SEISMIC RETROFITTING COLUMNS AND BEAMS WITH CARBON-FIBER REINFORCED POLYMER USING ETABS17 TO RESIST EARTHQUAKE DRIFT AND MAGNITUDE ACCORDING TO BNBC 2020

By

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A thesis submitted to the Department of Civil Engineering in partial fulfillment for the degree of Bachelor of Science in Civil Engineering



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Section: 22C

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DECLARATION

It is hereby declared that this thesis/project or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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Dedicated

to

"In the name of Allah, the Most Gracious, the Most Merciful.
To my beloved family and cherished teachers,
We dedicate this thesis to you with profound gratitude. Your unwavering support, encouragement, and wisdom have been my guiding lights throughout this academic journey. May Allah bless you abundantly for your kindness, patience, and dedication.
To our parents, who sacrificed so much to provide us with education and love, we are forever indebted. Your prayers and blessings have carried us through every challenge.
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To our thesis supervisor and our Co-Ordinator Kushal Acharja Topu sir as he helped us completing our thesis, we dedicate this thesis, as his courage gave us the motivation to climb up the ladder and keep our courage at peak.
Also, we would like to dedicate this thesis to our former Co-Ordinator and lecturer Md. Rakib Hossain sir currently on his M. Sc. Degree at King Fahad University of Petroleum and Minerals, Dhahran, Saudi Arabia, as he helped us completing this thesis project and gave us instruction to achieve our goal.
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May this work be a reflection of the knowledge imparted by our teachers, the love bestowed upon us by our family, and the divine wisdom granted by Allah.
Bismillah.
Obediently Yours,
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Mostafizur Rahman Sagar

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Sumia Akther Oyshe"

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ABSTRACT

Bangladesh, as a developing country is on a brink of earthquake disaster as it sits on 3 of the tectonic plates. So, this study investigates seismic drift and earthquake response limit according to moment magnitude method of a four storied RC building and stair room roof as fifth story without and with carbon fiber reinforced polymer (CFRP) of Seismic Zone 3 according to BNBC 2020. The study has been done on a pre-existing building at Shimultoly, Joydebpur, Gazipur, Dhaka, Bangladesh. The building was made according to BNBC 2006. The results, as it turns out there were no displacements to be found and maximum drift in stories changes its value from story to story as there are some unusual differences between drifts in stories as, cases of drifts decreasing in the upper stories of building were found. Using CFRP, it decreases about 45%-53% of maximum story drift and resist earthquakes magnitude of 7 instead of magnitude o 6. As the building was constructed on 2019 it was built according to BNBC 2006 with some modification according to recent material types which is pretty much similar to recent BNBC 2020 code. So, an analysis has been done by ETABS-17 to find about displacement and drift of this building with and without CFRP according to BNBC 2020 standards and find out if this building can withstand earthquakes in all seismic zone of Bangladesh and if it can what will be limit of this structure’s earthquake response at the brink of collapse.

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CHAPTER 1
INTRODUCTION

1.1 Background and Motivations

Earthquake is a natural disaster occurring from time to time and sometimes causing disasters which are irreparable and life threatening and also causes deaths on an uncountable amount. On February 6, 2023, a 7.8 magnitude earthquake hit southern and central Türkiye and northern and western Syria at 04:17 am (local Türkiye time), causing over 50,000 deaths in Türkiye, recording as the number 5th most disastrous earthquake of 21st century [1] and around more than 8000 people in Syria[2] and lord knows how many were injured. On September 8th, 2023, a 6.8-magnitude earthquake struck central Morocco at 11:11 pm local time. It resulted in 3000 fatalities and over 5000 injuries [3]. After passing 19 minutes of the main shock an aftershock of 4.9 magnitude was felt [4]. In September 28, 2018, Indonesia suffered an earthquake if 7.5 causing death of 2,700 people, almost 156,000 houses destroyed or damaged, and more than 930,000 people affected cause of the tsunami that occurred cause of the earthquake [5]. There are many other cases of disastrous earthquake in the region of Asia. The deadliest earthquake of the 21st century occurred in Indonesia on December 26, 2004. With a magnitude of 9.2-9, it claimed over 227,000 lives. Additionally, impacted were Sri-Lanka, India, and other nations [6]. Many more earthquakes have structed the Asian region in this 21st century and to ensure safety of people and property it is essential to build our home and houses according to regional mapping properties of land and make them earthquake resistant.

Most of the disastrous earthquake of 21st century has structed the regions of Asia and Bangladesh a developing country of Asia is no different from the risk of extreme magnitude of earthquake. Bangladesh in this 21st century has felt some earthquakes from magnitude from 4.5 to 6.2[7]. Although there weren't that disastrous there has been cases of injuries of more than 200 people in each earthquake. Also, Bangladesh happens to be most tectonically active regions in the world as it sits where three tectonic plates meet, the Indian Plate, the Eurasian Plate, and the Burmese Plate [8]. So, it is most important to make buildings strong and earthquake resistant according to the recent BNBC 2020 (Bangladesh National Building Code-2020). But what about the buildings before that or the ones that are poorly constructed. Retrofitting is one of the options that can be done for reinforcing the columns and beams. There are some ways to retrofit column and beams but some of them affect the bearing capacity of column and beams as well as increase the total dead load of the constructed building. For example, RC rebar, and

steel plate retrofitting are ways to increase the capacity of building as well as the increase the total weight of building causing increase in dead load of building [9]. But another way of retrofitting is CFRP (Carbon fiber reinforced polymer). CFRP are most effective way to reinforce pre-existing column and beams also way to reinforce new building for future prevention of any disasters. As CFRP is lightweight and flexible it is easy to use there is no need of any concrete damaging, carving or breaking [10]. You just need epoxy and carbon fiber rolls which can be applied by one or two experienced workers and an engineer with knowledge of this kind of retrofitting. As carbon fiber is flexible and lightweight, though it becomes harder than steel and CFRP are also used to make airplane body, bullet resisting armor and it has 3 or 4 times more tension force then of a normal steel plate [11]. Retrofitting with CFRP may be costly but it is effective and safe to use on concrete beams and columns and it is most effective for resisting for its flexibility and tension force properties.

1.2 Research Objectives and Overview

Our research focused on reinforcing a building made before the BNBC 2020 to know if the building is accurate and will it be able to withstand earthquake lateral loads and the drift caused by that load according to BNBC 2020. This procedure contains involvement of analysis software which can give us results of drift analysis and how to reinforce if we need to use reinforcement to resist the earthquake drift. So, our main objectives for this study involves are buildings made according to BNBC 1993/2006 accurate according to BNBC 2020? Will those buildings be able to withstand the lateral earthquake loads of the four seismic zones of Bangladesh? And if they cannot what kind of reinforcement can be used which will not affect the total weight of the buildings as well as it will reinforce the building vastly as the four seismic zones of Bangladesh as the seismic zone factors are the main factors that defines how much of lateral load will be applied and they will give us moment and acceleration to every story of building. According to that lateral load and zone factors our drift results will vary and we shall compare it with BNBC 2020 drift requirements so that we can verify if the building will be able to withstand the drift caused by lateral load. According to some of previous study and availability of post reinforcement procedure for an existing buildings column and beams, there are several ways like retrofitting of steel plates, using RC layer to reinforce, using steel angle sections in corners. As there are many ways to reinforce there are some limitations as RC reinforcements, steel plate retrofitting and steel angle on corners these procedure increases dead weight of building and we can only retrofit columns using these methods and even if we retrofit beams its possible there will be crack on the cement layer which will be used to hide these

retrofits. As a result, there may be some complications for retrofitting in beams. But another method of reinforced retrofitting is using of FRP material like Carbon Fiber Reinforced Polymer (CFRP). This CFRP can be used to retrofit columns, beams as well as slabs to increase the load bearing capacity and also reduce drift and acceleration of upper stories without changing much of the self-weight of the building. Also, an analyzing software is in need to find the drift and acceleration of the building. For this, we chose ETABS-17 software as it met our analysis procedure and results requirements procedure.

According to our procedure of work and looking at previous studies our main goal of this study are,

- To assess if buildings built under BNBC 1996/2006 can resist lateral loads per BNBC 2020.
- To identify suitable CFRP types to reduce story drift.
- To analyze the impact of CFRP retrofitting on structural performance.
- To evaluate if retrofitting meets BNBC 2020 standards.
- To investigate noticeable changes in earthquake magnitude scales during earthquakes.
- To identify future research directions in earthquake resistance and retrofitting.

1.3 Organization of the thesis

Chapter 1: Introduction and Objective

Our study focused on recent events of earthquake which struck, and made a destruction and it can be seen that earthquake magnitude which are 6 and greater are able to do destruction and it can be prevented just by making the building reinforced. As no building is earthquake safe it has to be resistant to a limit where it will give safety to the people living in the building and one way to ensure it is drift check. Which is commonly used and effective in all places as earthquake hits the structure has to take that shaking and be in the same shape after a drift in a certain period of time. So, our study focused on drift as well as what will be the magnitude of earthquake in the brink of collapse if any disasters happen. So, we decided retrofitting method with CFRP as recently it has become popular and for data analysis, we chose ETABS 17 as its basic but accurate software out there for structural analysis.

Chapter 2: Literature Review

Previous earthquakes show from magnitude 1-5 may not be devastating but is able to do some damage to structure and earthquakes 6 to higher are the devastating one as they hold much power to destroy poorly build buildings and able to do great damages. As our further research, retrofitting is an effective way to secure damaged beam and columns and it is able make the structure strong to resist earthquake.

Chapter 3: Methodology

To achieve our main goal, we collected data of a previously built 4 story building on Gazipur which is in seismic zone 3. The building had irregular dimension on slab as well as its column and beams are different. So, this building was chosen for this study and we used ETABS 17 to analyze the model and get results. But CFRP properties is not naturally implemented in ETABS 17. Also, BNBC 2020 is not present on ETABS 17 so we used user reference on ETABS 17 and described what we want to do.

Chapter 4: Results and Discussion

Found results show that our structure is normally in acceptable ratio in case of drift check and is able to withstand earthquake as it has no displacements in case earthquake hits because of its drift ratio is lot less than its limited drift. Also, as earthquake resistant property the magnitude of earthquake resistance is in a standard value to ensure safety of the people living in the building and after retrofitting drift reduces vastly as well as resistance of earthquake power is 10 times greater than before.

Chapter 5: Conclusions and Future Work

As our study ends, we find that this building on seismic zone 3 has great potential to resist earthquake and retrofitting with CFRP will give it more potential to resist earthquake. But we saw a change in drift as it is increasing it decreases on upper floor and then again increases. This needs further study as why this happens.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

The recent earthquake of Türkiye and Syria which came with a price of more than 50,000 people's deaths caught attention of the whole world. As Bangladesh in brink of earthquake disasters while sitting on 3 of the tectonic plates it's also in the Asia region as many earthquakes struct this region recently it has become essential to make structures earthquake resistance for safety of every individual lives. So, according to BNBC 2020 it is possible to build recent buildings earthquake resistance using reinforced concrete structure as it is in the BNBC 2020 manual. But for structures before BNBC 2020, we found retrofitting is an efficient way to increase the capacity of building as many types of retrofitting has been done and tested on many buildings using many simulations software and practically on building as well as recent structural engineers suggest retrofitting with FRP (Fiber reinforced polymer) like SFRP (Sisal fiber reinforced polymer), CFRP (Carbon fiber reinforced polymer), GFRP (Glass fiber reinforced polymer) for buildings for making them earthquake resistant for the future. As for how to verify it will become earthquake resistance. For existing structure, a simple and effective way is use of analysis software like CSI ETABS, SAP2000, STAAD or Simulia Abaqus. As there were some studies related to study retrofitting of SFRP as retrofits using ETABS analysis software there are some studies focused on CFRP and GFRP retrofits as ETABS do have property for steel plate retrofitting but do not have a property for carbon fiber and glass fiber retrofit. But it is possible to make steel property to behave like carbon fiber or glass fiber as it is possible to change the modulus of elasticity and tensional force on etabs material data. Using this as advantages ad taking idea from previous works of ETABS which focused on drift analysis, time analysis, response spectrum analysis, and pushover analysis and using the drift limit for earthquake according to BNBC 2020 rules and equations this study focused if the drift limit is in limit to prevent earthquake sway/drift if an earthquake occurs according to all seismic zones of Bangladesh.

2.2 Content

Bangladesh, as it sits on the meeting point of three tectonic plates, the Indian plate, The Burmese plate and the Eurasian plate, considered as most tectonically active region in the world and as recently the occurrence of earthquakes has increased it is essential to ensure safety of

people and structure. To ensure safety of old structures which are in kind of good condition, retrofitting is a process to follow as there are many types of retrofitting process exists. But there are limitations and some things to consider as,

- Cost for retrofitting.
- Changes of dead weight.
- Possibility of corrosion.
- Future response in case of earthquake.

Considering these things, the kinds of retrofitting and their limitations are,

I. SFRP (Sisal fiber reinforced polymer).

This kind of fiber are found easily as rope fiber, coconut fiber, papers, and other wastage which then collected and produced as sisal fiber polymer and then cut in sheet fiber. These kind of fiber polymers are easily found and cost are less then every other fiber polymer and retrofitting materials. As these are easily found these have some limitations due to its elasticity and its organic property. As it has low limit of plasticity and elasticity. Due to this reason this polymer has low bearing capacity and as these are organic materials these polymers dissolves after a while and if we use this with concrete it will dissolve and make a hollow which may result in crack later.

II. GFRP (Glass fiber reinforced polymer).

Glass fiber reinforced polymer are thin layer of sheet like sand paper but not thick like sand paper. Usually, 0.05mm thick and used wrapping 2 or 3 layers together. GFRP are mostly used on inner layer of column and beam with rebars as GFRP is a sandy sheet it bonds when mixture of concrete when its poured. Also, as wrapping on the outside GFRP works a catalyst to ensure there will be no crack after making of column or beam. GFRP also have some limitations as this kind of FRP must be applied while or instant after finishing of settling time but yes it can also be used after construction but as GFRP do not have a higher plasticity it may not work as well as it should while it bonding with concrete will not be possible.

III. CFRP (Carbon fiber reinforced polymer).

CFRP is one of the most used FRP material for its plasticity and flexibility. This is also a thin layer of sheet like GFRP and can be used with rebar or outside of concrete slab, column and beam and it’s one of the best ways to retrofit any crack or to ensure future crack prevention. This kind of retro fit method maybe one of the best ways but this CFRP has one limitation that is cost. CFRP are usually so highly cost. For example, 100meter roll cost about 200USD. So

not everyone can buy CFRP and use this to reinforce their building. This is mostly used for larger project which have a large amount of cost.

IV. Steel plate retrofitting.

Another one of the mostly used retrofitting method is steel plate. It is used in four corners of the column or used in four directional ways of a column as steel plates. This kind of retrofitting is costly but not as costly as CFRP. Though it is not as good as CFRP's elasticity limit and steel plates are irresistible to corrosion. Also, steel pates will increase the dead weight of the building as to hide the steel plate an extra thick layer of concrete has to be used.

According to our limitations it can be seen CFRP may be costly but its long lasting, corrosion less, no risk of breaking or dissolving, and its high elasticity limit will not let any crack form and CFRP sheets are becoming popular recently for its high elasticity and its ability to resist earthquake and lateral drifts, displacements, and acceleration. Many software like ABAQUS, SIKA let's do analysis according to CFRP properties as it has integrated CFRP properties materials. But software like ETABS or SAP do not have these properties. Although it is possible to define materials according to their elasticity property, tension and compressibility properties we were able to determine CFRP properties and using the idea from previous few of the works from researches this was determined as the most effective way to retrofit.

2.3 Summary

Earthquake, recently it's been very frequent and it may not be felt that much but if its magnitude is greater than 5 it can do irreparable harm. For example, 2023 earthquake on Türkiye-Syria earthquake was 7.8 magnitude which epicenter was Türkiye and it hit Syria with a magnitude of 5 with an aftershock and it did a leave devastating history for both Türkiye and Syria. So, retrofitting previously build structures are recommended after a certain period of time. As, retrofitting with CFRP is now becoming popular and CFRP are recently getting cheaper it will be widely used in the near future and some researchers are working on it. But to use this CFRP to its fully potential and to know and recognize its full strength there must be some way to use it to its full potential which we tried to do and it will be discussed in our next chapter of methodology.

CHAPTER 3
METHODOLOGY

3.1 Introduction

For this study specific type of building has been selected which was built before 2020. Also, the building holds an irregular dimension of slab and column and beam dimensions along with an irregular grid placement. As regular dimensional buildings hold a uniform load transfer property it is recommended to use an irregular dimensional building for analysis as it will clarify any kind of irregular problems found in buildings as there was in this study which are discussed later on. Also, we had to find what kind of CFRP is available in Bangladesh as CFRP's are way too costly to be available normally. For analysis of the building using CFRP analysis software CSI ETABS 17 was used. The results we considered are story drift and acceleration analysis with the response spectrum analysis according to the time period mentioned in BNBC 2020.

3.2 Methodology Overview

This research paper is done by ETABS-17 analysis with a pre-existing building made on 2019 on Gazipur, Dhaka. This analysis contains drift check of each story and results of how much a CFRP can strengthen a building.

3.2.1 Study Area

The building is 58ft (17.6784m) tall with five stories (includes stair room roof as one story), each floor is 10ft (3.048m) tall and the foundation is 8ft (2.4384m) from the foundation base. The study has been done on an existing building at Shimultoly, Joydebpur, Gazipur, Dhaka on Seismic Zone-III (seismic intensity: severe). It has zone factor of Z=0.28.

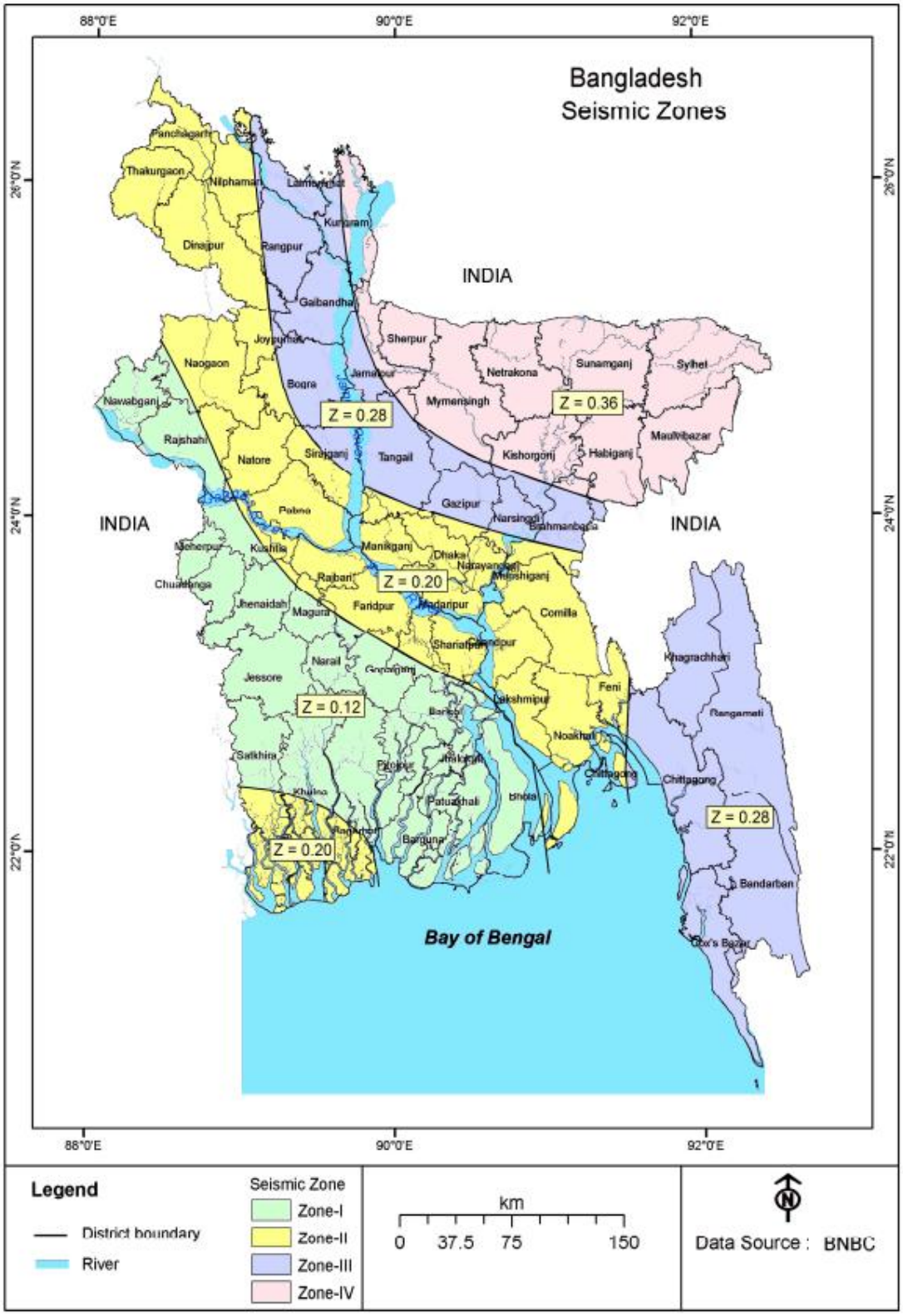


Figure 3-1. Seismic zone of Bangladesh

3.2.2 Data Collection

The data collection method consists of 5 steps work.

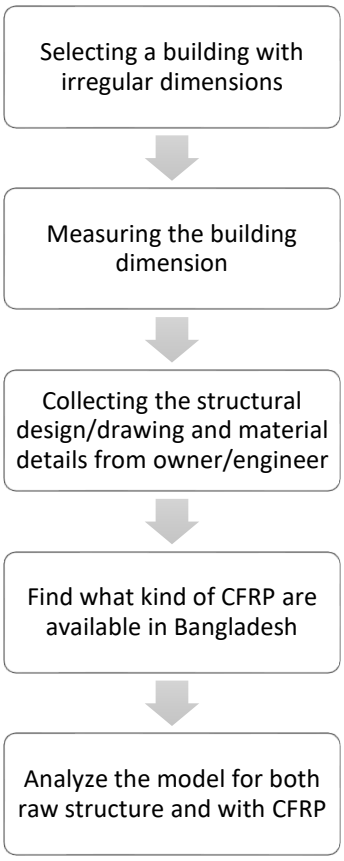


Figure 3-2. Methodology of Data Collection.

3.2.3 Material details

Materials used in this model was according to BNBC 2006 but with some modifications to make the structure stronger. This gives us the opportunity to praise the engineer who designed this was well aware about seismic loads and took precaution to prevent any disasters. The material properties used in this building are,

Table 3-1: Type of Concrete.

Type of concrete	Compression Strength (psi)
Column Concrete	3500
Slab Concrete	2500
Beam Concrete	3500

- Weight density of all concrete is 150 lb./ft^3

Table 3-2. Types of Rebar.

Type of Rebar	Tensile Strength (ksi)	Modules of elasticity (lb./in$^{2)}$	Minimum yield strength (ksi)	Minimum tensile strength (ksi)	Avg. yield strength (ksi)	Avg. tensile strength (ksi)
Main Rebar	72.5	29000000	72.500	108.75	79.750	119.625
Tie rebar	72.5	29000000	72.500	108.75	79.750	119.625
Rebar for stair	60	29000000	60.000	90.000	66.000	99.000

- Weight density of all rebar is 490 lb./ft^3

Table 3-3. Details for CFRP.

Type of Material	Tensile Strength (ksi)	Modules of elasticity (lb./in$^{2)}$	Minimum yield strength (ksi)	Minimum tensile strength (ksi)	Avg. yield strength (ksi)	Avg. tensile strength (ksi)
CFRP 1 (WFC 200)	450	32633490.99	450	675.513	495.376	743.064
CFRP 2 (WFC 300)	530	32633490.99	530	796.533	796.533	796.533

- Specific weight density of CFRP is 0.06. This information is provided by Shanghai wolfix new materials Co. Ltd. WFC-200 and WFC-300[12] CFRP sheets [12]. These properties are laminated properties as they are measured after using CFRP with epoxy adhesive.

3.2.4 Buildings Structural Design and Details

Table 3-4. Column Dimensions and reinforcements (Tie bars are 10mm bars).

Column Name	Column Dimensions and reinforcements			
	Base/Pile Column	G.F to 3rd Floor Column	4th floor column	Stair Room Roof Column
C1	23”x23”x13” (12-16 MM)	20" X 20" X 10" (12-16 MM)	20" X 20" X 10" (12-16 MM)	20" X 20" X 10" (12-16 MM)
C2	18”x18 (8-20 MM)	15" X 15" (8-20 MM)	15" X 15" (4-20 MM + 4-16 MM)	

C3	18"X21" (10-20MM)	15" X 18" (10-20 MM)	15" X 18" (6-20 MM+ 4-16 MM)	15" X 18" (6-20 MM + 4-16 MM)
C4	18" X 23" (8-20 MM + 4-16 MM)	15" X 20" (8-20 MM + 4-16 MM)	15" X 20" (8-20 MM + 4-16 MM)	
C5	18" X 27" (14-20 MM)	15" X 24" (14-20 MM)	15" X 24" (8-20 MM + 6-16 MM)	15" X 24" (8-20 MM + 6-16 MM)
C6	15" X 33" (14-16 MM)	12" X 30" (14-16 MM)	12" X 30" (14-16 MM)	

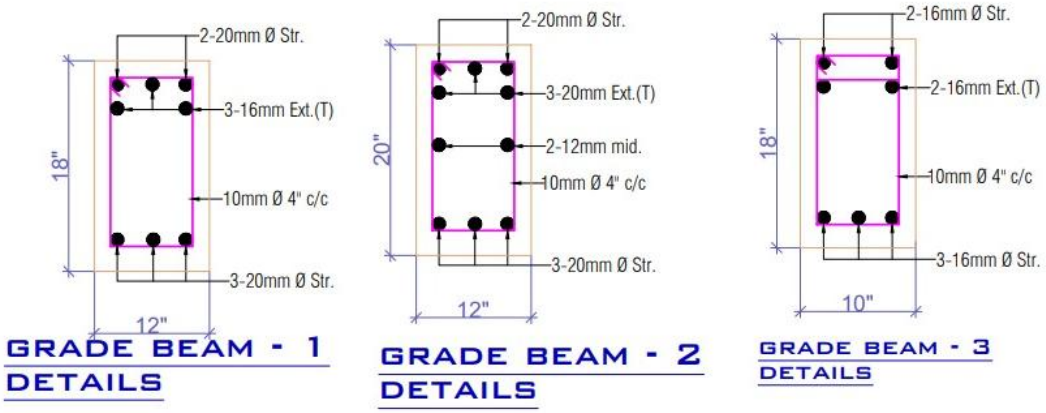


Figure 3-3. Grade Beam Details

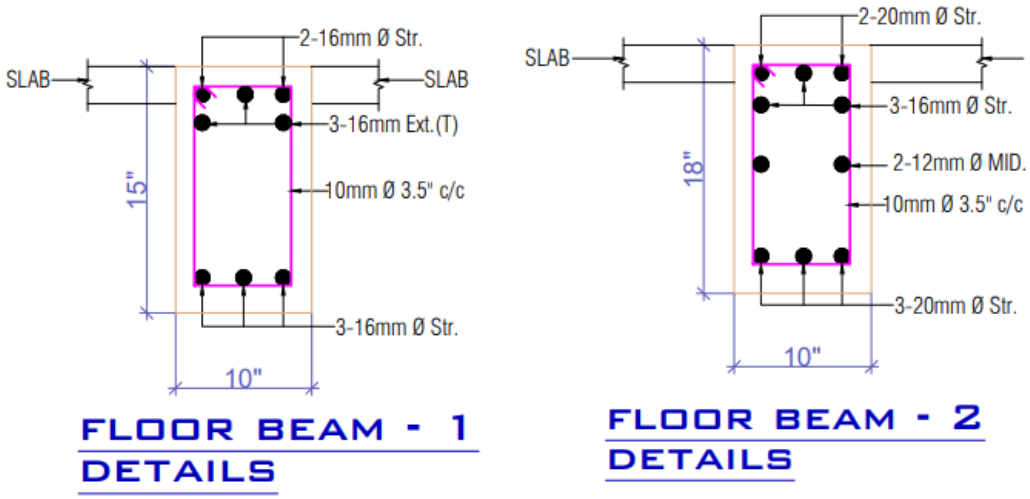


Figure 3-4. Floor Beam Details.

- Grade Beam 1 and Floor Beam 1 used as external beams
- Grade beam 2 and Floor Beam 2 has been used as internal beams.
- Grade beam 3 and Floor beam 1 has been used on L shaped column.

The building is on Seismic Zone-III with irregular type dimension. According to BNBC 2020 the structure type is Design Category III with plan irregularity type V [BNBC 2020, Sec 2.5.13.1; page 3226] [13].

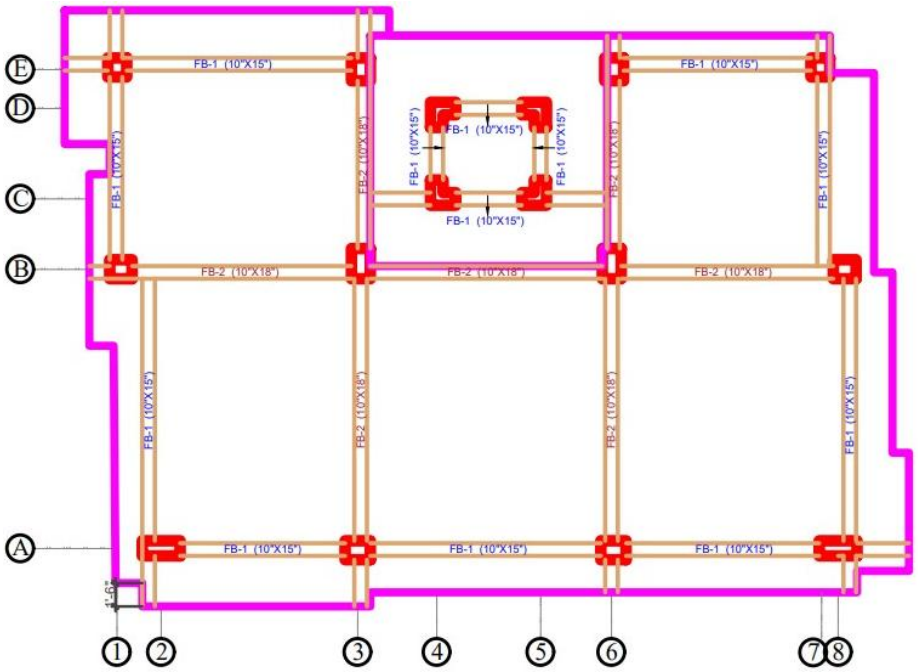


Figure 3-5. Typical Floor Plan (Slab, Columns and Beams).

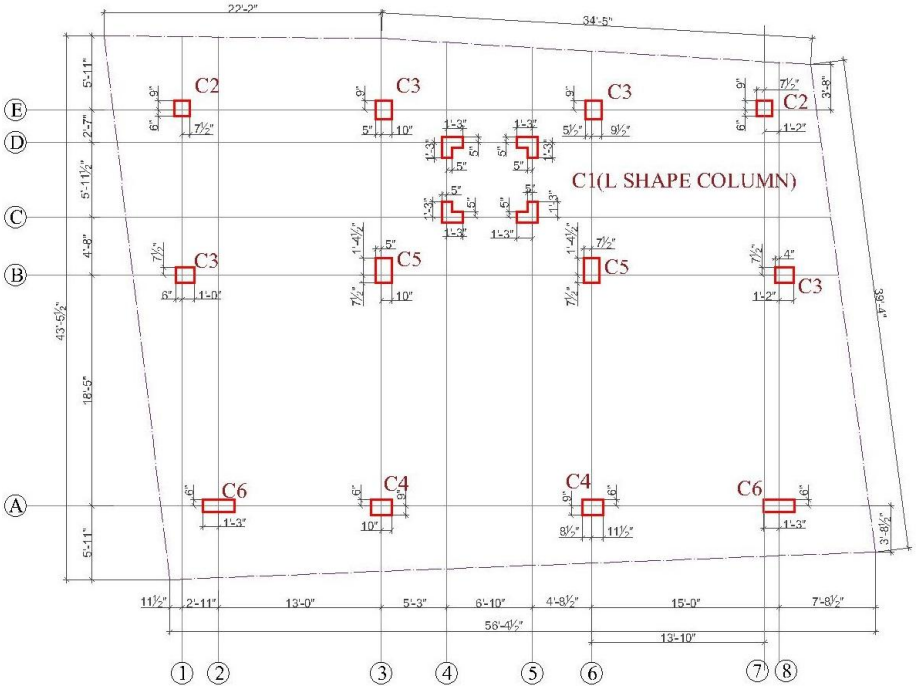


Figure 3-6. Pile and Column Layout.

3.2.5 Data Analyzing Method

Implementing all the data needed on ETABS-17 we analyzed the building according to BNBC 2020 load combinations. As the building is in Seismic Zone 3 the analyze method considers some modifications for its drift nature and we analyzed the building for all seismic zone 1, 2, 3, 4. All the load combinations are.

Table 3-5. Load combination for seismic zone.

- Load combination for seismic zone 1, 2, 3 and 4

1)1.4D	9)1.2D-1.6Wx+.5Lr	17)1.277D+0.3Ex -Ey+L	25)0.823D+Ex -0.3Ey
2)1.2D+1.6L+.5Lr	10)1.2D+1.6Wy +0.5Lr	18)1.277D-0.3Ex +Ey+L	26)0.823D-Ex +0.3Ey
3)1.2D+1.6Lr+L	11)1.2D-1.6Wy +.5Lr	19)1.277D-0.3Ex -Ey+L	27)0.823D-Ex -0.3Ey
4)1.2D+1.6Lr +0.8Wx	12)1.277D+Ex +0.3Ey+L	20)0.9D+1.6Wx	28) 0.823D+0.3Ex +Ey
5)1.2D+1.6Lr -0.8Wx	13)1.277D+Ex -0.3Ey+L	21)0.9D-1.6Wx	29) 0.823D+0.3Ex -Ey
6)1.2D+1.6Lr +0.8Wy	14)1.277D-Ex +0.3Ey+L	22)0.9D+1.6Wy	30)0.823D-0.3Ex +Ey
7)1.2D+1.6Lr -0.8Wy	15)1.277D-Ex -0.3Ey+L	23)0.9D-1.6Wy	31)0.823D-0.3Ex -Ey
8)1.2D+1.6Wx +.5Lr	16)1.277D+0.3Ex +Ey+L	24)0.823D+Ex +0.3Ey	32) Envelope

- Note that envelope contains a sum of all the load combination of the specific seismic zone.

3.2.6 Earthquake Magnitude Finding Process

For earthquake magnitude, moment magnitude (M) method was used. For calculation used formula,

$M = \frac{2}{3} \log_{10} M_0 - 10.7$[14]

here,

$M_0 = \mu AD$[15]

M_0= Earthquake moment in dyne cm

μ= Modulus of rigidity

A= Total affected area (Seismic zone district area)

D= Allowable drift

Modulus of rigidity was found by hooks law,

$E=2G(1+\upsilon)$[16]
$G=^{0.5E}/_{(1+\upsilon)}$
here,
E=Modulus of Elasticity
G= Modulus of Rigidity
υ= Poisson's Ratio

3.2.7 Data Implementations and Limitations

After collecting the dimension and design, rebar data, materials used in according to our methods the model was implemented according to collected data on ETABS-17 and according to BNBC 2020 we used load patterns and load combination for analysis. But there were some limitations that we faced during this process but we did overcome them. The limitations we faced are,

- Absence of BNBC 2020 property on ETABS-17

ETABS-17, as well as other versions of ETABS, do not have the specific properties and parameters for analyzing structures according to the Bangladesh National Building Code (BNBC) 2020. This means that ETABS cannot directly analyze the implemented model using the wind load and earthquake load categories specified in BNBC 2020. Previous research studies have typically used the Uniform Building Code UBC 97 and UBC 91[17] as a substitute for analyzing structures in Bangladesh. UBC 94 has similar properties and parameters to BNBC 2020, making it a suitable choice for our model's lateral earthquake and wind load analysis.

- Absence of CFRP in ETABS-17

ETABS-17 does not have carbon fiber reinforcement in its material properties, so the model's material data was not defined. To address this, the model was adapted to user settings as steel plate property for CFRP. Epoxy does not have tension or compressive force, so no definition was needed. The properties of CFRP on steel plate, such as modulus of elasticity, density, and tensile strength, were defined. The steel plate works as a CFRP harden plate with epoxy, as it does not have any tension or compressive force and we used section designer option to retrofit the column as a composite column[18].

By this method we overcome our limitations and achieved our analysis.

3.2.8 Retrofitting with CFRP

- Columns

For columns 0.2 inch of CFRP thickness with epoxy resin, length has been defined with less tie bars as internal tie bars have been removed and a layer of 0.5ich thick cement was applied as they hide the CFRP sheet in sight.

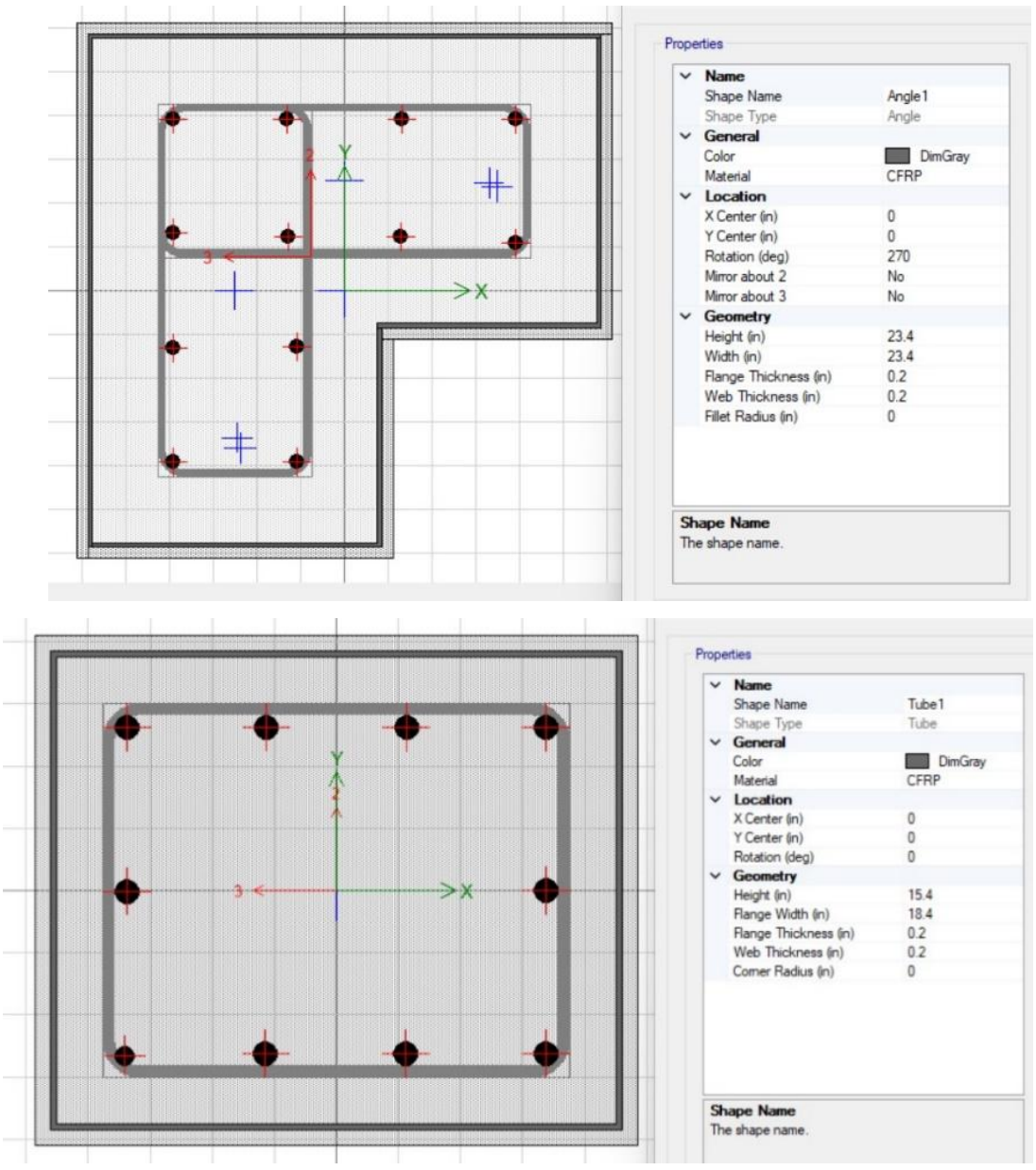


Figure 3-7. CFRP retrofitting of Column.

- Beams

Same as columns, thickness of 0.2 inch for CFRP and thickness of 0.5inch to cover the CFRP. Internal tie bars have been removed and as upper portion of beam (about 5inch+0.2inch) are inside of slab it cannot be retrofitted with CFRP.

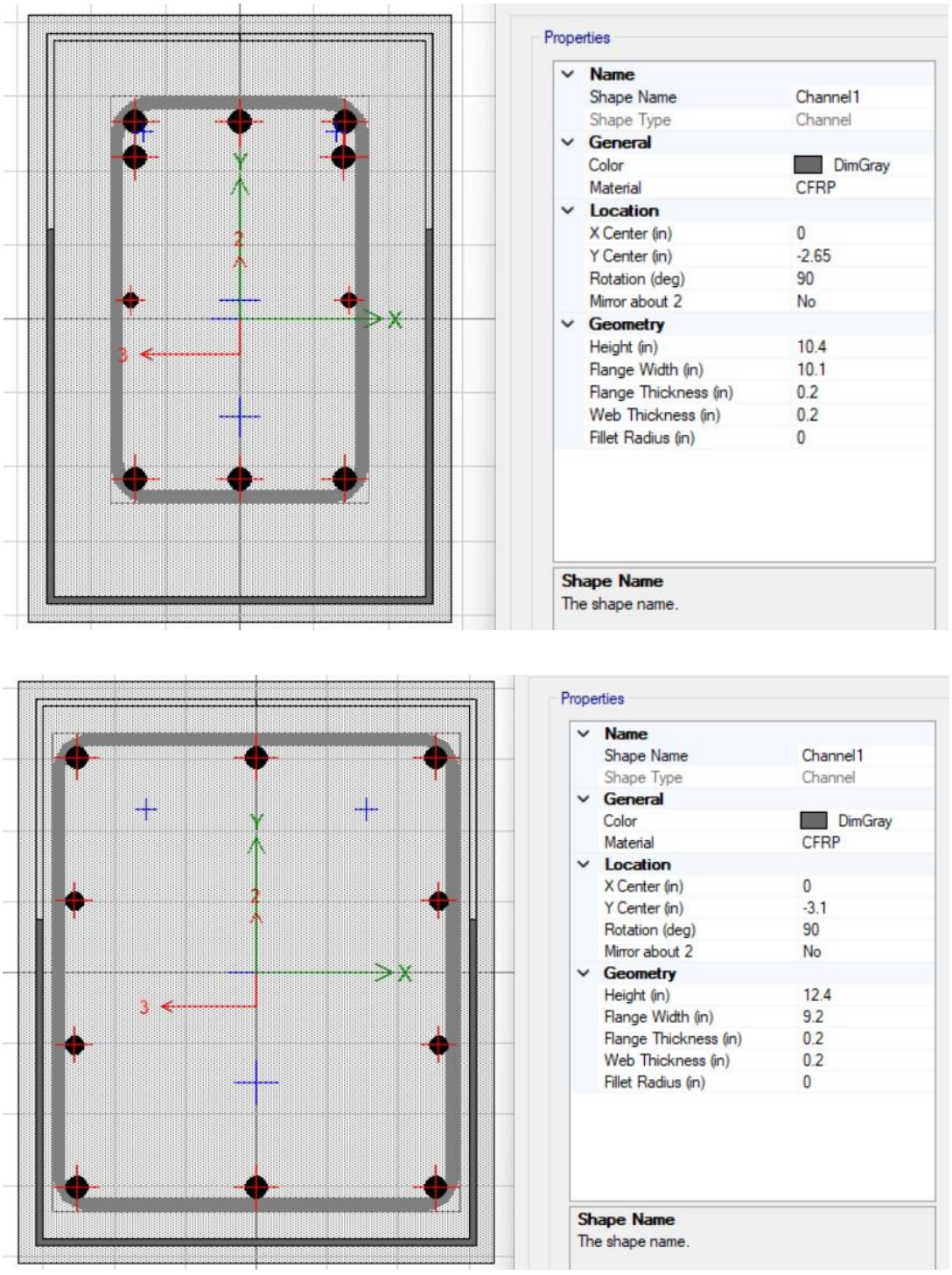


Figure 3-8. CFRP retrofitting of Beams.

3.3 Summary

By overcoming some limitations, we implemented our data and analyzing method in ETABS 17 and analyzed the model according to BNBC 2020 standards and found the results which will be discussed in the next chapter.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Introduction

According to our study it was found, as the building was made with materials similar to recent strong rebar and bonding materials (Ex. Cement and Bricks) the structure withstands wind sway and earthquake drifts according to its serviceability. As its drift limit was ok our next target, we have to retrofit this building for future earthquake disasters to lessen the damage. As Shanghai Wolfix New Materials Co., Ltd. supplies CFRP sheets in Bangladesh after contacting them we found two types of CFRP is cost friendly WFC-200 and WFC-300. Upon getting the properties of these CFRP sheets we input the details in ETABS 17 and analyze the model and found significant changes in analyze results as drift was decreased vastly and earthquake resistance response was 10 times larger than without CFRP retrofit.

4.2 Specific Aim 1

The results contain the basic model results with 2 types of CFRP available in Bangladesh by Shanghai wolfix new materials Co. Ltd. WFC-200 and WFC-300 CFRP sheets with epoxy. According to BNBC-2020 Table 6.2.21 allowable drift limit for Structures, other than masonry shear wall structures, 4 stories or less with interior walls, partitions, ceilings and exterior wall systems that have been designed to accommodate the story drifts with occupancy category I and II is $0.025h_{sx}$ [BNBC-2020] and according its site class.

Table 4-1. Drift limit (According to occupancy category and site class).

Story	Drift Limit (in.) (mm)
Stair Room Roof	0.3 (7.62)
Typical Story 4	0.3 (7.62)
Typical Story 3	0.3 (7.62)
Typical Story 2	0.3 (7.62)
Typical Story 1	0.3 (7.62)
Plinth Level	0.4 (10.16)

4.2.1 Analysis without Carbon Fiber

- This analysis contains only our basic model of structure. According to our load combination we found maximum drift on each story are found on envelope.

Table 4-2. Maximum drift found Without CFRP.

Story	Load Combination	Maximum Drift (Direction) (mm)
Plinth Level	Seismic Zone 1	0.140081 (X)
	Seismic Zone 2	0.140081 (X)
	Seismic Zone 3	0.140081 (X)
	Seismic Zone 4	0.140081 (X)
Typical Story 1	Seismic Zone 1	0.417805 (X and Y)
	Seismic Zone 2	0.557073 (X and Y)
	Seismic Zone 3	0.836625 (X and Y)
	Seismic Zone 4	0.836625 (X and Y)
Typical Story 2	Seismic Zone 1	0.682828 (X and Y)
	Seismic Zone 2	0.910438 (X and Y)
	Seismic Zone 3	1.365676 (X and Y)
	Seismic Zone 4	1.821914 (X and Y)
Typical Story 3	Seismic Zone 1	0.297688 (X and Y)
	Seismic Zone 2	0.396926 (X and Y)
	Seismic Zone 3	0.595376 (X and Y)
	Seismic Zone 4	0.794853 (Y and Y)
Typical Story 4	Seismic Zone 1	0.408559 (X and Y)
	Seismic Zone 2	0.544731 (X and Y)
	Seismic Zone 3	0.817118 (X and Y)
	Seismic Zone 4	1.089492 (X and Y)
Stair Room Roof	Seismic Zone 1	0.989742 (X and Y)
	Seismic Zone 2	1.319698 (X and Y)
	Seismic Zone 3	1.979569 (X and Y)
	Seismic Zone 4	2.639440 (X and Y)

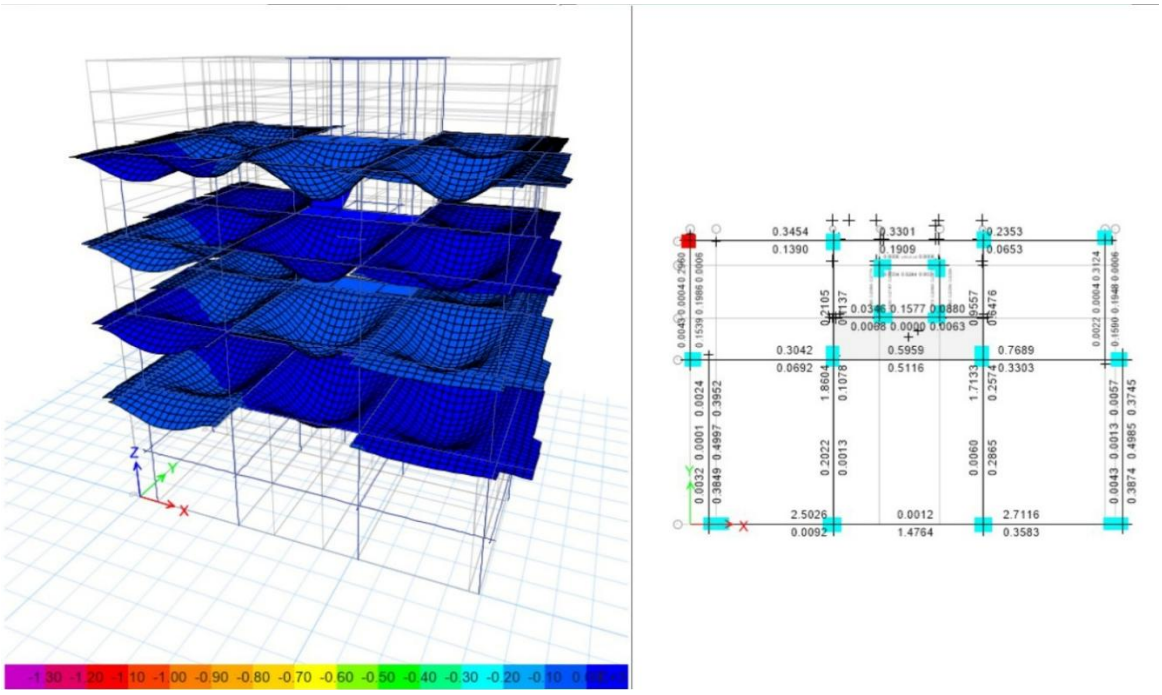


Figure 4-1. Failure in column.

4.2.2 Retrofitted with CFRP WFC-200

Retro fitting with CFRP WFC-200 with epoxy.

- Thickness of CFRP with epoxy resin: 0.2 inch
- Cement layer to cover CFRP: 0.5 inch.

Table 4-3. Maximum drift with CFRP WFC-200.

Story	Load Combination	Maximum Drift (Direction) (in.)
Plinth Level	Seismic Zone 1	0.0636832 (X)
	Seismic Zone 2	0.0636832 (X)
	Seismic Zone 3	0.0636832 (X)
	Seismic Zone 4	0.0638344 (X)
Typical Story 1	Seismic Zone 1	0.225659 (X and Y)
	Seismic Zone 2	0.3008984 (X and Y)
	Seismic Zone 3	0.4513326 (X and Y)
	Seismic Zone 4	0.6017888 (X and Y)
Typical Story 2	Seismic Zone 1	0.3683 (X and Y)
	Seismic Zone 2	0.4910836 (X and Y)
	Seismic Zone 3	0.7366254 (X and Y)
	Seismic Zone 4	0.9821672 (X and Y)

Typical Story 3	Seismic Zone 1	0.160528 (X and Y)
	Seismic Zone 2	0.2140458 (X and Y)
	Seismic Zone 3	0.321856 (X and Y)
	Seismic Zone 4	0.4289662 (X and Y)
Typical Story 4	Seismic Zone 1	0.2203812 (X and Y)
	Seismic Zone 2	0.293878 (X and Y)
	Seismic Zone 3	0.4408424 (X and Y)
	Seismic Zone 4	0.5877814 (X and Y)
Stair Room Roof	Seismic Zone 1	0.5340958 (X and Y)
	Seismic Zone 2	0.7121144 (X and Y)
	Seismic Zone 3	1.0671716 (X and Y)
	Seismic Zone 4	1.4222288 (X and Y)

4.2.3 Retrofitting with CFRP WFC-300

Retro fitting with CFRP WFC-300 with epoxy

- Thickness of CFRP with epoxy resin: 0.2 inch
- Cement layer to cover CFRP: 0.5 inch

Table 4-4. Maximum drift with CFRP WFC-300.

Story	Load Combination	Maximum Drift (Direction) (in.)
Plinth Level	Seismic Zone 1	0.0629348 (X)
	Seismic Zone 2	0.0629348 (X)
	Seismic Zone 3	0.0629348 (X)
	Seismic Zone 4	0.0630868 (X)
Typical Story 1	Seismic Zone 1	0.2215488 (X and Y)
	Seismic Zone 2	0.295402 (X and Y)
	Seismic Zone 3	0.4430576 (X and Y)
	Seismic Zone 4	0.5907806 (X and Y)
Typical Story 2	Seismic Zone 1	0.361569 (X and Y)
	Seismic Zone 2	0.482092 (X and Y)
	Seismic Zone 3	0.723138 (X and Y)
	Seismic Zone 4	0.964184 (X and Y)
Typical Story 3	Seismic Zone 1	0.1575816 (X and Y)
	Seismic Zone 2	0.2101088 (X and Y)
	Seismic Zone 3	0.3151632 (X and Y)
	Seismic Zone 4	0.420243 (X and Y)
Typical Story 4	Seismic Zone 1	0.2163826 (X and Y)
	Seismic Zone 2	0.2884986 (X and Y)
	Seismic Zone 3	0.4327652 (X and Y)
	Seismic Zone 4	0.5770118 (X and Y)

Stair Room Roof	Seismic Zone 1	0.5243168 (X and Y)
	Seismic Zone 2	0.6990842 (X and Y)
	Seismic Zone 3	1.048639 (X and Y)
	Seismic Zone 4	1.3981684 (X and Y)

- BNBC 2020 suggests amplifying model displacement to occupancy category to check story drift, but our base model and analysis found no displacements. It was checked by BNBC 2020 2.7.5 Load Computability for Serviceability 3 [page 689] load combination of,

    1. D+0.5L+0.7Wx
    2. D+0.5L-0.7Wx
    3. D+0.5L+0.7Wy
    4. D+0.5L-0.7Wy

The study used the maximum drift value as the basis for results, but no displacement value was found. The design engineer informed us that the structure was designed for its irregular dimensions, and there was some displacement according to BNBC 2006 standards. However, according to BNBC 2020, no displacement was found.

Additionally, ETABS 17 and later versions show no displacement if there is no break or deformation in the column and beams, and the structure is stable with all loads and support joints.

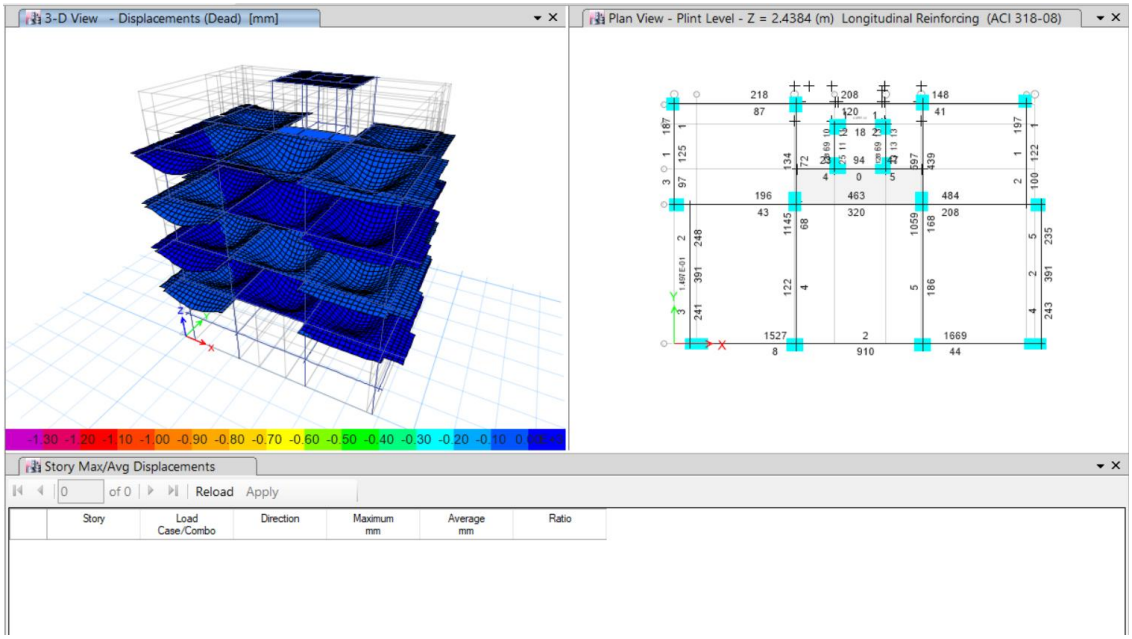


Figure 4-2. Found Displacements of Plan (No Displacements).

4.2.4 Earthquake Response (Moment Magnitude Limit) on Seismic Zones

- Calculation for Moment Magnitude Scale of Earthquake (For Seismic Zone 4)

$M = \frac{2}{3} \log_{10} M_0 - 10.7$[14]

here,

$M_0=\mu AD$[15]

M_0= Earthquake moment in dyne cm

μ= Modulus of rigidity

A= Total affected area (Seismic zone district area)

D= Allowable drift

Modulus of rigidity was found by hooks law,

$E=2G(1+\upsilon)$[16]

$G=\frac{0.5E}{(1+\upsilon)}$

here,

E=Modulus of Elasticity

G= Modulus of Rigidity

υ= Poisson's Ratio

For,

E=Modulus of Elasticity

Modulus of elasticity (Rebar)= 29000000 lb./in^2= 2x10^{11} N/m^2

Modulus of elasticity (CC)= 3750√fc'= 3750*√4000= 237170.82 lb./in^2

=1635235240.882 N/m^2

Modulus of elasticity (CFRP)= 334083868.37 lb./in^2= 303427187917.71 N/m^2

Modulus of elasticity (Without CFRP) = 2.01635235x10^{11}

Modulus of elasticity (With CFRP) = 5.05062423x10^{11}

Poisson's Ratio ≈ 0.3 [with and without CFRP)

Now,

$G=\frac{0.5E}{(1+\upsilon)}$

Modulus of rigidity (Without CFRP) = 1.55104027x10^{11}

Modulus of rigidity (With CFRP) = 3.88509556x10^{11}

Now,

$M_0=\mu AD$

Here,

Total remaining Displacement D= allowed drift-found maximum drift

μ= Modulus of rigidity

A= Area of selected partial seismic zone= 2636.58 km^2

Without CFRP= 1.6x10^{11}*2636580000*(0.00762-0.0014222288)

=1.07938361x10^{18} Nm = 2.5345x10^{18}x10^7

= 2.533x10^{25} dyne.cm (1Nm=10^{7}dyne.cm)

With CFRP= 3.9x10^{11}x2636580000x(0.00762-0.0013981684)

[WFC-300] =1.43219496x10^{18} Nm=6.3813x10^{18} x10^7

= 6.3813x10^{25} dyne.cm

Now,

$M = \frac{2}{3} \log_{10} M_0 - 10.7$

Without CFRP= $\frac{2}{3} \log_{10} (2.533 \times 10^{25}) - 10.7$
=16.94-10.7
=6.24

With CFRP=$\frac{2}{3} \log_{10} (6.3813 \times 10^{25}) - 10.7$
=17.21-10.7
=6.52

Table 4-5. Seismic Magnitude Limit (Moment Magnitude).

Structure Type	Seismic Zone	Area of Seismic District	Earthquake Magnitude	Maximum Drift (mm)
Without CFRP	Seismic Zone 1	2,407.01 km^2	6.23(Rajshahi District)	0.989742
	Seismic Zone 2	2,052.86 km^2	6.17 (Faridpur District)	1.319698
	Seismic Zone 3	1,741.53 km^2	6.09 (Gazipur District)	1.979569
	Seismic Zone 4	2,636.58 km^2	6.1 (Habiganj District)	2.639440
CFRP WFC-200	Seismic Zone 1	2,407.01 km^2	6.86 (Rajshahi District)	0.5340958
	Seismic Zone 2	2,052.86 km^2	6.5 (Faridpur District)	0.7121144
	Seismic Zone 3	1,741.53 km^2	6.39 (Gazipur District)	1.0671716
	Seismic Zone 4	2,636.58 km^2	6.5 (Habiganj District)	1.4222288
CFRP WFC-300	Seismic Zone 1	2,407.01 km^2	7 (Rajshahi District)	0.5243168
	Seismic Zone 2	2,052.86 km^2	6.57 (Faridpur District)	0.6990842
	Seismic Zone 3	1,741.53 km^2	6.41 (Gazipur District)	1.048639
	Seismic Zone 4	2,636.58 km^2	6.5 (Habiganj District)	1.3981684

4.2.5 Discussion of the Found Result

According to our found results it can be seen that around 45%-53% of typical story drift has been reduced. Also, it is seen that some drift increases as we travel on 1st and 2nd floor but again decreases as we travel to 3rd floor and increases on upper floor. This may be cause for wind sway and column size and reinforcement. As for same maximum drift in X and Y direction this have been cause for reinforcement and dimension changes as same problem was found on reddit[19] and discussing the matter with experts as no displacements were found on this issue occurred for slab irregularity as the slab in this structure are in an irregular shape and the building also do have an irregularity type V according to BNBC 2020. Also, as maximum

drift found on plinth level this is caused cause of irregularity of grade beams as they do not have a column end on B grid in plinth level from 2A to 2B and 7B to 7E.

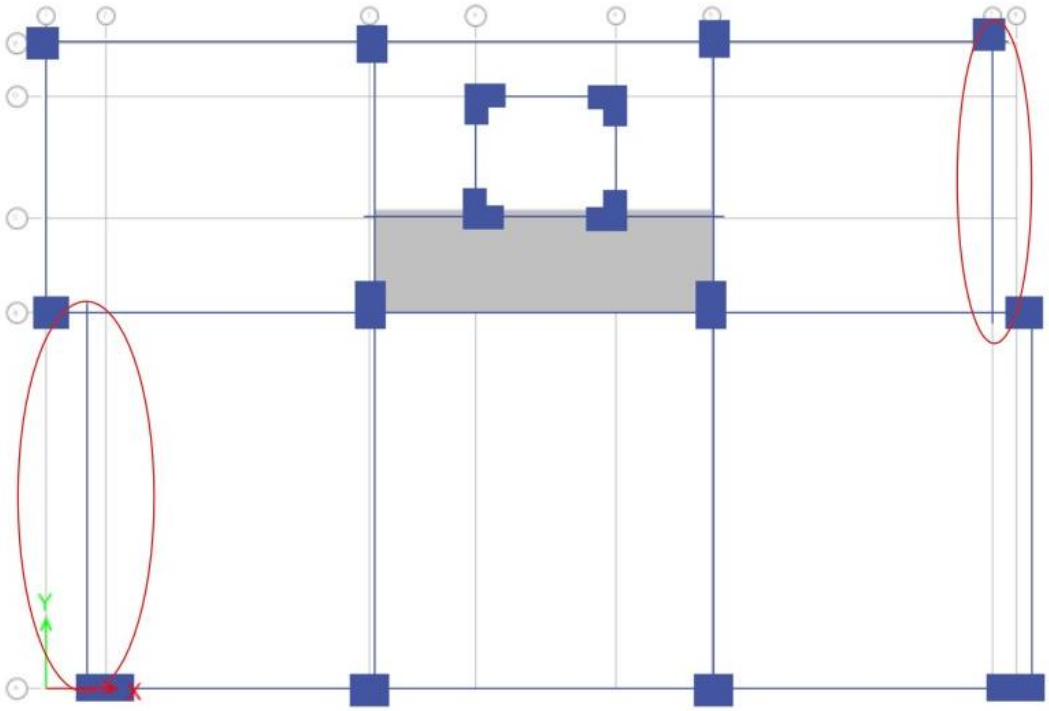


Figure 4-3. Irregularity of grade beams.

For earthquake response limitation we found without CFRP the resisting moment magnitude was between was 6.1-6.3 where with CFRP the magnitude resistance found was from 6.4 to 7.0 this may not be that much but according to moment magnitude method an earthquake of 7.00 is 10 times more powerful than an earthquake of 6.00[20] as it's a log-based calculation. So, yes, it is a lot.

4.3 Summary

According to our results, CFRP retrofit decreases about 45%-55% drift. This amount is a lot in case of earthquake as it can resist earthquake up to magnitude of 7 which is 10 times stronger earthquake then from magnitude of 6 earthquake which was resisted without CFRP retrofit. According to previous studies this amount of drift reduction was meant to be found and the resistance of earthquake magnitude is moderate per standards of BNBC 2020.

CHAPTER 5
CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

According to our analysis carbon fiber is one of the best ways to retrofit a beam or column as they are actually more durable and elastic than steel and not corrosive also their elastic nature and easy to install process gives it a good reason of using but as it is too costly not everyone can use it. With CFRP gave us about 45%-53% less drift. As found on previous researches the amount of drift reduced was about 25%. For earthquake magnitude the result shows earthquake resistance increased 10 times larger per moment magnitude method which is a large difference according to Hiroo Kanamori the creator of moment magnitude scale and other researchers.

5.2 Limitations and Recommendations for Future Works

Further research is needed for the reason why there were no story displacement found on any of the floor and also why there were changes in story drift also why there were decrease of story drift on upper floors. Also, we must see why maximum drift on base wasn't so different on two types of CFRP polymer even though we used different strength CFRP's.

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APPENDIX

Appendix A

Table A 1. Max Drift on Envelope Max without CFRP (Seismic Zone 1).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Max	X	0.038967	0.019484	2
Stair Room Roof	Envelope Max	Y	0.038967	0.019484	2
Typical Story 4	Envelope Max	X	0.016085	0.007993	2.012
Typical Story 4	Envelope Max	Y	0.016085	0.008034	2.002
Typical Story 3	Envelope Max	X	0.01172	0.00586	2
Typical Story 3	Envelope Max	Y	0.01172	0.00586	2
Typical story 2	Envelope Max	X	0.026883	0.01343	2.002
Typical story 2	Envelope Max	Y	0.026883	0.013442	2
Typical Story 1	Envelope Max	X	0.016449	0.007197	2.286
Typical Story 1	Envelope Max	Y	0.016449	0.008225	2
Plint Level	Envelope Max	X	0.005515	0.002757	2

Table A 2. Max Drift on Envelope Min without CFRP (Seismic Zone 1).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Min	X	0.038967	0.019484	2
Stair Rom Roof	Envelope Min	Y	0.038967	0.019484	2
Typical Story 4	Envelope Min	X	0.016085	0.008042	2
Typical Story 4	Envelope Min	Y	0.016085	0.008042	2
Typical Story 3	Envelope Min	X	0.01172	0.005858	2.001
Typical Story 3	Envelope Min	Y	0.01172	0.00586	2
Typical story 2	Envelope Min	X	0.026883	0.013442	2
Typical story 2	Envelope Min	Y	0.026883	0.013442	2
Typical Story 1	Envelope Min	X	0.016449	0.008225	2
Typical Story 1	Envelope Min	Y	0.016449	0.008225	2
Plint Level	Envelope Min	X	0.002028	0.000945	2.145

Table A 3. Max Drift on Envelope Max without CFRP (Seismic Zone 2).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Max	X	0.051956	0.025978	2
Stair Room Roof	Envelope Max	Y	0.051956	0.025978	2
Typical Story 4	Envelope Max	X	0.021447	0.010675	2.009
Typical Story 4	Envelope Max	Y	0.021447	0.010716	2.001
Typical Story 3	Envelope Max	X	0.015627	0.007813	2
Typical Story 3	Envelope Max	Y	0.015627	0.007813	2
Typical story 2	Envelope Max	X	0.035844	0.017918	2
Typical story 2	Envelope Max	Y	0.035844	0.017922	2
Typical Story 1	Envelope Max	X	0.021932	0.009959	2.202
Typical Story 1	Envelope Max	Y	0.021932	0.010966	2
Plint Level	Envelope Max	X	0.005515	0.002757	2

Table A 4. Max Drift on Envelope Min without CFRP (Seismic Zone 2).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Min	X	0.051956	0.025978	2
Stair Room Roof	Envelope Min	Y	0.051956	0.025978	2
Typical Story 4	Envelope Min	X	0.021447	0.010723	2
Typical Story 4	Envelope Min	Y	0.021447	0.010723	2
Typical Story 3	Envelope Min	X	0.015627	0.007813	2
Typical Story 3	Envelope Min	Y	0.015627	0.007813	2
Typical story 2	Envelope Min	X	0.035844	0.017922	2
Typical story 2	Envelope Min	Y	0.035844	0.017922	2
Typical Story 1	Envelope Min	X	0.021932	0.010966	2
Typical Story 1	Envelope Min	Y	0.021932	0.010966	2
Plint Level	Envelope Min	X	0.001961	0.000889	2.206
Plint Level	Envelope Min	Y	0.000183	0.000092	2

Table A 5. Max Drift on Envelope Max without CFRP (Seismic Zone 3).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Max	X	0.077935	0.038967	2
Stair Room Roof	Envelope Max	Y	0.077935	0.038967	2
Typical Story 4	Envelope Max	X	0.03217	0.016038	2.006
Typical Story 4	Envelope Max	Y	0.03217	0.016081	2.001
Typical Story 3	Envelope Max	X	0.02344	0.01172	2
Typical Story 3	Envelope Max	Y	0.02344	0.01172	2
Typical story 2	Envelope Max	X	0.053766	0.026883	2
Typical story 2	Envelope Max	Y	0.053766	0.026883	2
Typical Story 1	Envelope Max	X	0.032899	0.015484	2.125
Typical Story 1	Envelope Max	Y	0.032899	0.016449	2
Plint Level	Envelope Max	X	0.005515	0.002757	2
Plint Level	Envelope Max	Y	0.000659	0.000329	2

Table A 6. Max Drift on Envelope Min without CFRP (Seismic Zone 3).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Min	X	0.077935	0.038967	2
Stair Room Roof	Envelope Min	Y	0.077935	0.038967	2
Typical Story 4	Envelope Min	X	0.03217	0.016085	2
Typical Story 4	Envelope Min	Y	0.03217	0.016085	2
Typical Story 3	Envelope Min	X	0.02344	0.01172	2
Typical Story 3	Envelope Min	Y	0.02344	0.01172	2
Typical story 2	Envelope Min	X	0.053766	0.026883	2
Typical story 2	Envelope Min	Y	0.053766	0.026883	2
Typical Story 1	Envelope Min	X	0.032899	0.016449	2
Typical Story 1	Envelope Min	Y	0.032899	0.016449	2
Plint Level	Envelope Min	X	0.001828	0.000777	2.354
Plint Level	Envelope Min	Y	0.000303	0.000151	2

Table A 7. Max Drift on Envelope Max without CFRP (Seismic Zone 4).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Max	X	0.103913	0.051956	2
Stair Room Roof	Envelope Max	Y	0.103913	0.051956	2
Typical Story 4	Envelope Max	X	0.042893	0.021402	2.004
Typical Story 4	Envelope Max	Y	0.042893	0.021445	2
Typical Story 3	Envelope Max	X	0.031253	0.015627	2
Typical Story 3	Envelope Max	Y	0.031253	0.015627	2
Typical story 2	Envelope Max	X	0.071688	0.035844	2
Typical story 2	Envelope Max	Y	0.071688	0.035844	2
Typical Story 1	Envelope Max	X	0.043865	0.021009	2.088
Typical Story 1	Envelope Max	Y	0.043865	0.021932	2
Plint Level	Envelope Max	X	0.005515	0.002757	2
Plint Level	Envelope Max	Y	0.000797	0.000399	2

Table A 8. Max Drift on Envelope Min without CFRP (Seismic Zone 4).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Min	X	0.103913	0.051956	2
Stair Room Roof	Envelope Min	Y	0.103913	0.051956	2
Typical Story 4	Envelope Min	X	0.042893	0.021447	2
Typical Story 4	Envelope Min	Y	0.042893	0.021447	2
Typical Story 3	Envelope Min	X	0.031253	0.015627	2
Typical Story 3	Envelope Min	Y	0.031253	0.015627	2
Typical story 2	Envelope Min	X	0.071688	0.035844	2
Typical story 2	Envelope Min	Y	0.071688	0.035844	2
Typical Story 1	Envelope Min	X	0.043865	0.021932	2
Typical Story 1	Envelope Min	Y	0.043865	0.021932	2
Plint Level	Envelope Min	X	0.001695	0.000665	2.551
Plint Level	Envelope Min	Y	0.000441	0.00022	2

Table A 9. Max Drift on Envelope Max with CFRP WFC-200 (Seismic Zone 1).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Max	X	0.021027	0.010514	2
Stair Room Roof	Envelope Max	Y	0.021027	0.010514	2
Typical Story 4	Envelope Max	X	0.008678	0.004297	2.02
Typical Story 4	Envelope Max	Y	0.008678	0.004333	2.003
Typical Story 3	Envelope Max	X	0.00632	0.00316	2
Typical Story 3	Envelope Max	Y	0.00632	0.00316	2
Typical story 2	Envelope Max	X	0.0145	0.007241	2.003
Typical story 2	Envelope Max	Y	0.0145	0.00725	2
Typical Story 1	Envelope Max	X	0.008885	0.003978	2.233
Typical Story 1	Envelope Max	Y	0.008885	0.004439	2.002
Plint Level	Envelope Max	X	0.002508	0.001254	2

Table A 10. Max Drift on Envelope Min with CFRP WFC-200 (Seismic Zone 1).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Min	X	0.021027	0.010514	2
Stair Room Roof	Envelope Min	Y	0.021027	0.010514	2
Typical Story 4	Envelope Min	X	0.008678	0.004339	2
Typical Story 4	Envelope Min	Y	0.008678	0.004339	2
Typical Story 3	Envelope Min	X	0.00632	0.003158	2.001
Typical Story 3	Envelope Min	Y	0.00632	0.00316	2
Typical story 2	Envelope Min	X	0.0145	0.00725	2
Typical story 2	Envelope Min	Y	0.0145	0.00725	2
Typical Story 1	Envelope Min	X	0.008885	0.004442	2
Typical Story 1	Envelope Min	Y	0.008885	0.004442	2
Plint Level	Envelope Min	X	0.000902	0.000411	2.193

Table A 11. Max Drift on Envelope Max with CFRP WFC-200 (Seismic Zone 2).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Max	X	0.028036	0.014018	2
Stair Room Roof	Envelope Max	Y	0.028036	0.014018	2
Typical Story 4	Envelope Max	X	0.01157	0.005744	2.014
Typical Story 4	Envelope Max	Y	0.01157	0.005781	2.002
Typical Story 3	Envelope Max	X	0.008427	0.004213	2
Typical Story 3	Envelope Max	Y	0.008427	0.004213	2
Typical story 2	Envelope Max	X	0.019334	0.009663	2.001
Typical story 2	Envelope Max	Y	0.019334	0.009667	2
Typical Story 1	Envelope Max	X	0.011846	0.005467	2.167
Typical Story 1	Envelope Max	Y	0.011846	0.005923	2
Plint Level	Envelope Max	X	0.002508	0.001254	2
Plint Level	Envelope Max	Y	0.000264	0.000132	2

Table A 12. Max Drift on Envelope Min with CFRP WFC-200 (Seismic Zone 2).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Min	X	0.028036	0.014018	2
Stair Room Roof	Envelope Min	Y	0.028036	0.014018	2
Typical Story 4	Envelope Min	X	0.01157	0.005785	2
Typical Story 4	Envelope Min	Y	0.01157	0.005785	2
Typical Story 3	Envelope Min	X	0.008427	0.004213	2
Typical Story 3	Envelope Min	Y	0.008427	0.004213	2
Typical story 2	Envelope Min	X	0.019334	0.009667	2
Typical story 2	Envelope Min	Y	0.019334	0.009667	2
Typical Story 1	Envelope Min	X	0.011846	0.005923	2
Typical Story 1	Envelope Min	Y	0.011846	0.005923	2
Plint Level	Envelope Min	X	0.000865	0.000379	2.28
Plint Level	Envelope Min	Y	0.000106	0.000053	2

Table A 13. Max Drift on Envelope Max with CFRP WFC-200 (Seismic Zone 3).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Max	X	0.042054	0.021027	2
Stair Room Roof	Envelope Max	Y	0.042054	0.021027	2
Typical Story 4	Envelope Max	X	0.017356	0.008638	2.009
Typical Story 4	Envelope Max	Y	0.017356	0.008676	2
Typical Story 3	Envelope Max	X	0.01264	0.00632	2
Typical Story 3	Envelope Max	Y	0.01264	0.00632	2
Typical story 2	Envelope Max	X	0.029001	0.0145	2
Typical story 2	Envelope Max	Y	0.029001	0.0145	2
Typical Story 1	Envelope Max	X	0.017769	0.008444	2.104
Typical Story 1	Envelope Max	Y	0.017769	0.008885	2
Plint Level	Envelope Max	X	0.002508	0.001254	2
Plint Level	Envelope Max	Y	0.000342	0.000171	2

Table A 14. Max Drift on Envelope Min with CFRP WFC-200 (Seismic Zone 3).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Min	X	0.042054	0.021027	2
Stair Room Roof	Envelope Min	Y	0.042054	0.021027	2
Typical Story 4	Envelope Min	X	0.017356	0.008678	2
Typical Story 4	Envelope Min	Y	0.017356	0.008678	2
Typical Story 3	Envelope Min	X	0.01264	0.00632	2
Typical Story 3	Envelope Min	Y	0.01264	0.00632	2
Typical story 2	Envelope Min	X	0.029001	0.0145	2
Typical story 2	Envelope Min	Y	0.029001	0.0145	2
Typical Story 1	Envelope Min	X	0.017769	0.008885	2
Typical Story 1	Envelope Min	Y	0.017769	0.008885	2
Plint Level	Envelope Min	X	0.000791	0.000316	2.504
Plint Level	Envelope Min	Y	0.000182	0.000091	2

Table A 15. Max Drift on Envelope Max with CFRP WFC-200 (Seismic Zone 4).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Max	X	0.056072	0.028036	2
Stair Room Roof	Envelope Max	Y	0.056072	0.028036	2
Typical Story 4	Envelope Max	X	0.023141	0.011532	2.007
Typical Story 4	Envelope Max	Y	0.023141	0.01157	2
Typical Story 3	Envelope Max	X	0.016853	0.008427	2
Typical Story 3	Envelope Max	Y	0.016853	0.008427	2
Typical story 2	Envelope Max	X	0.038668	0.019334	2
Typical story 2	Envelope Max	Y	0.038668	0.019334	2
Typical Story 1	Envelope Max	X	0.023692	0.011421	2.074
Typical Story 1	Envelope Max	Y	0.023692	0.011846	2
Plint Level	Envelope Max	X	0.002514	0.001257	2
Plint Level	Envelope Max	Y	0.000419	0.00021	2

Table A 16. Max Drift on Envelope Min with CFRP WFC-200 (Seismic Zone 4).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Min	X	0.056072	0.028036	2
Stair Room Roof	Envelope Min	Y	0.056072	0.028036	2
Typical Story 4	Envelope Min	X	0.023141	0.01157	2
Typical Story 4	Envelope Min	Y	0.023141	0.01157	2
Typical Story 3	Envelope Min	X	0.016853	0.008427	2
Typical Story 3	Envelope Min	Y	0.016853	0.008427	2
Typical story 2	Envelope Min	X	0.038668	0.019334	2
Typical story 2	Envelope Min	Y	0.038668	0.019334	2
Typical Story 1	Envelope Min	X	0.023692	0.011846	2
Typical Story 1	Envelope Min	Y	0.023692	0.011846	2
Plint Level	Envelope Min	X	0.000716	0.000252	2.841
Plint Level	Envelope Min	Y	0.00026	0.00013	2

Table A 17. Max Drift on Envelope Max with CFRP WFC-300 (Seismic Zone 1).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Max	X	0.020642	0.010321	2
Stair Room Roof	Envelope Max	Y	0.020642	0.010321	2
Typical Story 4	Envelope Max	X	0.008519	0.004217	2.02
Typical Story 4	Envelope Max	Y	0.008519	0.004254	2.003
Typical Story 3	Envelope Max	X	0.006204	0.003102	2
Typical Story 3	Envelope Max	Y	0.006204	0.003102	2
Typical story 2	Envelope Max	X	0.014235	0.007108	2.003
Typical story 2	Envelope Max	Y	0.014235	0.007117	2
Typical Story 1	Envelope Max	X	0.008722	0.003906	2.233
Typical Story 1	Envelope Max	Y	0.008722	0.004357	2.002
Plint Level	Envelope Max	X	0.002462	0.001231	2

Table A 18. Max Drift on Envelope Min with CFRP WFC-300 (Seismic Zone 1).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Min	X	0.020642	0.010321	2
Stair Room Roof	Envelope Min	Y	0.020642	0.010321	2
Typical Story 4	Envelope Min	X	0.008519	0.00426	2
Typical Story 4	Envelope Min	Y	0.008519	0.00426	2
Typical Story 3	Envelope Min	X	0.006204	0.0031	2.001
Typical Story 3	Envelope Min	Y	0.006204	0.003102	2
Typical story 2	Envelope Min	X	0.014235	0.007117	2
Typical story 2	Envelope Min	Y	0.014235	0.007117	2
Typical Story 1	Envelope Min	X	0.008722	0.004361	2
Typical Story 1	Envelope Min	Y	0.008722	0.004361	2
Plint Level	Envelope Min	X	0.000885	0.000404	2.194

Table A 19. Max Drift on Envelope Max with CFRP WFC-300 (Seismic Zone 2).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Max	X	0.027523	0.013762	2
Stair Room Roof	Envelope Max	Y	0.027523	0.013762	2
Typical Story 4	Envelope Max	X	0.011359	0.005638	2.015
Typical Story 4	Envelope Max	Y	0.011359	0.005675	2.002
Typical Story 3	Envelope Max	X	0.008272	0.004136	2
Typical Story 3	Envelope Max	Y	0.008272	0.004136	2
Typical story 2	Envelope Max	X	0.01898	0.009486	2.001
Typical story 2	Envelope Max	Y	0.01898	0.00949	2
Typical Story 1	Envelope Max	X	0.01163	0.005367	2.167
Typical Story 1	Envelope Max	Y	0.01163	0.005815	2
Plint Level	Envelope Max	X	0.002462	0.001231	2
Plint Level	Envelope Max	Y	0.00026	0.00013	2

Table A 20. Max Drift on Envelope Min with CFRP WFC-300 (Seismic Zone 2).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Min	X	0.027523	0.013762	2
Stair Room Roof	Envelope Min	Y	0.027523	0.013762	2
Typical Story 4	Envelope Min	X	0.011359	0.005679	2
Typical Story 4	Envelope Min	Y	0.011359	0.005679	2
Typical Story 3	Envelope Min	X	0.008272	0.004136	2
Typical Story 3	Envelope Min	Y	0.008272	0.004136	2
Typical story 2	Envelope Min	X	0.01898	0.00949	2
Typical story 2	Envelope Min	Y	0.01898	0.00949	2
Typical Story 1	Envelope Min	X	0.01163	0.005815	2
Typical Story 1	Envelope Min	Y	0.01163	0.005815	2
Plint Level	Envelope Min	X	0.000849	0.000372	2.28
Plint Level	Envelope Min	Y	0.000104	0.000052	2

Table A 21. Max Drift on Envelope Max with CFRP WFC-300 (Seismic Zone 3).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Max	X	0.041285	0.020642	2
Stair Room Roof	Envelope Max	Y	0.041285	0.020642	2
Typical Story 4	Envelope Max	X	0.017038	0.008479	2.009
Typical Story 4	Envelope Max	Y	0.017038	0.008517	2
Typical Story 3	Envelope Max	X	0.012408	0.006204	2
Typical Story 3	Envelope Max	Y	0.012408	0.006204	2
Typical story 2	Envelope Max	X	0.02847	0.014235	2
Typical story 2	Envelope Max	Y	0.02847	0.014235	2
Typical Story 1	Envelope Max	X	0.017444	0.008289	2.104
Typical Story 1	Envelope Max	Y	0.017444	0.008722	2
Plint Level	Envelope Max	X	0.002462	0.001231	2
Plint Level	Envelope Max	Y	0.000337	0.000168	2

Table A 22. Max Drift on Envelope Min with CFRP WFC-300 (Seismic Zone 3).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Min	X	0.041285	0.020642	2
Stair Room Roof	Envelope Min	Y	0.041285	0.020642	2
Typical Story 4	Envelope Min	X	0.017038	0.008519	2
Typical Story 4	Envelope Min	Y	0.017038	0.008519	2
Typical Story 3	Envelope Min	X	0.012408	0.006204	2
Typical Story 3	Envelope Min	Y	0.012408	0.006204	2
Typical story 2	Envelope Min	X	0.02847	0.014235	2
Typical story 2	Envelope Min	Y	0.02847	0.014235	2
Typical Story 1	Envelope Min	X	0.017444	0.008722	2
Typical Story 1	Envelope Min	Y	0.017444	0.008722	2
Plint Level	Envelope Min	X	0.000776	0.00031	2.505
Plint Level	Envelope Min	Y	0.00018	0.00009	2

Table A 23. Max Drift on Envelope Max with CFRP WFC-300 (Seismic Zone 4).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Max	X	0.055046	0.027523	2
Stair Room Roof	Envelope Max	Y	0.055046	0.027523	2
Typical Story 4	Envelope Max	X	0.022717	0.01132	2.007
Typical Story 4	Envelope Max	Y	0.022717	0.011359	2
Typical Story 3	Envelope Max	X	0.016545	0.008272	2
Typical Story 3	Envelope Max	Y	0.016545	0.008272	2
Typical story 2	Envelope Max	X	0.03796	0.01898	2
Typical story 2	Envelope Max	Y	0.03796	0.01898	2
Typical Story 1	Envelope Max	X	0.023259	0.011212	2.075
Typical Story 1	Envelope Max	Y	0.023259	0.01163	2
Plint Level	Envelope Max	X	0.002468	0.001234	2
Plint Level	Envelope Max	Y	0.000413	0.000206	2

Table A 24. Max Drift on Envelope Min with CFRP WFC-300 (Seismic Zone 4).

Story	Load Case/Combo	Direction	Max Drift	Avg. Drift	Ratio
Stair Room Roof	Envelope Min	X	0.055046	0.027523	2
Stair Room Roof	Envelope Min	Y	0.055046	0.027523	2
Typical Story 4	Envelope Min	X	0.022717	0.011359	2
Typical Story 4	Envelope Min	Y	0.022717	0.011359	2
Typical Story 3	Envelope Min	X	0.016545	0.008272	2
Typical Story 3	Envelope Min	Y	0.016545	0.008272	2
Typical story 2	Envelope Min	X	0.03796	0.01898	2
Typical story 2	Envelope Min	Y	0.03796	0.01898	2
Typical Story 1	Envelope Min	X	0.023259	0.01163	2
Typical Story 1	Envelope Min	Y	0.023259	0.01163	2
Plint Level	Envelope Min	X	0.000703	0.000247	2.844
Plint Level	Envelope Min	Y	0.000256	0.000128	2

Appendix B

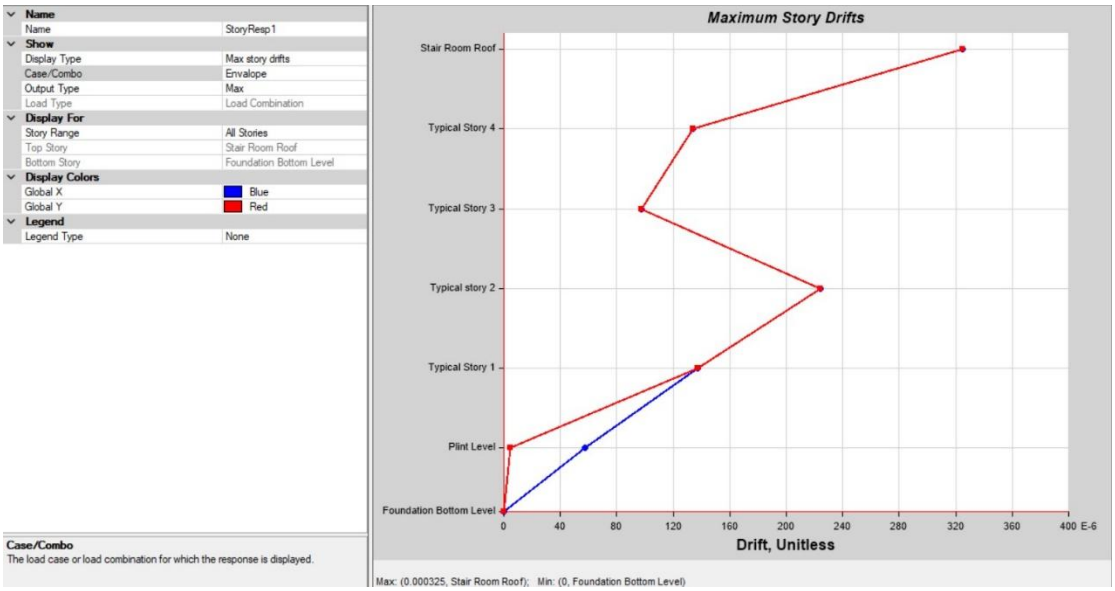


Figure B 1. Maximum Story Drift (Seismic Zone 1 without CFRP).

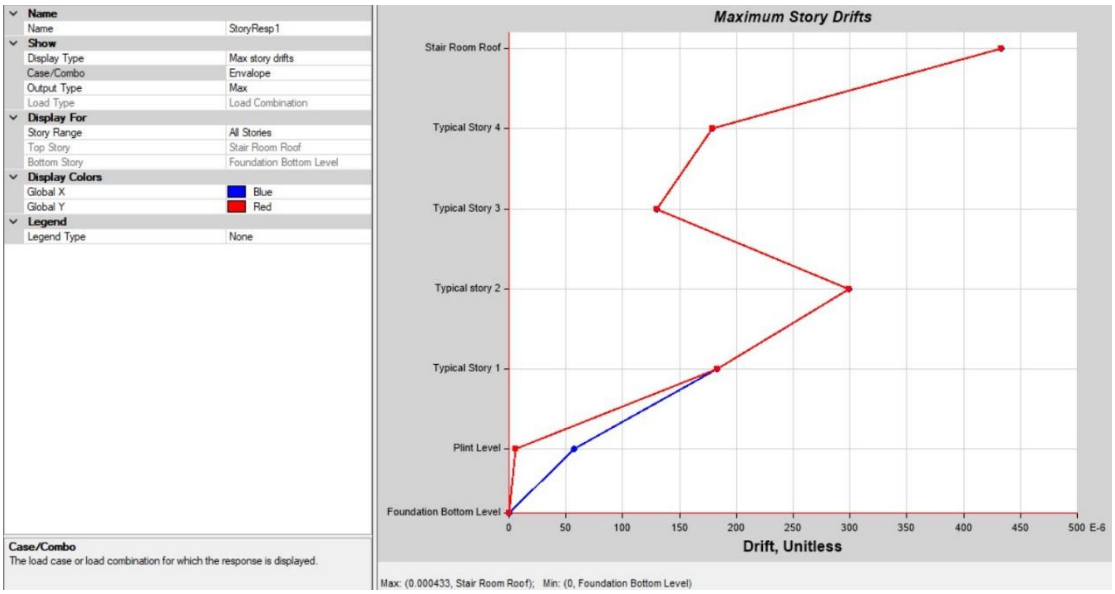


Figure B 2. Maximum Story Drift (Seismic Zone 2 without CFRP).

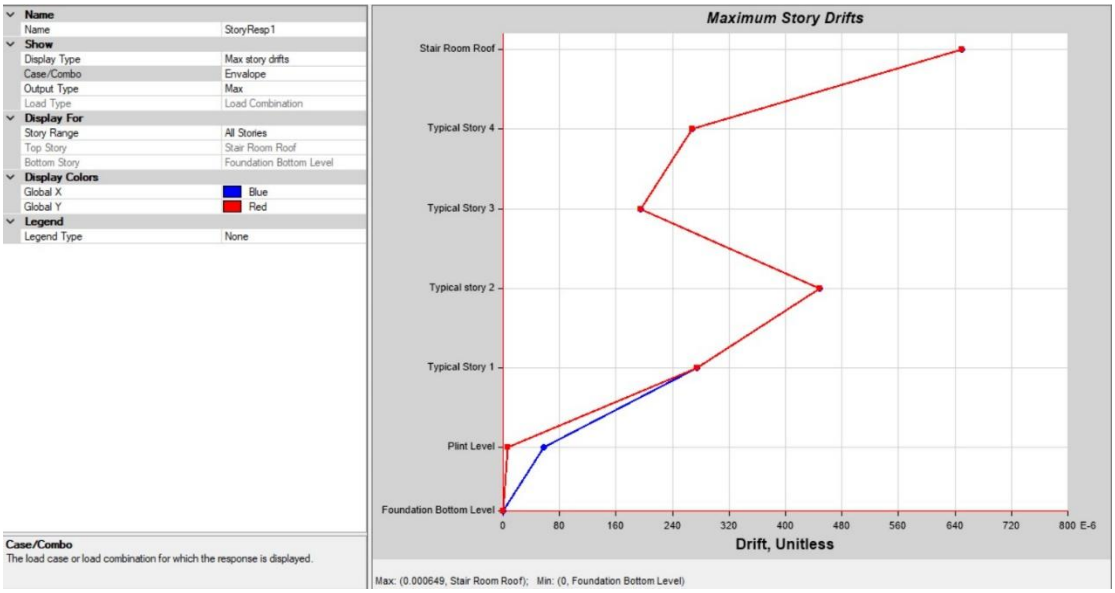


Figure B 3. Maximum Story Drift (Seismic Zone 3 without CFRP).

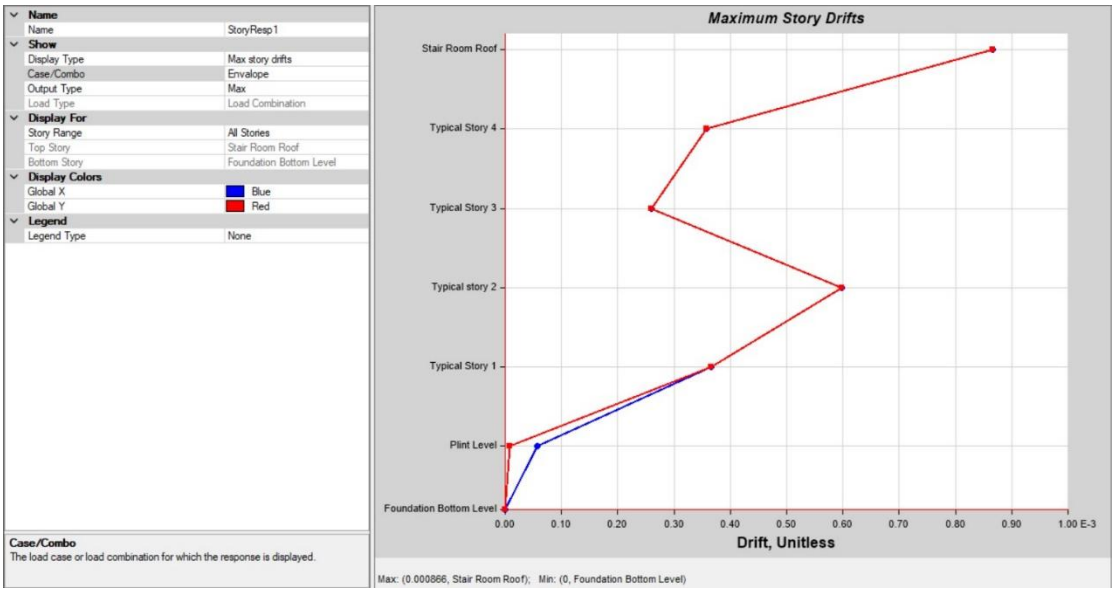


Figure B 4. Maximum Story Drift (Seismic Zone 4 without CFRP).

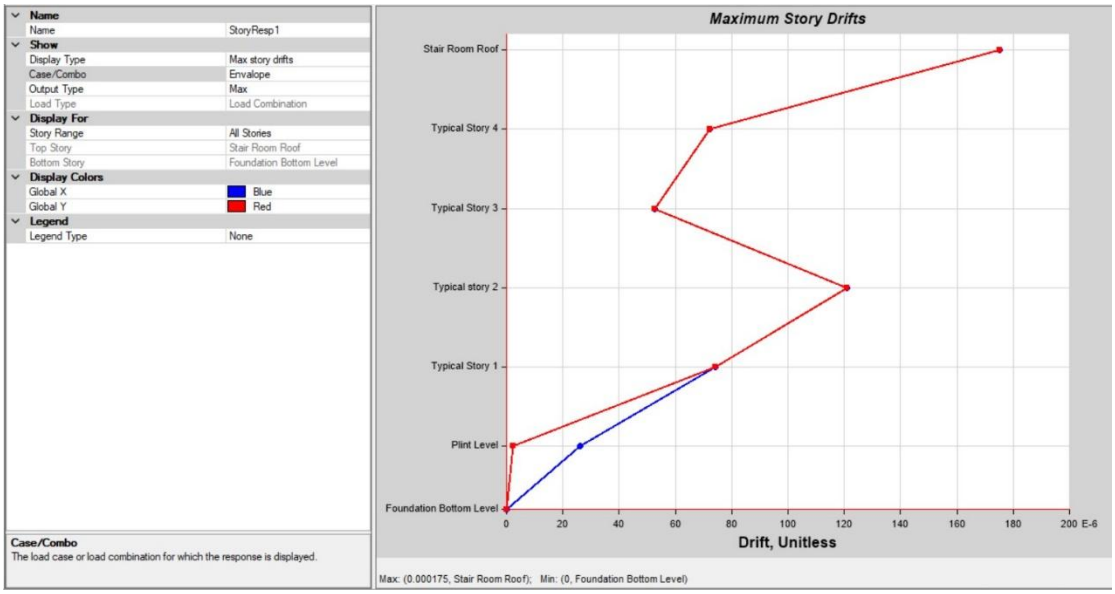


Figure B 5. Maximum Story Drift (Seismic Zone 1 with CFRP WFC-200).

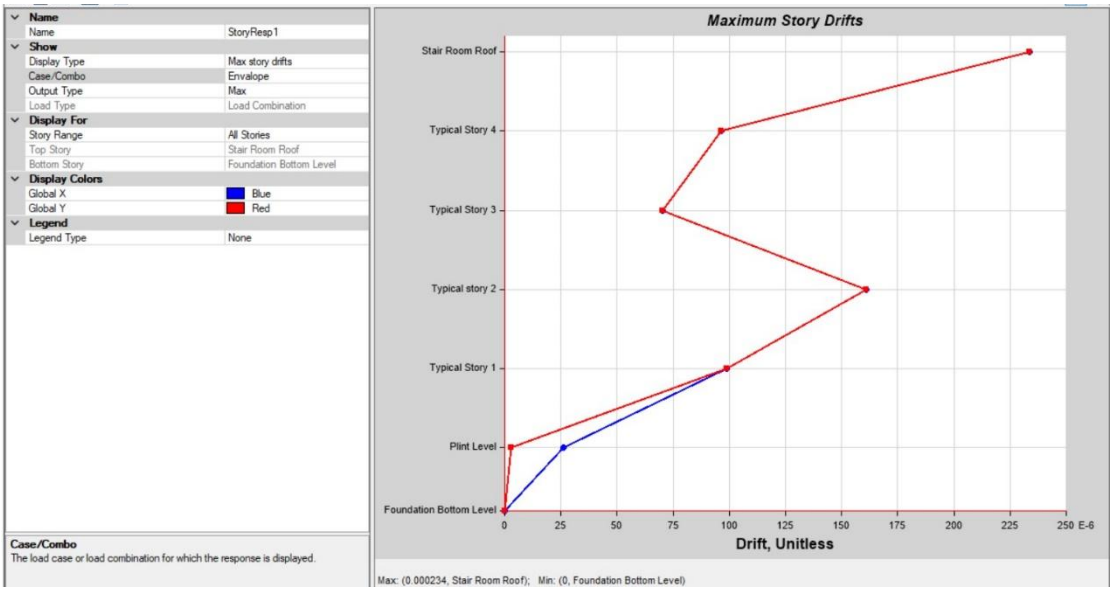


Figure B 6. Maximum Story Drift (Seismic Zone 2 with CFRP WFC-200).

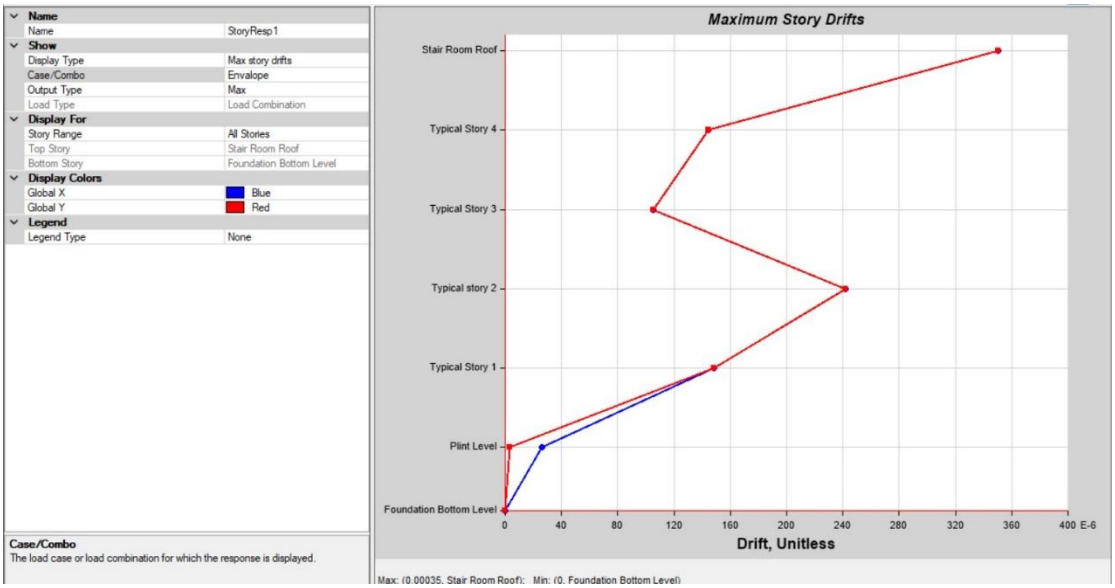


Figure B 7. Maximum Story Drift (Seismic Zone 3 with CFRP WFC-200).

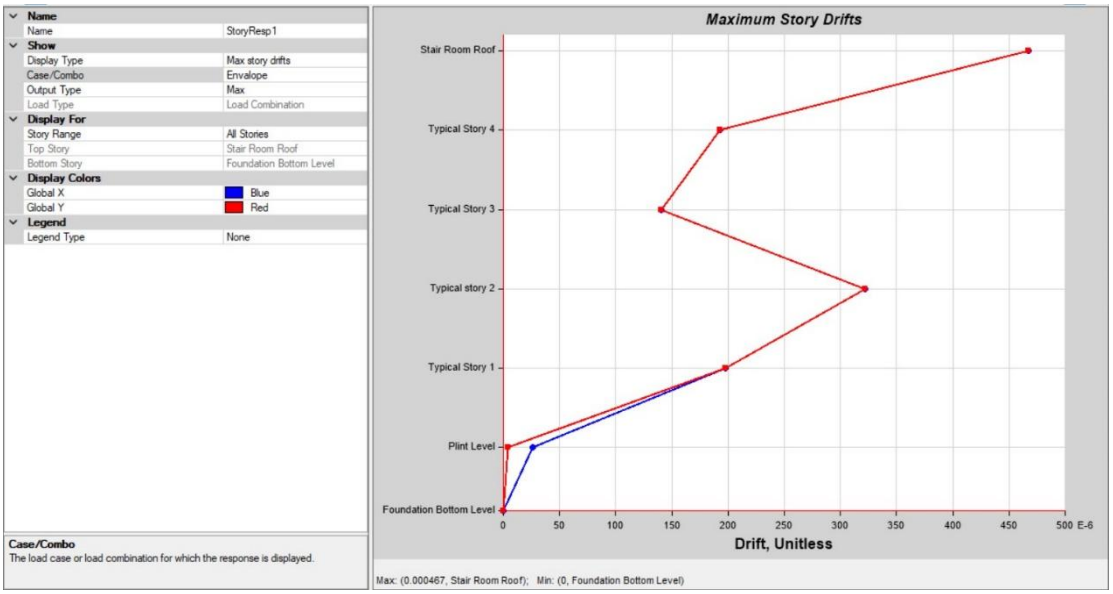


Figure B 8. Maximum Story Drift (Seismic Zone 4 with CFRP WFC-200).

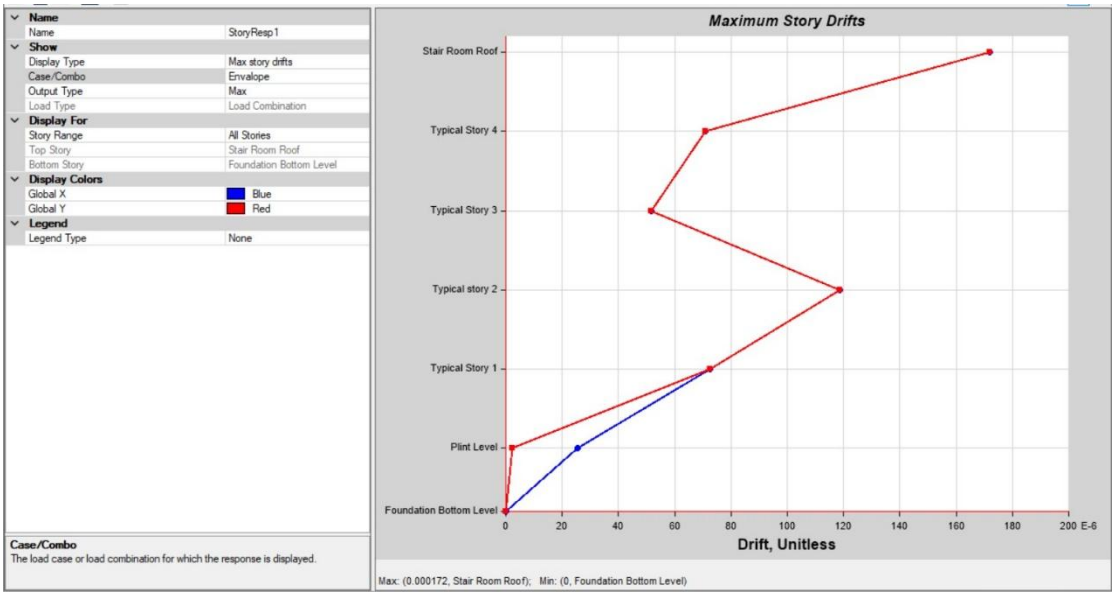


Figure B 9. Maximum Story Drift (Seismic Zone 1 with CFRP WFC-300).

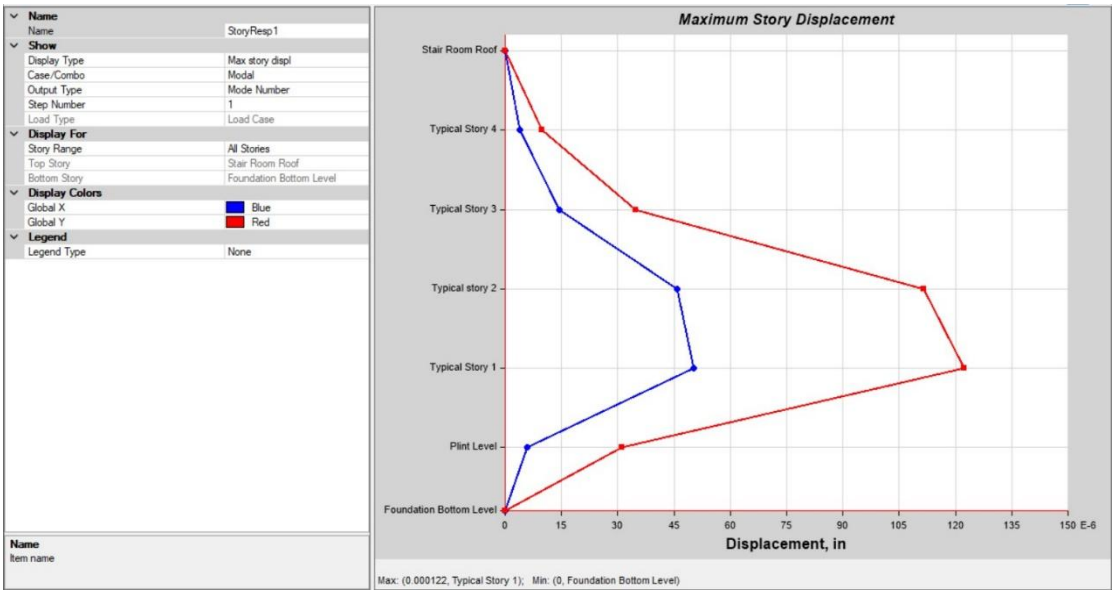


Figure B 10. Maximum Story Drift (Seismic Zone 2 with CFRP WFC-300).

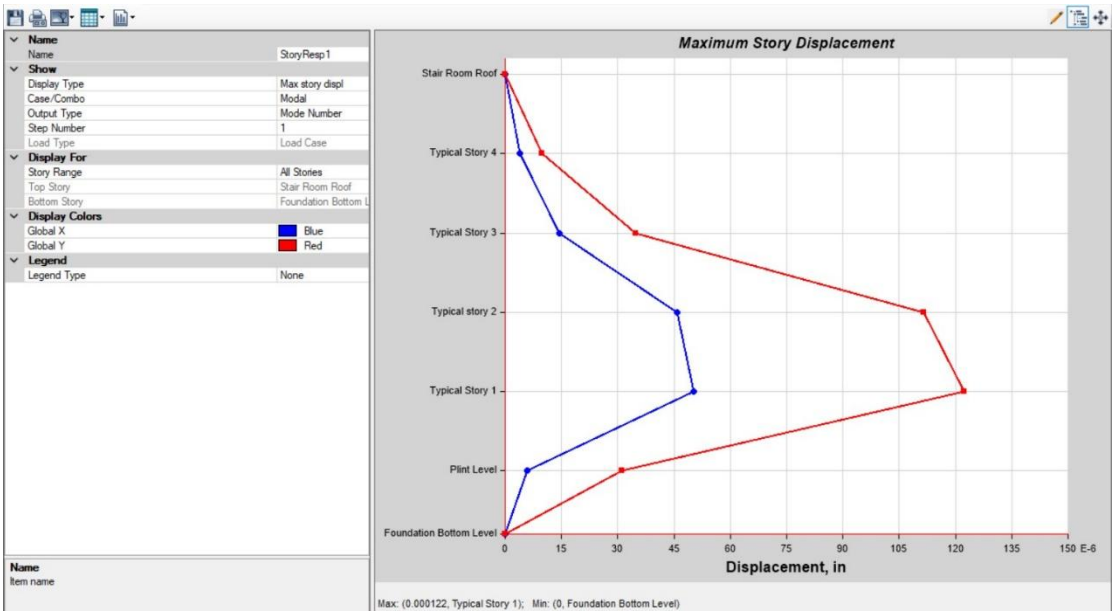


Figure B 11. Maximum Story Drift (Seismic Zone 3 with CFRP WFC-300).

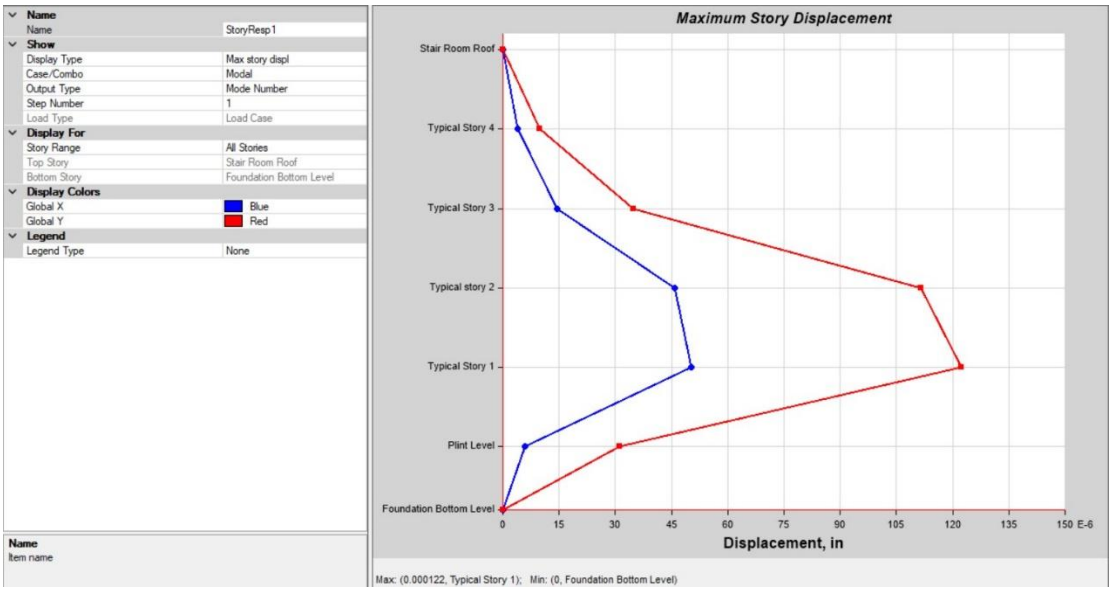


Figure B 12. Maximum Story Drift (Seismic Zone 4 with CFRP WFC-300).