INVESTIGATION ON STRUCTURAL PERFORMANCE OF ROOFTOP GARDENING FOR HIGHRISE RESIDENTIAL BUILDINGS IN DHAKA CITY

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ABSTRACT

Rooftop gardening on existing building structures is becoming popular in Dhaka due to the reduction of open space due to the increasing population. The load from rooftop gardening may cause mass irregularity in a reinforced concrete high-rise structure. In recent times, it has been observed that structural irregularities are one of the major concerns of structural damage. Irregularities in a high-rise multistoried structure are weak points in a building that may become the source for failure of one element or even total collapse of the building against lateral load such as an earthquake. People are now concerned about the structural performance of buildings for external loads. A significant variation in the performance of the same structure may occur for different loading configurations. For rooftop gardening, a better evaluation of the structure's performance can be observed by software analysis for rooftop gardening gravity load. This study aims to evaluate the performance of a 16-story high-rise structure in Dhaka city with a rooftop gardening system against gravity load due to soil pressure and compared with the same structure without rooftop gardening. With the help of story drift, maximum displacement, p-delta effect, pushover curve, and base share, the performances of the structure are evaluated by pushover analysis in ETABS software by imposing gardening load following Bangladesh National Building Code-2020 (BNBC) to observe the structural behavior. Based on the finite element analysis results, the structural analysis parameters demonstrate insignificant variation for rooftop gardening in high-rise structures although some precautions should be executed.

Keywords: *rooftop gardening, response spectrum analysis, pushover analysis, pushover curve, mass irregularity.*

1. INTRODUCTION

Today's world is on the cusp of growing urbanization, making sustainable agriculture difficult. Over 50% of the world's population presently lives in urban regions, and by the year 2030, that number will rise to 70% due to the draw of cities (Eigenbrod & Gruda, 2015). More people mean more food production, which requires more arable land. It has been estimated that conventional farming would need 109 million hectares of new land to support the world's population by 2050 (Islam et al., 2019). However, the agriculture sector decreased by 0.19 percent between 2005 and 2011 rather than a gain (Eigenbrod & Gruda, 2015). In developing nations like ours, this value is more significant. This decreasing rate continues year after year cause of the heavy population rate. To solve this problem and secure food for the increasing population, urban agriculture can be the best replacement. Urban agriculture may give city dwellers access to fresh vegetables, improve their diets, and significantly reduce household spending. The increased popularity of rooftop gardening is also due to the vegetated surfaces' ability to absorb sound (Chowdhury et al., 2020). The fear of health risks while consuming market veggies is present in some people's minds in the modern era of widespread pesticide usage and declining soil fertility. Although rooftop gardening might seem like a little step, it represents a giant leap forward for sustainability and mitigating the dangers of climate change (Ritesh Kumar et al., 2019). Installing a rooftop garden on a ten-story residential building can result in an average saving of 2% to 8% of the total energy used annually (Wasim et al., 2016).

Bangladesh is the nation with the densest population, with 170 million people. Population growth is 1.01 percent, and the GDP growth rate is 7.01 percent. According to a study, Bangladesh's HDI index in 1995, 2005, and 2015 was 0.427, 0.506, and 0.588. In 2025, the HDI index is projected to be around 0.660. According to this HDI score, Bangladesh's development progress is somewhat modest when compared to other countries (M.I.Sourav & Nafiz, 2020).

Based on the findings of Sadashiva's research it examined regular structures, which had a constant mass on every floor and a constant inter-story drift ratio or uniform stiffness distribution over their height. The structures performed inelastic dynamic time-history analysis using code design seismic recordings. The first floor, mid-height, and roof were considered separately while building irregular constructions with floor masses 1.5, 2.5, 3.5, and 5 times larger than conventional constructions. The irregular structures are meant to tolerate the same drifts as conventional ones. (Sadashiva et al., 2009)

Dhaka, the capital of Bangladesh, is one of the most densely populated cities in the world. The rapid population increase against comparatively inadequate land has introduced a new construction tradition in Dhaka over the past few years. Because of less space alone with greenery in the city, people are now appreciating rooftop gardening in high-rise buildings as a source of refreshment, fresh food, and entertainment. Rooftop gardening can be beneficial and environmentally friendly and given financial support sometimes, but at the same time, unorganized settings of rooftop gardening can be hazardous for the structure. According to JR Kumar, B Natasha, and KC Suraj's 2019 study, rooftop farming significantly influences the urban environment by lowering the cost of stormwater management and carbon dioxide emissions (Kumar et al., 2019). LY Astee and NT Kishnani (2010) consider rooftop framing acceptable for Singapore's public houses. By carrying out this plan, domestic vegetable production may expand by 700%, meeting 35.5% of domestic demand (Astee & Kishnani, 2010).

Gardening on a building roof is one kind of superimposed dead load, and it can vary according to the design of the building. Residential buildings are typically designed for dead and live loads following the building code. In most cases, additional loads due to gardening on the roof are neglected in the general building design process and later installed without structural analysis. If the building is not properly designed, this may lead to severe damage to the building structure in the seismic event, such as soft and weak story problems & and mass irregularity problems.

In this paper, structural assessment is performed through ETABS counting parameters such as story displacement, slab deflection, p-delta effect, story drift, base share, torsional irregularity, pushover curve, and plastic hinge formation for a 16-story RC residential building with and without rooftop gardening. Based on the static analysis, response spectrum analysis, and pushover analysis the effect of rooftop gardening is evaluated for the high-rise RC frame structure. Typical rooftop gardening in Dhaka is shown in Figure 1.

Figure1: Rooftop Garden in Dhaka

2. METHODOLOGY

To gain an improved understanding and visual representation of the impact of rooftop gardening, two distinct models were examined, and the findings are arranged in a comparison manner. Rooftop loads on high-rise structures can create mass irregularity resulting in variances of structural performance. To ensure consistency in structural analysis, the BNBC-2020 guidelines are adhered to resulting in the assignment of identical structure elements.

To evaluate the structural effect of rooftop gardening in RC residential high-rise structures, two identical models are analyzed. The structure without rooftop gardening is named as Bare Frame Model and the structure with rooftop gardening is named as Rooftop Garden Model.

The performance of the ETABS structural model is examined in terms of story displacement, story drift, hinge pattern, base shear, time period, and slab deflection. These parameters were obtained by pushover analysis and non-linear static analysis.

2.1 Model Description

The analysis focused on a standard 16-storey building model, represented in Figures 2 and 3. The model's dimensions were measured at 25 meters in length and 18 meters in width. To preserve the model's simplicity, a bay measuring 5x3 was selected, with a span length of 5m in the X direction and 6m in the Y direction. The slab thickness was assumed as 125mm.

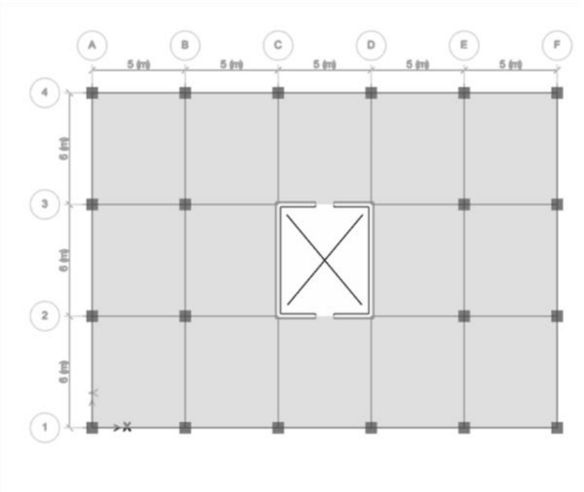


Figure 2: Plan view of the model

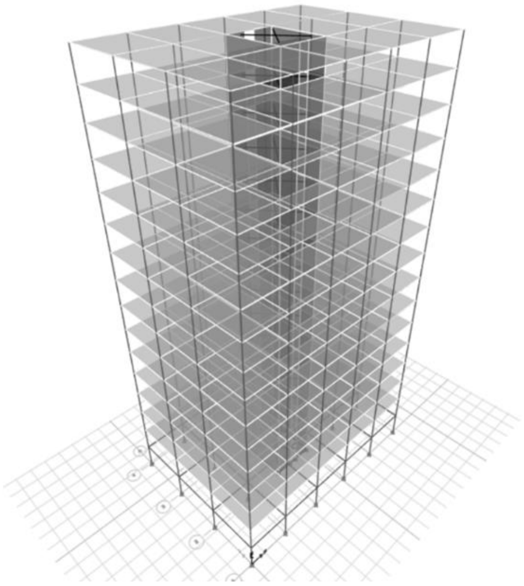


Figure 3: 3D view of the model

The building's specifications are provided in tables 1-4, which are being examined for study.

Table 1: Load cases consideration of building design

Types of Loads	**Corresponding values**
Live load	2.00 KN/m^2
Floor finish	1.00 KN/m^2
Roof live load	1.00 KN/m^2
Rooftop Garden live load	4.8 KN/m^2

Table 2: Materials specification for building analysis

Specification types	**Corresponding values**
Strength of steel, f_y	500 MPa
Strength of concrete, f'_c (shear wall and column)	24 MPa
Strength of concrete, f'_c (beam and slab)	20 MPa

Table 3: Building Specification

Specification types	**Corresponding values**
Span length in the X-axis	5 m
Span length in the Y-axis	6 m
Grade beam size	300 mmX500 mm
Floor beam size	250 mmX500 mm
Column size	625 mmX625 mm
Shear wall thickness	250 mm
Slab thickness	125 mm

Table 4: Design specification

Specification types	**Corresponding values**
Zone co-efficient	0.20
Seismic design category	C
Basic wind speed	65.7 m/s
Response reduction factor	5
Importance factor, I	1
Exposer Category	A

Types of primary loads and the combination of loads that are used:

I. Dead load (Self weight of structure)
II. Live load (Residential zone and rooftop gardening load)
III. Wind load (In both X and Y directions)
IV. Earthquake load (Both in X and Y directions)

Following basic load combinations with appropriate safety factors were used for the finite element analysis as per BNBC-2020.

Table 5: Basic load combinations

SI. NO	**Load Combinations**
1.	1.4(D+L)
2.	1.2(D+L+T)1.6(L+H)+0.5R
3.	1.2D+1.6R+(L OR 0.8W)
4.	1.2D+1.6W+L+0.5R
5.	1.2D+E+L
6.	0.9D+1.6W+1.6H
7.	0.9D+E+1.6H

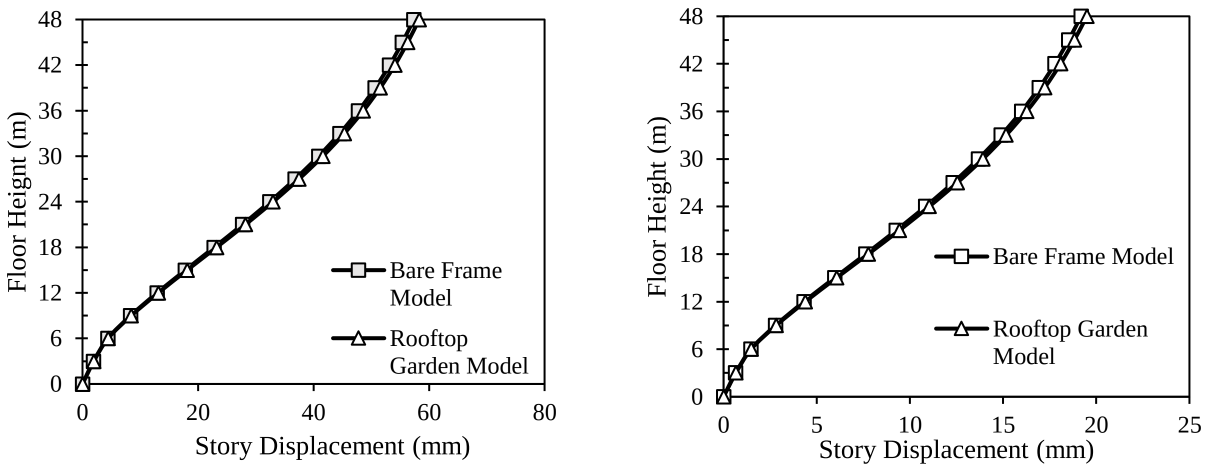
3. RESULT AND ANALYSIS

3.1 Static Analysis

Static analysis examines how a structure behaves under constant loads, like gravity and lateral loads. It ensures that the structure is in a state of static equilibrium, where forces and moments are balanced. This analysis is often categorized as linear static and nonlinear static. This analysis assumes linear elastic behavior for simplicity. Static analysis is used to assess load distribution, check code compliance, and ensure the stability and safety of structures under static conditions. It is a foundational step for designing a structure. Although dynamic or nonlinear analyses may be required for certain scenarios.

3.1.1 Story Displacement

The comparative stories displacement of the two models is illustrated in Figure 4, showing the displacement in both the X and Y-directions. The largest displacement occurs at the roof level for both models, as the lateral loads cause an increase in the sway of the structure with each additional story. The rooftop garden model has the greatest displacement of 58.293 mm in the X-direction, surpassing the bare frame model by 1.6%. The bare frame model experiences a maximum displacement of 19.18 mm in the Y-direction, which is 66.56% higher than the displacement in the X-direction. The difference between the highest displacement of the two models in the Y-direction of two models is only 0.31mm which is nearly insignificant.



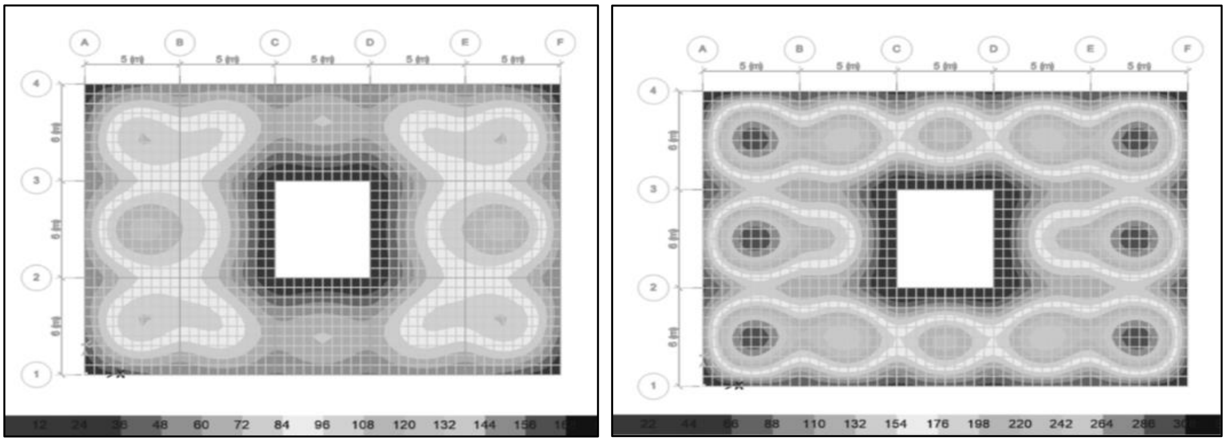
(a) (b)

Figure 4: Story displacement for Bare Frame Model and Rooftop Garden Model along (a) X direction and (b)Y direction.

3.1.2 Roof Slab Deflection

The roof slab deflection is evaluated for live load in both models, and the comparison is illustrated in Figure 5 Slabs without rooftop gardening do not experience much concerning deflection.

However, roof slabs with gardening loads tend to deflect more, and the areas of deflection are indicated clearly in the figure. The rooftop garden load may not be sufficient for a 125mm thick slab which is primarily designed for regular roof slabs.

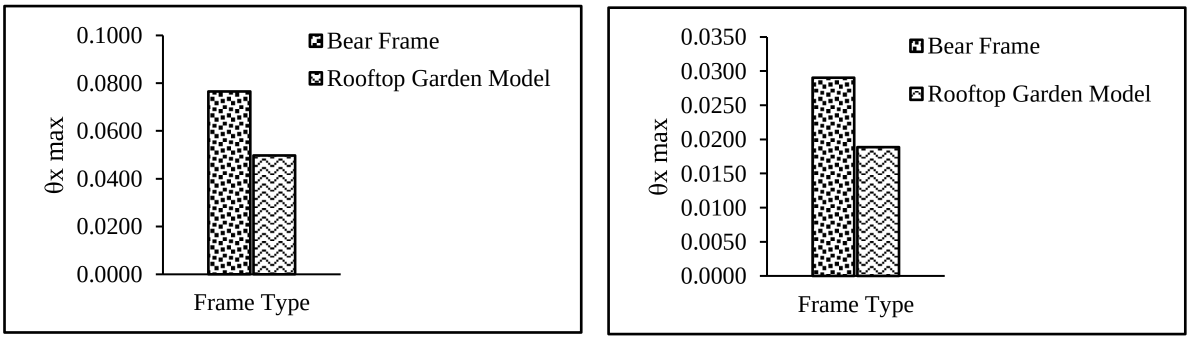


(a) (b)

Figure 5: Roof slab deflection for Bare Frame Model and Rooftop Garden Model along (a) X direction and (b)Y direction.

3.1.3 P-Delta Effect

The largest P-Delta effect occurs at a value of θ_x equal to 0.0765 in the X-direction of the Bare Frame Model, as depicted in Figure 6. The Rooftop Garden Model exhibits a reduction of 34.94% in the P-Delta effect when the value of θ_x is 0.0498. The value of θ_x is relatively less in the X-direction compared to the Y-direction. The Bare Frame model achieves a maximum value of 0.0290, whereas the Rooftop gardening model experiences 34.91% less effect compared to the Bare Frame model.



(a) (b)

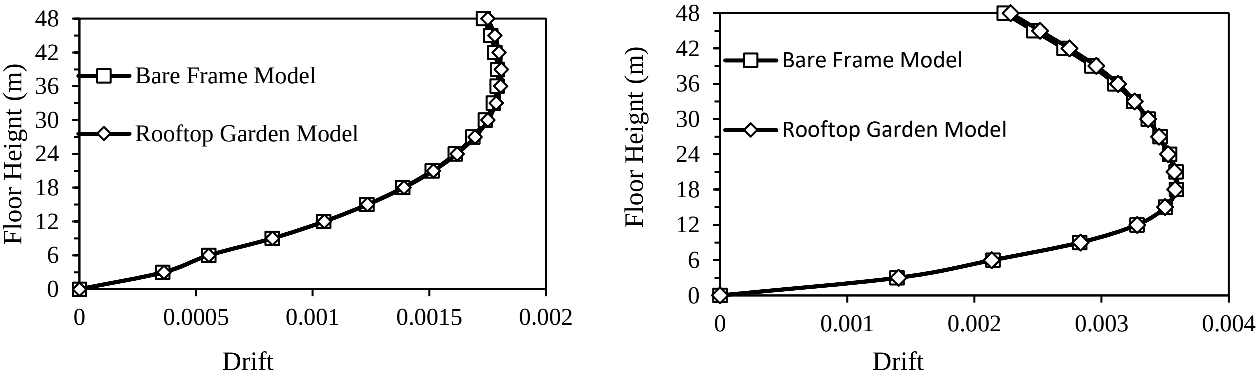
Figure 6: P-Delta effect for Bare Frame Model and Rooftop Garden Model along (a) X direction and (b)Y direction.

3.2 Response Spectrum Analysis

Response Spectrum Analysis is a vital method in structural engineering that is used to assess the dynamic behaviour of structures subjected to seismic or other dynamic loads. It is particularly important for designing structures to withstand earthquakes, where the ground motion is complex and difficult to predict accurately. This dynamic analysis method employs a response spectrum, derived from seismic data, to represent ground motion and considers multiple modes through the mode superposition technique. Accurate modelling of damping is essential to influence the dynamic response. The results guide engineers in designing structures that can withstand seismic forces and comply with safety codes.

3.2.1 Story Drift

The two models display the greatest amount of story drift in the X-direction at a height of 18m (equivalent to the 5th floor) from the ground. The rooftop garden model exhibits the highest story drift, measuring at 0.003579, which is 0.26% greater than that of the bare frame model. Both the bare frame and rooftop garden models experience a reduction of around 49.62% in high-story drift in the Y-direction. However, the maximum drift occurs at a height of 39 meters (12th floor). When comparing the two models, there is no obvious disparity in story drift.

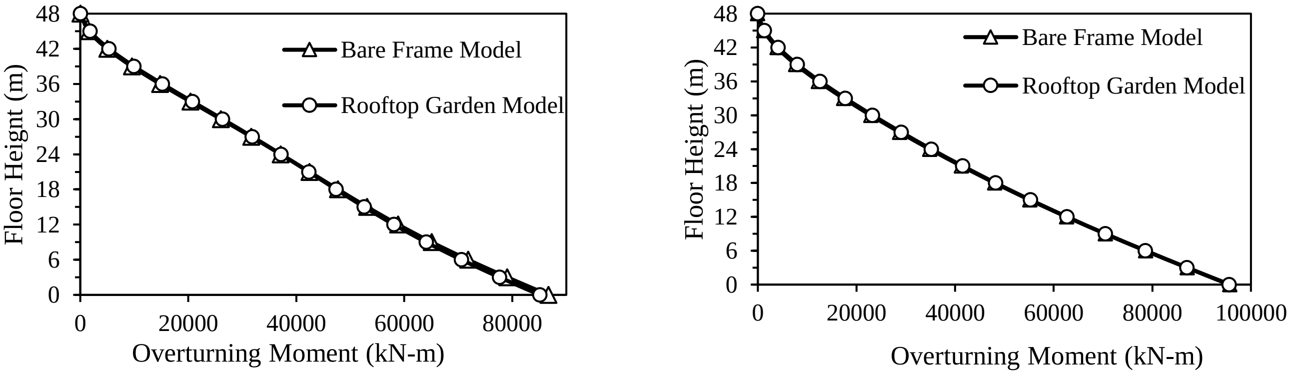


(a) (b)

Figure 8: Story drifts for Bare Frame Model and Rooftop Garden Model along (a) X direction and (b)Y direction.

3.2.2 Overturning Moment

The graph compares the overturning moment of the structure in both the X and Y directions. The rooftop garden model has a 1.85% reduction in moment compared to the bare frame model, which has the maximum recorded overturning moment of 86692.89 KN-m in the X-direction. Both models experience approximately 9.4% less overturning moment in the Y-direction compared to the X-direction. The rooftop garden model experiences a significant load on the rooftop, resulting in the lowest moment of 95622 KN-m.

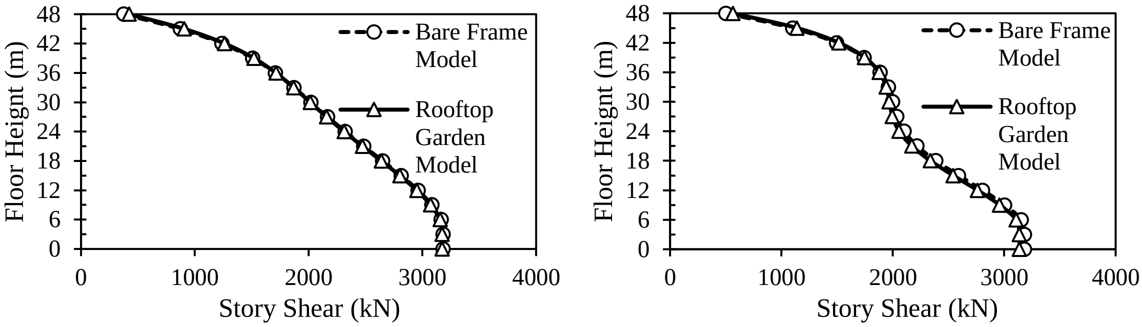


(a) (b)

Figure 9: Overturning moment for Bare Frame Model and Rooftop Garden Model Along (a) X direction and (b)Y direction.

3.2.3 Story Shear

The axial shear is computed for each floor and displayed in Figure 9 for both directions of the structure. In all scenarios, the ground floor experiences the highest magnitude of story shear. The Bare Frame model exhibits the maximum shear value of 3181.31 KN-m, surpassing the model with a rooftop garden by a margin of 1.4%. The shear difference between the two models is determined to be 10.344 KN-m in the Y-direction.



(a) (b)

Figure 10: Story shear for Bare Frame Model and Rooftop Garden Model along (a) X direction and (b)Y direction.

3.2.4 Base Shear

The bare frame Model yields a maximum base shear of 3181 KN. Figure 11 illustrates the comparison of base shear between the two models. The rooftop gardening model exhibits 1.4% less base shear compared to the bare frame model. It is because there is a heavy rooftop due to gardening and it creates a mass irregularity in the structure. Mass irregularity can affect the base shear and the dynamic response of the structure, depending on the frequency and mode shape of the seismic excitation.

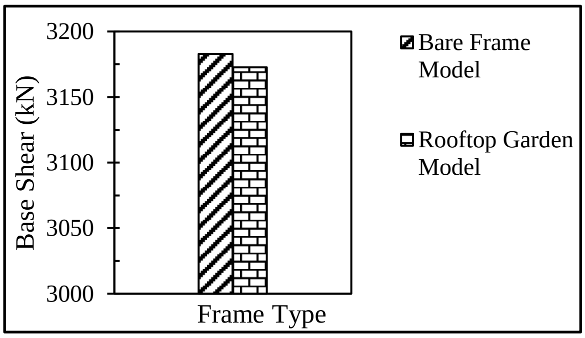


Figure 11: Base shear for Bare Frame Model and Rooftop Garden Model

3.2.5 Torsional Irregularity

The bare frame structure experiences less torsional irregularity, recorded by a Δmax/Δavg ratio of 1.002, owing to the minimal variation in load distribution across the various stories. The garden load causes additional deformation on the structure of the rooftop garden model, resulting in some irregularity. This is evident from the Δmax/Δavg ratio of 1.003, as shown in Figure 12.

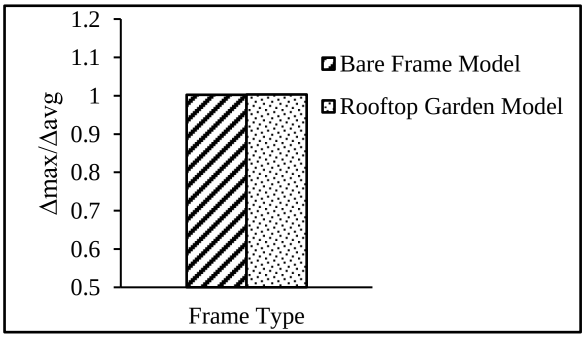


Figure 12: Torsional irregularity for Bare Frame Model and Rooftop Garden Model along X direction

3.3 Pushover Analysis

Pushover analysis, also known as non-linear static analysis, is a structural engineering technique used to evaluate the seismic performance of buildings. Unlike Response Spectrum Analysis, which focuses on dynamic effects, pushover analysis is a static procedure that simulates the progressive collapse of a structure under lateral loads, such as those from an earthquake. The analysis involves applying horizontal forces incrementally to the structure, typically at the top floor, until a predefined performance level or collapse mechanism is reached (Dya & Oretaa, 2015). By capturing the inelastic behavior of materials and structural elements, pushover analysis provides valuable insights into the overall seismic capacity and potential weak points of a structure.

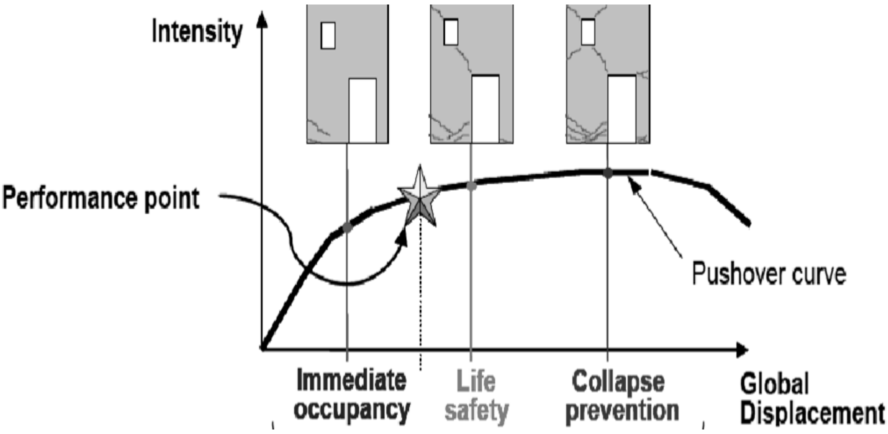


Figure 13: Performance level of structure by pushover analysis

3.3.1 Pushover Curve

A comparison of pushover curves which are obtained from performing nonlinear static pushover analysis is shown in the figure below. The pushover cure displays the relationship between base shear and displacement, which is acquired using pushover analysis. Structures with rooftop gardens have lower base shear values against target displacement. The base shear for the bare frame structure is 27.64% more for the highest displacement compared to the rooftop garden frame.

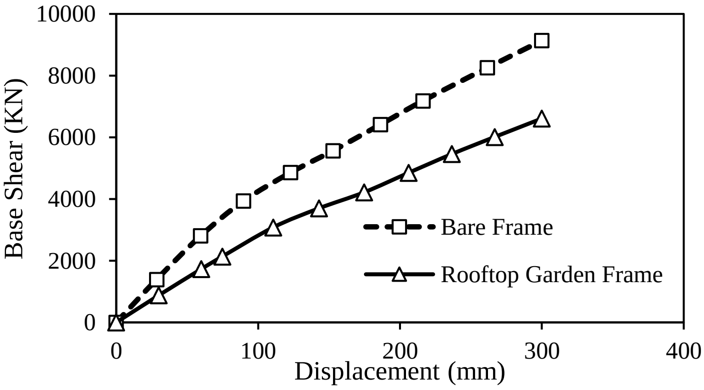
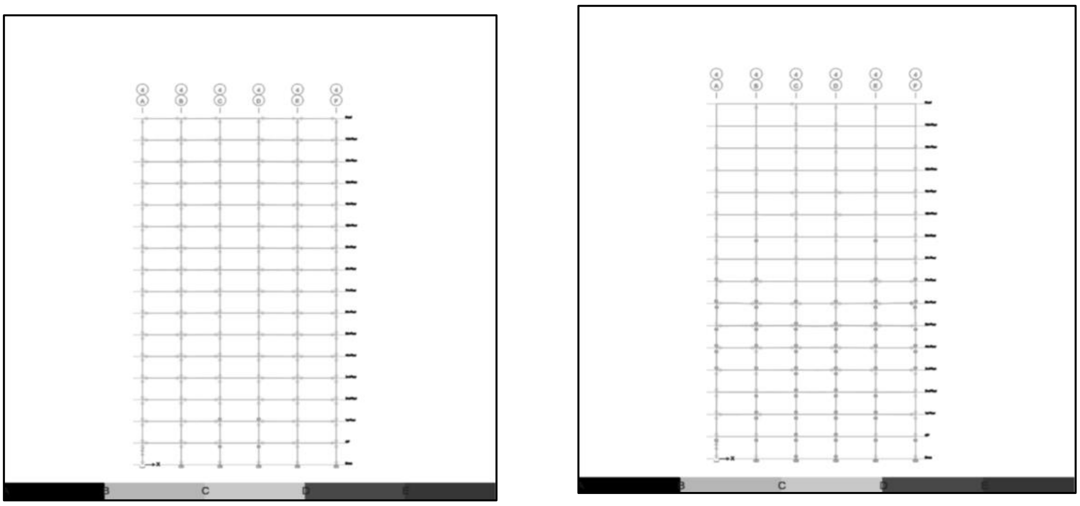


Figure 14: Pushover curve for Bare Frame Model and Rooftop Garden Frame Model

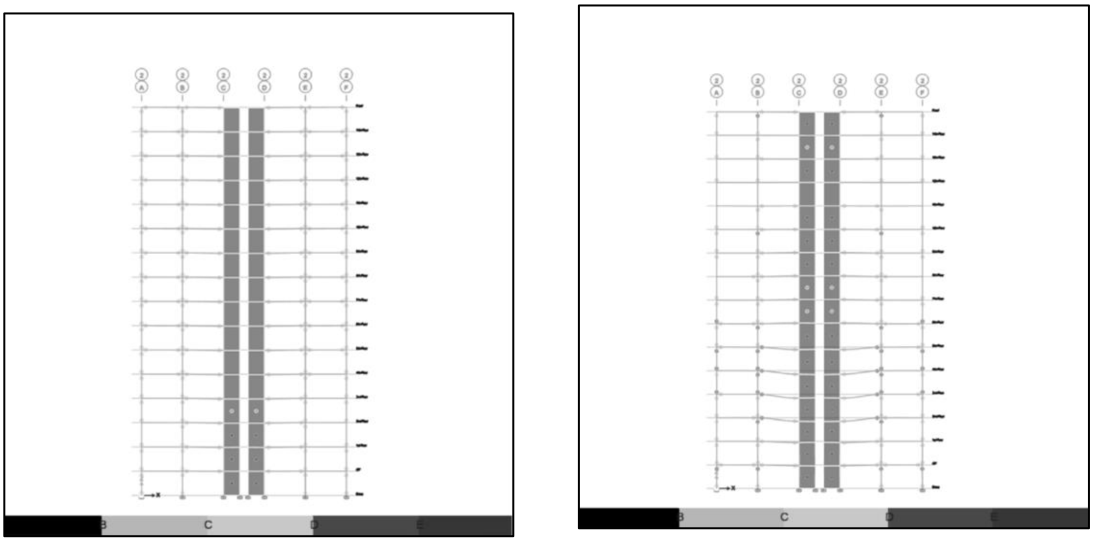
3.3.2 Plastic Hinges Formation

Figures 15 and 16 reflect the plastic hinge patterns of the structure in the X-direction at Grid-4 and Grid-2, respectively. Upon examining the pattern, it is evident that the bare frame model experiences minimal CP (Collapse Prevention) plastic hinge throughout the whole structure. Conversely, in the model with a rooftop garden, several CP (Collapse Prevention) plastic hinges are observed to have formed in the columns of the mid-lower stories. In Grid-4, a nearly identical pattern is found, but there are hinges formed in the flexural members that link to the shear wall. Plastic hinges occur at points where bending moments reach their maximal value. However, there are nearly no changes in the plastic hinge patterns for the Y direction as it is the structural longer side with more stiffness.



(a) (b)

Figure 15: Plastic hinge formation in Grid-4 for (a) Bare Frame Model and (b) Rooftop Garden Model along X direction.



(a) (b)

Figure 16: Plastic hinge formation in Grid-2 for (a) Bare Frame Model and (b) Rooftop Garden Model along X direction.

4. CONCLUSION

This study assessed the structural performance of rooftop gardening for existing residential buildings in Dhaka city, as per BNBC 2020. Two distinct numerical models were created in the finite element software ETABS. The subsequent significant observations were recorded for each model through three analysis methods.

From the static analysis story displacement, slab deflection, and P-Delta effect are compiled. There is no significant difference in story displacement between the Bare Frame Model and the Rooftop Garden Model. The Rooftop Garden Model roof slab having garden load deflects more than the Bare Frame Model. The deflections can be reduced by designing the roof slab with increasing thickness. There is a significant difference in the P-Delta effect. Rooftop Garden Model has less P-Delta effect as the rooftop garden load is a gravity load and it reduces the Diaphragm Center of Mass Displacement, which may be considered as a positive effect from high-rise structure design.

The Dynamic behavior of the structure is analyzed by response spectrum analysis observing five different structural behavior aspects. The story drift, overturning moment, and story shear don't make any significant difference for the rooftop garden load. The difference becomes less considerable while analyzing the models in Y-direction with more structural stiffness. The rooftop garden model exhibits more story drift and story shear than the bare frame model, particularly in the X direction with less structural stiffness. Due to the additional gravity load on the rooftop, the rooftop garden model experiences fewer overturning moments. The base shear is also less due to the same reason for the rooftop garden model. However, there is very little amount of difference recorded for torsional irregularity.

As for pushover analysis, some plastic hinge formation changes for the Rooftop Garden Model were noticed in the X direction, overall analysis exhibits insignificant structural changes. Therefore, it is necessary to consider the effect of rooftop gardening in analyzing a structure as it deflects the roof slab more and creates some weak zones in the mid portion of the large slab. Although it does not make any significant changes in some cases, it should be considered during structure design to avoid seismic risk levels and decrease the probability of collapse of the structure. Overall, the rooftop garden does not pose a significant structural concern in high-rise RC frame structure design.

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