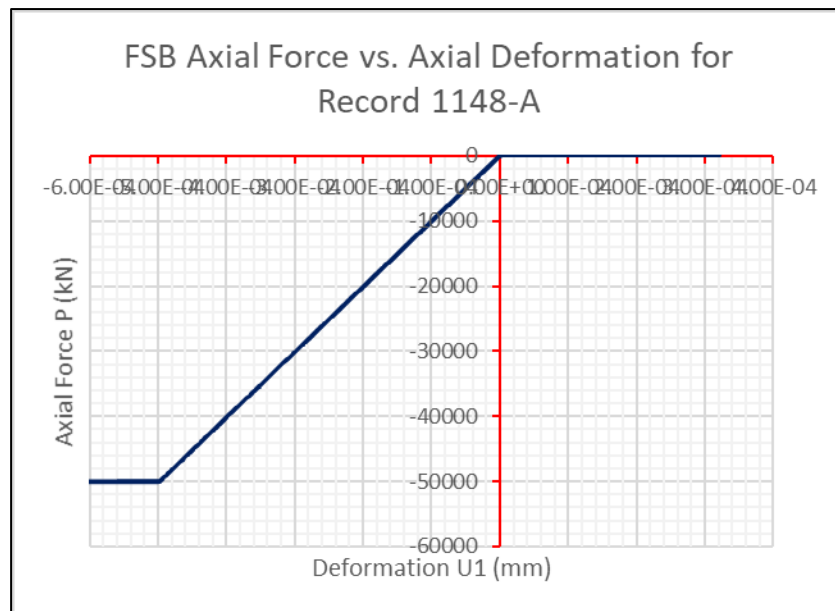


Figure 5.93: Fsb axial force vs. u1 deformation hysteresis graph for 1148-A record.

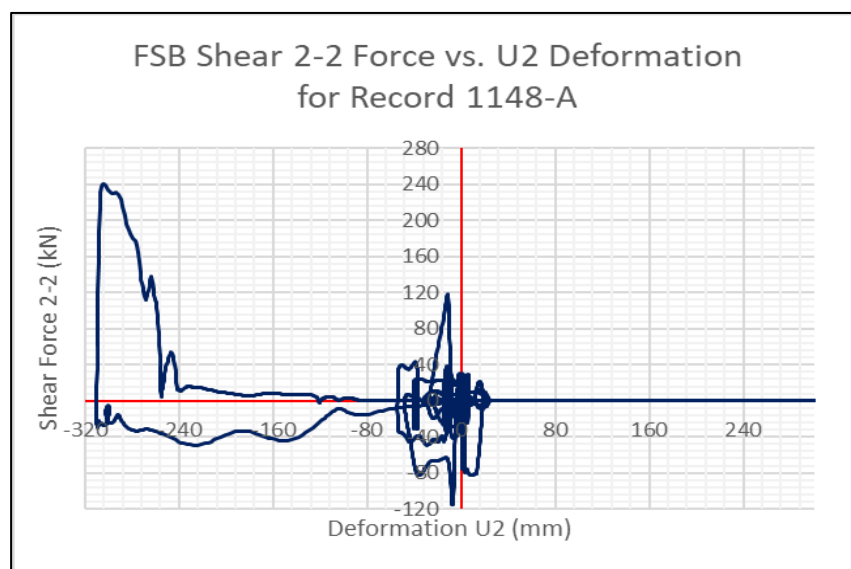


Figure 5.94: Fsb shear 2-2 force vs. u2 deformation hysteresis graph for 1148-a record.

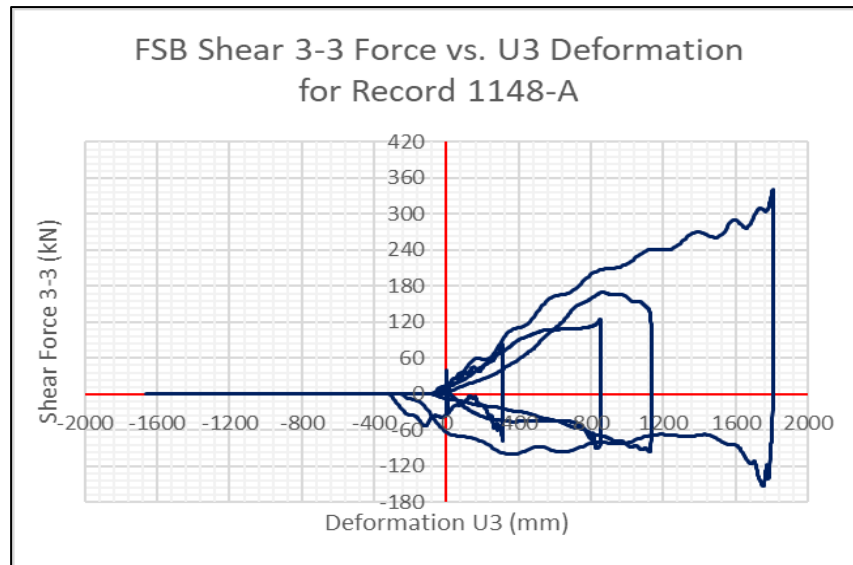


Figure 5.95: Fsb shear 3-3 force vs. u3 deformation hysteresis graph for 1148-a record.

Buckling controls of the lead rubber bearing can be done by calculating critical buckling load for each shear strain level. Below table shows critical buckling load at predefined shear strains and graph yields the axial force vs. shear strain history for the most critical lead rubber bearing with critical buckling load lines.

Table 5.70: Axial force vs. shear strain values corresponding to factor of safety=1.33 and factor of safety=1.00.

γ (%)	$P_{\max}$ (kN)	
	FoS=1.33	FoS=1.00
0	60033	79843
50	48312	64255
100	36876	49045
200	16316	21461

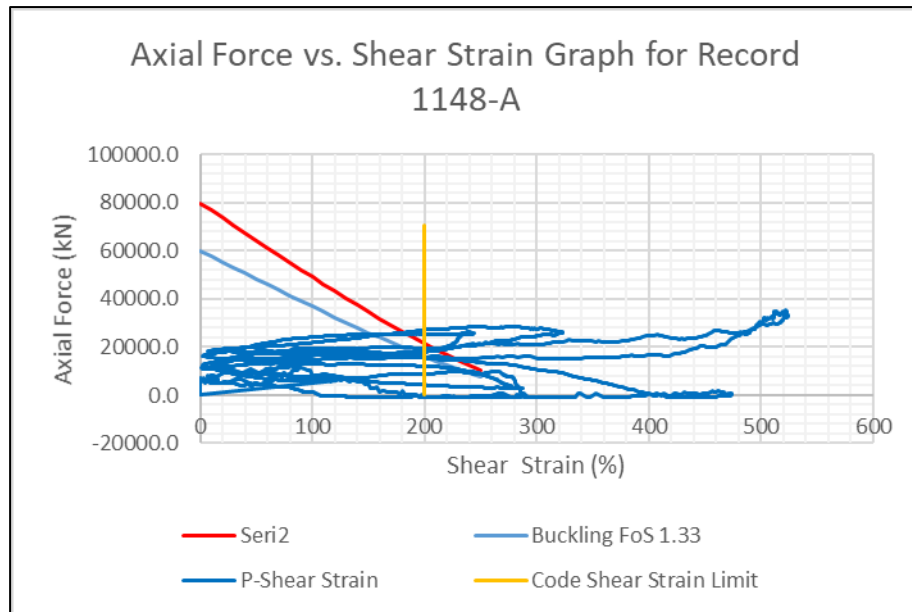


Figure 5.96: Lrb axial vs shear strain results for 1148-a record.

5.3.3.3. Comparison of Isolated and Fixed Base Structure

- Base Shear

The elastic base shear comparison for fixed and isolated structures is presented with following two graphs. It can be seen that for DD-2 level earthquakes the isolated structure was exposed to almost same amounts of base shear force with its fixed base counterpart but the isolation system is failed to comply with the target base shear force which is 10% of the seismic weight (~24000 kN), again the base isolation produced a good pattern for force distribution over the height of the structure.

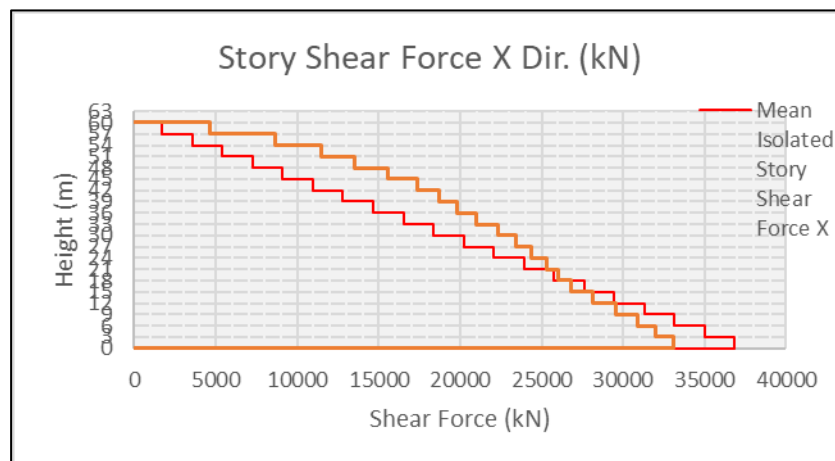


Figure 5.97: Mean isolated vs. fixed base story shear forces x direction.

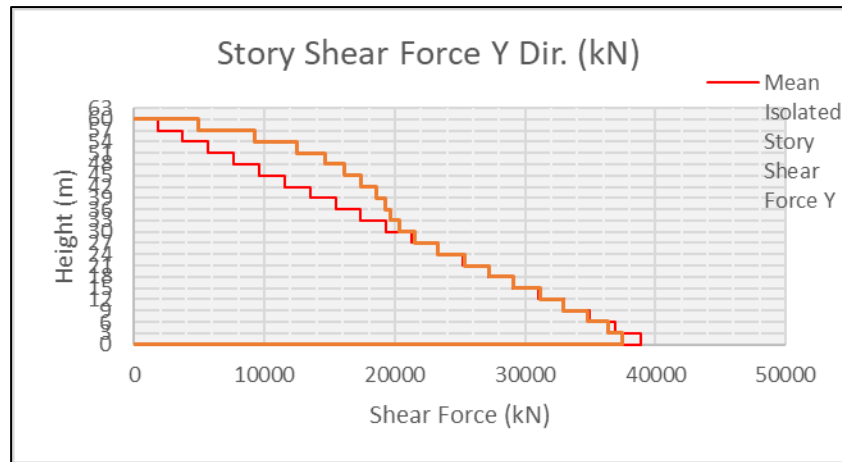


Figure 5.98: Mean isolated vs. fixed base story shear forces y direction.

- Displacement

Base isolated building have again reduced the displacement demand of its fixed base counterpart by reducing the displacement from ~250-230 mm to ~180-140 mm.

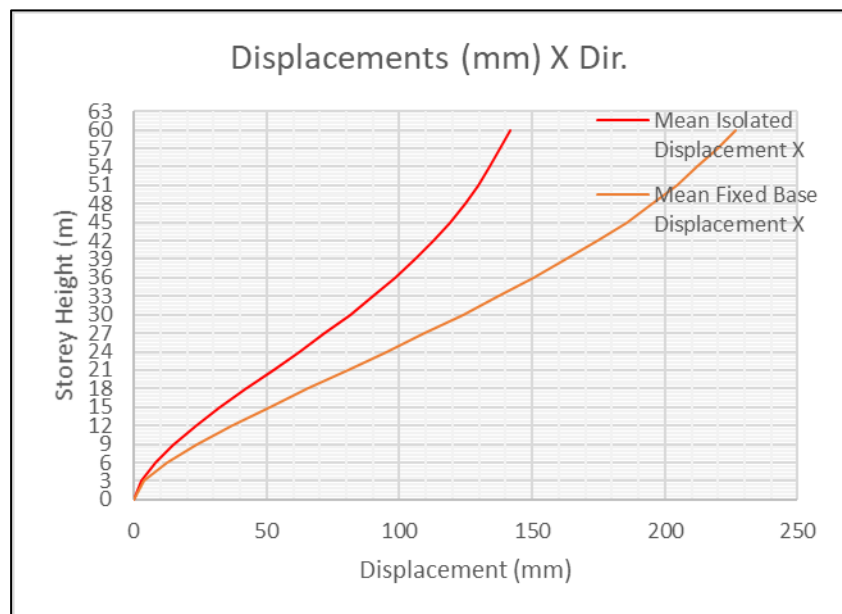


Figure 5.99: Mean isolated vs. fixed base displacements x direction.

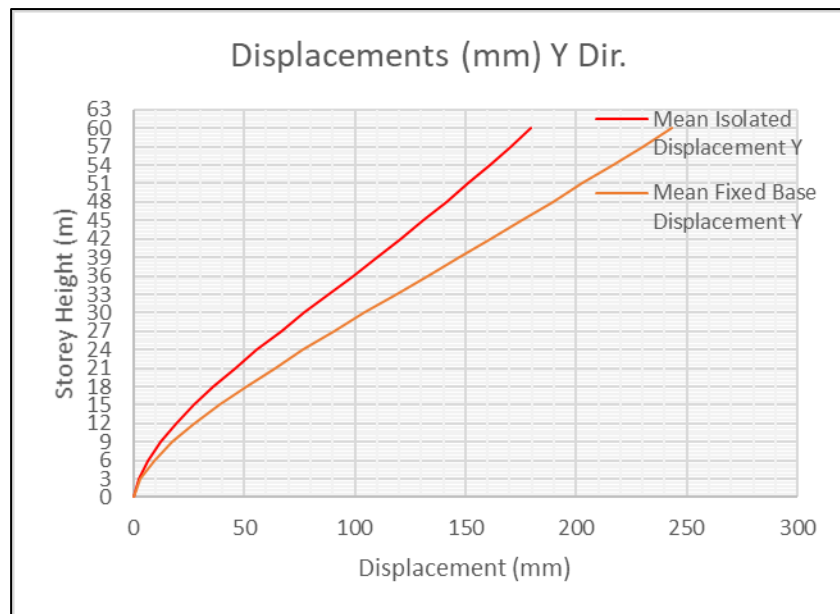


Figure 5.100: Mean isolated vs. fixed base displacements y direction.

- Drift

The structure is complied with the code limitation which is $0.005h_i$. The drifts of first 2 stories are almost the same but it is obvious that seismic isolation produced better results for higher stories.

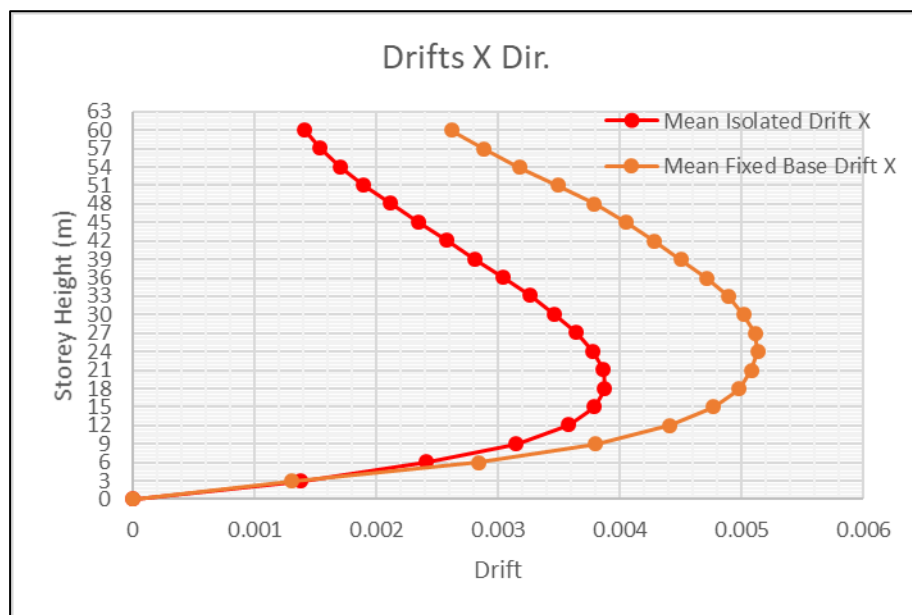


Figure 5.101: Mean isolated vs. fixed base drifts x direction.

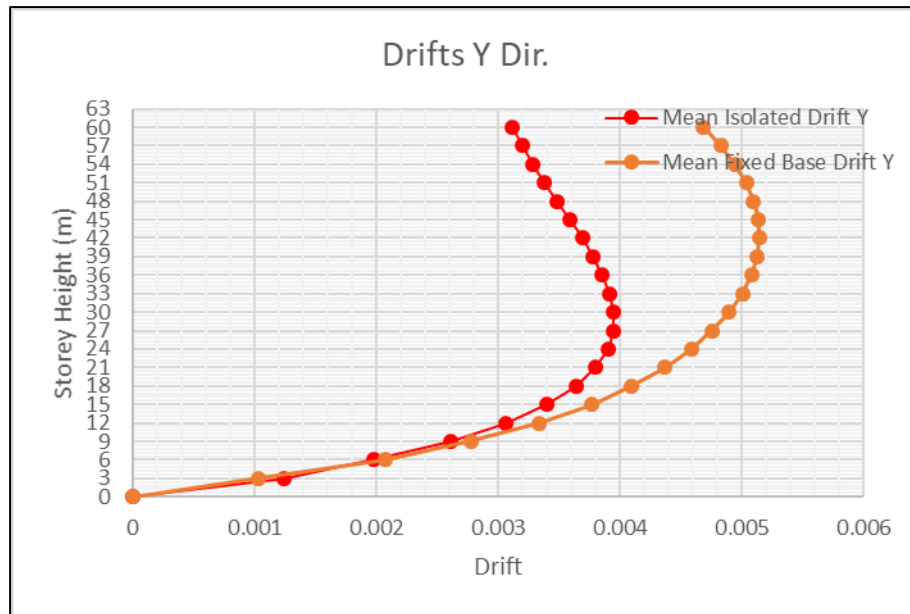


Figure 5.102: Mean isolated vs. fixed base drift y direction.

- Substructure

The average of maximum displacements at isolation level obtained from the nonlinear time history analyses is 0.601 m which is larger than the linear analysis result 0.437 m. The average of maximum axial loads for lead rubber bearing isolators have obtained to be 18940 kN which is almost the same as the linear design force 18260 kN, obtained from DD-1 level spectral analysis.

6. CONCLUSION

The purpose of this study was to understand the behavior and earthquake performance of seismically isolated mid height buildings. The question was aroused because the still draft Turkish Building Seismic Code '16 has a section that deals with the design of seismic isolation design. As a country which has some amount of buildings being mid-height and being built in areas which has high seismicity, the application of seismic isolation technology can be the answer for reducing the earthquake induced losses.

The theory of seismic isolation is well understood and practiced all around the world, it aims to separate the vibration of ground motion to the superstructure by elongation of period. This aim proved to be very successful for low to mid-rise buildings, because the rigid body behavior assumption is valid, on the other hand, for mid-rise buildings the assumption is not valid anymore. The more the height of the building, the larger the size of the isolators causing shorter isolated periods which then prevents the required separation of vibrational properties.

Analysis results have shown that, in terms of drift and displacement, adoption of seismic isolation nearly halved the displacement demand for 10 and 15 story buildings, however for 20 story building this did not seem to be the case. However, story shears seem to exceed the allowed/desired 10% of the seismic weight of the structure which was also the criteria for linear analysis and design of the seismic isolation system. Additionally seismic isolation seems to organize the distribution of story shear forces more regularly through the height of the structure, this is not the case for their fixed base counterparts because of the effect of “higher mode effects”. Analysis results for substructure have yielded that, nonlinear time history analysis have produced larger amount of displacement values than linear analysis. The gap between these two values were increased as the story number. This is thought to be caused from failing of rigid body behavior of the superstructure.

The isolator compressive bearing capacities for all three story structures are proven to be satisfying, but tensile behavior is observed for isolators under corner columns and perimeter columns of shear walls. Corner isolator tensile phenomena can be explained very easily by, being on the corner which causes the lowest axial force, and the being at the perimeter which causes being the furthest element on the

lever arm. However, the tensile forces of isolators under the columns closest to the shear walls is not very easy to catch. The effect of rocking behavior of shear walls deals some work on this area.

It seems that obtaining higher damping values (~20-25%) for this type of structures comes with a tradeoff, it shortens the structures natural period of vibration. If the period is desired to be lengthened, which can be done with lead rubber isolators by reducing the diameter of the lead plug, ending up lower damping values (~10-15%). This problem generally is overcome by using additional/supplemental damping devices, such as fluid dampers, creating the so called “hybrid systems”.

Finally, the statement that says “in-structure damping is more effective where seismic isolation fails” can very well be true. Further explorations and comparison could be produced in this area of study.

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BIOGRAPHY

Çağrı Dikmen was born in 1989 in the city of Ankara. After completing his high school education in Istanbul, he went to Sakarya University to get his bachelor's degree in civil engineering which he got in 2013. Later on, in 2015 he went to Gebze Technical University Graduate School of Natural and Applied Sciences Department of Civil Engineering Earthquake and Structural Engineering Program in order to get his master's degree. Currently, he's working for OSM Engineering and Consulting.