COST COMPARISON OF CFRP AND STEEL PLATE RETROFITTING OF RC COLUMNS UNDER CONTROLLED DRIFT

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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

Department of Civil Engineering

Sonargaon University

147/I, Green Road, Dhaka-1215, Bangladesh

Section: 26A+27A

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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 Baker Hossain 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.
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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,
Adullah Al Mahmud

Md Rakib Hasan

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ABSTRACT

Retrofitting of existing reinforced concrete (RC) buildings has been a major solution to raise structural capacity, deal with deformation, and prolong service life, especially in cases where the original structures lacked enough stiffness or ductility. As two of the most popular methods for strengthening, retrofitting with steel plates and carbon fiber reinforced polymer (CFRP) have different merits in terms of stiffness improvement, load-carrying capacity, installation needs, and total cost efficiency. For example, while steel plates can significantly increase the strength of a structure, they also increase the dead load considerably as well as require the welding to be done, which is labor-intensive and needs surface preparation. On the other hand, CFRP is a lightweight, high-strength composite material which can be very quickly applied with almost no architectural disruption. This research solely compares these two retrofitting systems by analytical modeling through ETABS and the comparison is based on their impact on stiffness, drift reduction, and structural elements' response, especially beams and columns. Since Bangladesh is located in a seismically active area that is affected by the Himalayan arc, Dauki fault, and Indo-Burman ranges, the retrofitted building model is also checked under BNBC 2020 earthquake loads to see if each method can effectively bring old BNBC 1993/2006-designed structures up to the current drift and lateral load requirements.

The findings display that there are clear performance and cost trade-offs: steel plates can give high gains of stiffness but increase the weight of the structure and the complexity of installation, whereas CFRP can achieve very high strength-to-weight ratio and the application is quicker even though the material cost is higher. Thus, the research acts as a comparative performance-cost study that is of assistance to engineers in making the right choice of the most feasible and efficient method for retrofitting to enhance both the seismic resistance and the structural reliability of the existing reinforced concrete buildings in Bangladesh.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1.1 Background and Motivations

In general, reinforced concrete (RC) structures necessitate the retrofitting process after a considerable period of use, or when they suffer from damages, changes in live load, or alterations in design codes. The case is very serious in seismic areas, for instance in Bangladesh, which is situated close to the major tectonic boundaries (the Himalayan arc, the Dauki fault, and the Indo-Burman ranges). Alike that, there are lots of old RC buildings that were designed to the previous codes (e.g., BNBC 1993 / BNBC 2006), and hence they may not satisfy the drift, stiffness, or ductility requirements when checked against the latest standard (BNBC 2020). It happens that in most cases, the choice of demolishing the buildings and building new ones is not feasible; thus, the option of retrofitting by strengthening existing structural members provides a cheap and quick solution to achieve the goals of extending the service life, enhancing seismic performance, and adjusting to updated load demands.

Among the most various ways of retrofitting, the two generally come to a main consideration for RC beams, columns, and frame elements, namely: the use of external steel plates, and the bonding or wrapping with Fiber-Reinforced Polymer (FRP) material, particularly Carbon Fiber Reinforced Polymer (CFRP). By means of steel plate strengthening (or jacketing), the load-carrying capacity as well as the stiffness of the structure can be majorly raised as a result of adding a large amount of external reinforcement. Nevertheless, the method also has some cons: the increased dead load, more complicated installation (usually done by welding or bolting), surface preparation, the emergence of corrosion problems, and architectural or functional disruption during retrofit. In contrast, CFRP is a lightweight material that possesses very high tensile strength, a high strength-to-weight ratio, excellent corrosion resistance, and it can be applied in a building that is in use with no or very little disturbance to the building use or aesthetics. Therefore, these features make CFRP the most preferable material in the application of seismic retrofit to the existing RC structures.

Due to these opposing advantages and disadvantages - steel plates providing high stiffness and strength but increasing dead load and requiring a labor-intensive installation, while CFRP having a high strength-to-weight ratio and easier application but usually a higher material cost and debonding issues a systematic, quantitative comparison is absolutely necessary for engineers to make the right decision about the most suitable retrofit strategy, especially in earthquake-prone areas such as Bangladesh. Hence, the current study employs analytical modeling (through ETABS) to compare these two retrofit systems (steel-plate vs CFRP) concerning the improvement of stiffness, reduction of drift, and the response of structural elements (beams and columns) under seismic design loads as per BNBC 2020. This local engineer's decision-making tool, a performance–cost comparative study, intends to serve as a means of selecting the most feasible and efficient retrofitting strategy of existing RC buildings to achieve two-fold benefits, i.e., increase of seismic resistance and structural reliability without the unnecessary increment of dead load or excessive costs.

1.2 Research Objectives and Overview

Retrofitting of existing reinforced concrete (RC) buildings has become a main focus in areas that are highly prone to earthquakes, especially where the old design codes were lacking in strength, stiffness, or ductility requirements. Numerous RC structures in Bangladesh were designed based on the older versions of BNBC (1993/2006), which generally do not meet the drift limits, lateral load demands, or detailing requirements of BNBC 2020. Consequently, the implementation of the steel plate-retrofitting method and the Carbon Fiber Reinforced Polymer (CFRP) application has been the most popular way to upgrade the separations of the earthquake of old buildings.

In brief, these two methods are quite different structurally, from their installation procedures, the material usage, price and even the performance of their service lifetime, although their effectiveness is equally proven. To elaborate more, one can mention that the use of steel plates will bring major advantages in terms of increasing the strength and stiffness of the structure, but at the same time it will increase the dead load and require a work-intensive process, such as welding and surface preparation. On the other hand, CFRP offers more advantages in terms of high strength-to-weight ratio, easiness of the application, and minimal architectural disturbance, but it is associated with a higher material cost and issues such as debonding which can occur if the installation is not done properly.

In light of these vastly different properties, an analytical comparison is important to show the extent of each retrofitting method on the key seismic performance parameters. As a result, this work builds an existing RC structure model in ETABS, implements both retrofitting plans, and determines their effects on the stiffness, inter-story drift, and the structural response of beams and columns under earthquake loads according to BNBC 2020. The study, in its final stage, hints at whether each method can bring a moment older RC building up to the present standard while also taking into account the factors of structural effectiveness and cost.

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

- To model an existing RC building in ETABS and determine its drift performance according to BNBC 2020 seismic loads.
- To apply retrofit methods steel plates and CFRP in the same building model to analyze their impact on drift reduction.
- To Compare the extent to which each of the two retrofitting methods helps to improve the total lateral stiffness and control of the drift.
- To find out what method gives more efficient drift improvement if weight increase, installation effort, and relative cost are taken into account.

1.3 Organization of the thesis

Chapter 1: Introduction and Objective

The research work presented here is basically an evaluation of the seismic vulnerability of existing RCC buildings in Bangladesh with the help of BNBC 2020 provisions. Moreover, it also advocates retrofitting as a viable and green alternative to the demolition and reconstruction of buildings. An irregular ten, story RC building was modeled in ETABS, and Section Designer was utilized for applying steel plate jacketing and CFRP wrapping techniques. As there were software limitations, the researchers simulated CFRP using steel plate properties. The research has identified inter, story drift, lateral stiffness, and cost efficiency as the main parameters and at the same time, the structural weight, installation complexity, and the availability of the workforce have also been taken into consideration. Therefore, by handling all these requirements, it has offered engineers a real, world working framework for the selection of retrofit methods whereby safety, economy, and resilience are properly balanced.

Chapter 2: Literature Review

This study combines an analytical technique focused on drift with the energy of evaluating the different strategies for retrofitting existing RCC buildings in Bangladesh as per BNBC 2020. A G+9 story irregular RC building was modeled in ETABS and the seismic loads were applied according to the updated code provisions. Section Designer was used to carry out two different retrofitting techniques of steel plate jacketing and CFRP wrapping, where CFRP was represented by using the properties of steel plate due to the lack of functionality of the software. The analysis made inter, story drift and lateral stiffness the main performance parameters but also considered the material cost, added structural weight, installation complexity, and availability of the workforce. This combined approach offers an actual working framework for the selection of retrofitting methods.

Chapter 3: Methodology

The study proposes a comparative analytical approach to review two popular methods of retrofitting concrete buildings for seismic zones in Bangladesh: steel plate jacketing and Carbon Fiber Reinforced Polymer (CFRP) wrapping. Both scenarios were modeled in ETABS for a typical multi, story RC building built according to BNBC 2020 standards. Besides mechanical parameters like inter, story drift and lateral stiffness, the comprehensive performance evaluation of the retrofitting methods also considers practical aspects such as structural weight, installation complexity, and cost efficiency. This framework thus facilitates a comparative assessment of retrofit strategies in terms of their effectiveness and practicality for seismic resilience enhancement.

Chapter 4: Results and Discussion

A comparison of Carbon Fiber Reinforced Polymer (CFRP) wrapping and steel plate jacketing with BNBC 2020 earthquake code permits reveals that both methods significantly improve the seismic resistance of reinforced concrete (RC) structures; however, the degree of their effectiveness varies depending on the different building levels. Steel plates contribute more to the rigidity of the structure and facilitate a reduction in the inter-story drift of the upper stories, thus indicating a better capability of the building to withstand lateral forces, whereas the use of CFRP has been found to result in better drift control at the plinth and first stories, where the shear demand and the stress concentration are particularly high. From a financial perspective, CFRP is a more economical option that helps to lower the retrofit cost in comparison with steel plates. Therefore, CFRP can be considered as a feasible and compelling option for the retrofitting of RC buildings, especially in the case of limited budget projects.

Chapter 5: Conclusions and Future Work

Retrofitting with steel plates is known to increase lateral displacement control of the upper floors by making the structure more rigid. On the other hand, Carbon Fiber Reinforced Polymer (CFRP) is very good for the walls of lower levels like the plinth and first floor where the requirements for confinement and ductility are the highest. Both traditional methods of resisting earthquakes deal with the seismic forces in different ways and therefore the stabilization of the structure is targeted at the different heights of the building. In terms of the cost, CFRP is an affordable way to increase the seismic performance of a structure without compromising on safety. In this way, these two techniques provide building engineers with feasible solutions to the problem of strengthening concrete framed buildings in earthquake, prone areas and at the same time increasing their capacity to withstand the next earthquake.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

The seismic vulnerability of existing Reinforced Concrete (RC) buildings that have been designed using older code provisions has led to a wide range of analytical research that aims to find effective retrofitting strategies. As structural analysis software is improving, researchers are turning more and more to numerical modeling for evaluating the seismic performance as well as the deformation of the existing buildings. Out of the tools that are available, ETABS has become one of the most widely used platforms to investigate the behavior under lateral load, the change of the stiffness, and the inter-story drift in multi-story RC structures that are subjected to earthquake loading in accordance with the code. The literature covered in this section is devoted to the ETABS-based analytical examinations that measure the effectiveness of different retrofitting methods in enhancing the seismic performance, mainly as regards the reduction of the drift. The comparative research of different methods for the improvement of stiffness, such as steel-plate strengthening and CFRP retrofitting, has been given the greatest attention, as these two techniques are mostly used for the upgrading of the existing RC buildings. The reviewed papers give the understanding of the influence of the methods on lateral stiffness, structural mass, and drift behavior through numerical modeling. This review uncovers the research gap about Bangladesh, as very few ETABS-based analytical comparisons using BNBC 2020 seismic provisions have been made. By consolidating the present ETABS-centric studies, the literature review serves as a foundation for the current study that intends to perform drift-based analysis of a single RC building model for comparative purposes of retrofitting by steel-plate and CFRP methods.

2.2 Content

There has been a lot of research over the years on how the different RC elements behave after being retrofitted with CFRP. One such example is the experimental work, where it has been demonstrated that wrapping the RC beams with CFRP sheets can not only bring back the strength and stiffness to the level of the original ones, but also can be higher(Tiwary et al., 2022). Specifically, a single study quantified the changes resulting from CFRP retrofit of an RC frame in terms of peak load, initial stiffness, and ductility, where these parameters were increased by 43.9 %, 39.3 %, and 30.1 % correspondingly(Zhou et al., 2024). The research with the eight-story RC frame fitted with CFRP and subjected to long-duration seismic records revealed the improvement of the structural response to seismic loading(Ekraghanbari, 2022a). Meanwhile, the performance of the steel plate retrofit has also been confirmed. The modularized steel-plate jacketing of RC beams has been reported to raise flexural capacity even three times, ductility two times, and energy dissipation capacity seven times(Kim & Lee, 2021). Besides, comparative studies of beams retrofitted with steel plates and CFRP have unveiled a significant dilemma: while steel plates provide robustness and ductility, the increased weight and complexity may cause practical limitations(Ercan, Arisoy, et al., 2018).

The seismic performance assessment and retrofitting of old reinforced concrete (RC) structures have been major themes in research, mainly by analytical modeling through the use of structural analysis software, notably ETABS. Due to its ability to construct the model of multi-story RC structures, implement code-based earthquake loading, and record the key seismic response parameters like lateral displacement and inter-story drift, ETABS has been a tool of choice in studies of seismic performance. Plenty of journal and conference papers have utilized ETABS to conduct seismic performance assessment of buildings designed according to older seismic codes and to evaluate the effectiveness of the retrofitting strategies under new earthquake provisions. A handful of ETABS-based analytical studies have explored the application of steel-plate retrofitting for the seismic strengthening of RC buildings. The reports from these studies indicate that the method of steel-plate strengthening greatly elevates the lateral stiffness and decreases inter-story drift since the capacity of the beams and columns to resist the lateral load is enhanced during earthquake excitation. Nonetheless, the researchers have also acknowledged that the rise in stiffness is accompanied by the increase in structural mass, which in turn causes the rise in seismic demand and base shear. Earthquake analyses based on ETABS clearly demonstrate such a compromise whereby better drift control is achieved at the cost of higher inertia forces(Ercan, Arısoy, et al., 2018). There are several research works in the form of journals and conferences that have been analyzed extensively through ETABS simulations about the use of CFRP retrofitting. In these studies, the CFRP strengthening of the frame is usually considered in the change of the structural stiffness or corresponding material properties. Their ETABS seismic analysis outcomes demonstrate that the application of a carbon fiber-reinforced polymer (CFRP) is very effective in lowering lateral displacement and inter-story drift while the increase in the dead load is not significant. Hence, CFRP turns out to be quite effective for the control of seismic drift, especially in structural systems where the addition of mass is not desirable(Ekraghanbari, 2022b). Comparative ETABS-based studies published in journals and conference proceedings have highlighted distinct performance differences between steel-plate and CFRP retrofitting techniques. While steel-plate retrofitting often yields greater stiffness enhancement and lower drift values, CFRP retrofitting achieves comparable drift reduction with minimal impact on the building's dynamic characteristics. ETABS earthquake response analyses indicate that CFRP-retrofitted buildings experience improved deformation control with less amplification of seismic forces compared to steel-retrofitted counterparts(Lin et al., 2024). ETABS-based earthquake analysis has been a significant tool in determining the conformity of local RC structures to the latest seismic codes in areas with frequent earthquakes like Bangladesh. Nevertheless, there has been very little published research in journals and at conferences that has considered a direct comparison of steel-plate and CFRP retrofitting methods under BNBC 2020 seismic provisions. Consequently, the current research moves to fill this void by conducting a drift-focused ETABS earthquake analysis of just one RC building model to assess and compare the performance of steel-plate and CFRP retrofitting in meeting the seismic drift requirements set by the code.

2.3 Summary

Most of the existing reinforced concrete (RC) buildings that were designed based on older seismic codes are not sufficiently resistant to the new earthquake requirements. That is why a lot of analytical research for retrofitting these buildings has been done. Due to the progress in the numerical modeling, ETABS has become a tool that is widely used for investigation of the lateral load behavior, stiffness changes, and inter-story drift in multi-story RC structures. The literature survey indicates that the research has mostly been focused on the retrofitting with steel-plates and CFRP, which are the two techniques that alter stiffness, mass, and drift in a different way. Steel-plate strengthening, as a result, very much increases the stiffness and reduces the drift but at the same time, it also significantly increases the mass which leads to higher seismic forces. While CFRP retrofitting, on the other hand, makes the structure stiffer and causes the drift to be lower but there is very little added weight, hence it is very beneficial in the case where the increase of mass is not allowed. The comparative ETABS-based studies always point out these trade-offs. However, a significant research gap is present in Bangladesh where very few studies have been conducted on this matter. Few studies have been carried out to compare these two retrofitting methods by using BNBC 2020 provisions. This gap is the reason for the current research drift which is a single RC building ETABS analysis to compare steel-plate and CFRP retrofitting to satisfy BNBC 2020 seismic drift requirements.

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 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 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

This study considers an existing reinforced concrete (RC) building representative of typical 10 story residential structure in Bangladesh. The building was originally designed according to earlier versions of the Bangladesh National Building Code (BNBC 1993/2006). An analytical model of the building is developed in ETABS to evaluate its drift performance and to assess the effectiveness of steel-plate and CFRP retrofitting techniques under the seismic loading provisions of BNBC 2020. Also, the building is in seismic zone 2 Ashulia, Savar, Dhaka.

Figure -3-1. Seismic zone of Bangladesh

3.2.2 Data Collection

The data collection method consists of 5 steps work.

- Collect building geometry and structural layout.
- Collect material properties of concrete and reinforcement details.
- Collect gravity load data (dead and live loads) as per BNBC provisions.
- Collect seismic parameters from BNBC 2020.
- Collect inter-story drift results from ETABS output after analysis.

3.2.3 Material details

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 500DWR	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 B420DWR	29000000	60.000	90.000	66.000	99.000

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

Table 3-3. Details of CFRP and steel plate.

Type of Material	Modules of elasticity (lb./in^2)	Minimum yield strength (lb./in^2)	Minimum tensile strength (lb./in^2)	Avg. yield strength (lb./in^2)	Avg. tensile strength (lb./in^2)
CFRP	32633491	531022	796533	584124	876187
Steel Plate	29007545	48587	72518	53446	79770

3.2.4 Buildings Structural Design and Details

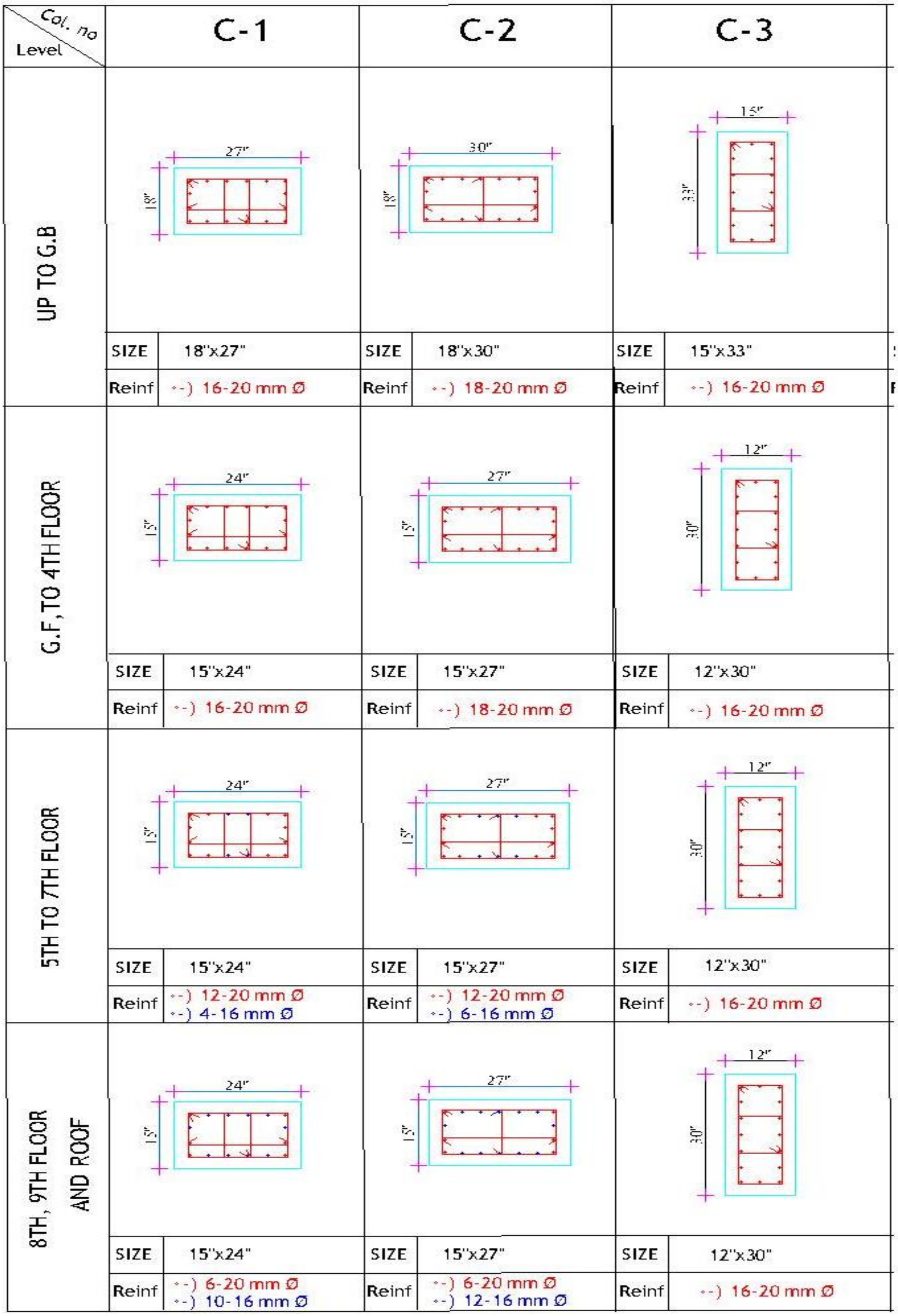
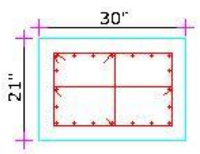
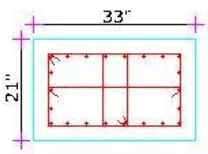
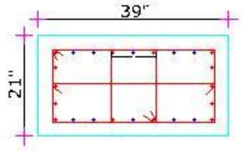


Figure 3-2 Square Column Details (C1 to C3)

Level \ Col. no	C-4	C-5	C-6	Cover	TIES
UP TO G.B				Clear Cover 3" AND 1½"	10mmØ @ 4"/6"/4"c/c
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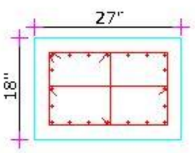
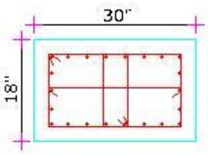
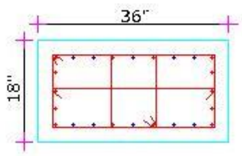
G.F, TO 4TH FLOOR					
	SIZE 18"x27"	SIZE 18"x30"	SIZE 18"x36"		
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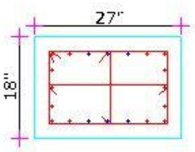
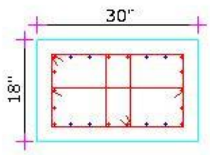
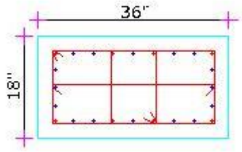
5TH TO 7TH FLOOR					
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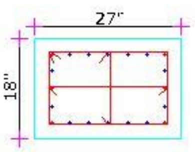
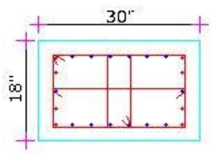
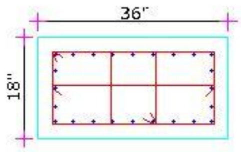
8TH, 9TH FLOOR AND ROOF					
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Figure 3-3. Square Column Details (C-4 to C-6).

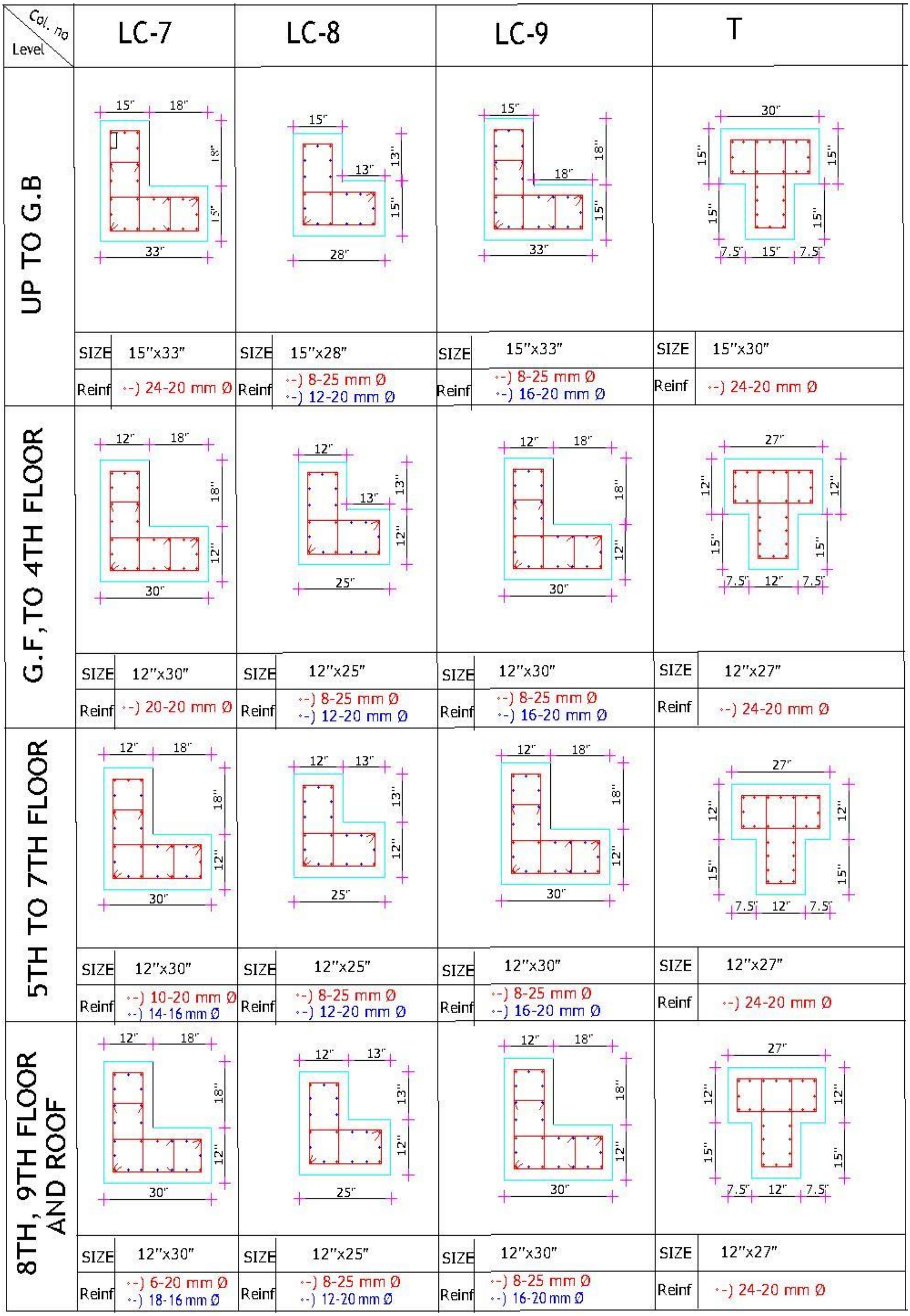

Figure 3-4. L and T column Details.

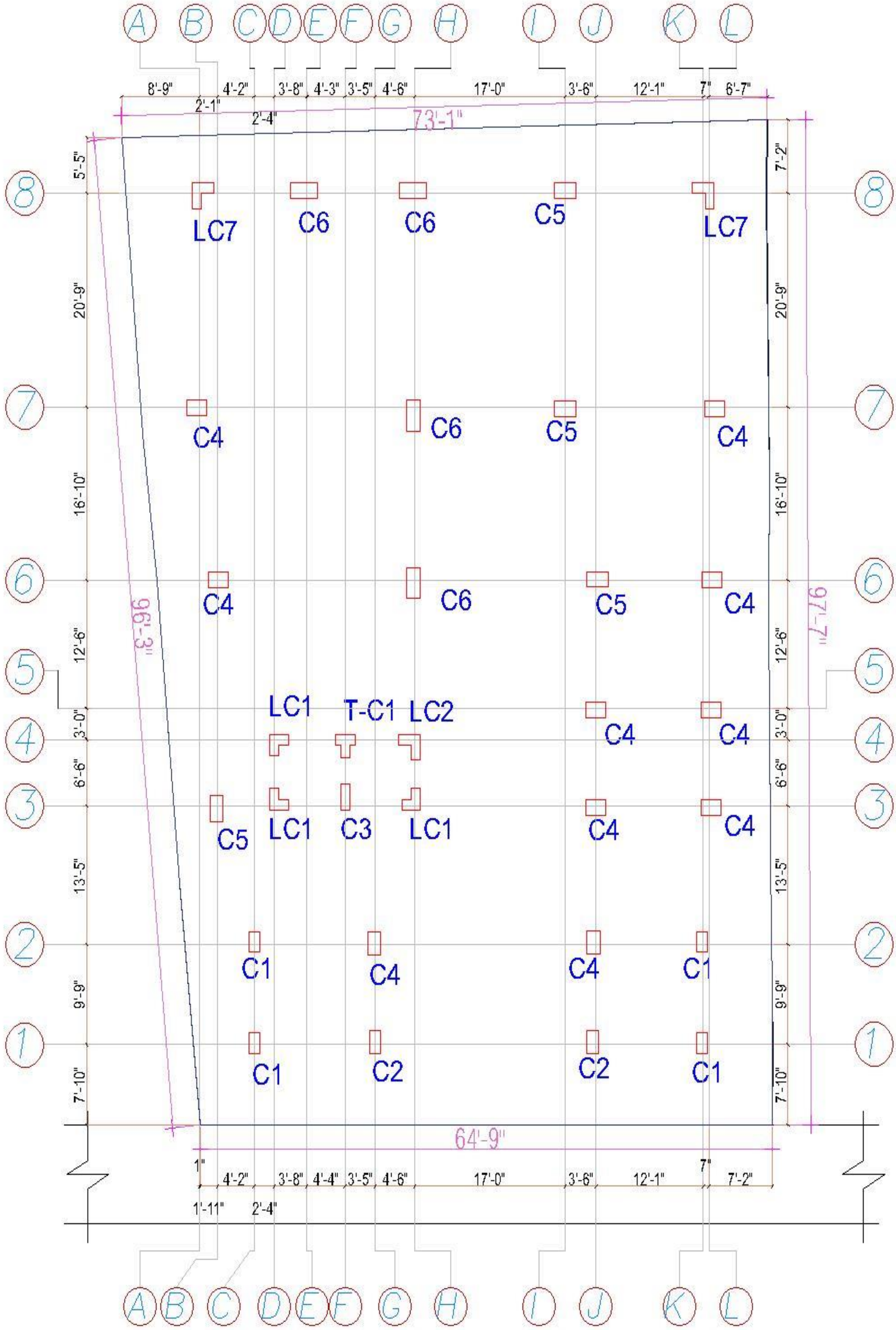

Figure 3-5. Column Layout Plan.

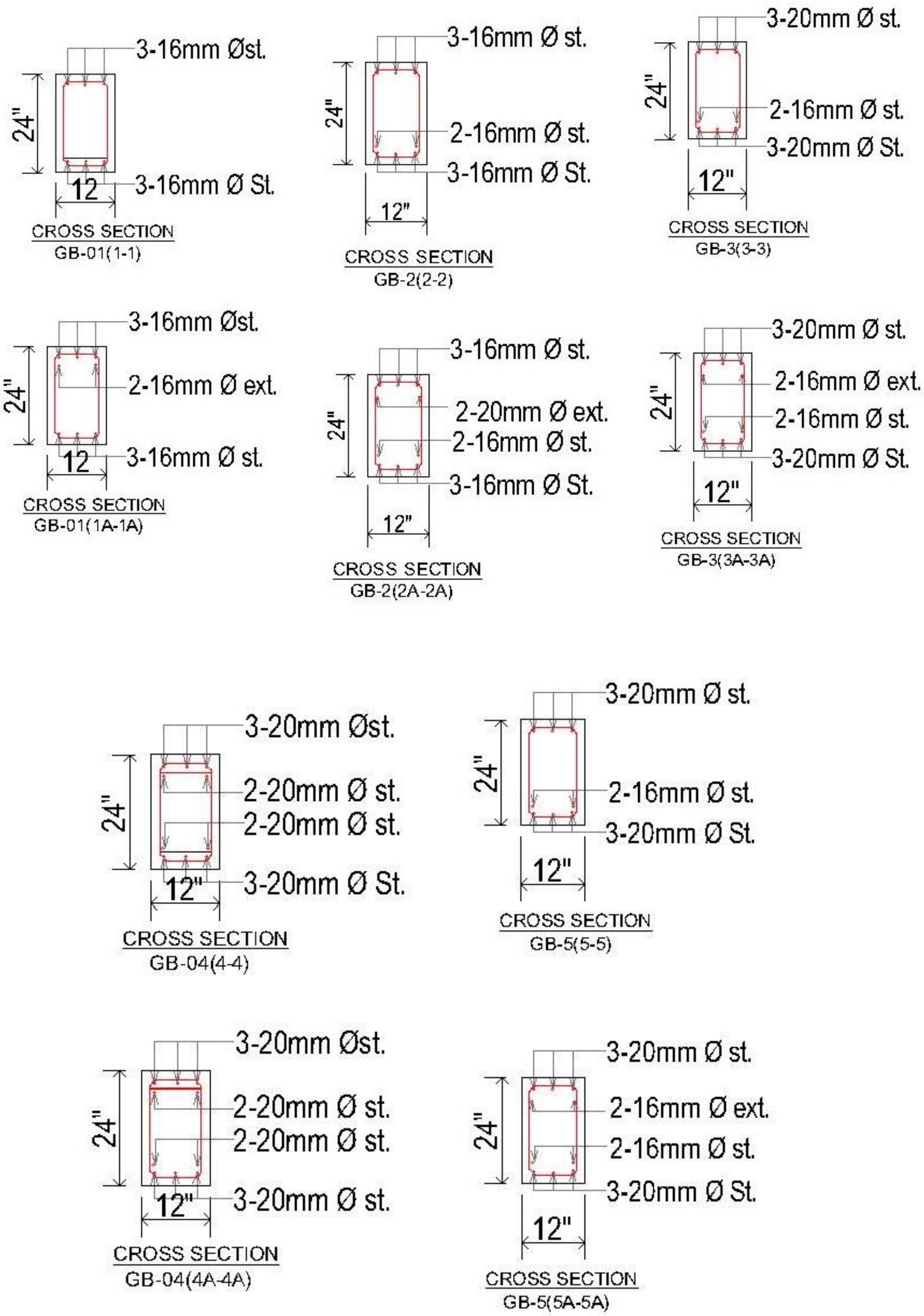

Figure 3-6. Grade Beam Details.

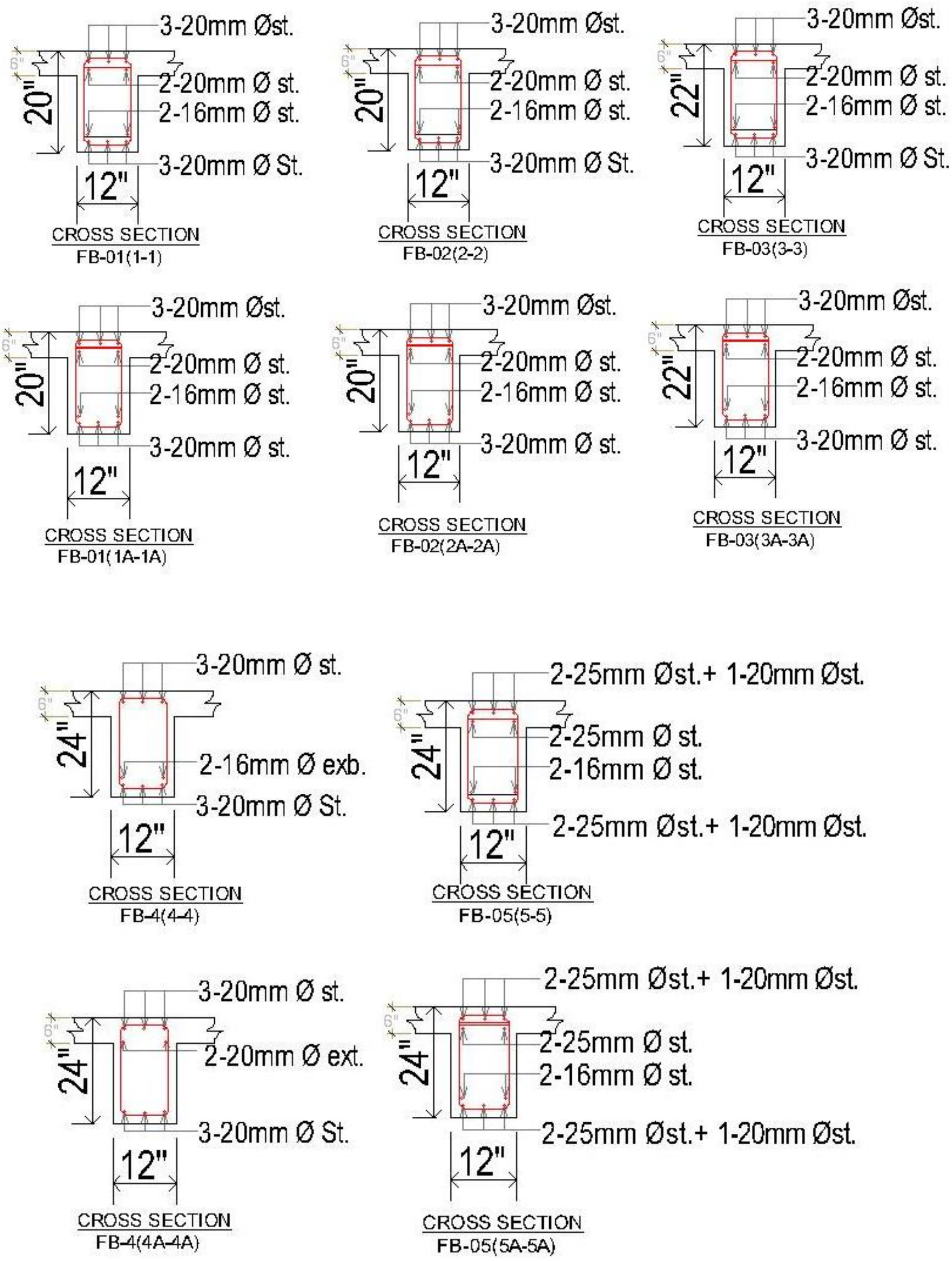

Figure 3-7. Floor Beam details,

3.2.5 Data Analyzing Method

Implementing all the data needed on ETABS we analyzed the building according to BNBC 2020 load combinations. As the building is in Seismic Zone 2 with soil type SC the analyze method considers some modifications for its drift nature and we analyzed the building for all seismic zone. All the load combinations are and load cases are.

Table 3-4 Load Cases.

Types of loads	Load Values
Dead load	Self-weight
Live load	Residential= 2.02 kN/m^2
Floor finish	1.2 kN/m^2
Partition wall load	6.4 kN/m
Parapet wall load	2.4 kN/m
Lift Load (Only in lift beams)	5.548 KN/m

Table 3-5 Load combination for seismic zone.

- Load combination.

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

3.2.6 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 CFRP in ETABS

ETABS lacks material properties for carbon fiber reinforcement, therefore the model's material data was left undefined. In order to fix this, the model was changed to user settings for steel plate property for CFRP. Since the epoxy does not have a tensile or compressive force, it was not necessary to give a definition. The properties of a CFRP on a steel plate like modulus of elasticity, density, and tensile strength were specified. The steel plate serves as a CFRP harden plate with epoxy, as it does not have any tension or compressive force and we have used the section designer option to retrofit the column as a composite column(Ahmad & Singh, 2022).

- Basis for selecting CFRP Retrofitting

Carbon Fiber Reinforced Polymer (CFRP) was chosen as the structural material to retrofit the columns because of its excellent mechanical properties and the benefits associated with its use as an alternative method for the structural upgrade of existing buildings. In fact, CFRP has very high tensile strength and modulus of elasticity, and it is very light, thus the dead weight imposed on the structure is reduced. Its high resistance to corrosion is very useful, especially when such a structure is strengthened by steel, which may eventually deteriorate. Moreover, CFRP can be easily bonded with epoxy resin on its outer surface, which guarantees a fast installation without the need for the suspension of the normal building operations. These benefits make it very effective in increasing ductility, confinement, and dissipation capacity when used on reinforced concrete structural columns.

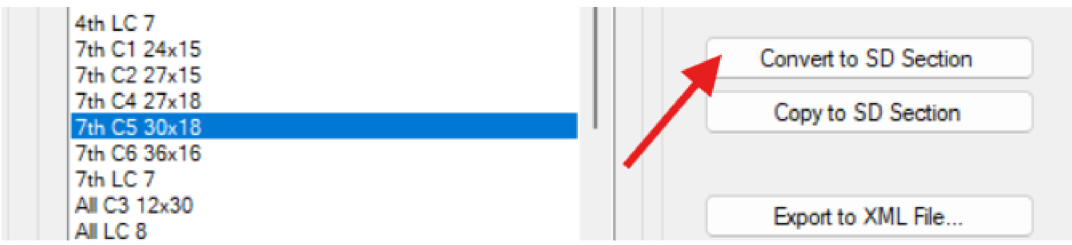

Figure 3-8. SD Section in ETABS.

3.2.7 Retrofitting with CFRP and Steel Plate

- CFRP

For columns 0.08 inch of CFRP thickness with epoxy resin was applied in the model in ETABS software.

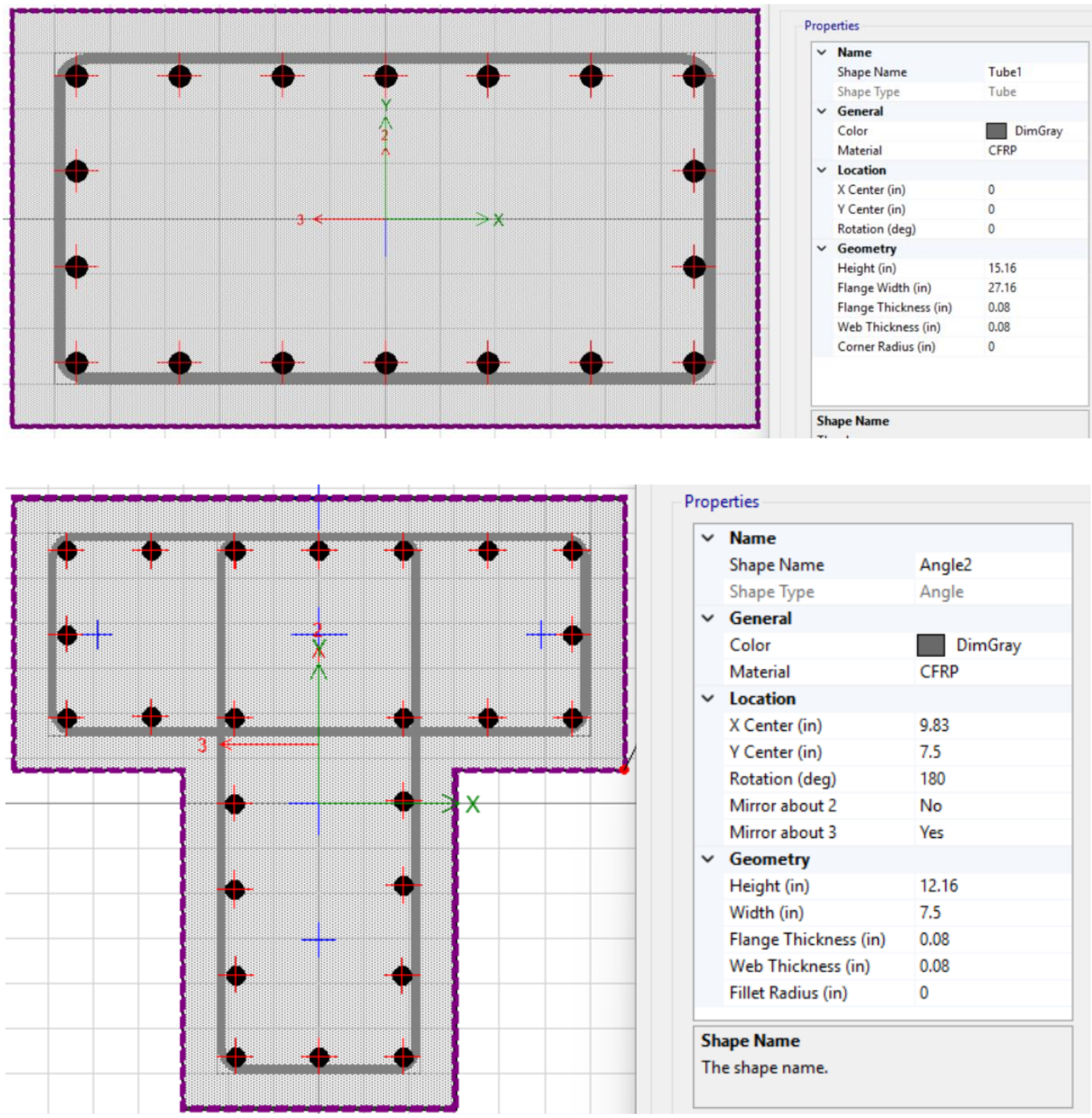

Figure 3-9 CFRP retrofitting of Column.

- Steel Plates

Same as before, thickness of 0.2-inch steel plate has been retrofitted in the columns.

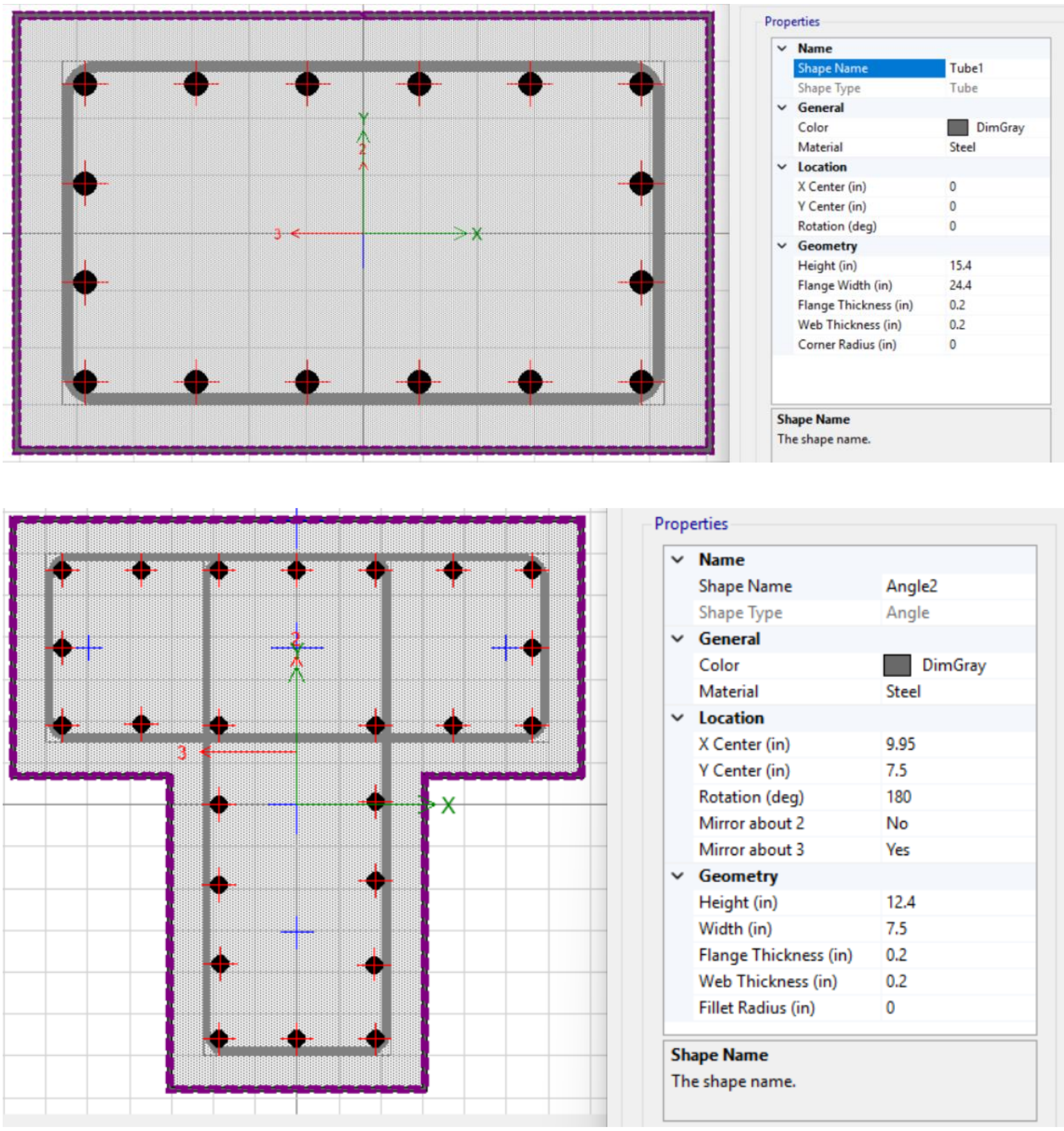

Figure 3-10 Steel plate retrofitting of Columns.

3.3 Summary

The research work entailed the assessment of the earthquake resistance capability of a ten, story irregular pattern reinforced concrete building located at Savar, Dhaka through ETABS following BNBC 2020 provisions. The study began with the depiction of the building in terms of geometry, materials, and loads and later modeling the structural details such as different types of columns, i.e., square, L-shaped, and T-shaped with proper reinforcement. The analysis is done by applying the seismic load cases and 32 combinations to evaluate drift and strength capacity. Because ETABS did not have the properties of CFRP, a steel plate proxy was used to simulate the behavior of CFRP, while epoxy was left out from the modeling. The installation of CFRP wrapping and steel plate confinement were the retrofitting techniques that were both performed to improve the ductility, confinement, and energy dissipation of the building, thus preparing the ground for further performance assessment.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Introduction

Carbon Fiber Reinforced Polymer (CFRP) and steel plate retrofitting of reinforced concrete structures subjected to seismic loading. Structural models were created in ETABS as per BNBC 2020 guidelines, and the inter-story drift along with cost efficiency were taken as the main parameters for the evaluation. Generally, steel plate retrofitting was able to achieve lower drift values in most of the stories, however, CFRP appeared to be a close runner, particularly in the lower levels such as Story 1 and Plinth. This price benefit of CFRP, combined with sufficient drift control, makes CFRP a technologically feasible and economically attractive alternative to be used in the rehabilitation of the existing RC buildings for seismic resistance enhancement.

4.2 Specific Aim 1

The main objective of this study is to determine the seismic vulnerability of the current reinforced concrete (RCC) buildings in Bangladesh based on the seismic provisions of BNBC 2020, and to check if it is technically and economically viable to retrofit using Carbon Fiber Reinforced Polymer (CFRP) jacketing instead of completely demolishing and reconstructing the buildings. Firstly, a generic multi, story RC building is taken into consideration for the modeling purpose in a software ETABS and the main parameter of the study is the inter, story drift capacity of the structure. In order to attain the targeted parameter of structural response, both fiber composite and steel jacket reinforcement techniques have been tried on the same building model for comparison. Their efficiency in terms of reducing the drift by upgrading the lateral stiffness and controlling the displacement was measured for all stories. Besides the performance aspect, the study also looked at the two methods in terms of material cost, ease of installation, work force availability, and increase in structural weight. The comparative analysis, thus, provides a good base for the scenario where a residential building is changed to commercial building with the main focus on the safety, cost and environment. Meanwhile, the study intends to facilitate the resilient urban development by proposing retrofit solutions that harmonize seismic performance with real life limitations of construction work.

4.2.1 Drift Comparison

Allowed drift limit for this G+9 Story building is 0.0025hx. Which is 0.03 inches.

Table 4-1 Maximum drift found on CFRP and Steel Plate Model.

Story	Without Retrofitting Drift (inch)	CFRP Drift (inch)	Steel Plate Drift (inch)
Roof Level	0.035635	0.030821	0.025984
Story 10	0.020246	0.017979	0.015373
Story 9	0.014298	0.01405	0.013793
Story 8	0.014082	0.013812	0.013546
Story 7	0.013992	0.01368	0.013392
Story 6	0.01393	0.013564	0.013248
Story 5	0.013847	0.013407	0.013244
Story 4	0.013455	0.013391	0.013674
Story 3	0.01419	0.013155	0.013728
Story 2	0.014008	0.012342	0.013435
Story 1	0.016423	0.010631	0.013783
Plinth Level	0.039914	0.029031	0.035442

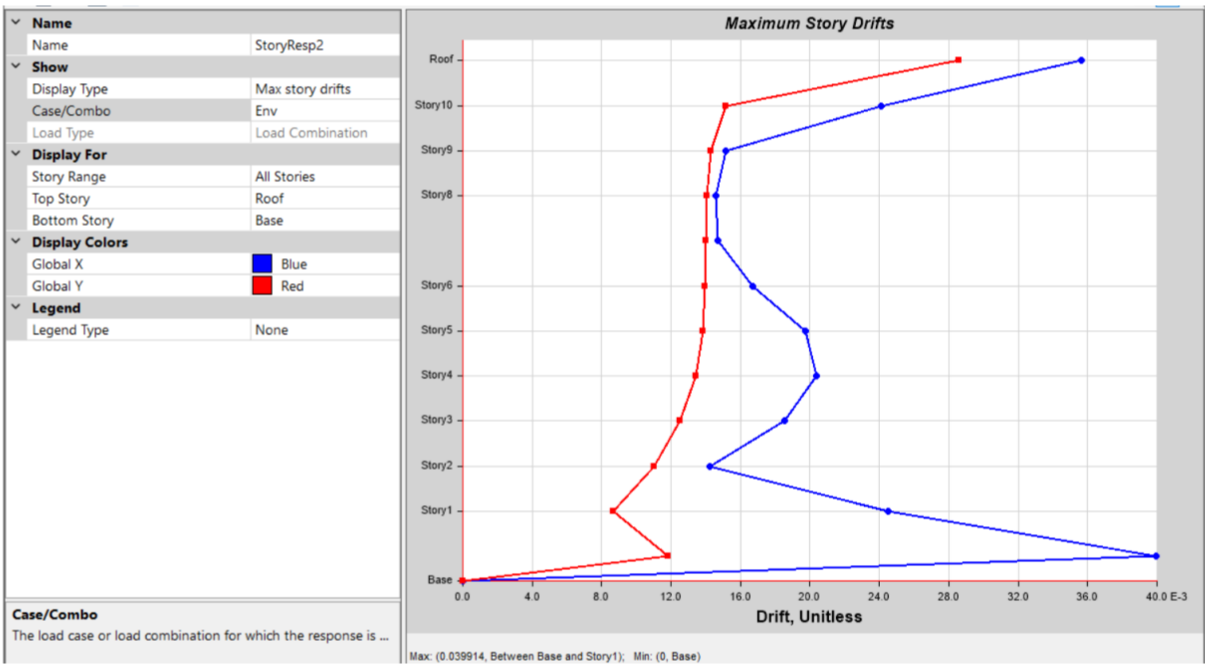

Figure 4-1. Max Story Drift Without Retrofitting.

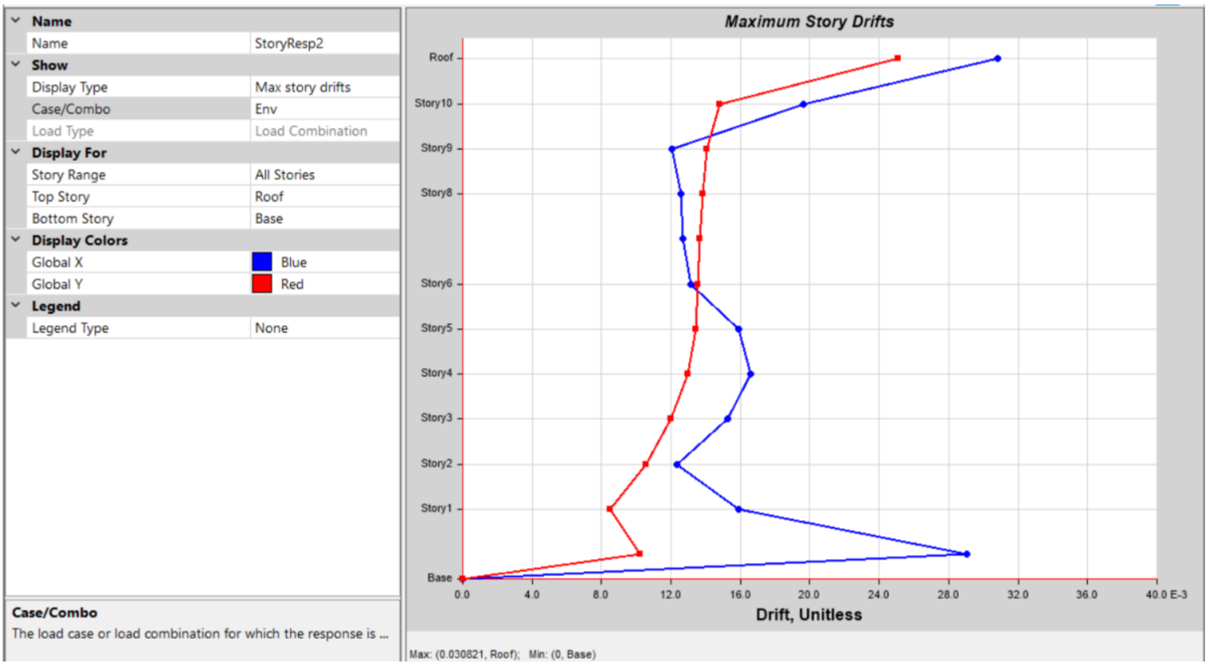

Figure 4-2. Max Story Drift CFRP Retrofitted.

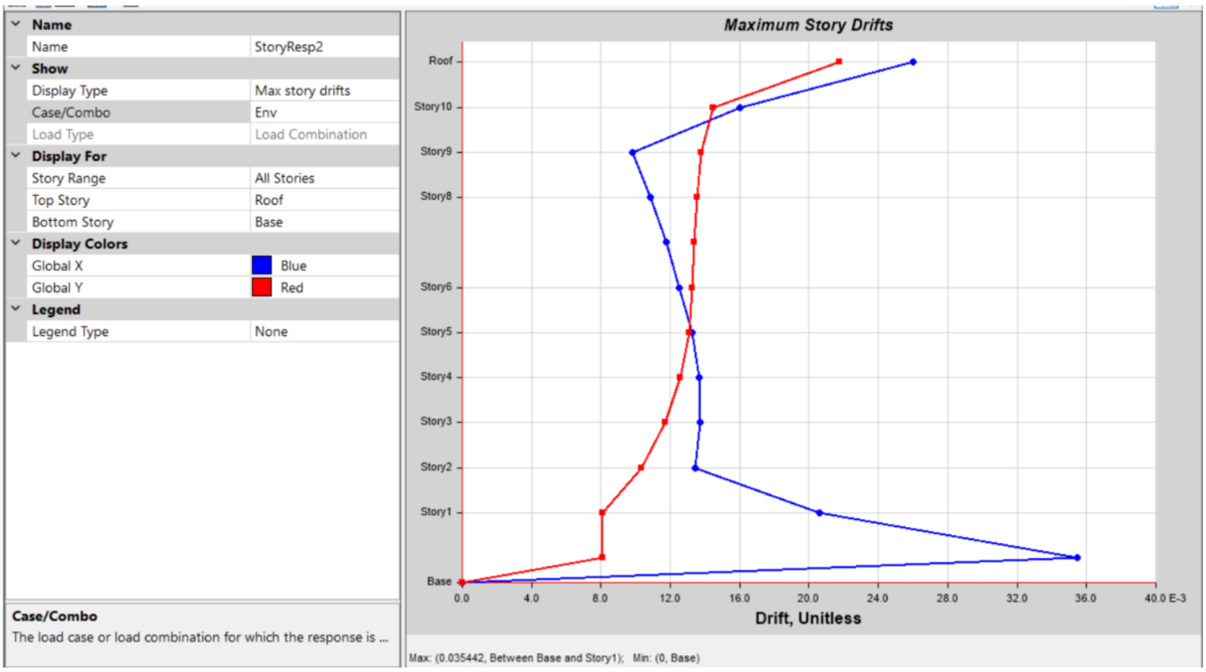

Figure 4-3. Max Story Drift Steel Plate Retrofitted.

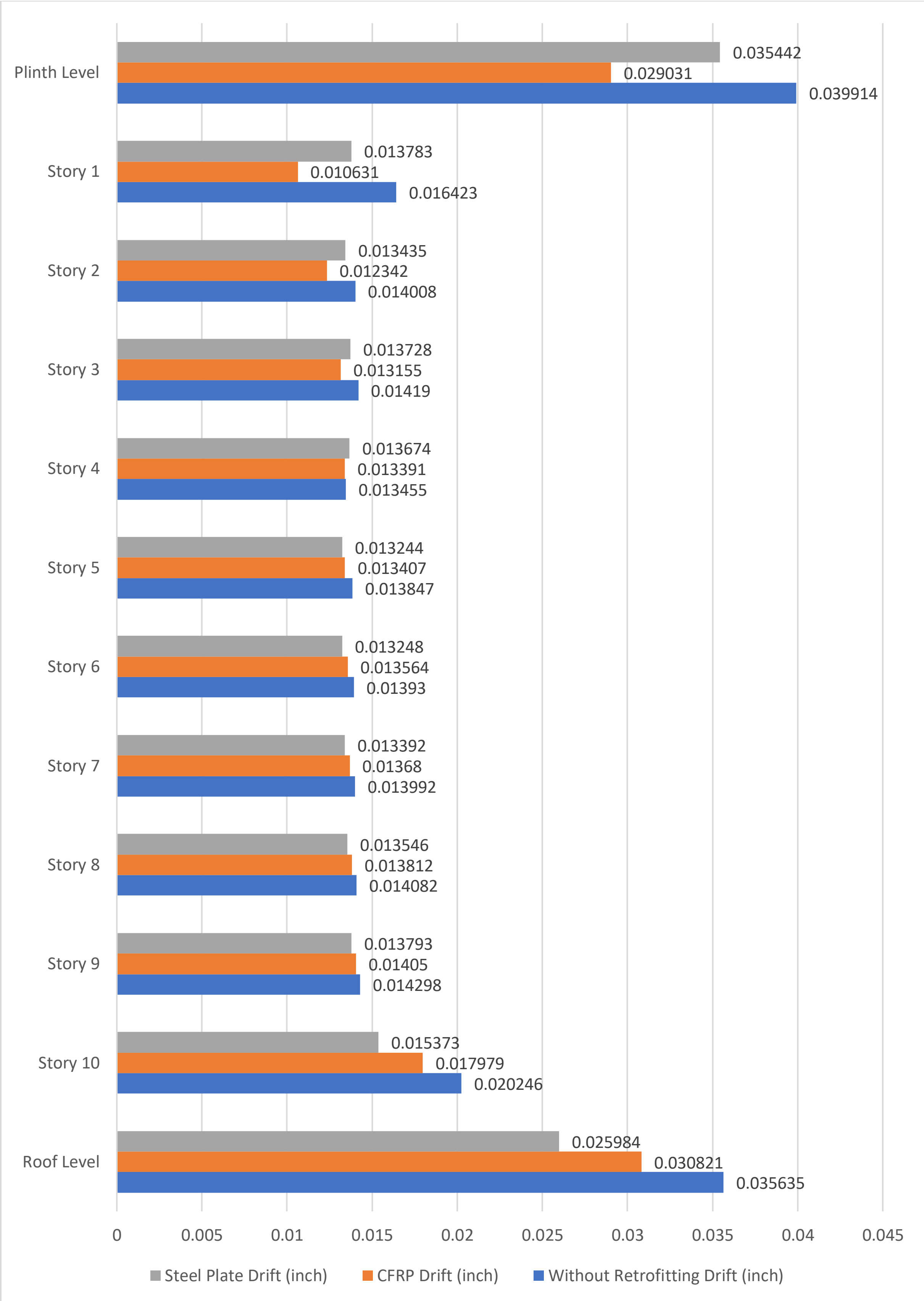

Figure 4-4. Maximum Drift per Story.

4.2.2 Cost Comparison

Table 4-2 Cost comparison between CFRP and Steel Plate.

Material	Area to be retrofitted	Cost Reason (Avg Per Column)	Costing
Steel Plate	$1987m^2 \approx 2000\ m^2$ (Only Columns)	Steel plate material	4000 BDT/m²
		Concrete chipping / roughening	350 BDT/m²
		Anchor drilling & fixing	300 BDT/m²
		Welding & plate fixing	500 BDT/m²
		Surface finishing & painting	200 BDT/m²
		Steel retrofit cost per Sq/m	≈ 5350 BDT/m²
		Total steel retrofit cost	≈ 10,700,000 BDT
CFRP	$1987m^2 \approx 2000\ m^2$ (Only Columns)	CFRP sheet material	3,000 BDT/m²
		Epoxy + labor	700 BDT/m²
		Surface preparation	500 BDT/m²
		CFRP cost per Sq/m	≈ 4,200 BDT/m²
		Total CFRP cost	≈8,400,000 BDT

Figure 4-5 Retrofitting process of Steel plate.

Figure 4-6. CFRP Retrofitting.

4.2.3 Discussion of the Found Result

The comparative study of the two retrofitting methods, i.e., CFRP and steel plate, indicates that these methods exhibit different behavior and cost features when exposed to a seismic loading condition simulated in ETABS as per BNBC 2020 guidelines.

- Drift Performance Analysis

The findings show that the inter, story drift values were mostly lower in the case of steel plate retrofitting, which is evident at most levels, especially from the second story to the roof. It can be inferred that steel plates help to increase the structure's stiffness and thus make it more resistant to the application of lateral seismic forces. In contrast, CFRP retrofitting had better performance only at the plinth and first story levels where control of drift is vital due to the highest shear demand and stress concentration. The short, range effect of this performance suggests that CFRP can provide better confinement and more significant flexibility in the areas that are most vulnerable to the seismic hazard, thus becoming an excellent reinforcement choice in those zones. But in CFRP it can be seen in lower stories, drift is significantly lower than normal condition and steel plate retrofitting. Also, in the 1st and ground floor the drift is

30% lower than normal condition and 20% lower than steel plate and, in a building, lower stories are critical. So lower drift in the lower stories is an advantage of CFRP for structural stability and integrity.

- Cost Efficiency Comparison

Economically, CFRP retrofitting turned out to be cheaper in terms of cost. The total cost of steel plate retrofitting was estimated to be around 10,700, 000 BDT, while the cost of CFRP retrofitting was close to 8,400, 000 BDT, thus achieving a cost reduction of about 21.5%. The steel plates could have been used to provide slightly better drift control in the upper stories; however, the monetary benefit of CFRP along with its acceptable seismic performance makes it a viable option for the rehabilitation of the budget, constrained projects. The compromise between structural effectiveness and economic feasibility by reiterating the potential of CFRP for a vast application of retrofitting existing RC buildings in earthquake, prone areas.

4.3 Summary

Retrofitting with steel plates enhances lateral displacement control in upper stories by raising the rigidity, whereas CFRP performs the best in lower stories particularly at the plinth and first levels where lateral displacement is reduced by 30% when compared to the non-retrofitted conditions and 20% in comparison with steel plates, thus stabilizing the most vulnerable areas. On the economic side, CFRP is approximately 21.5% less expensive, hence it is a cost, effective solution that balances seismic performance and affordability, and a smart decision for RC building retrofitting in seismic areas.

CHAPTER 5
CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

A comparative study between the two retrofitting techniques, carbon fiber reinforced polymer (CFRP) and steel plate jacketing, indicates that both methods significantly enhance the seismic performance of the existing reinforced concrete (RC) structure. However, their effectiveness changes by level and monetary factors. The lateral drift in the upper stories is controlled a little more effectively by the steel plate retrofitting, which indicates an increase in stiffness at higher elevations of the building. Such a behavior reveals that steel plates are especially efficient in enhancing the overall rigidity of the structure when bending flexural demands dominate. While that is the case, the CFRP retrofitting shows lower drift values in the lower stories and at the plinth level consistently, which are the most critical zones normally during seismic events due to higher shear forces and the concentration of lateral loads. After all, the performance improvement in these regions is very significant as the damage that originates in the lower levels can be the cause of the whole structure's instability. What makes CFRP different is that it can effectively reduce drift in these vulnerable areas, thus making it the most appropriate method for seismic strengthening of existing RC buildings. Regarding the money aspect, the CFRP retrofitting seems to be more advantageous, with approximately 21 - 22% of the cost of the steel plate method, according to rough estimates. This cost-saving measure, along with its relatively simple installation, less labor requirement, and non-interference with existing structural members, makes CFRP a very nice working practice solution. Besides, the lightness of CFRP does not result in a significant increase in the dead load of the structure, which is an important aspect of seismic design. Overall, the findings point to the carbon fiber reinforced polymer as a best choice in terms of enhanced seismic performance, cost effectiveness, and ease of construction. These advantages make CFRP an especially suitable and viable option for the seismic rehabilitation of RC buildings in Bangladesh, where economic constraints and constructability are two of the main factors considered in retrofitting decisions.

5.2 Limitations and Recommendations for Future Works

1. Nonlinear Time-History Analysis

Future studies should incorporate nonlinear dynamic analysis using multiple ground motion records to capture realistic inelastic behavior and validate the drift trends observed in this study.

2. Experimental Validation

Laboratory-scale testing of CFRP- and steel-retrofitted columns or beam–column joints would provide physical evidence to support the numerical findings and refine material behavior assumptions.

3. Long-Term Durability Assessment

Investigating the long-term performance of CFRP under environmental conditions typical of Bangladesh—such as humidity, temperature variation, and UV exposure—would help determine maintenance requirements and lifecycle costs.

4. Optimization of Retrofit Layout

Future research could explore different CFRP wrapping configurations, fiber orientations, or hybrid retrofitting (CFRP + steel) to identify the most efficient strengthening strategy.

5. Broader Structural Typologies

Extending the analysis to irregular buildings, soft-story structures, or masonry-infilled frames would help generalize the applicability of CFRP retrofitting across a wider range of building types.

6. Cost–Benefit and Lifecycle Analysis

A more detailed economic evaluation—including installation time, maintenance, and service life—would provide a comprehensive understanding of the long-term value of CFRP compared to steel plates.

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APPENDIX

Appendix A

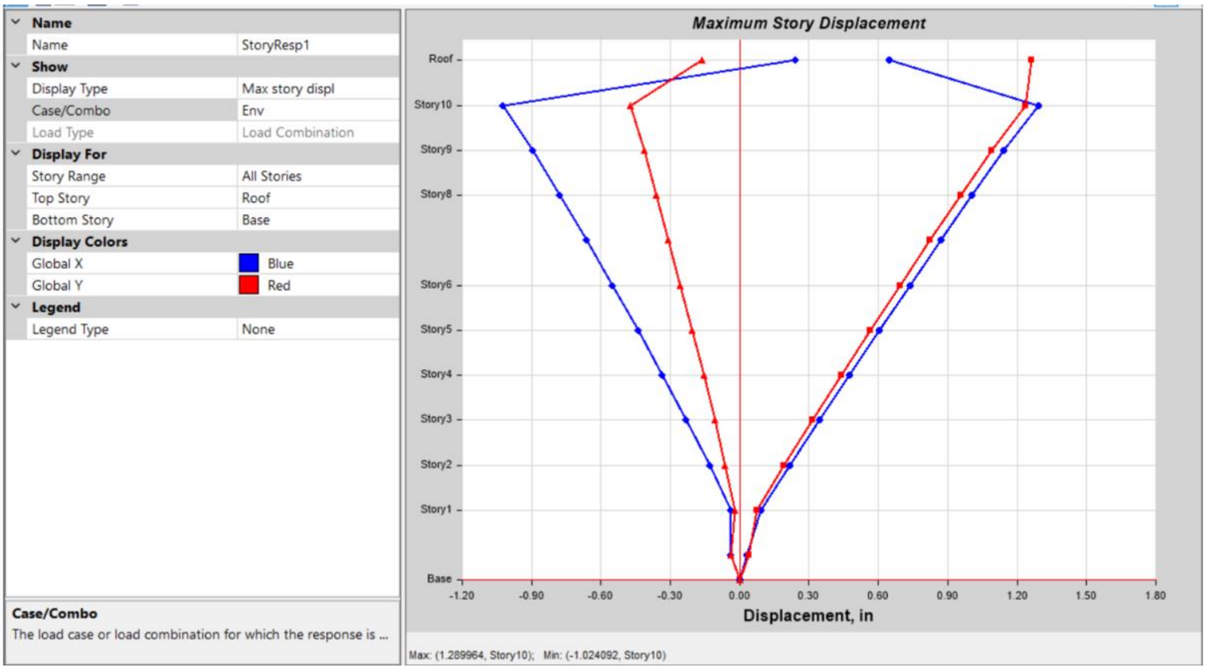

Figure 5-1. Max Displacement Without Retrofitting.

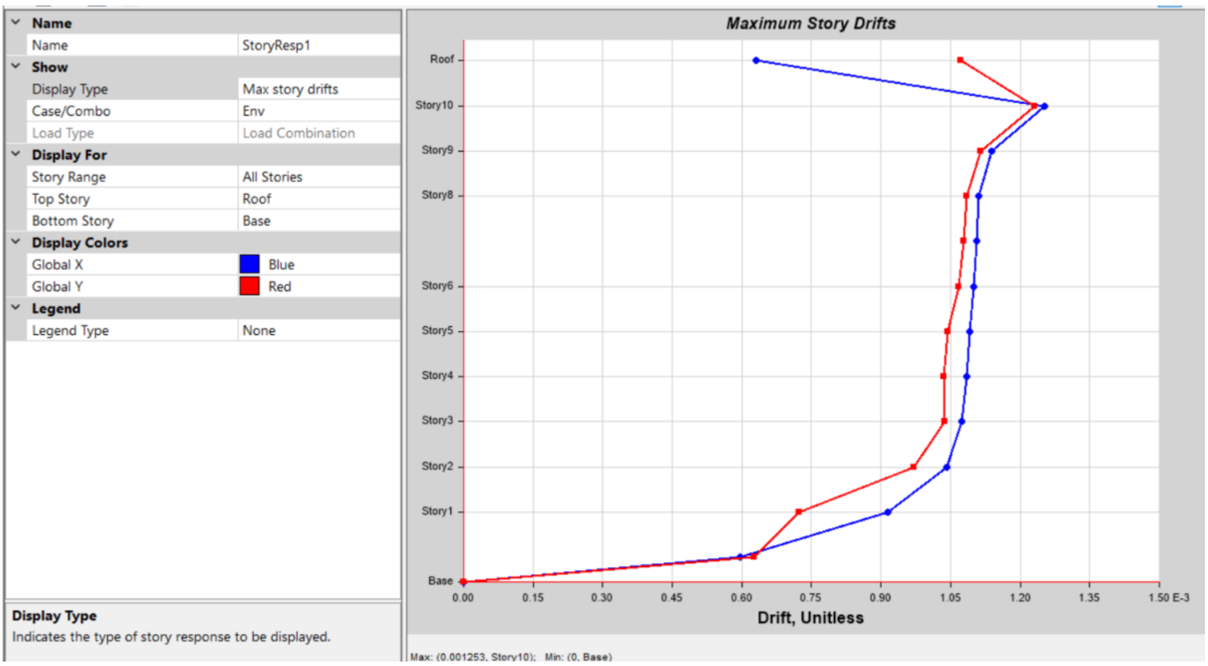

Figure 5-2. Max Drift Without Retrofitting.

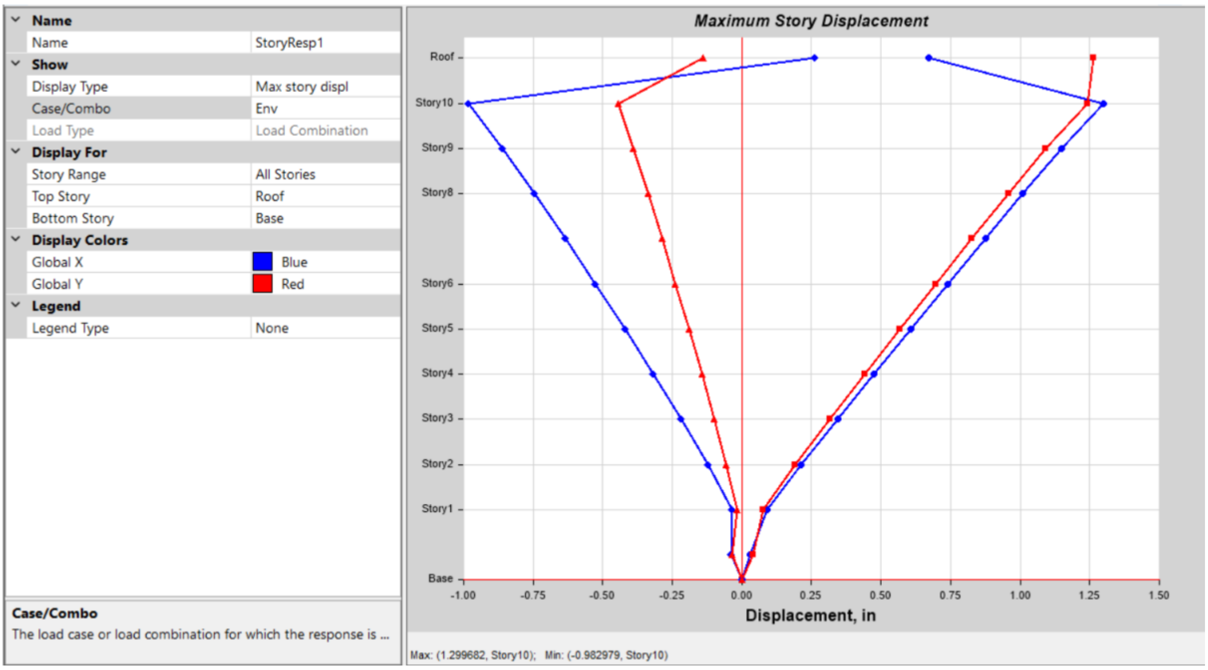

Figure 5-3. Max Displacement CFRP Retrofitting.

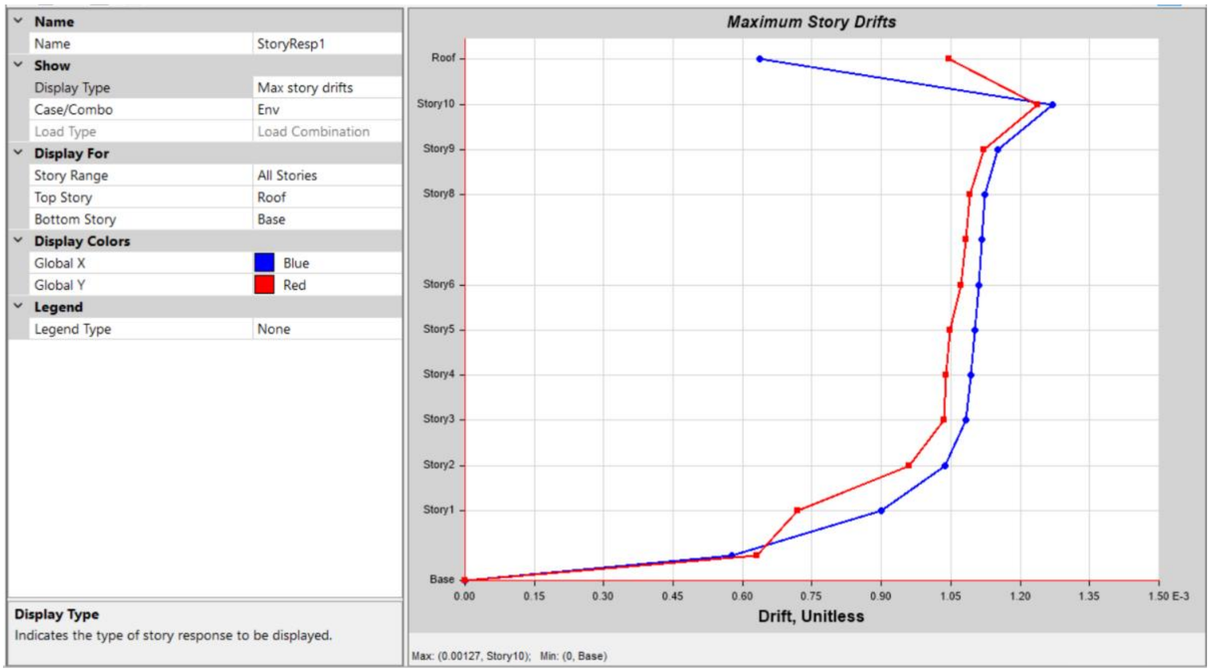

Figure 5-4. Max Drift CFRP Retrofitting.

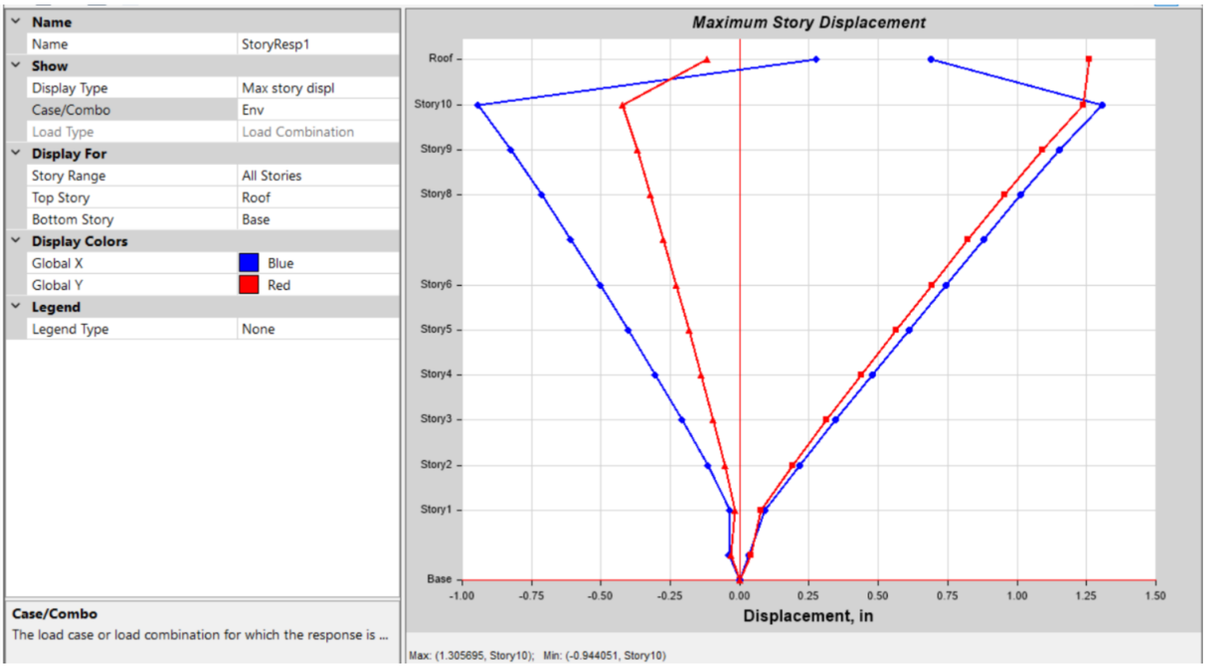

Figure 5-5. Max Displacement Steel Plate Retrofitting.

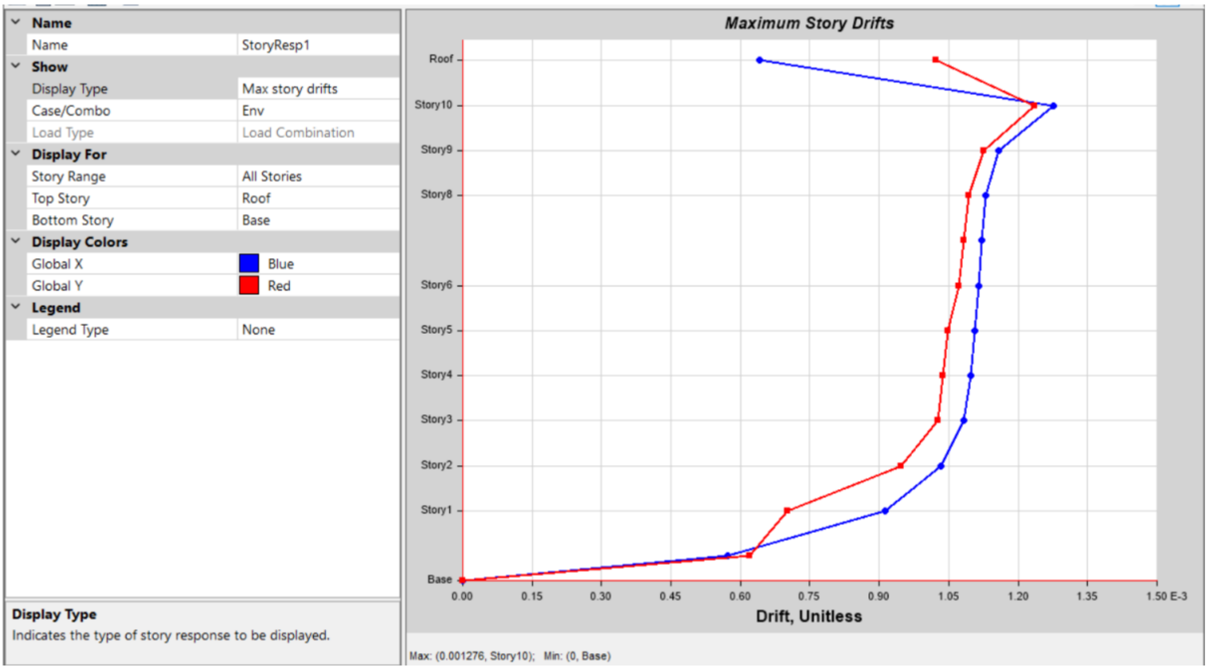

Figure 5-6. Max Drift Steel Plate Retrofitting.

Appendix B

Table 5-1. Max Drift Without Retrofitting.

Story	Output Case	Step Type	Direction	Drift	X ft	Y ft	Z ft
Roof	Env	Max	X	0.00063	9.125	29.1667	115.5
Roof	Env	Max	Y	0.001071	57.875	32.6667	115.5
Story10	Env	Max	X	0.001253	57.5208	-4.0833	105.5
Story10	Env	Max	Y	0.001231	61.9167	83.75	105.5
Story9	Env	Max	X	0.001138	57.5208	-4.0833	95.5
Story9	Env	Max	Y	0.001115	61.9167	83.75	95.5
Story8	Env	Max	X	0.001111	57.5208	-4.0833	85.5
Story8	Env	Max	Y	0.001086	61.9167	83.75	85.5
Story7	Env	Max	X	0.001106	57.5208	-4.0833	75.5
Story7	Env	Max	Y	0.001078	61.9167	83.75	75.5
Story6	Env	Max	X	0.001099	57.5208	-4.0833	65.5
Story6	Env	Max	Y	0.001068	61.9167	83.75	65.5
Story5	Env	Max	X	0.00109	57.5208	-4.0833	55.5
Story5	Env	Max	Y	0.001043	61.9167	83.75	55.5
Story4	Env	Max	X	0.001084	57.5208	-4.0833	45.5
Story4	Env	Max	Y	0.001036	61.9167	83.75	45.5
Story3	Env	Max	X	0.001075	57.5208	-4.0833	35.5
Story3	Env	Max	Y	0.001037	61.9167	83.75	35.5
Story2	Env	Max	X	0.001041	57.5208	-4.0833	25.5
Story2	Env	Max	Y	0.00097	61.9167	83.75	25.5
Story1	Env	Max	X	0.000916	6.2917	10	15.5
Story1	Env	Max	Y	0.000724	44.4999	0.2917	15.5
Plinth Level	Env	Max	X	0.000474	44.4999	0.2917	5.5
Plinth Level	Env	Max	Y	0.000626	41.4167	83	5.5

Table 5-2. Max Displacement without Retrofitting.

Story	Output Case	Step Type	Direction	Maximum in	Average in	Ratio
Roof	Env	Max	X	0.641952	0.553861	1.159
Roof	Env	Max	Y	1.259324	0.58554	2.151
Story10	Env	Max	X	1.181989	0.283296	4.172
Story10	Env	Max	Y	1.141486	0.455027	2.509
Story9	Env	Max	X	1.044656	0.253373	4.123
Story9	Env	Max	Y	1.005016	0.40107	2.506
Story8	Env	Max	X	0.920006	0.226706	4.058
Story8	Env	Max	Y	0.881482	0.352723	2.499
Story7	Env	Max	X	0.798231	0.200459	3.982
Story7	Env	Max	Y	0.761194	0.305683	2.49
Story6	Env	Max	X	0.677004	0.173952	3.892
Story6	Env	Max	Y	0.641733	0.258826	2.479
Story5	Env	Max	X	0.556478	0.147081	3.783
Story5	Env	Max	Y	0.523339	0.212188	2.466
Story4	Env	Max	X	0.436643	0.118692	3.679
Story4	Env	Max	Y	0.407637	0.166313	2.451
Story3	Env	Max	X	0.317474	0.090072	3.525
Story3	Env	Max	Y	0.29273	0.120544	2.428
Story2	Env	Max	X	0.199348	0.062015	3.215
Story2	Env	Max	Y	0.177598	0.074371	2.388
Story1	Env	Max	X	0.084434	0.031241	2.703
Story1	Env	Max	Y	0.069884	0.030567	2.286

Table 5-3. Max Drift CFRP Retrofitting.

Story	Output Case	Step Type	Direction	Drift	X ft	Y ft	Z ft
Roof	Env	Max	X	0.000637	9.125	29.1667	115.5
Roof	Env	Max	Y	0.001046	57.875	32.6667	115.5
Story10	Env	Max	X	0.00127	57.5208	-4.0833	105.5
Story10	Env	Max	Y	0.001236	61.9167	83.75	105.5
Story9	Env	Max	X	0.001151	57.5208	-4.0833	95.5
Story9	Env	Max	Y	0.001122	61.9167	83.75	95.5
Story8	Env	Max	X	0.001124	57.5208	-4.0833	85.5
Story8	Env	Max	Y	0.001092	61.9167	83.75	85.5
Story7	Env	Max	X	0.001117	57.5208	-4.0833	75.5
Story7	Env	Max	Y	0.001083	61.9167	83.75	75.5
Story6	Env	Max	X	0.00111	57.5208	-4.0833	65.5
Story6	Env	Max	Y	0.001072	61.9167	83.75	65.5
Story5	Env	Max	X	0.001102	57.5208	-4.0833	55.5
Story5	Env	Max	Y	0.001048	61.9167	83.75	55.5
Story4	Env	Max	X	0.001094	57.5208	-4.0833	45.5
Story4	Env	Max	Y	0.001039	61.9167	83.75	45.5
Story3	Env	Max	X	0.001082	57.5208	-4.0833	35.5
Story3	Env	Max	Y	0.001035	61.9167	83.75	35.5
Story2	Env	Max	X	0.001038	57.5208	-4.0833	25.5
Story2	Env	Max	Y	0.000961	61.9167	83.75	25.5
Story1	Env	Max	X	0.000899	6.2917	10	15.5
Story1	Env	Max	Y	0.000719	44.4999	0.2917	15.5
Plinth Level	Env	Max	X	0.00047	44.4999	0.2917	5.5
Plinth Level	Env	Max	Y	0.00063	41.4167	83	5.5

Table 5-4. Max Displacement CFRP Retrofitting.

Story	Output Case	Step Type	Direction	Maximum in	Average in	Ratio
Roof	Env	Max	X	0.664043	0.57731	1.15
Roof	Env	Max	Y	1.26151	0.594518	2.122
Story10	Env	Max	X	1.193172	0.302139	3.949
Story10	Env	Max	Y	1.146542	0.465977	2.461
Story9	Env	Max	X	1.053695	0.269679	3.907
Story9	Env	Max	Y	1.009295	0.410842	2.457
Story8	Env	Max	X	0.927346	0.240919	3.849
Story8	Env	Max	Y	0.884786	0.361204	2.45
Story7	Env	Max	X	0.803985	0.21264	3.781
Story7	Env	Max	Y	0.763651	0.312956	2.44
Story6	Env	Max	X	0.681289	0.184119	3.7
Story6	Env	Max	Y	0.643509	0.264972	2.429
Story5	Env	Max	X	0.559287	0.15521	3.603
Story5	Env	Max	Y	0.524499	0.21725	2.414
Story4	Env	Max	X	0.437967	0.124856	3.508
Story4	Env	Max	Y	0.408162	0.170331	2.396
Story3	Env	Max	X	0.317395	0.094211	3.369
Story3	Env	Max	Y	0.292792	0.123572	2.369
Story2	Env	Max	X	0.198182	0.063985	3.097
Story2	Env	Max	Y	0.177749	0.076579	2.321
Story1	Env	Max	X	0.083356	0.031533	2.643
Story1	Env	Max	Y	0.070849	0.032214	2.199

Table 5-5. Max Displacement Steel Plate Retrofitting.

Story	Output Case	Step Type	Direction	Drift	X ft	Y ft	Z ft
Roof	Env	Max	X	0.000642	9.125	29.1667	115.5
Roof	Env	Max	Y	0.001021	57.875	32.6667	115.5
Story10	Env	Max	X	0.001276	57.5208	-4.0833	105.5
Story10	Env	Max	Y	0.001234	61.9167	83.75	105.5
Story9	Env	Max	X	0.001157	57.5208	-4.0833	95.5
Story9	Env	Max	Y	0.001125	61.9167	83.75	95.5
Story8	Env	Max	X	0.001129	57.5208	-4.0833	85.5
Story8	Env	Max	Y	0.001093	61.9167	83.75	85.5
Story7	Env	Max	X	0.001121	57.5208	-4.0833	75.5
Story7	Env	Max	Y	0.001083	61.9167	83.75	75.5
Story6	Env	Max	X	0.001114	57.5208	-4.0833	65.5
Story6	Env	Max	Y	0.001072	61.9167	83.75	65.5
Story5	Env	Max	X	0.001106	57.5208	-4.0833	55.5
Story5	Env	Max	Y	0.001048	61.9167	83.75	55.5
Story4	Env	Max	X	0.001098	57.5208	-4.0833	45.5
Story4	Env	Max	Y	0.001037	61.9167	83.75	45.5
Story3	Env	Max	X	0.001083	57.5208	-4.0833	35.5
Story3	Env	Max	Y	0.001028	61.9167	83.75	35.5
Story2	Env	Max	X	0.001034	57.5208	-4.0833	25.5
Story2	Env	Max	Y	0.000947	61.9167	83.75	25.5
Story1	Env	Max	X	0.000913	6.2917	10	15.5
Story1	Env	Max	Y	0.000702	44.4999	0.2917	15.5
Plinth Level	Env	Max	X	0.000472	44.4999	0.2917	5.5
Plinth Level	Env	Max	Y	0.000621	41.4167	83	5.5

Table 5-6. Max Displacement Steel Plate Retrofitting.

Story	Output Case	Step Type	Direction	Maximum in	Average in	Ratio
Roof	Env	Max	X	0.682557	0.597236	1.143
Roof	Env	Max	Y	1.257917	0.598958	2.1
Story10	Env	Max	X	1.200721	0.318412	3.771
Story10	Env	Max	Y	1.145736	0.472362	2.426
Story9	Env	Max	X	1.060331	0.283948	3.734
Story9	Env	Max	Y	1.008578	0.416422	2.422
Story8	Env	Max	X	0.933063	0.253446	3.682
Story8	Env	Max	Y	0.883651	0.365745	2.416
Story7	Env	Max	X	0.80889	0.223494	3.619
Story7	Env	Max	Y	0.762194	0.316525	2.408
Story6	Env	Max	X	0.685518	0.193331	3.546
Story6	Env	Max	Y	0.641903	0.267654	2.398
Story5	Env	Max	X	0.562847	0.162762	3.458
Story5	Env	Max	Y	0.522822	0.219092	2.386
Story4	Env	Max	X	0.440857	0.130827	3.37
Story4	Env	Max	Y	0.406376	0.171359	2.371
Story3	Env	Max	X	0.319687	0.098548	3.244
Story3	Env	Max	Y	0.291095	0.123871	2.35
Story2	Env	Max	X	0.20017	0.066578	3.007
Story2	Env	Max	Y	0.176765	0.07642	2.313
Story1	Env	Max	X	0.085598	0.032749	2.614
Story1	Env	Max	Y	0.071307	0.032134	2.219