SEISMIC VULNERABILITY ASSESSMENT AND EVALUATION OF THE COST-EFFECTIVENESS OF RETROFITTING TECHNIQUE RATHER THAN RECONSTRUCTION OF RCC BUILDINGS USING ETABS

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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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Sonargaon University(SU)

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

Section: 25C

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Dedicated

to

“Our Respectful Teachers & Parents”

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ABSTRACT

The increasing frequency and intensity of seismic events have raised significant concerns about the structural safety of existing reinforced concrete (RCC) buildings, particularly in developing regions. This study provides a comprehensive assessment of the seismic vulnerability of such structures and investigates the cost-effectiveness of the retrofitting technique (Column Jacketing Method) as an alternative to the complete reconstruction of any endangered RCC building. The vulnerable columns are retrofitted by the Column Jacketing Method using fiber-reinforced polymer (FRP) and analyzed in ETABS following BNBC 2020. The results reveal that well-planned retrofitting can substantially improve structural performance while reducing financial and environmental burdens associated with demolition and new construction. This research supports retrofitting as a technically durable and economically rational approach for enhancing the seismic resilience of existing RCC buildings.

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CHAPTER 1
INTRODUCTION

1.1 Background and Motivations

In the past decades, seismic intensity has increased both in high-risk and low-risk zones, raising global concern over the stability of structures, especially in developing countries like Bangladesh, where huge masses of Reinforced Concrete (RCC) buildings are vulnerable due to aging material, poor design, negligence, and building codes have been lagging compared to modern standards. Bangladesh, located in a region prone to earthquakes, faces enormous challenges in safeguarding its reinforced concrete (RCC) structures, since most of them were constructed without proper seismic detailing. The vulnerability of these buildings, notably in highly populated cities like Dhaka and Chittagong, underlines the urgent need for the implementation of effective measures to reduce seismic risk. Certainly, the demolition and rebuilding of the non-conforming structures is often impractical and very costly, while retrofitting with its few disadvantages has turned out to be a more reasonable option that offers safety at lower cost and less disruption. The conventional methods of adding shear walls and concrete jacketing are used to increase the resistance to lateral loads, but these methods are very labor-intensive and can cause damage to the existing structure's integrity. On the other hand, CFRP (Carbon Fiber Reinforced Polymer) column jacketing has become a widely used technique because of its lightweight, high-strength, and corrosion-resistant properties that Not only allow ductility and energy absorption to be improved but also facilitate overall seismic performance without having to go through extensive demolition. The results of experimental studies and advanced simulations with ETABS, ABAQUS, and ANSYS have confirmed the capability of CFRP to diminish drift, displacement, and stresses, with strength enhancements figured out to be as much as 48% in compression. Nevertheless, the initial price of CFRP is higher, yet, the process of retrofitting using this technique continues to be labeled as a green and an effective method, albeit more research is needed in the areas of irregular building configurations, hybrid retrofitting methods, and site preparation.

In this research, retrofitting of failed structural elements with column jacketing using CFRP is analyzed, along with the seismic performance of an existing structure using ETABS according to BNBC 2020, and it is cost-effectiveness is also shown.

1.2 Research Objectives and Overview

This study investigates the seismic vulnerability of existing reinforced concrete (RCC) structures in Bangladesh and evaluates the feasibility of retrofitting as a strategic alternative to total reconstruction. In light of the updated BNBC 2020 standards, many existing buildings—particularly those intended for conversion from residential to commercial use—require structural strengthening to meet modern safety and load requirements. The focus of this research is on the use of Carbon Fiber Reinforced Polymer (CFRP) column jacketing. The study presents this technique as a single, technique, super, efficient, and environmentally friendly anti, seismic solution that intends to raise the column load capacity and the overall structural stability of the building without the massive use of labor, machines, and time, consuming processes of demolishing and rebuilding. Through the use of ETABS for structural simulation, the research determines how CFRP can serve as a method to repair the damaged parts and decrease the lateral drift. Moreover, the synopsis of the work, long research reflects on the turn of the retrofit as an economic and ecological way, which also may result in the minimization of the material waste and shortening of construction time. The investigators set out to draft a comparative study, technical and financial, which shows retrofitting as a green, less disruptive, and cheaper way of urban seismic hazard mitigation.

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

- To assess seismic vulnerability and failure points in RCC buildings using ETABS per BNBC 2020 standards.
- To evaluate the efficacy of CFRP column jacketing in enhancing lateral strength and minimizing inter-story drift.
- To determine necessary seismic upgrades for the safe structural conversion of residential buildings to commercial use.
- To compare retrofitting and reconstruction regarding cost, time, and sustainability, while identifying future FRP research paths.

1.3 Organization of the thesis

Chapter 1: Introduction and Objective

This study assesses the seismic risk of RCC buildings in Bangladesh under BNBC 2020 and proposes CFRP column jacketing as a low, cost, green alternative solution to rebuilding. ETABS analyses reveal that CFRP enhances load, carrying capacity, lowers story drift, and generally strengthens the structure, more so for those changed into commercial usage. A technical and financial evaluation agrees that retrofitting is less polluting and less expensive, and further research should focus on superior FRP, hybrid retrofitting, and structural health monitoring.

Chapter 2: Literature Review

In this paper, RCC buildings in Bangladesh are at a high seismic risk due to the use of outdated seismic codes and poor construction practices. Traditional retrofitting is both expensive and inconvenient. On the other hand, CFRP provides a long, lasting, corrosion, free, and therefore designer, friendly solution that is able to restore the ductility and strength of the structure. Test results indicate the compressive capacity is up to 48% higher. Through ETABS, ABAQUS, ANSYS analyses and further considering BNBC 2020 edition, the use of CFRP is a cheaper, less disruptive reparation method. Though this is still a subject of research for irregularities in the buildings, hybrid systems, and the local code development.

Chapter 3: Methodology

The methodology evaluates the seismic vulnerability of the structure and the efficacy of CFRP jacketing in RCC buildings through performance, based modeling in ETABS. A residential building, which was converted to commercial use, in Seismic Zone III was analyzed under BNBC 2020 load cases and combinations. Retrofitting was simulated by wrapping the columns and beams with CFRP laminates bonded with epoxy and protected with a cover to reflect a realistic installation. Hence, a comparison of pre, and post, retrofitting behavior was possible, which demonstrated the improvement of stiffness, strength, and confinement and, thereby, establishing CFRP as a viable solution for seismic resilience in Bangladesh.

Chapter 4: Results and Discussion

The comparative structural analysis revealed that while the residential model adequately resisted seismic loads without overstress, its adaptation for commercial use exposed significant deficiencies, including excessive drift and failure of critical members. Subsequent retrofitting with Carbon Fiber Reinforced Polymer (CFRP) jacketing effectively restored stability, reduced story drift by 35–50%, and ensured compliance with BNBC 2020 drift limitations. Cost evaluation further demonstrated that CFRP retrofitting (≈4.0 million BDT) is markedly more economical than full reconstruction (≈9.8 million BDT), underscoring its dual advantage as both a technically viable and financially efficient strategy for enhancing seismic resilience in deficient structures.

Chapter 5: Conclusions and Future Work

The research finds that wrapping reinforced concrete columns with CFRP helps them to better resist earthquakes by stabilizing, strengthening, and lowering drifts, and also being cheaper and less polluting than rebuilding. Refitting enables residential buildings to be changed into commercial ones safely and with less time, waste, and work. Next, researchers might consider testing the method on high, rise buildings, comparing CFRP to GFRP and steel, evaluating the effects of dynamic loads, performing life, cycle cost analyses, verifying simulations through experiments, and looking into eco, friendly materials and recycling methods to enhance durability over time.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Seismic vulnerability in reinforced concrete (RCC) structures has been an area of concern across the globe, and in developing countries like Bangladesh, rapid urbanization, inadequate construction methods, and outdated seismic codes have made the situation even more challenging. In the past several decades, technical approaches to improve the vulnerability of existing deficient structures in seismic regions using methods like concrete jacketing and shear wall addition have been investigated by researchers, and the methods were found to be successful in upgrading resistant capacity. However, in most of these methods, there is an issue of substantial economic expenditure and weight addition to the structure. In the past couple of decades, Carbon Fiber Reinforced Polymers (CFRP) have come into focus for their light weight, higher strength, and resistance to corrosion, with better confinement, ductility, and drift capacity compared to other methods, with no substantial demolition or renovation of the existing structure required, acting as an additional benefit for their adoption. Literature emphasizes that CFRP can be used effectively to improve tensile and flexural strength, decrease displacement between stories, and improve energy absorbing capacity, primarily for the retrofitting of columns in seismic regions. While in some cases, there is a possibility of greater improvement in the stability of the structure, it has been observed in recent years that CFRP retrofitting can be used as an effective, economical, and less disruptive strategy in global seismic design codes like BNBC 2020. Highly advanced software available in the market like ETABS, ABAQUS, and ANSYS has helped validate the performance of CFRP retrofitting in simulations, thereby validating the performance characteristics during seismic loading. This body of available literature identifies CFRP, despite being in the initial phase of their development, as a material of significant interest to the global community in mitigating seismic forces and, in addition, also establishes the need for further investigation in the study of irregular behavior of structures, and other techniques related to retrofitting in the focus of researchers.

2.2 Content

The seismic vulnerability of reinforced concrete (RCC) buildings is well documented within the literature to date, with special focus being on developing nations such as

Bangladesh that face rapid urbanization, lack appropriate construction standards, and rely on old codes that contribute largely to the high vulnerability of buildings within these nations. Most buildings constructed within cities such as Dhaka and Chittagong were also designed and built with less consideration for seismic details; therefore, they present high vulnerability to drifts, soft-story collapse failure, and brittle failure. In Bangladesh, many existing RCC buildings were constructed without seismic detailing, making them highly vulnerable to earthquake-induced damage, especially in urban centers like Chittagong and Dhaka [1]. Demolishing and rebuilding the existing seismically deficient structure is highly impractical and also uneconomical. More viable as an alternative, retrofitting techniques have become increasingly effective and popular, offering greater safety at a lower cost and damage. Retrofitting is a process of structural members in numerous ways. Of these, concrete jacketing and shear wall addition are among the most effective retrofitting methods for improving lateral load resistance in RCC buildings, especially when analyzed using ETABS software [2], but the column jacketing method using Carbon Fiber Reinforced Polymer (CFRP) has proven particularly effective. The DCR value, story drift, and story displacement can be significantly decreased after retrofitting with Concrete Column Jacketing, and this method is proven to be less costly than the reconstruction [3]. CFRP, one of the classes of Fiber Reinforced Polymers (FRP), is a lightweight, high-strength composite material resistant to corrosion. Unlike RC retrofitting, which adds extra weight, length, and width, it also damages the previous structure as we need to drill holes in columns and beams for jacketing [4]. Using CFRP in masonry buildings significantly reduces stresses and enhances structural stiffness—up to 48% when applied to walls—and emphasizes it is effectiveness for retrofitting, leading to more durable, crack-free, and sustainable structures [5].

Currently, CFRP is being used extensively in the construction field as CFRP can significantly improve the tensile strength, ductility, and energy absorbing characteristics of structural members. CFRP retrofitting can reduce structural drift significantly, and in this process, further investigation is needed to explain some irregular displacement and drift patterns [6]. It is use in construction is increasing due to it is durability and performance when subjected to seismic loads, and thus it has become a crucial material in the current retrofits. Buildings with irregular designs are more prone to loss during earthquakes, hence a detailed risk assessment has to be carried out, generally with the help of tools like ETABS [7].

A Comparison of reconstruction and seismic retrofitting of a low-rise garment factory in Bangladesh states that reconstruction is more cost-effective and provides greater improvements in structural stability, drift reduction, and seismic performance than retrofitting [8]. Retrofitting using CFRP can be costly, but effective and safe to apply to concrete columns and beams, and the most commonly used resisting material due to it is flexural and tensile strength properties. CFRP retrofitting simulations require advanced software like ABAQUS, ANSYS, or LS-DYNA [9].However, conventional upgrading methods that include concrete jacketing, shear wall retrofitting, and steel bracing have been widely adopted despite high costs associated with increased stiffness and strength; however, they also occur with high costs that will be associated with architectural works within densely populated cities. Within this regard and due to considerations, such as high cost associated with architecture works that include high densities within cities and high costs that specifically include high densities within cities such as Dhaka and Chittagong, Fiber-Reinforced Polymers Material (FRPM) commonly known as Carbon Fiber-Reinforced Polymers (CFRP) has been viewed as the preferred alternative that presents high strength and lightness. This technique enhances ductility and energy absorption characteristics within buildings through effective reduction of drifts between stories that do not result in any damage. It has also been noted within our literature that the use of CFRP has no notable effects on the strength and rigidity within buildings; however, improved emphases on strengths associated with compressive forces by about 48% within masonry walls has enhanced its use within buildings. Our literature has also highlighted that despite experimental studies within buildings using CFRP that present improved characteristics within buildings by improved emphases using about 48% compressive forces within masonry walls; however, its use within buildings may be less preferable when contrasted with reconstruction that presents improved performance. However, recent emphases by nations such as Bangladesh on seismic standards associated with BNBC 2020 using advanced materials such as CFRP through the use of software that include ETABS, ABAQUS, ANSYS, and LS DYNA has widely adjudicated on its efficiency. Our theoretical literature has therefore highlighted CFRP retrofitting as one of the appropriate materials used with seismic hazards within Bangladesh; however, research gaps and emphases within relevant theoretical literature on its performance associated with irregular buildings, perspectives associated with traditional retrofitting through combination with CFRP materials within buildings along with integration associated within health monitoring within buildings. These shortcomings emphasize the importance of ongoing research work in cost optimization, Eco benefits, as well as the need for developing location-specific guidelines to facilitate the effective and repeatable implementation of CFRP retrofitting technology in the Bangladeshi construction sector.

2.3 Summary

Seismic vulnerability in reinforced concrete (RCC) buildings is a major concern in Bangladesh because of rapid urbanization, outdated codes, and poor construction practices, which have made the structures highly prone to drifts, soft, storey collapse, and brittle failure; however, while conventional retrofitting methods such as concrete jacketing, shear walls, and steel bracing enhance the strength, they are expensive, heavy, and cause a lot of inconvenience in the densely populated areas. Carbon Fiber Reinforced Polymers (CFRP) have therefore become a viable option due to their characteristics of being light in weight, having high strength, being corrosion, resistant, and having the ability to improve ductility, confinement, and energy absorption without causing significant demolition or renovation, and the studies are showing as much as 48% improvement in the compressive strength of masonry walls. After being verified with advanced software like ETABS, ABAQUS, ANSYS, and also being acknowledged in BNBC 2020, CFRP retrofitting is getting popular as an affordable and less disruptive solution, however, more research is still required on aspects such as the seismic behavior of irregular buildings, hybrid retrofitting strategies, cost optimization, eco, benefits, and location, specific guidelines so that the implementation of this technology in the construction sector of Bangladesh can be done effectively.

CHAPTER 3
METHODOLOGY

3.1 Introduction

This analysis uses a performance-based structural evaluation for seismic vulnerability and retrofitting efficiency through CFRP jacketing of RCC buildings. The methodology integrates computational modeling, material characterization, and load pattern simulation for the comparison of pre- and post-retrofitting behavior under seismic conditions. ETABS 17 was used to model two building typologies, one residential and the other commercial, with realistic geometric and material parameters. Retrofitting was done by applying CFRP properties from Sika CarboDur through section designer tools. The load cases and patterns are defined according to BNBC 2020, including the effect of gravity, live load, and lateral seismic action. The structural performance was then evaluated by vulnerability mapping and identifying elemental weaknesses regarding lateral load resistance and failure modes. This approach will make it possible to have a comparative study of structural resilience before and after CFRP intervention and to analyze the effectiveness of the different fiber-reinforced retrofitting strategies for Zone III seismic regions.

3.2 Methodology Overview

A G+2-story residential building was chosen for retrofitting. As we converted it into a commercial office, Response Spectrum Analysis (RSA) was done. RSA is mandatory for high-rise buildings, as this building is in Seismic Zone III with occupancy category III in Chittagong district. For the soil type SD, RSA is mandatory. In ETABS, for lateral loads (seismic and wind), ASCE7-05 lateral loads were used, and load combinations were used according to the BNBC 2020 standard. For FRP, Carbon Fiber Reinforced Polymer (CFRP) is used. CFRP details have been collected from SIKA CarboDur, a product imported by SIKA Bangladesh.

3.2.1 Structural Components & Properties

The grade of concrete mixture, using reinforcements and CFRP details, story height, zone factor, area of building, slab thickness, beam and column details are elaborated in Table 3-1 and 3-2.

Table 3-1 Material & Members Details.

Type	Details
Grade of Concrete	M30
Grade of Steel	500DWR
Thickness of Slab	0.127m
Zone III (Zone Factor)	0.28
Area of Building	$230m^2$
Typical Story Height	3m
Beam Dimensions (mm)	GB 305X407; FB 305X381
Column Dimensions (mm)	Above Plinth Level:305X305; 254X381; 305X254; 305X381; 305X457. Below Ground Level: 381X381; 330X457; 381X330; 381X457; 381X533.
CFRP	Maximum Yield Strength= $3.06x10^6$ kN/m^2

- **Cement-Concrete Mixture Details**

M30 concrete is a design mix concrete with a target characteristic compressive strength of 30MPa, although it is designed to achieve a mean strength of around 38MPa to compensate for material and workmanship uncertainties.

In contrast to the general grades of concrete, the M30 concrete does not have a fixed nominal ratio but generally approaches 1:0.75:1.5 (Cement: Sand: Aggregates). Actually, the mix proportions are determined in the lab to keep the water-cement ratio fixed at 0.40 to 0.45.

Due to its high density, the concrete is the material of choice for columns, beams, foundations, and concrete slabs in multi-story residential and commercial structures.

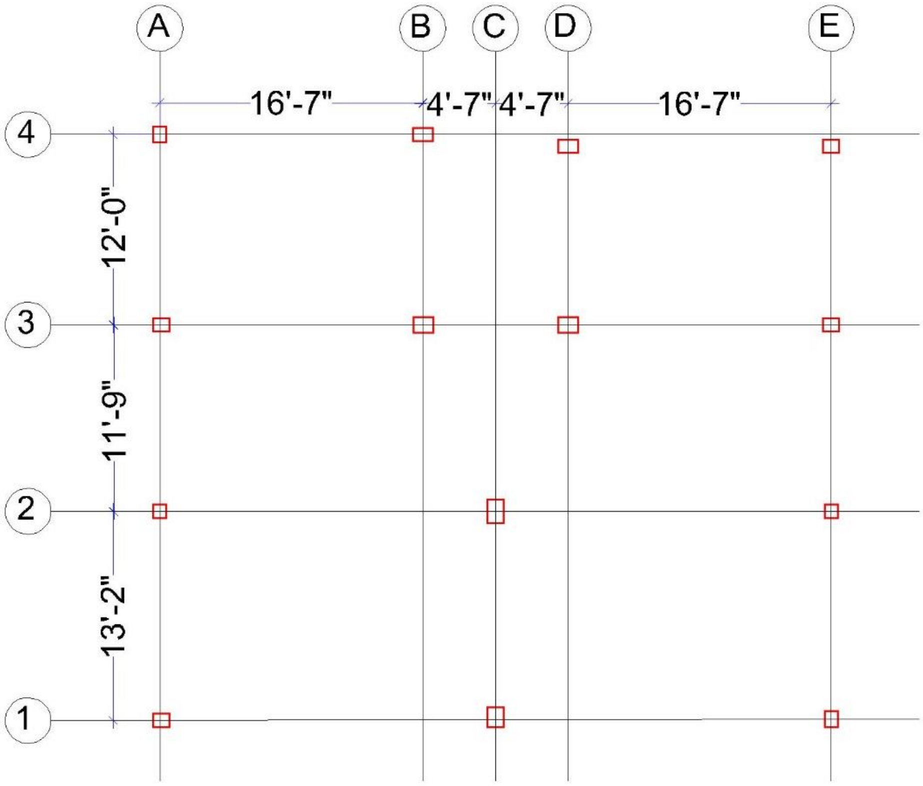

Figure 3-1. Column Layout Plan.

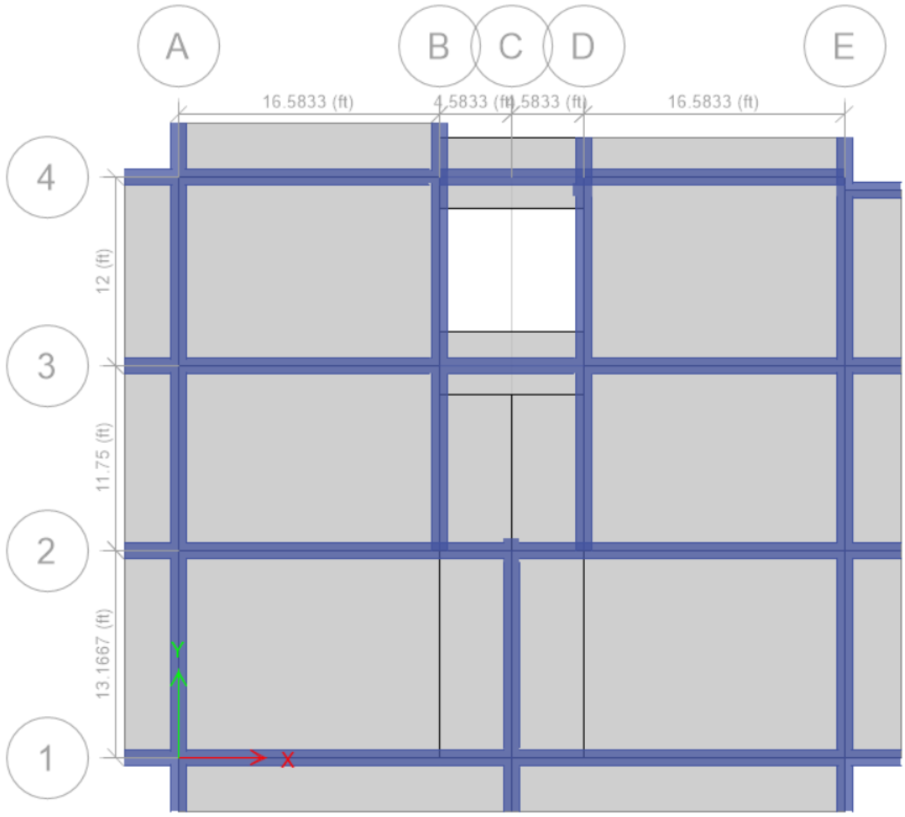

Figure 3-2. Beam and Slab Layout From ETABS.

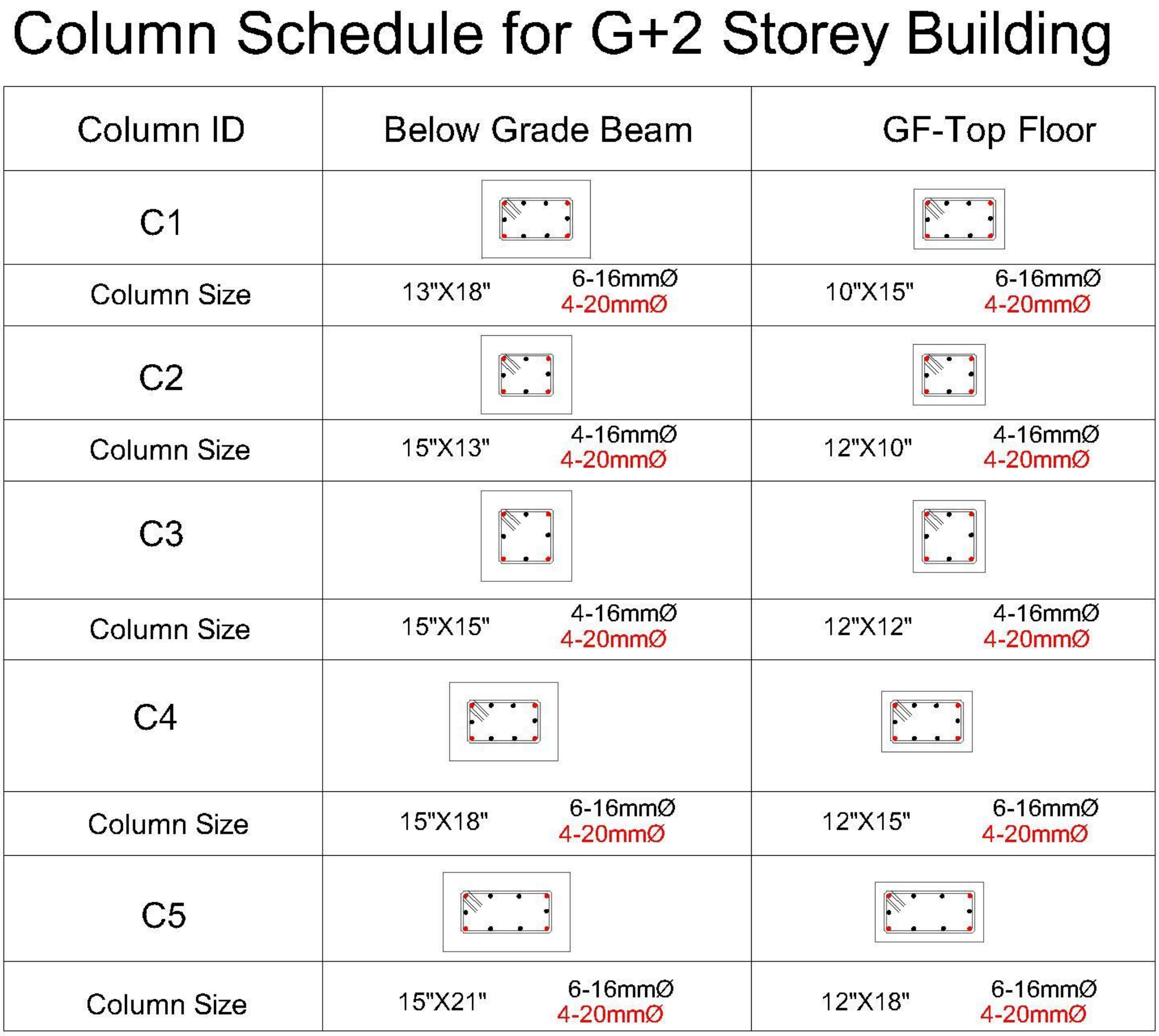

Figure 3-3. Column Schedule of the Building.

Table 3-2. Rebar Details

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	96.642	79.750	106.3068
Tie rebar	72.5	29000000	72.500	96.642	79.750	106.3068
Rebar for stair	60	29000000	60.000	90.000	66.000	99.000

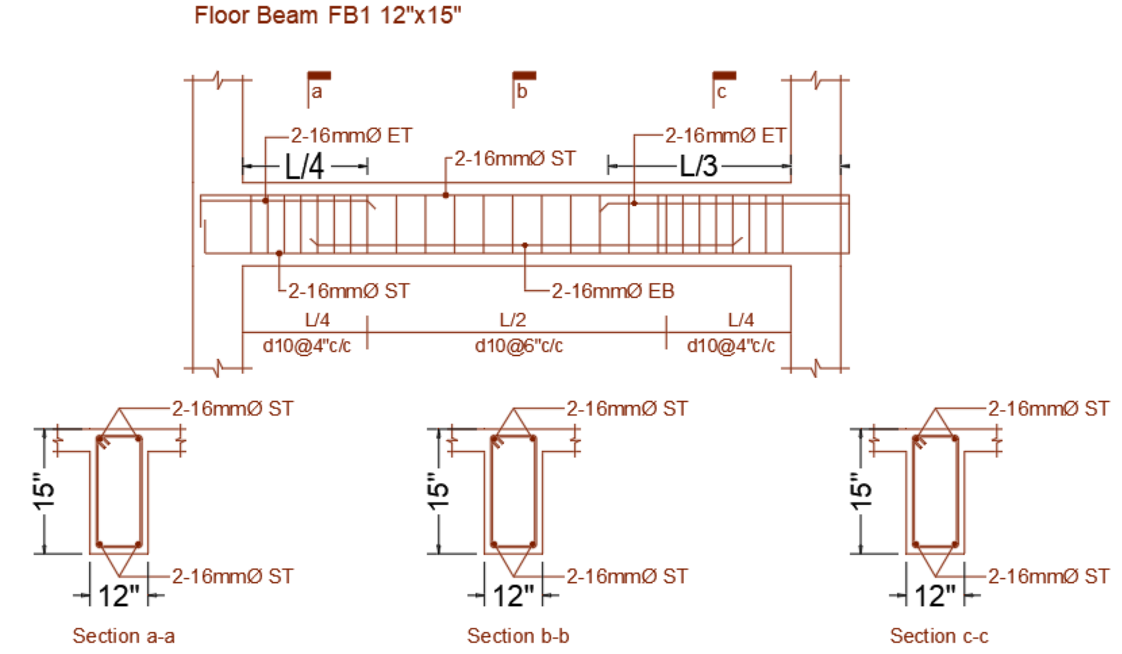

Figure 3-4. Floor Beam Details.

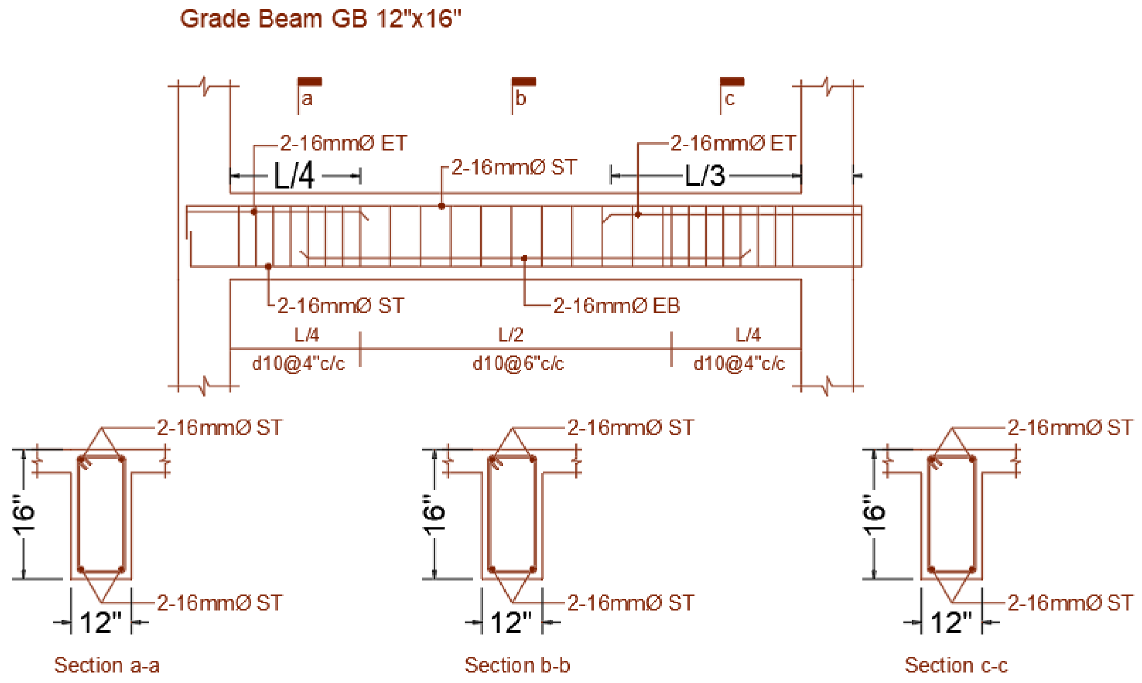

Figure 3-5. Grade Beam Details.

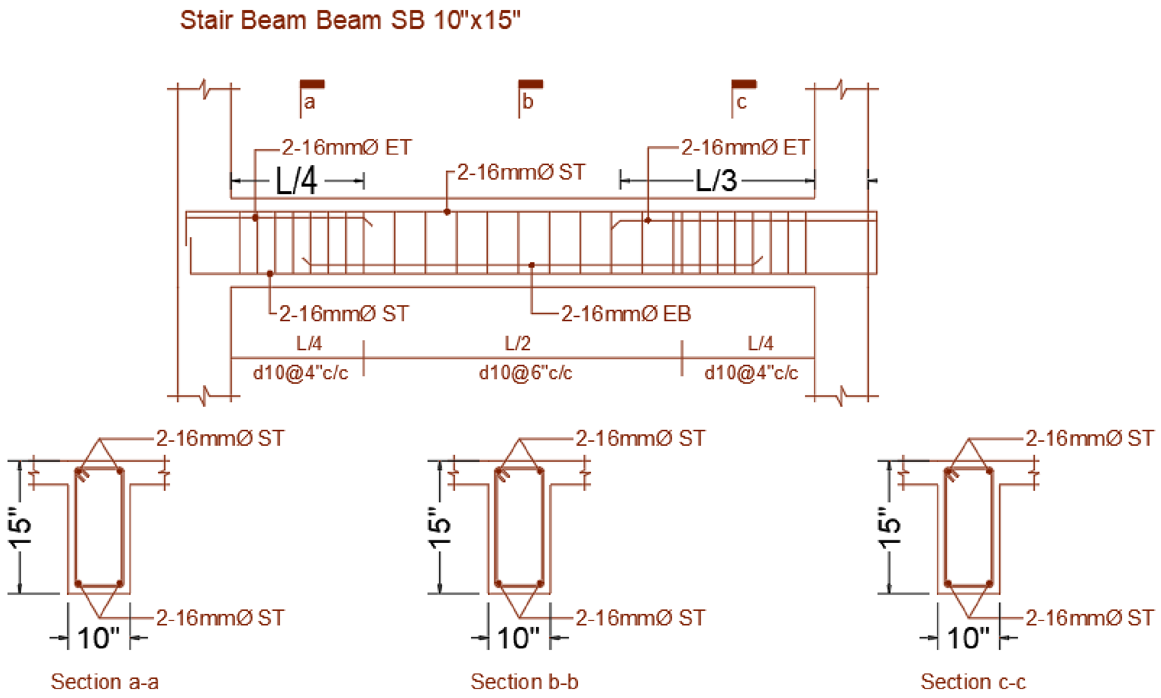

Figure 3-6. Stair Beam Details.

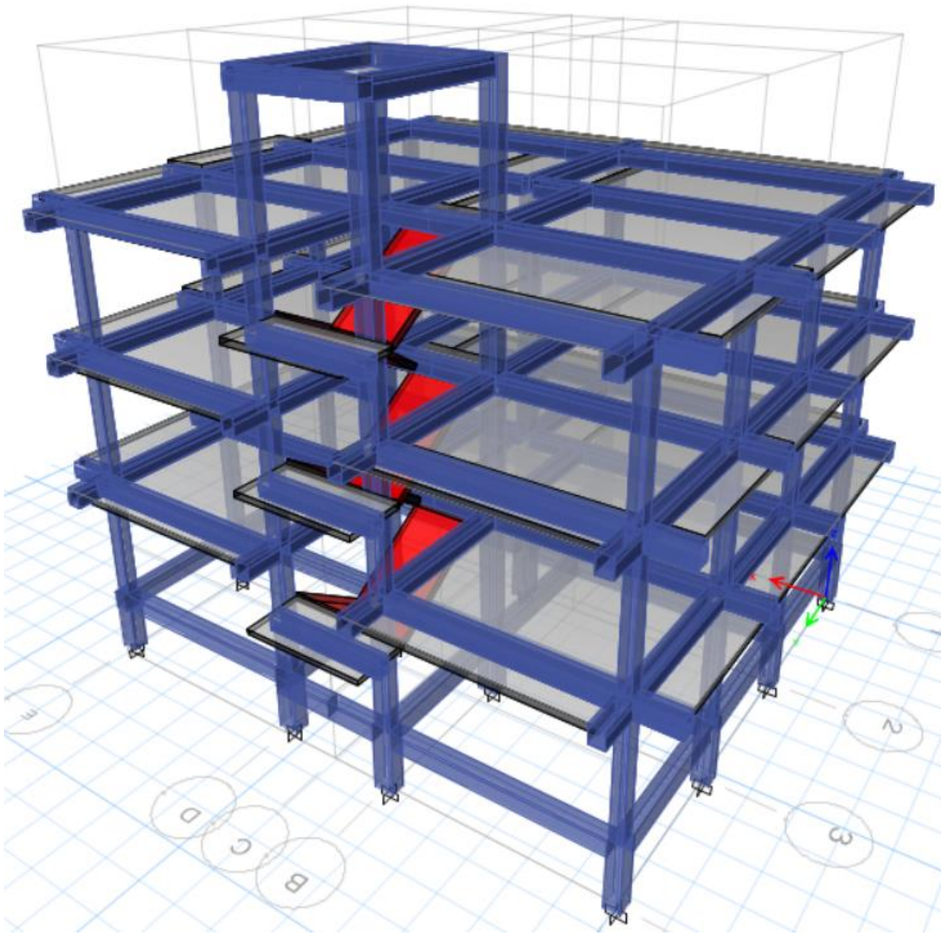

Figure 3-7. Building Elevation in ETABS.

Table 3-3. CFRP Details

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)
Epoxy	-	-	-	-	-	-
CFRP (SIKAWRAP-601C)	490	3550523820	450	675.513	495.376	743.064

- **Absence of CFRP in ETABS**

As ETABS does not provide a material definition for carbon fiber-reinforced polymer (CFRP), the material model was modified for this purpose. This is achieved by referring to the properties of a steel plate. To replicate the specific properties of the material for better functionality in the project, the values of the modulus of elasticity, density, and tensile strength were manually amended for CFRP. As the epoxy acts merely as a binding agent and has no import for tensile or compression strength, it was not considered while defining the materials. The Section Designer feature of ETABS is applied for the analysis of the strengthened column with the modified steel plate acting as the strengthened CFRP.

3.2.2 Load Cases & Combinations (BNBC 2020)

Table -3-4. Applied Load Cases.

Types of loads	Load Values
Dead load	Self-weight
Live load	Residential= 2.02 kN/m^2; Commercial= 4.80 kN/m^2
Floor finish	1.2 kN/m^2
Partition wall load	6.4 kN/m
Parapet wall load	2.4 kN/m

Table 3-5. Applied Load Combinations.

(1) 1.4D	(2) 1.2D + 1.6L + 0.5Lr	(3) 1.2D + 1.6Lr + L
(4) 1.2D + 1.6Lr + 0.8Wx	(5) 1.2D + 1.6Lr - 0.8Wx	(6) 1.2D + 1.6Lr + 0.8Wy
(7) 1.2D + 1.6Lr - 0.8Wy	(8) 1.2D + 1.6Wx + L + 0.5Lr	(9) 1.2D - 1.6Wx + L + 0.5Lr
(10) 1.2D + 1.6Wy + L + 0.5Lr	(11) 1.2D -1.6Wy + L + 0.5Lr	(12) 1.2D + Ex + L
(13) 1.2D - Ex + L	(14) 1.2D + Ey + L	(15) 1.2D - Ey + L
(16) 0.9D + 1.6Wx	(17) 0.9D - 1.6Wx	(18) 0.9D + 1.6Wy
(19) 0.9D - 1.6Wy	(20) 0.9D + Ex	(21) 0.9D - Ex

(22) 0.9D + Ey	(23) 0.9D - Ey	(24) Envelope

3.2.3 Study Area and Zone Details

Chittagong with a seismic intensity of Z=0.28, and soil type SC was selected for this analysis. Although there are some limitations as ETABS do not contain any properties according to BNBC 2020.

- **Absence of BNBC 2020 in ETABS**

In ETABS there are no lateral properties of BNBC 2020. But they are (lateral loads of earthquake and winds) are defined according to ASCE7-05 code. So, we used ASCE7-05 code to define lateral movements of the structure.

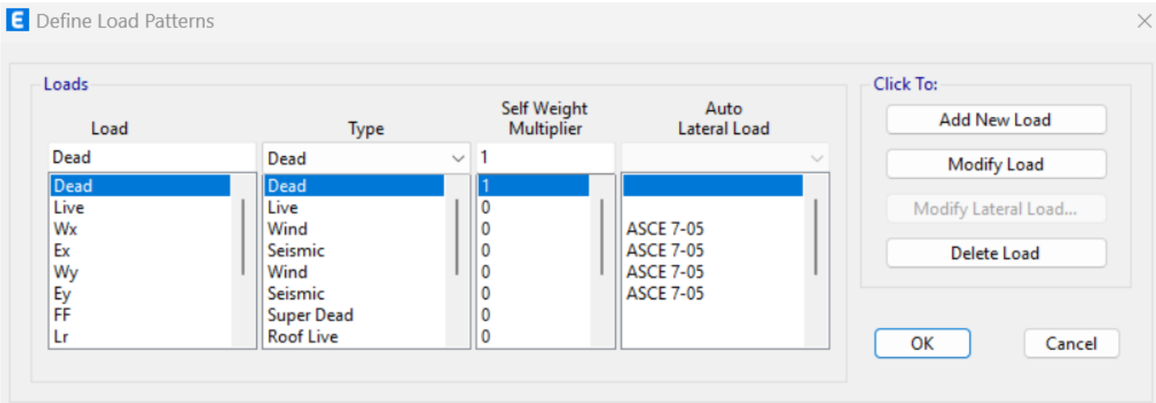

Figure 3-8. Seismic Zone Lateral Load Properties.

Table 3-6. Seismic Zone lateral Load Details.

Properties	Seismic Zone 3
Time period, T	0.472
System Overstrength, Omega	3
Response Modification, R	8 For SMRF
Deflection Amplification	5.5 For SMRF
Occupancy Category	1
0.2s Spectral Accel Ss	0.7
1s Spectral Accel S1	0.28
Long transition period	2
Fa	1.15
Fv	1.725
SDS	0.5367
SD1	0.322

Figure 3-9. Study Area of the Building.

3.2.4 CFRP Jacketing

Using ETABS 17 software, the existing structural system was retrofitted by the addition of CFRP strengthening to both the column and beam members, as shown in Figure 1. The retrofit model was created in the Section Designer module of ETABS, where the CFRP material properties were taken from the manufacturer standard of the Sika CarboDur systems. For the column upgrading, a CFRP jacket with an equivalent thickness of 0.2 inches was wrapped around the column section, bonded with epoxy resin to provide effective stress transfer from the concrete substrate to the CFRP layer.

In the same way, the beam members were strengthened by CFRP laminates with a thickness of 0.2 inches. To simulate real installation conditions and allow the CFRP layer to be sufficiently protected, a 0.5, inch, thick protective cover was additionally modeled on the CFRP. This modeling approach made it possible to reflect the enhanced stiffness, strength, and confinement effects of the CFRP retrofit in the analytical model and thus carry out a realistic assessment of the seismic performance of the retrofitted structure.

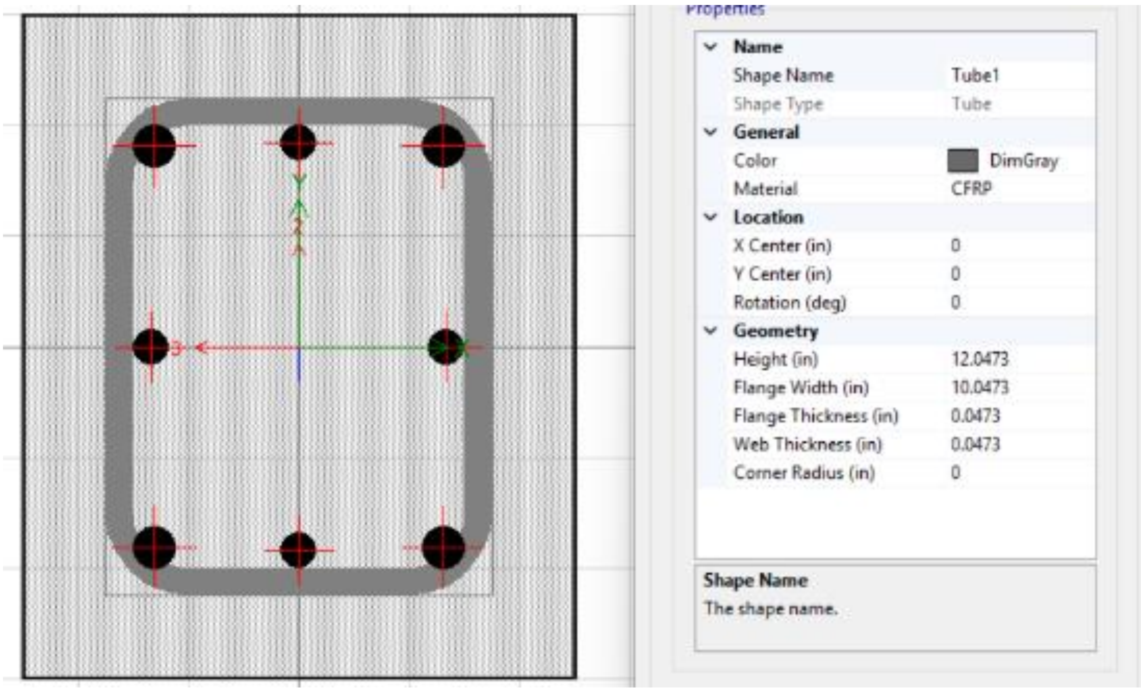

Figure 3-10. CFRP Jacketing of Column.

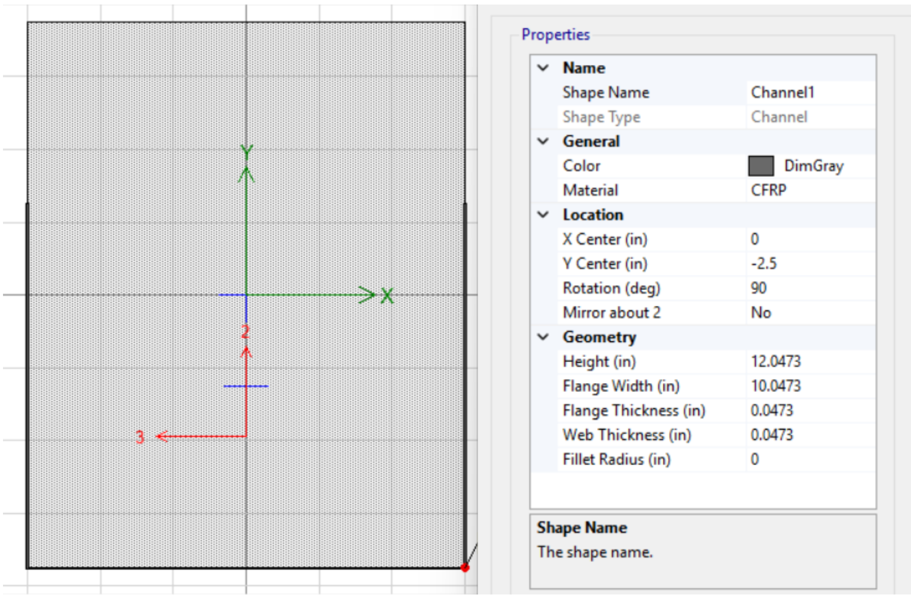

Figure 3-11. CFRP Jacketing of Beam.

3.3 Summary

The methodology performs a seismic vulnerability assessment followed by a performance, based structural evaluation to check the effectiveness of CFRP jacketing in RCC buildings. A residential building converted into a commercial structure in Seismic Zone III was modeled in ETABS. The material properties and structural parameters were set according to BNBC 2020 standards. The load cases were gravity, live, and lateral seismic actions, combined through the load combinations as per the code. Retrofitting was performed by wrapping the columns and beams with CFRP laminates bonded with the epoxy and protected with the cover to represent a real installation. Such a modeling approach allowed the comparative analysis of the behavior before and after the retrofitting, thus showing the increase in stiffness, strength, and confinement and providing a framework to evaluate systematically if CFRP is a viable solution for seismic resilience in Bangladesh.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Introduction

Seismic safety issues in mixed, use buildings have become one of the most talked, about problems especially in regions that showcase a substantial difference in structural demands for residential and commercial setups. A detailed study using ETABS as a modeling tool for analysis depicts that the issues of drift behavior and member stability arise when different load cases are applied. To eliminate these problems, the use of Carbon Fiber Reinforced Polymer (CFRP) jacketing is resorted to as a method of upgrading the building, thus changing its performance profile. The determination of the technical condition was complemented by the reflection on money that was compared with the huge investment that would be required for the full reconstruction of the building and the more targeted approach of retrofitting. The combination of these two perspectives results in the selection of the strategies that reconcile the ideas of resistance, feasibility, and savings.

4.2 Structural Performance Evaluation

The main goal is to figure out the working method of one practical retrofitting technique, i.e., how to apply Carbon Fiber Reinforced Polymer (CFRP) jacketing to strengthen those reinforced concrete buildings which show seismic vulnerability. The study is limited to the scenarios of the structures of the mixed-use type where residential and commercial load cases cause different kinds of stresses, therefore, making the buildings more likely to drift and member instability. ETABS modeling is considered as the analytical framework to locate the sources of the most severe structural weaknesses and to study the effect of the CFRP intervention on the structural behavior. Besides its technical aspect, the research also considers an economic view by comparing the cost of a complete reconstruction with the relatively low investment of a targeted retrofit. The intention of combining the analysis of structural performance with the cost evaluation is to make explicit the safety, resilience, and sustainability route that is still viable for the application in the real world.

4.2.1 Elemental Weakness Identification

In an attempt to perform structural analysis for two unlikely types of buildings, residential and commercial, certain clear distinctions were brought forth regarding their ability to resist lateral loads, especially those due to seismic activities.

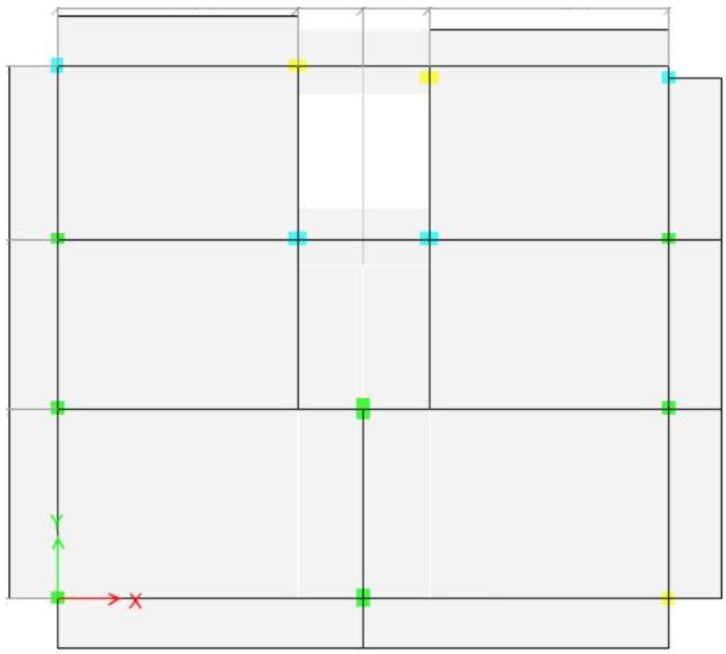

Figure 4-1. Vulnerability Check of Structural Members-Residential Model.

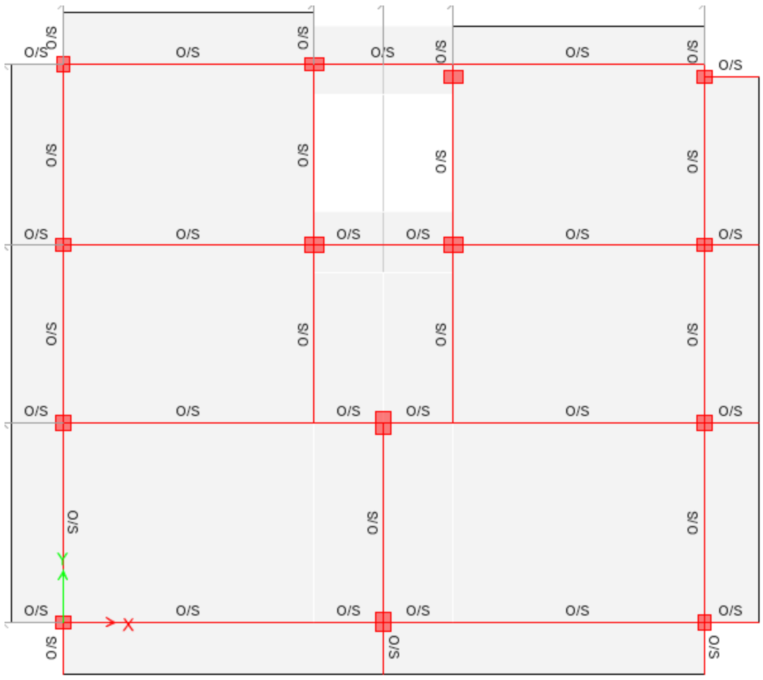

Figure 4-2. Vulnerability Check of Structural Members-Failed Commercial Model.

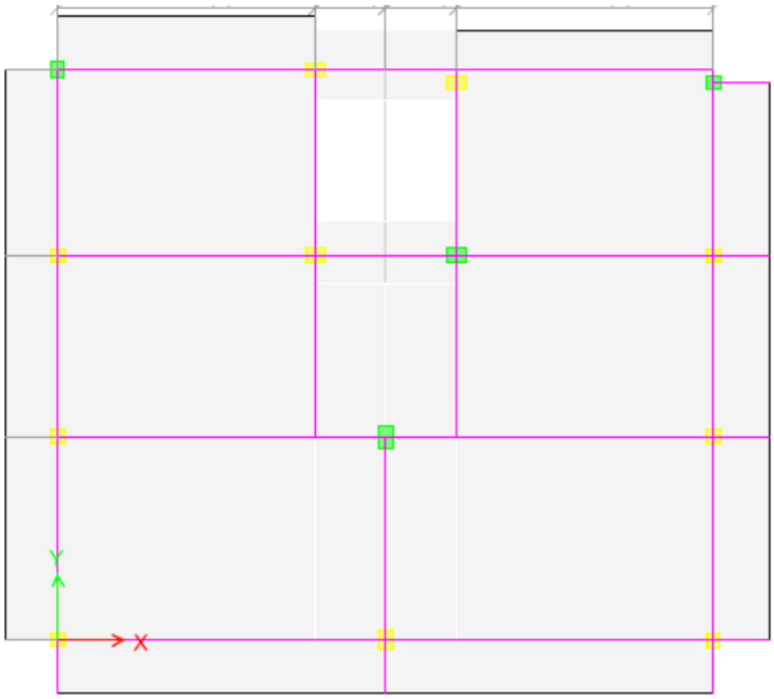

Figure 4-3. Vulnerability Check of Structural Members-Retrofitted Model (Final model).

Residential Model (Residential Load Cases)
In Figure 4-1, it can be seen that all the members and beams are stable and well-built as they are not overstressed (ETABS shows all failed overstressed members as red-colored members). As it was made for a residential dwelling, from analysis we see:

- All structural members were found to be designed adequately for gravity as well as lateral loads.
- Moreover, it satisfied the requirements of all the load cases, without the need for strengthening.
- The initial design was sufficient for the should-be residential seismic demand and type of occupancy.

Residential model with commercial configurations (Pre-Retrofit)
All the members fail in Figure 4-2 (All members are overstressed, indicated by red color) where we applied load cases for commercial use of that building. This analysis indicates:

- Commercial use has significantly more deficiencies under lateral load than residential use in structure.
- Response spectrum analysis showed that all the members would not meet the performance criteria.
- The overall performance deficiency was mostly due to the increased seismic demands, higher loads, and occupancies for commercial buildings.

Retrofitting Measures (Commercial load cases-Final model)
After retrofitting the model with CFRP in Figure 4-3, the model is stable and is suitable for commercial use. As this process was done by:

- Targeted retrofitting which has been implemented, focusing on critical structural members such as columns and beams.

- Strengthening techniques included integrating externally bonded FRP, to be precise, CFRP jacketing.
- Post-retrofitting analysis showed that the upgraded members successfully met all performance criteria under lateral loads and dynamic analysis.

The residential model met all structural demands without retrofitting, but adapting it for commercial use exposed weaknesses in key members due to higher seismic and occupancy loads. Retrofitting with section enlargement, reinforcement, and possible CFRP jacketing resolved these issues, and post-analysis confirmed compliance with performance standards.

4.2.2 Story Displacements

Table 4-1. Displacements of the Residential Model.

Story	Step Type	Direction	Max Disp.	Avg Disp.	Ratio
			mm	mm	
SR	Max	X	10.853	6.565	1.653
SR	Max	Y	12.687	7.519	1.687
Story 3	Max	X	5.353	3.788	1.413
Story 3	Max	Y	3.252	2.916	1.115
Story 2	Max	X	8.867	5.856	1.514
Story 2	Max	Y	5.088	4.429	1.149
Story 1	Max	X	10.483	7.343	1.428
Story 1	Max	Y	6.304	5.347	1.179
Plinth	Max	X	1.149	1.022	1.124
Plinth	Max	Y	1.556	1.063	1.464

Table 4-2. Displacements of the Failed Model.

Story	Step Type	Direction	Max Disp.	Avg Disp.	Ratio
			mm	mm	
SR	Max	X	15.91	9.816	1.621
SR	Max	Y	17.798	10.665	1.669
Story 3	Max	X	8.161	5.747	1.42
Story 3	Max	Y	3.909	3.775	1.036
Story 2	Max	X	13.191	8.658	1.524
Story 2	Max	Y	5.998	5.716	1.049
Story 1	Max	X	14.866	10.542	1.41
Story 1	Max	Y	7.85	6.833	1.149
Plinth	Max	X	2.01	1.737	1.157
Plinth	Max	Y	2.495	1.681	1.484

Table 4-3. Displacements of CFRP Retrofitted Model.

Story	Step Type	Direction	Max Disp.	Avg Disp.	Ratio
			mm	mm	
SR	Max	X	6.511	3.766	1.729
SR	Max	Y	5.895	3.296	1.789
Story 3	Max	X	1.726	1.509	1.144
Story 3	Max	Y	1.07	1.015	1.055
Story 2	Max	X	2.518	2.133	1.18
Story 2	Max	Y	1.634	1.534	1.065
Story 1	Max	X	3.533	2.98	1.186
Story 1	Max	Y	2.425	2.162	1.121
Plinth	Max	X	1.406	1.237	1.136
Plinth	Max	Y	1.393	1.161	1.2

4.2.3 Story Drift Analysis

Table 4-4. Drift of Residential Model.

Story	Drift (mm)
Stair Room Roof	0.051
Story 3	0.026
Story 2	0.043
Story 1	0.048
Plinth Level	0.016

Table 4-5. Drift of Failed Commercial Model.

Story	Drift (mm)
Stair Room Roof	0.147
Story 3	0.068
Story 2	0.114
Story 1	0.127
Plinth Level	0.04

Table 4-6. Drift of Retrofitted Model.

Story	Drift (mm)
Stair Room Roof	0.0507
Story 3	0.0143
Story 2	0.0209
Story 1	0.027
Plinth Level	0.023

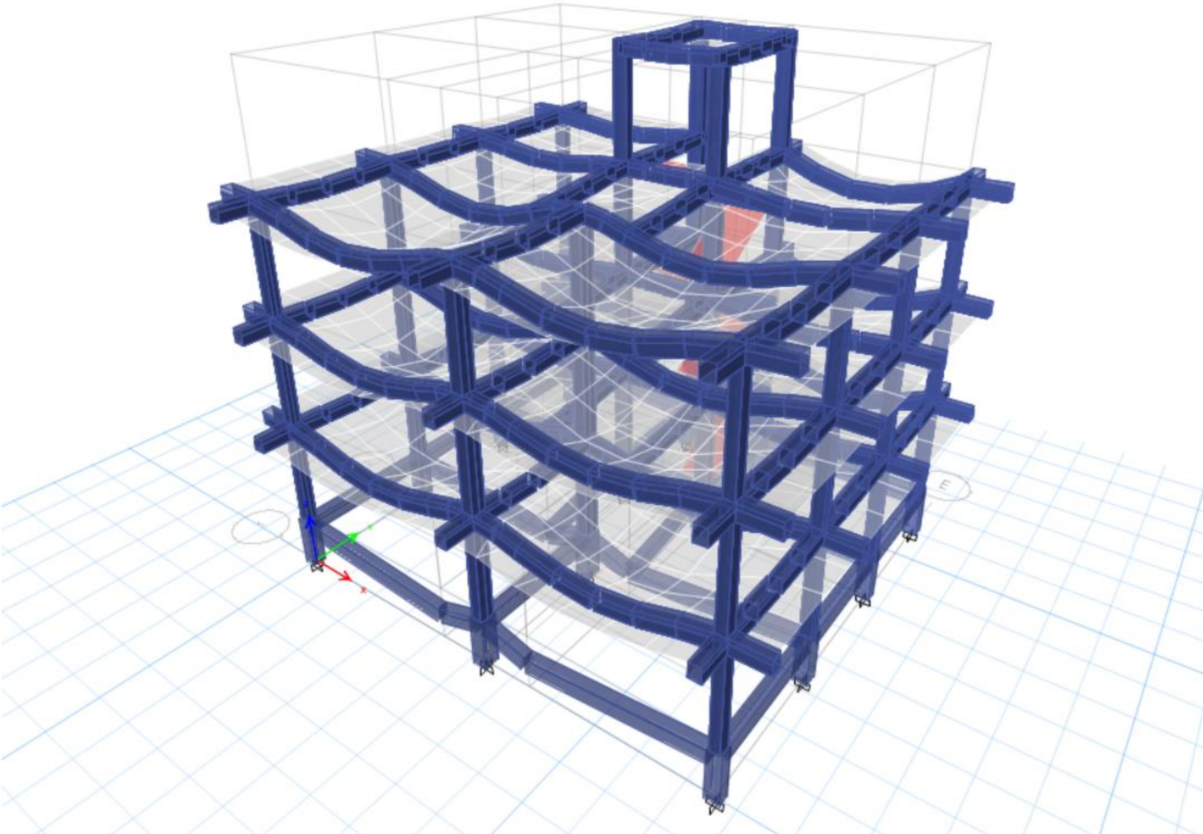

Figure 4-4. Deflected Shape of the Structure.

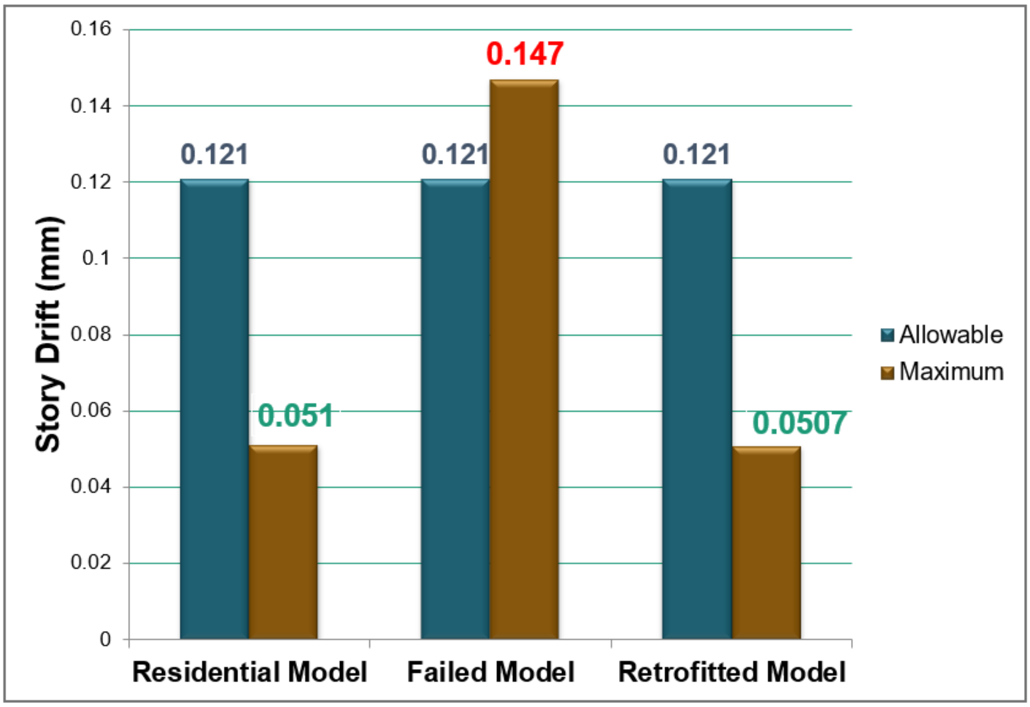

Figure 4-5. Maximum and Allowable Drift of the Models.

From drift analysis, there is a large amount of improvement in the behavior of the structure in terms of drift ratio by 35–50%. Three analysis models were used in this study. For the first model, it was a residential structure under commercial loads. It resulted in a drift of 0.051 mm. For a G+2 storied building of Occupancy Category III in Seismic Zone III, though the final building would be under BNBC 2020, the drift should not be greater than 0.020 h_{hx}; therefore, the allowable drift is 0.121 mm. This model was well within the acceptable limits. The second model was a case study of a commercial structure wherein there was an overlap of stresses in the columns and beams, leading to a drift of 0.147 mm, exceeding the allowed drift by the BNBC; therefore, it was structurally inadequate. For the third model wherein columns and beams were retrofitted by CFRP sheets, there was a large amount of drift reduction to 0.0507 mm (0.001997 in.), well below 60% of the allowed drift. Additionally, the results of the RSA analysis, as mandated in the case of a commercial structure, were further refined to drift of 0.014–0.027 mm (Figures 4-6 & 4-7), clearly well within acceptable limits to show improvement even in the Linear Static Analysis scenario, clearly establishing that retrofitting by CFRP sheets is an excellent means to restrict excessive drifts and could add significantly to the life of the structure, especially residential and commercial buildings loaded in excess of their design requirements.

4.3 Response Spectrum Analysis of the Model

As our model fails the commercial load patterns, we retrofitted the model with CFRP and analyzed it for commercial load patterns again and also did response spectrum analysis. The results show in response spectrum analysis indicates that the structural integrity is high and the drift for response spectrum also meets our drift limit criteria.

Table 4-7. Max Drift for RSX.

Story	Drift (mm)
Stair Room Roof	0.14
Story 3	0.0508
Story 2	0.0787
Story 1	0.119
Plinth Level	0.0965

Table 4-8. Max Drift for RSY.

Story	Drift (mm)
Stair Room Roof	0.17
Story 3	0.025
Story 2	0.043
Story 1	0.0711
Plinth Level	0.09

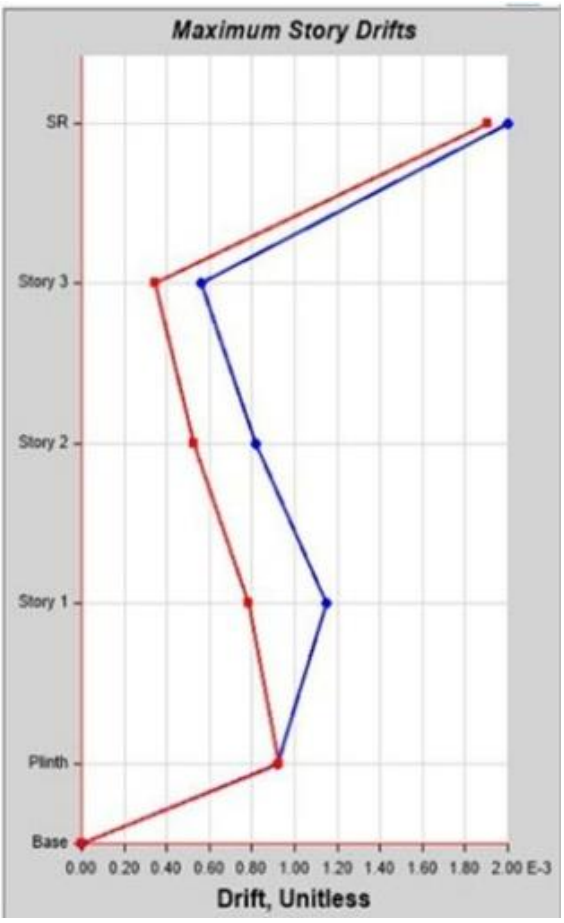

Figure 4-6. Residential Model. Max (0.051mm, SR)

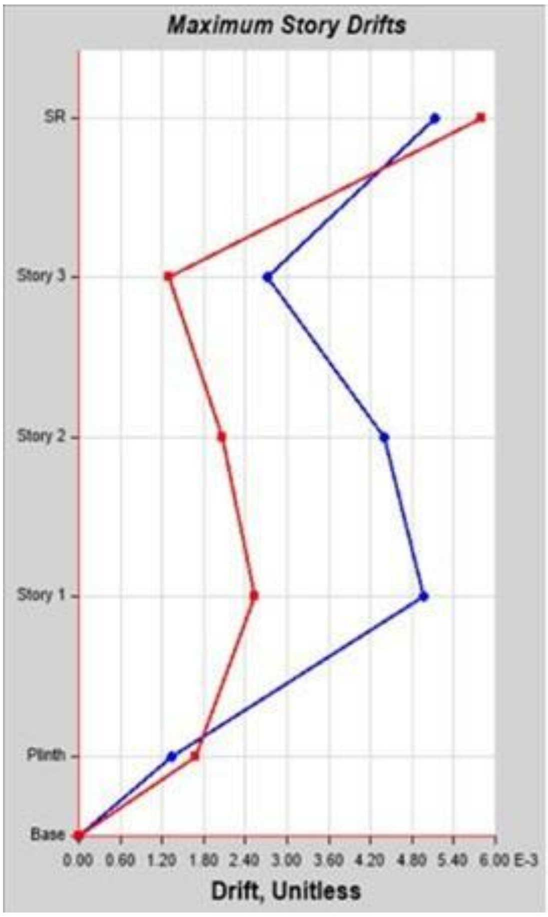

Figure 4-7. Commercial Failed Model. Max (0.147mm, SR)

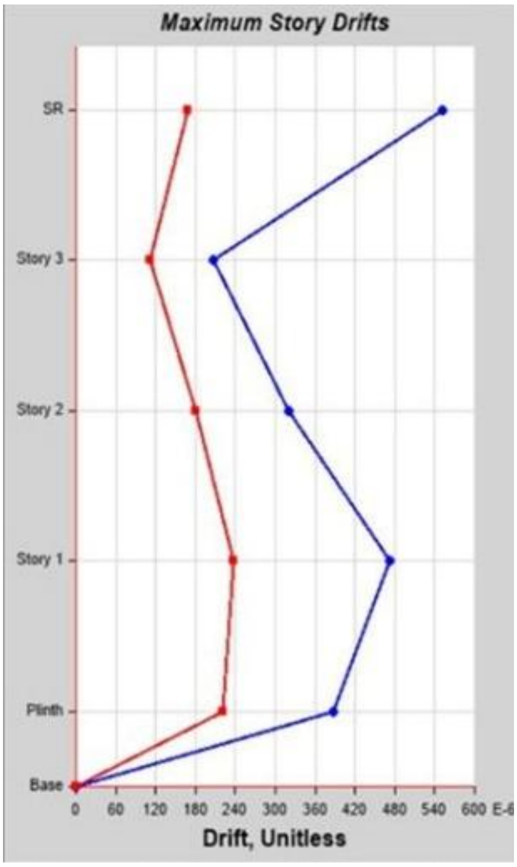

Figure 4-8. Comm. Model RSA X. Max (0.014mm, SR)

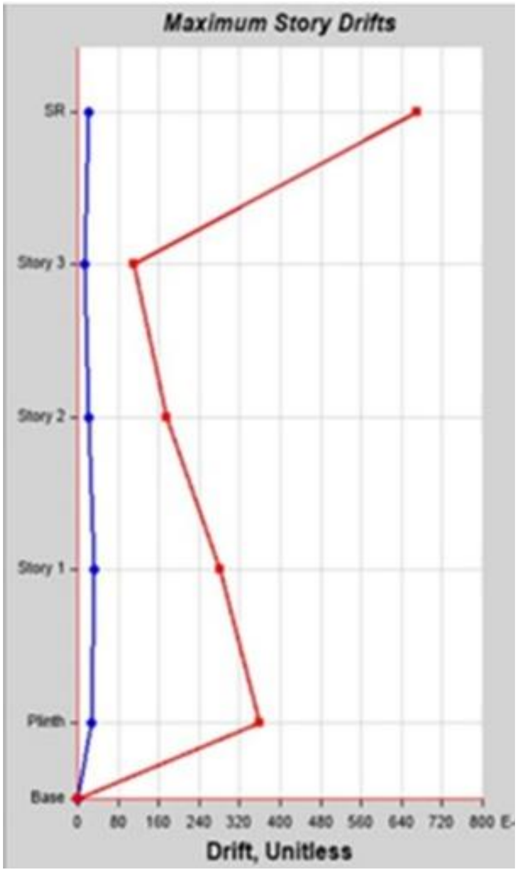

Figure 4-9. Comm. Model RSA Y. Max (0.017mm, SR)

4.3.1 Cost Analysis

Table 4-9. Reconstruction Cost.

Items	Required	Cost
Demolition Process	Contractual	500,000/=
Rebar	35000kg	3,080,000/=
Cement	3100 bags	1,550,000/=
Bricks	180000 nos	1,800,000/=
Sand (Red + Sylhet sand)	16000 cft	1,250,000/=
Maintenance	Contractual	200,000/=
Labor Charge	Contractual	1,000,000/=
Total	**Approx.**	**9,380,000/=**

Table 4-10. CFRP Retrofitting Cost.

Items	Required	Cost
CFRP	2310m	4,000,000/=
Maintenance & Labor	Approx.	15,000/=
Total		**4,015,000/=**

As can be seen, retrofitting (Table 4-1) will cost around 55% less than reconstruction (Table 4-2) and it is not time-consuming, as reconstruction and reconstruction will result in a present structure as waste. So, it is highly not recommended as materials have limited production and access.

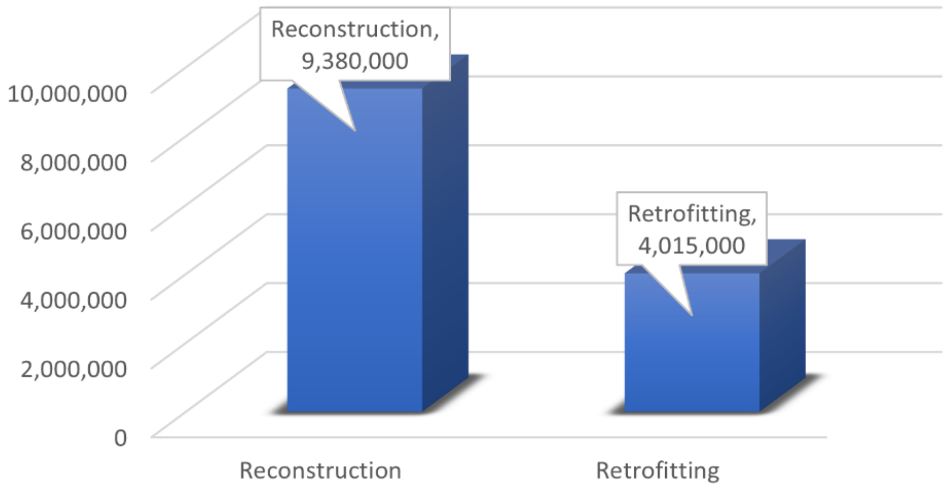

Figure 4-10. Cost Comparison between the Reconstructed Building and the CFRP Retrofitted Building.

4.3.2 Discussion

This study's findings unambiguously underscored the necessity for specific structural solutions when managing building occupancy changes through the imposition of seismic codes. The formerly designed preceding living model which catered for lower seismic and occupancy demand showed positive outcome under the analysis of ETABS, having no member stressed beyond the limit and the maximum story displacement being 0.051 mm which is within the limit prescribed by BNBC 2020 for Seismic Zone III. But when the same structure was examined under commercial load cases, it was already affected by massive member failure and a drift of 0.147 mm which was too much and thus made it obvious that it could not stand the lateral loads and dynamic stresses that were present in the scenario of such increased load cases and so the deficiency of the structure seen thus made it mandatory to retrofit and this matter was took care of through specific CFRP jacketing of the critical structural elements like columns and beams. Right after the anti-retrofitting analysis a lot of the structural stability was seen with one among others floor drift being reduced to 0.0507 mm which is only less than 60% of the limit allowable and even more improved to 0.014 mm and 0.017 mm in X and Y directions respectively in accordance with the Response Spectrum Analysis. The conclusion is such that not only the structural integrity can be restored through retrofitting but also its seismic resilience is enhanced making it a viable and technically smart option compared to total reconstruction. The reduction of drift of around 35–50% in all models speaks volume of the ability of CFRP to absorb seismic risks thereby proving its success especially for mixed-use buildings that are changing from residential to commercial functions, where the occupancy and load requirements are very much higher.

4.4 Summary

The research focused on three different models single, family housing, a commercial building (before retrofit), and a commercial building (after CFRP jacketing retrofit) whose seismic performance and drift behavior were measured with ETABS. The residential model met all the design criteria and did not show any members that were overstressed. Besides that, it managed to keep the drift much lower than the limits set by BNBC 2020. The commercial loading case, however, brought to light a disastrous scenario with the failure of almost all the members and drift exceeding the allowed limits, thus structurally confirming the inadequacy of the building. The use of CFRP sheets as a retrofitting method led to a very significant performance improvement: the checked members were all able to take the lateral and dynamic loads, and the drift was reduced by 3550%, with the RSA analysis giving the values even lower, i.e., 0.0140.017 mm. This is one of the cases where CFRP jacketing can be employed successfully, which is a cheap and technically reliable method that makes the unit more resistant to earthquakes, prolongs its life, and offers a mending alternative that is less disruptive than a full reconstruction of mixed, use buildings.

CHAPTER 5
CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

The study assesses seismic vulnerability in RCC structures using ETABS as per BNBC 2020, where column jacketing with Carbon Fiber Reinforced Polymer (CFRP) is used as a retrofitting technique. The column jacketing increases the overall stability of the structure, along with the column strength. The method reduces drift by up to 60% and increases the safety of damaged structural elements.

- When compared to reconstruction, retrofitting is proven to be more cost-effective, with:
  - CFRP retrofitting cost: 4 million BDT (approx.).
  - Full reconstruction cost: 9.3 million BDT (approx.).

According to our results, if the building is constructed according to code, we shall be able to retrofit residential buildings for the purpose of commercial use and, among them, CFRP retrofitting will be better as it is not time-consuming, less wastage, and can be done by simple methods. Unlikely for reconstruction, it is costly and time-consuming and requires a heavy workforce and machinery. Retrofitting can substantially reduce the cost of destruction and reconstruction of an existing building. Additionally, due to lower demolition waste and the conservation of existing materials, retrofitting can be considered as an environmentally friendly option. For future research, CFRP-FRP optimization and in-field performance monitoring can be studied.

5.2 Limitations and Recommendations for Future Works

- Research should be conducted not only on buildings with G+4 floors but also on the high-rise group of G+6, G+10 buildings to see if the method can be extended to larger seismic demands.
- Conduct trials wherein costs, efficacy, and endurance, among others, are the parameters to be compared for the three different strengthening methods of CFRP, GFRP, and steel jacketing.
- The dynamic load scenarios should take wind and torsional effects into consideration so that the complete stress spectra will be captured in mixed-use structures.

- Prepare a life-cycle cost analysis in which retrofitting with CFRP will be compared to demolition and rebuilding while incorporating local maintenance and durability into the discussion.
- Confirm the results of ETABS simulations with the small-scale laboratory tests of CFRP-strengthened members to avoid the gap between modeling and actual performance.
- Recyclable plastics will be replaced by biodegradable composites in the production process of CFRP and more recycling methods will be developed to achieve the sustainability goals.
- The testing in full-scale structures will be done to pilot projects that are confirming CFRP performance under real-world seismic and environmental conditions.
- Developing of hybrid-retrofitting techniques that would involve the combination of CFRP with steel bracing or dampers to provide greater resilience.
- Assessing the fire resistance and durability of CFRP under extreme environmental conditions (humidity, salinity, pollution).
- Use advanced simulation methods such as nonlinear time-history analysis and AI/ML predictive models.
- Be active in the flourishment of codes and standards for the use of CFRP in the field of retrofitting.
- Evaluate the socio-economic and policy issues involved in the sustainable retrofitting process, such as the barriers and incentives for adoption.
- The detection of strain and cracks in real-time will be enabled by incorporating smart monitoring systems with sensors in CFRP retrofitting.

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APPENDIX

Appendix A

Table 5-1. Residential Model Ex Drift Output.

Story	Output Case	Step	Direction	Drift	X (m)	Y (m)	Z (m)
SR	Ex	1	X	0.00179	5.0292	11.25	13.7
SR	Ex	1	Y	0.00034	5.0292	11.25	13.7
SR	Ex	2	X	0.00179	5.0292	11.25	13.7
SR	Ex	2	Y	0.00034	5.0292	11.25	13.7
SR	Ex	3	X	0.00179	5.0292	11.25	13.7
SR	Ex	3	Y	0.00034	5.0292	11.25	13.7
Story 3	Ex	1	X	0.00093	13.9954	0	10.6
Story 3	Ex	2	X	0.00093	13.9954	0	10.6
Story 3	Ex	3	X	0.00093	13.9954	0	10.6
Story 2	Ex	1	X	0.00152	13.9954	0	7.62
Story 2	Ex	2	X	0.00152	13.9954	0	7.62
Story 2	Ex	3	X	0.00152	13.9954	0	7.62
Story 1	Ex	1	X	0.00171	12.9032	0	4.57
Story 1	Ex	2	X	0.00171	12.9032	0	4.57
Story 1	Ex	3	X	0.00171	12.9032	0	4.57
Plinth	Ex	1	X	0.00046	0	0	1.52
Plinth	Ex	2	X	0.00046	0	0	1.52
Plinth	Ex	3	X	0.00046	0	0	1.52

Table 5-2. Residential Model Ey Drift Output.

Story	Output Case	Step	Direction	Drift	X (m)	Y (m)	Z (m)
SR	Ey	1	Y	0.002142	5.0292	11.2522	13.716
SR	Ey	2	Y	0.002142	5.0292	11.2522	13.716
SR	Ey	3	Y	0.002142	5.0292	11.2522	13.716
Story 3	Ey	1	Y	0.000463	-1.0414	0	10.668
Story 3	Ey	2	Y	0.000463	-1.0414	0	10.668
Story 3	Ey	3	Y	0.000463	-1.0414	0	10.668
Story 2	Ey	1	Y	0.000688	-1.0414	11.2522	7.62
Story 2	Ey	2	Y	0.000688	-1.0414	11.2522	7.62
Story 2	Ey	3	Y	0.000688	-1.0414	11.2522	7.62
Story 1	Ey	1	Y	0.000958	0	11.2522	4.572
Story 1	Ey	2	Y	0.000958	0	11.2522	4.572
Story 1	Ey	3	Y	0.000958	0	11.2522	4.572
Plinth	Ey	1	Y	0.00061	7.8486	7.5946	1.524
Plinth	Ey	2	Y	0.00061	7.8486	7.5946	1.524
Plinth	Ey	3	Y	0.00061	7.8486	7.5946	1.524

Table 5-3.Failed Model Ex Drift Output.

Story	Output Case	Step	Direction	Drift	X (m)	Y (m)	Z (m)
SR	Ex	1	X	0.003354	16.5	36.9167	45
SR	Ex	1	Y	0.000583	16.5	36.9167	45
SR	Ex	2	X	0.003354	16.5	36.9167	45
SR	Ex	2	Y	0.000583	16.5	36.9167	45
SR	Ex	3	X	0.003354	16.5	36.9167	45
SR	Ex	3	Y	0.000583	16.5	36.9167	45
Story 3	Ex	1	X	0.001692	45.9166	0	35
Story 3	Ex	2	X	0.001692	45.9166	0	35
Story 3	Ex	3	X	0.001692	45.9166	0	35
Story 2	Ex	1	X	0.002851	45.9166	0	25
Story 2	Ex	2	X	0.002851	45.9166	0	25
Story 2	Ex	3	X	0.002851	45.9166	0	25
Story 1	Ex	1	X	0.003404	42.3333	0	15
Story 1	Ex	2	X	0.003404	42.3333	0	15
Story 1	Ex	3	X	0.003404	42.3333	0	15
Plinth	Ex	1	X	0.000757	0	0	5
Plinth	Ex	2	X	0.000757	0	0	5
Plinth	Ex	3	X	0.000757	0	0	5

Table 5-4. Failed Model Ey Drift Output.

Story	Output Case	Step	Direction	Drift	X (m)	Y (m)	Z (m)
SR	Ey	1	Y	0.003932	16.5	36.9167	45
SR	Ey	2	Y	0.003932	16.5	36.9167	45
SR	Ey	3	Y	0.003932	16.5	36.9167	45
Story 3	Ey	1	Y	0.000864	-3.4167	0	35
Story 3	Ey	2	Y	0.000864	-3.4167	0	35
Story 3	Ey	3	Y	0.000864	-3.4167	0	35
Story 2	Ey	1	Y	0.001273	-3.4167	36.9167	25
Story 2	Ey	2	Y	0.001273	-3.4167	36.9167	25
Story 2	Ey	3	Y	0.001273	-3.4167	36.9167	25
Story 1	Ey	1	Y	0.001774	0	24.9167	15
Story 1	Ey	2	Y	0.001774	0	24.9167	15
Story 1	Ey	3	Y	0.001774	0	24.9167	15
Plinth	Ey	1	Y	0.00102	25.75	24.9167	5
Plinth	Ey	2	Y	0.00102	25.75	24.9167	5
Plinth	Ey	3	Y	0.00102	25.75	24.9167	5

Table 5-5. Failed Model RSA X Drift Output.

Story	Output Case	Step Type	Direction	Drift	X ft	Y ft	Z ft
SR	RS X	Max	X	0.00133	16.5	36.9167	45
SR	RS X	Max	Y	0.000427	16.5	36.9167	45
Story 3	RS X	Max	X	0.000466	45.9166	0	35
Story 3	RS X	Max	Y	0.000371	45.9166	36.0833	35
Story 2	RS X	Max	X	0.00082	45.9166	0	25
Story 2	RS X	Max	Y	0.000635	45.9166	0	25
Story 1	RS X	Max	X	0.000975	42.3333	0	15
Story 1	RS X	Max	Y	0.000684	0	0	15
Plinth	RS X	Max	X	0.000215	0	0	5
Plinth	RS X	Max	Y	0.000125	42.3333	0	5

Table 5-6. Failed Model RSA Y Drift Output.

Story	Output Case	Step Type	Direction	Drift	X ft	Y ft	Z ft
SR	RS Y	Max	X	0.000428	16.5	36.9167	45
SR	RS Y	Max	Y	0.001458	16.5	36.9167	45
Story 3	RS Y	Max	X	8.3E-05	-3.4167	36.9167	35
Story 3	RS Y	Max	Y	0.00032	-3.4167	0	35
Story 2	RS Y	Max	X	0.00012	0	36.9167	25
Story 2	RS Y	Max	Y	0.000483	-3.4167	36.9167	25
Story 1	RS Y	Max	X	0.000181	0	36.9167	15
Story 1	RS Y	Max	Y	0.000695	0	24.9167	15
Plinth	RS Y	Max	X	0.000105	25.75	36.0833	5
Plinth	RS Y	Max	Y	0.000379	25.75	24.9167	5

Table 5-7. CFRP Retrofitted Model Ex Drift Output.

Story	Output Case	Step	Direction	Drift	X (m)	Y (m)	Z (m)
SR	Ex	1	X	0.002133	16.5	36.9167	45
SR	Ex	2	X	0.002133	16.5	36.9167	45
SR	Ex	3	X	0.002133	16.5	36.9167	45
SR	Ex	1	X	0.000557	-3.4167	0	35
SR	Ex	2	X	0.000557	-3.4167	0	35
SR	Ex	3	X	0.000557	-3.4167	0	35
Story 3	Ex	1	X	0.000818	45.9166	0	25
Story 3	Ex	2	X	0.000818	45.9166	0	25
Story 3	Ex	3	X	0.000818	45.9166	0	25
Story 2	Ex	1	X	0.00115	42.3333	0	15
Story 2	Ex	2	X	0.00115	42.3333	0	15
Story 2	Ex	3	X	0.00115	42.3333	0	15
Story 1	Ex	1	X	0.000918	0	0	5
Story 1	Ex	2	X	0.000918	0	0	5
Story 1	Ex	3	X	0.000918	0	0	5
Plinth	Ex	1	X	0.002133	16.5	36.9167	45
Plinth	Ex	2	X	0.002133	16.5	36.9167	45
Plinth	Ex	3	X	0.002133	16.5	36.9167	45

Table 5-8. CFRP Retrofitted Model Ey Drift Output.

Story	Output Case	Step	Direction	Drift	X (m)	Y (m)	Z (m)
SR	Ey	1	Y	0.001865	16.5	36.9167	45
SR	Ey	2	Y	0.001865	16.5	36.9167	45
SR	Ey	3	Y	0.001865	16.5	36.9167	45
Story 3	Ey	1	Y	0.000323	-3.4167	0	35
Story 3	Ey	2	Y	0.000323	-3.4167	0	35
Story 3	Ey	3	Y	0.000323	-3.4167	0	35
Story 2	Ey	1	Y	0.00049	-3.4167	0	25
Story 2	Ey	2	Y	0.00049	-3.4167	0	25
Story 2	Ey	3	Y	0.00049	-3.4167	0	25
Story 1	Ey	1	Y	0.000756	21.1666	0	15
Story 1	Ey	2	Y	0.000756	21.1666	0	15
Story 1	Ey	3	Y	0.000756	21.1666	0	15
Plinth	Ey	1	Y	0.000916	25.75	24.9167	5
Plinth	Ey	2	Y	0.000916	25.75	24.9167	5
Plinth	Ey	3	Y	0.000916	25.75	24.9167	5

Table 5-9. CFRP Retrofitted Model RSA X Drift Output.

Story	Output Case	Step Type	Direction	Drift	X ft	Y ft	Z ft
SR	RS X	Max	X	0.000515	16.5	36.9167	45
SR	RS X	Max	Y	0.000117	16.5	36.9167	45
Story 3	RS X	Max	X	0.000184	-3.4167	0	35
Story 3	RS X	Max	Y	8.8E-05	-3.4167	0	35
Story 2	RS X	Max	X	0.000284	0	0	25
Story 2	RS X	Max	Y	0.000144	-3.4167	36.9167	25
Story 1	RS X	Max	X	0.000418	42.3333	0	15
Story 1	RS X	Max	Y	0.000188	0	0	15
Plinth	RS X	Max	X	0.000341	0	0	5
Plinth	RS X	Max	Y	0.000176	42.3333	24.9167	5

Table 5-10. CFRP Retrofitted Failed Model RSA Y Drift Output.

Story	Output Case	Step Type	Direction	Drift	X ft	Y ft	Z ft
SR	RS Y	Max	X	8.4E-05	16.5	36.9167	45
SR	RS Y	Max	Y	0.000604	16.5	36.9167	45
Story 3	RS Y	Max	Y	0.000101	-3.4167	0	35
Story 2	RS Y	Max	Y	0.000159	-3.4167	0	25
Story 1	RS Y	Max	Y	0.000249	0	0	15
Plinth	RS Y	Max	Y	0.000303	25.75	24.9167	5

Appendix B

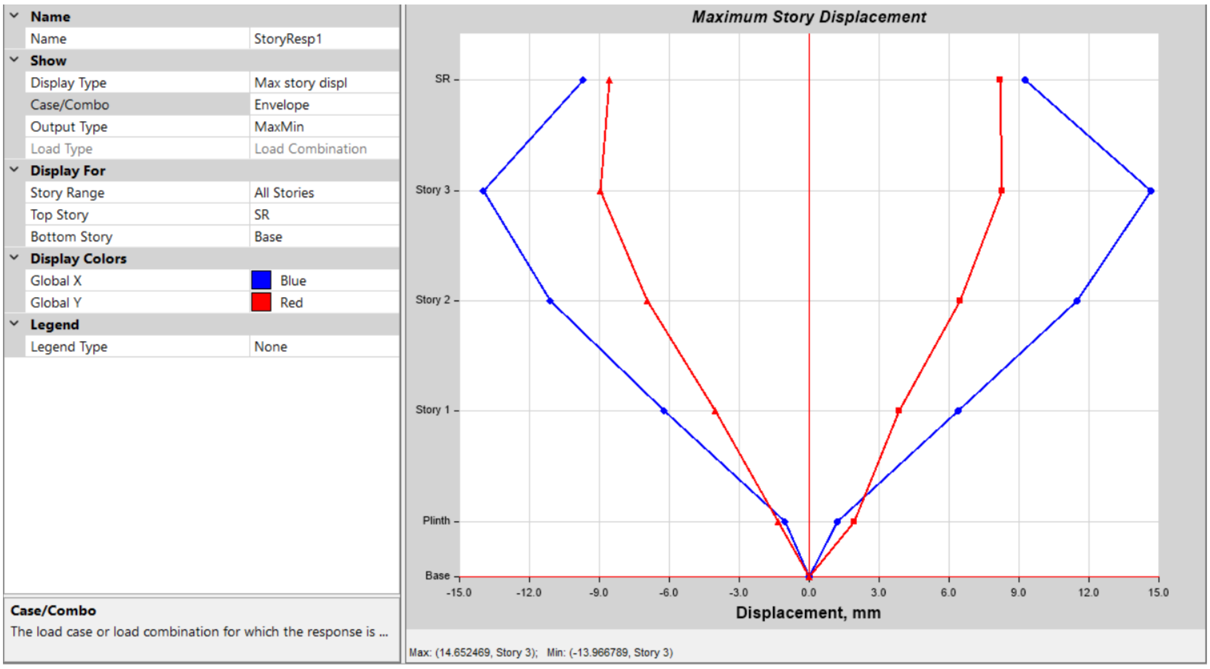

Figure 5-1. Displacements of Residential Model.

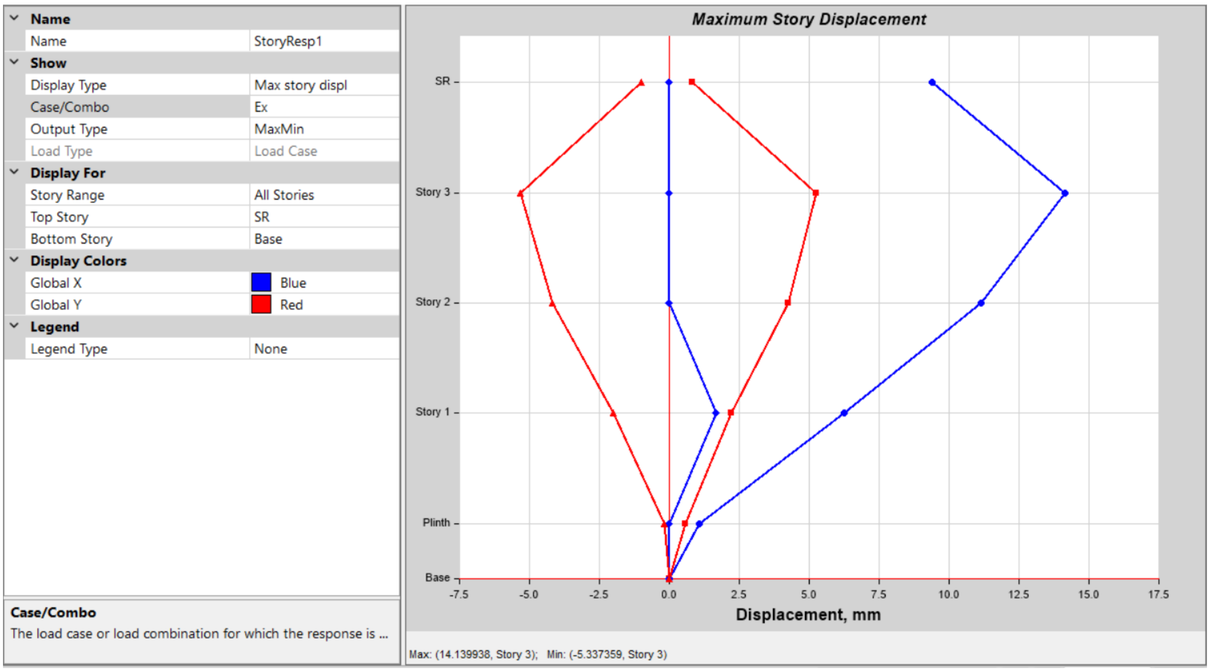

Figure 5-2. Ex Displacements of Residential Model.

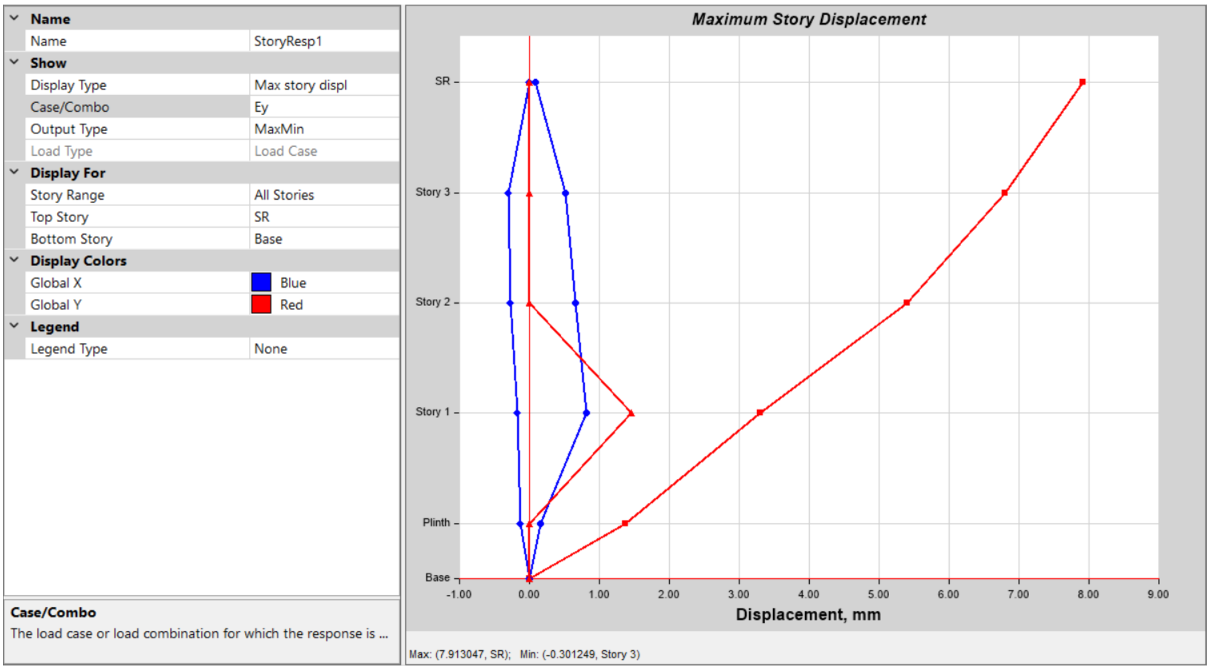

Figure 5-3. Ey Displacements of Residential Model.

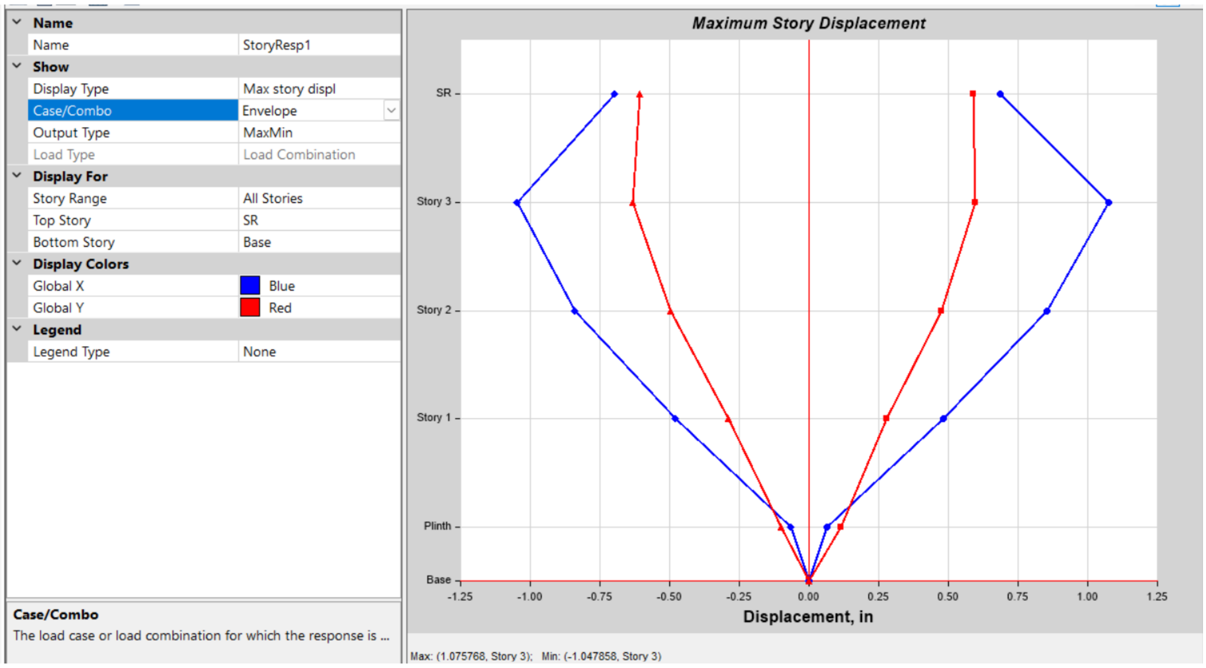

Figure 5-4. Displacements of Failed Commercial Model.

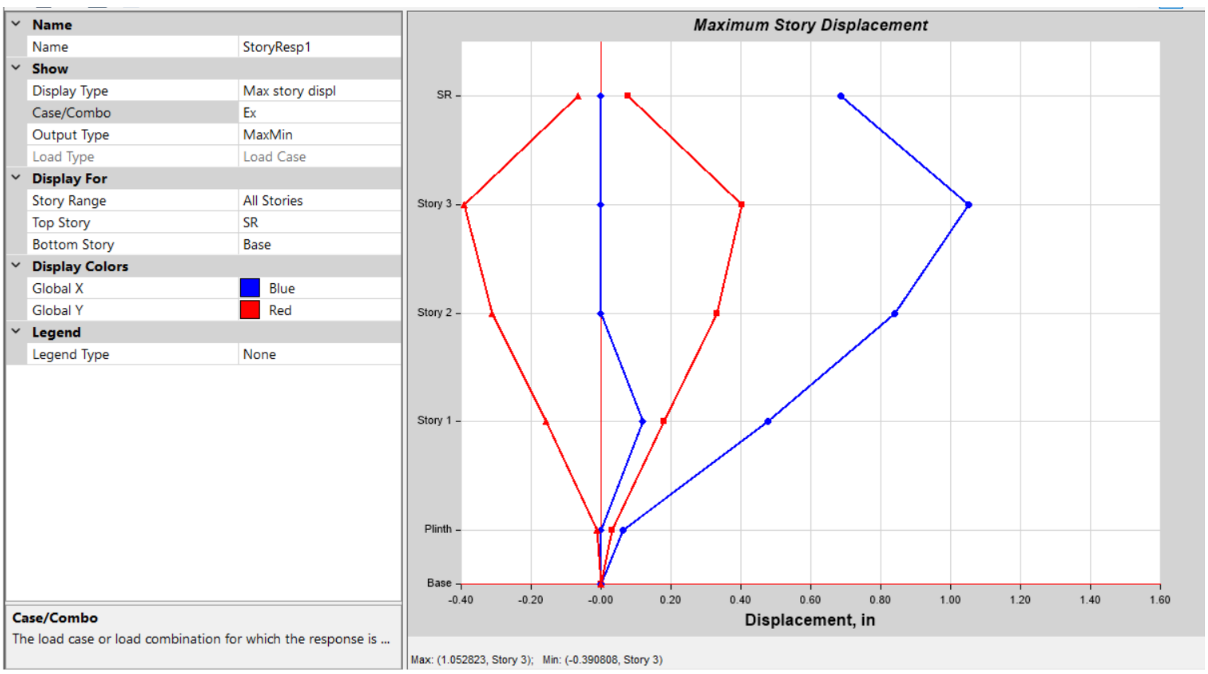

Figure 5-5. Ex Displacements of Failed Commercial Model.

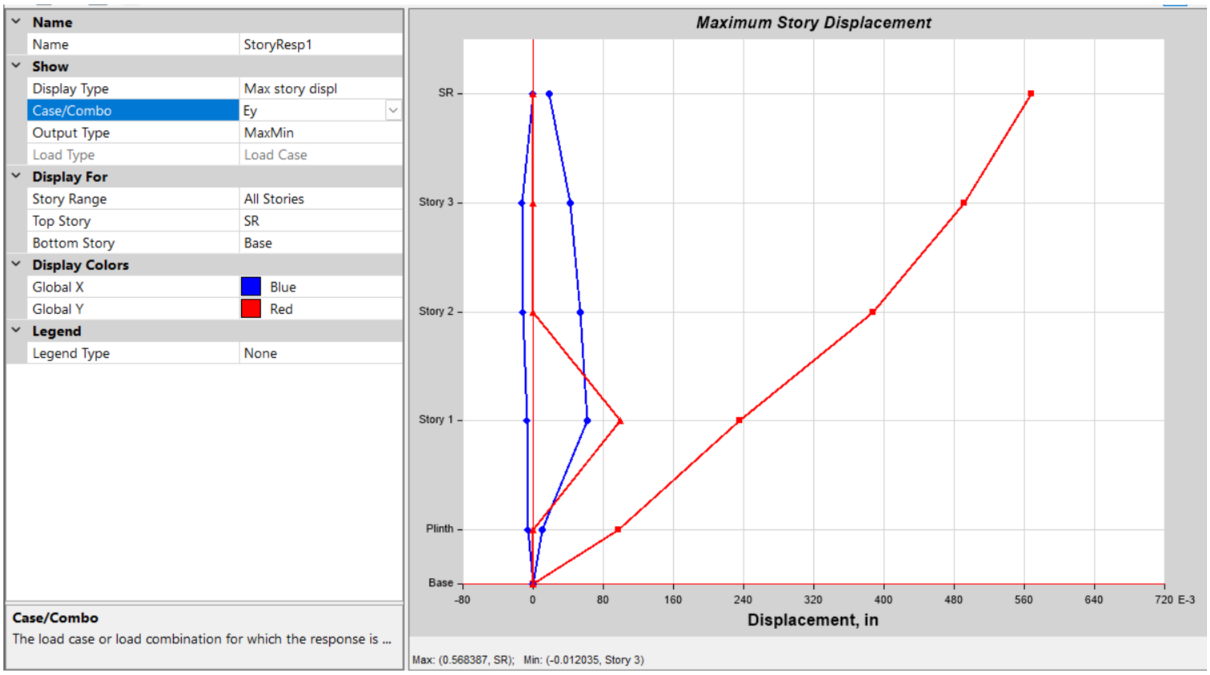

Figure 5-6. Ey Displacements of Failed Commercial Model.

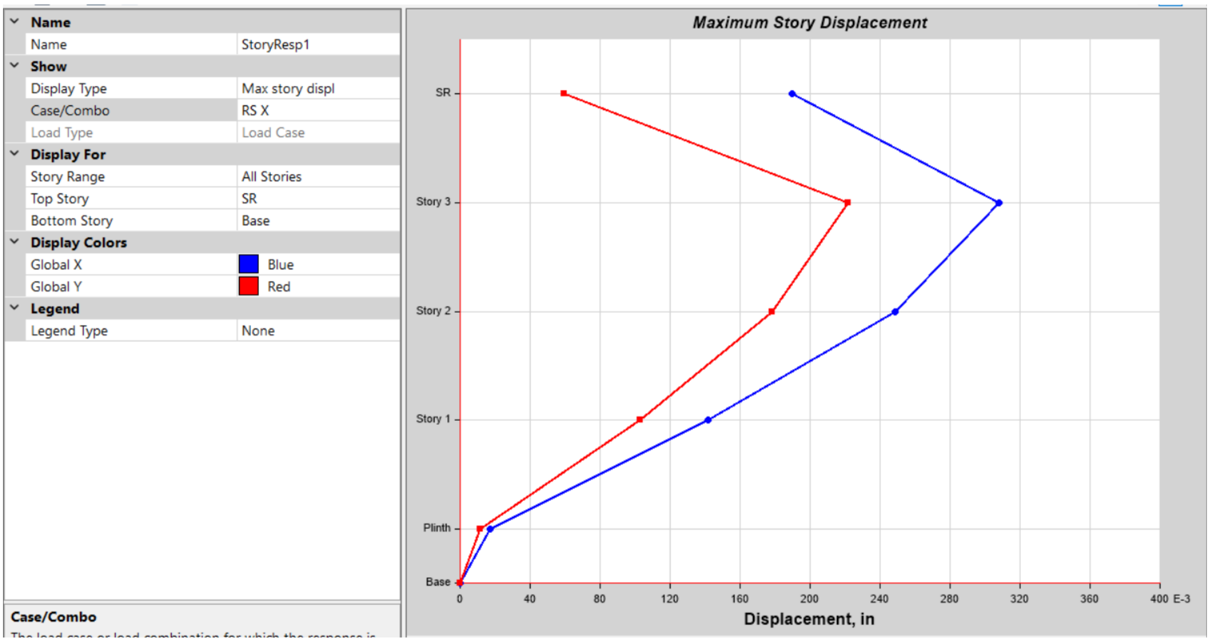

Figure 5-7. RSA X Displacements of Failed Commercial Model.

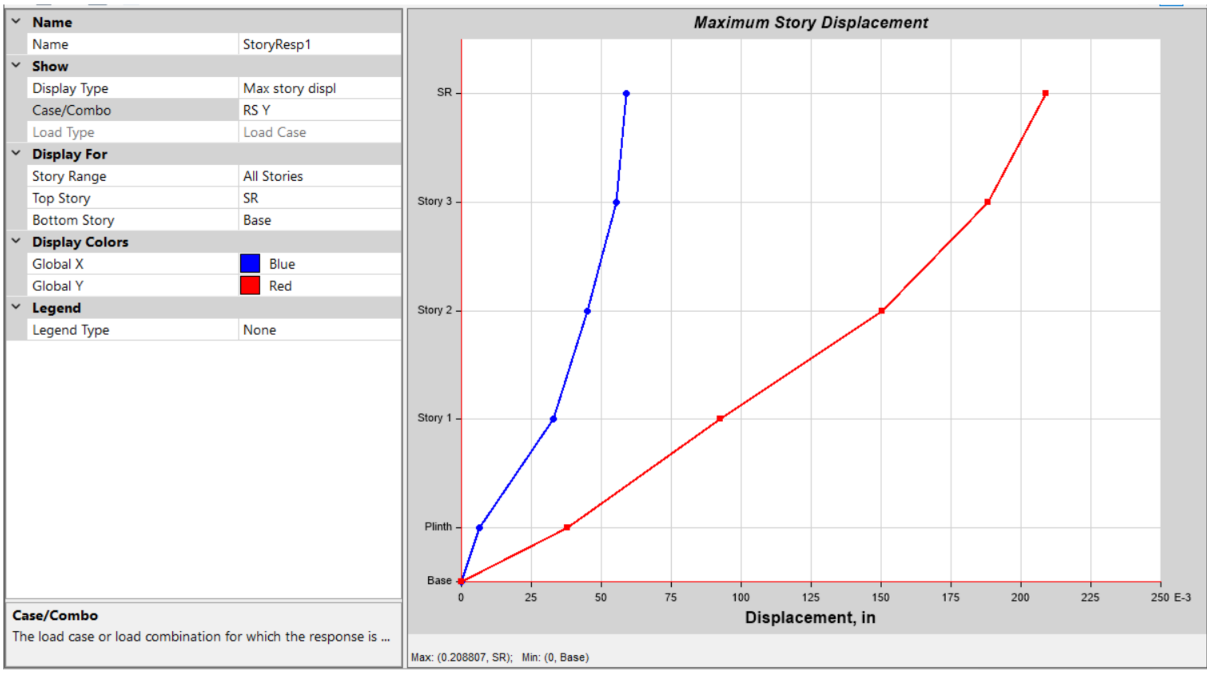

Figure 5-8. RAS Y Displacements of Failed Commercial Model.

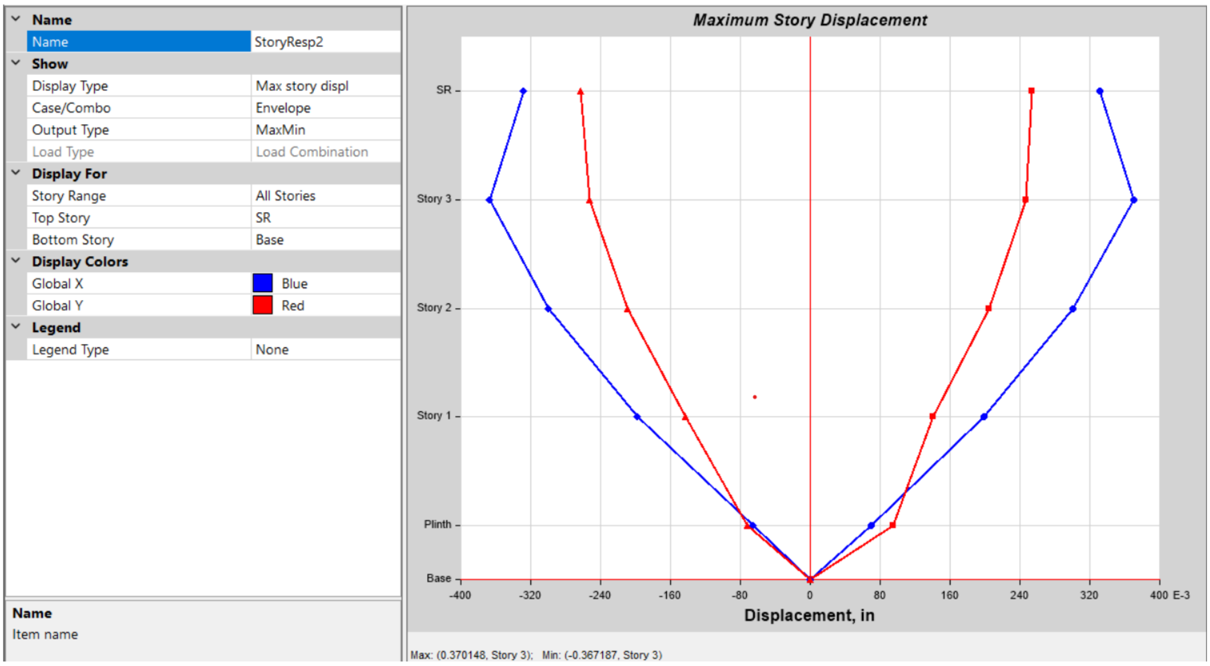

Figure 5-9. Displacements of CFRP Retrofitted Commercial Model.

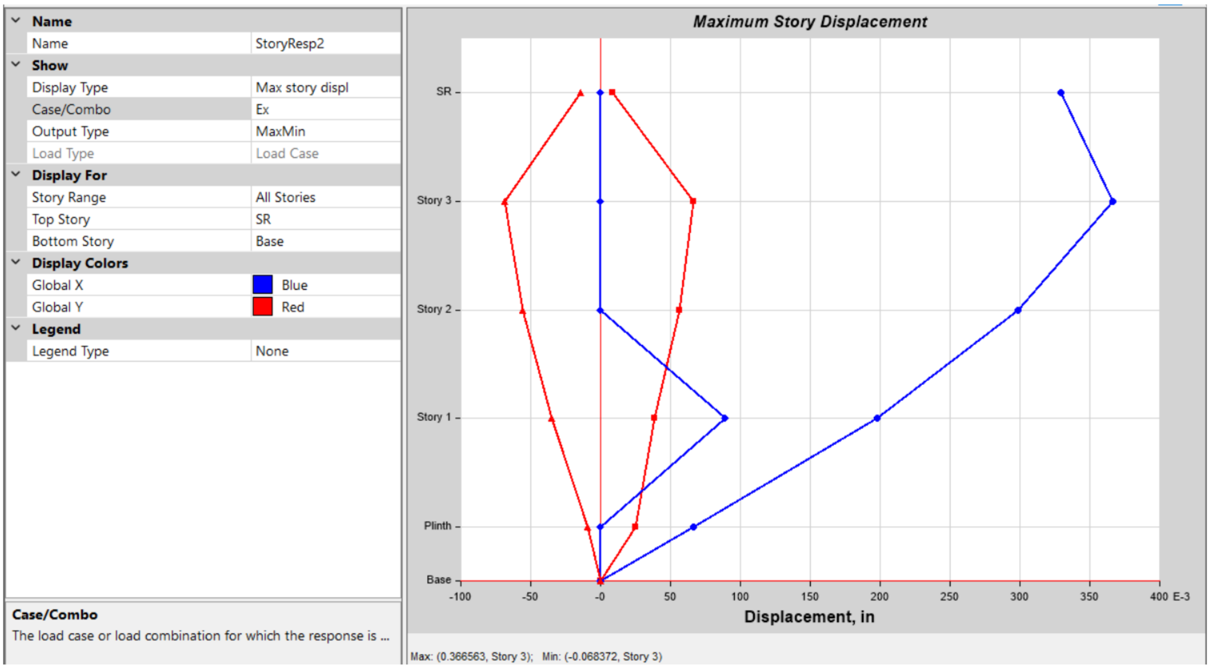

Figure 5-10. EX Displacements of CFRP Retrofitted Commercial Model.

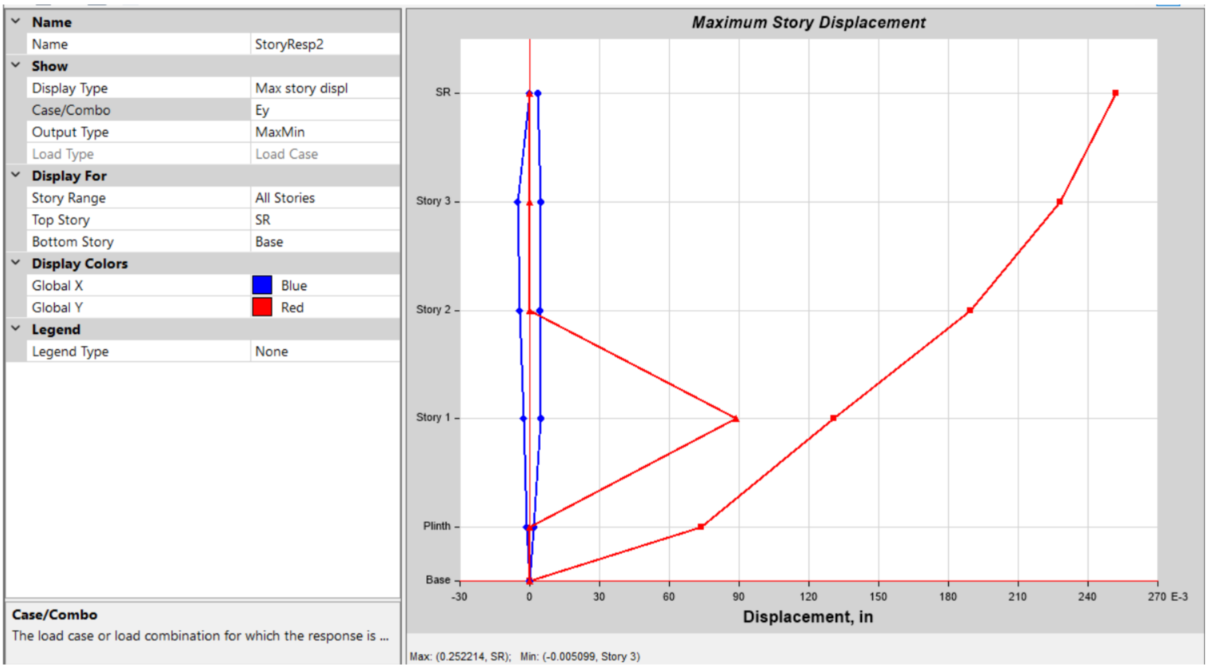

Figure 5-11. EY Displacements of CFRP Retrofitted Commercial Model.

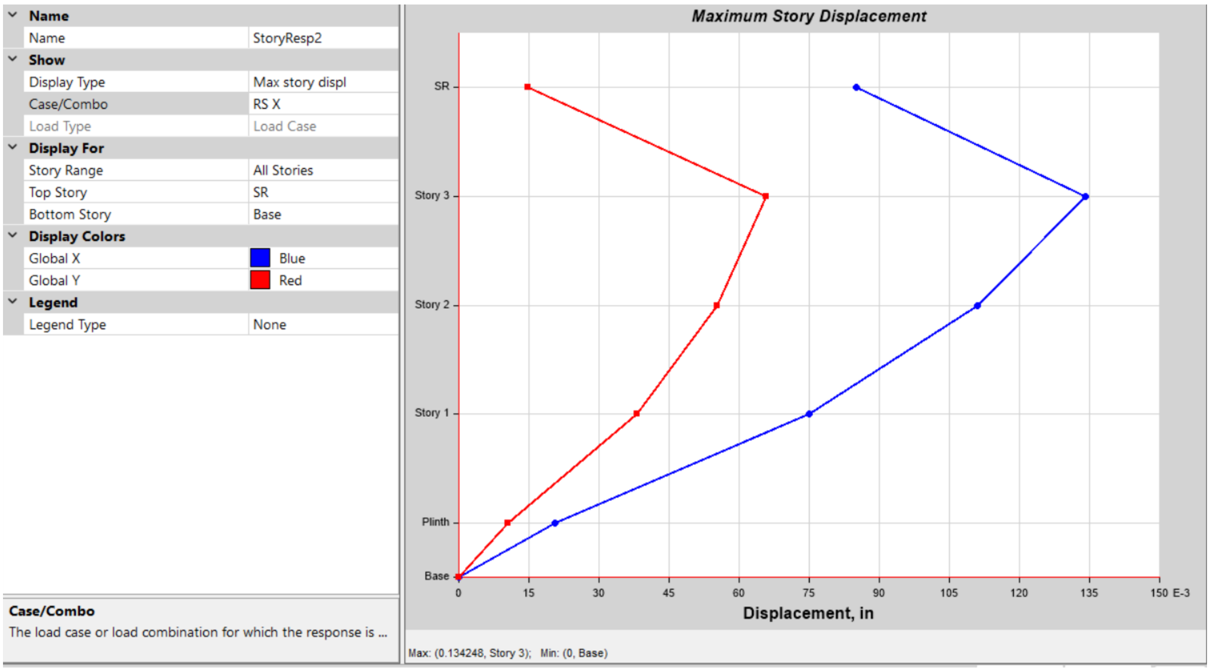

Figure 5-12. RSA X Displacements of CFRP Retrofitted Commercial Model.

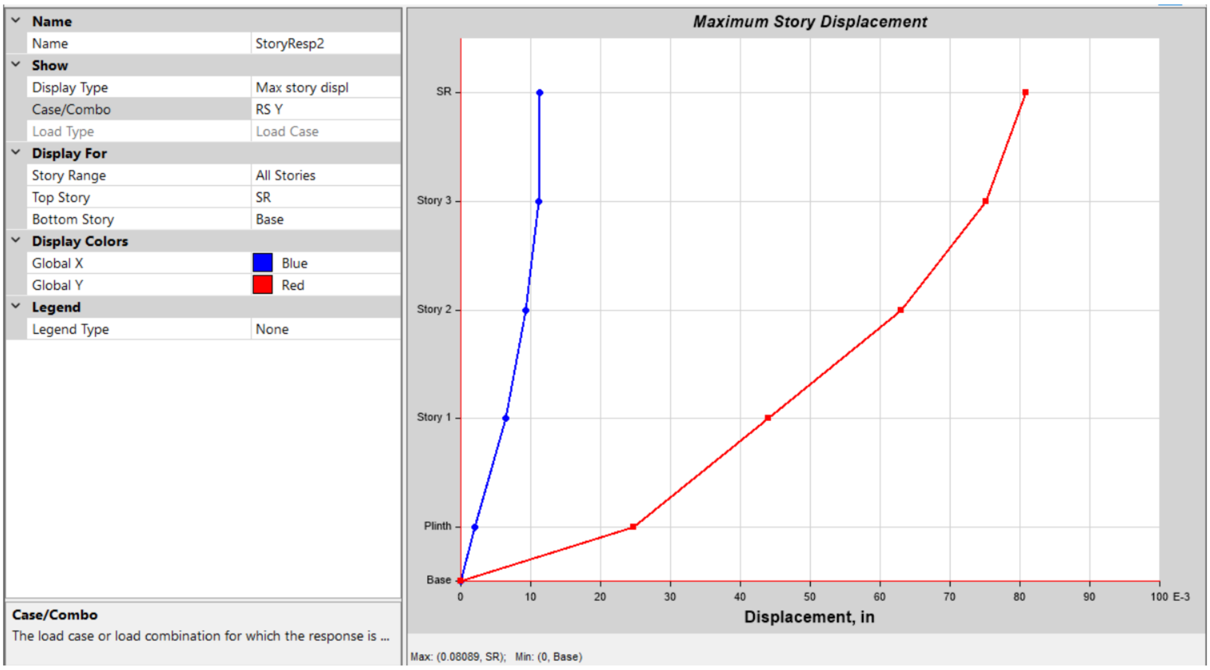

Figure 5-13. RSA Y Displacements of CFRP Retrofitted Commercial Model.