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Research Article

Seismic Performance Comparison of Flat Slab and RC Frame Structures Using Pushover Analysis

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Abstract

This study presents an in-depth investigation of seismic performance between flat slab and reinforced concrete (RC) frame structural systems using nonlinear static pushover analysis. This nonlinear static analysis technique generates capacity curves that identify potential failure modes, assess displacement demands, and determine performance levels for each structural system. The goal is to offer better directional insight into the variations of the structural performance for stability, safety, economic efficiency and to flag the pros and cons of each system. This study is significant for addressing the cases of seismically active regions where structural integrity is a key factor and small perimeter change can create disaster. The investigation employs methodology to evaluate the seismic capacity and performance of both structural systems under earthquake loading conditions. This study also evaluates fixed base conditions and uses material properties based on BNBC and geometrical properties of typical mid-rise buildings as limiting conditions. It develops detailed three-dimensional finite element models to simulate the nonlinear behavior of both structures. Results show that flat slab structures are more flexible and vulnerable to earthquakes, while RC frame buildings offer greater strength and better resistance to seismic forces. These findings highlight the importance of structural system selection in improving earthquake resilience.

Keywords

Conventional RC Frame Building, Flat Slab, Nonlinear Pushover Analysis, Seismic Analysis, Capacity Curve

1. Introduction

The seismic assessment and design of structures is required because of the occurrence of earthquakes. Earthquakes are caused by differential movements of the earth's crust. The result of these movements is the well-known 'ground shaking' that can lead to significant damage and/or collapse of buildings, infrastructure systems (e.g. dams, roads, bridges, viaducts etc.), landslides, when soil slopes lose their cohesion, liquefaction in sand and destructive waves or 'tsunamis' in the maritime environments.

The increasing vulnerability of tall structures of urban commodities to seismic events indicates careful investigation of building performance under earthquake loads. The effects of a seismic event on a structure are determined primarily by the histories of the three ground motion parameters ground acceleration, velocity and displacement with their specific frequency contents.

Historically, seismic design was an empirical approach, relying upon building codes and design guidelines. For decades building codes offered simplified strategies to design earthquake-resistant buildings based on empirical evidence

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from past earthquakes data. As the nature of seismic events continued to evolve, more sophisticated techniques such as, dynamic analysis and nonlinear modeling, are required to build earthquake resistant structures.

Pushover analysis became one of the essential methods to design structure under seismic loads. Push-over analysis is nonlinear and thus accounts for the real ultimate failure of material and their connections rather than the linear factors that traditional methods look to. It involves gradually applying lateral loads to a structure until it reaches a pre-defined target displacement or until it collapses. This analysis enables the engineers to see how the damage evolves and identifies the points of failure are in the structure. The pushover analysis method is especially useful in evaluating the post-elastic performance of a structure and its capacity to dissipate energy during earthquakes. According to Krawinkler et al., this shift in approach allowed for a better understanding of how buildings deform under seismic loads, leading to the development of more resilient structures [1].

1.1. Objective of the Study

The main objective of this research is to conduct a comparative analysis of the seismic performance of flat slab and reinforced concrete (RC) frame structures using pushover analysis. Specifically, the research aims to:

1) Evaluate and compare the seismic performance of flat slab and RC frame structures under earthquake-induced lateral loads.
2) Investigate key performance indicators such as maximum displacement, base shear, and failure modes for both structural systems.
3) Assess the influence of structural configuration and material properties on the seismic behavior of both systems.
4) To generate capacity curves for flat slab and conventional RC framed structures, highlighting differences in their seismic behavior.

1.2. Literature Review

The inadequacy of flat slab systems for seismic loading has been documented in recent research. As noted by De Luca et al, “flat slabs are not capable of resisting horizontal forces without the aid of additional strengthening measures such as shear walls or external bracing systems” [2]. However, RC frame structures have been known for dispersing the lateral forces effectively, which makes them a more resilient choice in the design of earthquake-resistant structures [3]. Further research by Apostolska et al. explored the seismic behavior of flat slab systems under lateral loading and it has been suggested that flat-slab systems tend to have much larger displacements and story drift. As a result, these systems are more flexible and undergo larger lateral deformations during earthquakes [4]. Chopra et al. discussed a detailed analysis of the design problem of flat slab buildings, especially requiring a careful consideration of the design of column-slab joints. They discovered that the flat slab system may experience punching shear failures during seismic events; therefore, they proposed developing connections with increased robustness and additional lateral bracing to improve the seismic performance of such systems [5].

The authors Miranda and Bertero explore the seismic behavior of reinforced concrete (RC) structures, specifically examining the strength reduction factors used in earthquake-resistant design. Their results indicated that RC frames can sustain large lateral displacements without reaching catastrophic failure, if the frame elements are detailed for sufficient ductility [6]. In addition, S. A. Hossain and A. Bagchi have investigated the effect of shear walls on seismic behavior of RC frame structures. They concluded that RC frame with shear walls is capable of withstanding substantial lateral loads, giving them extra stability against the lateral forces of seismic [7]. These studies have shown that RC frame structures perform better in earthquakes because they are stronger, more flexible, and more effective. A paper by Najam also reviews the evolution and challenges of Nonlinear Static Procedures (NSPs) for the seismic performance evaluation of existing buildings [10]. Nonlinear Static Procedures provide a means for estimating seismic demand in buildings without the extensive computational cost of dynamic analysis. Another study conducted by C. L. Nishanth compares the seismic performance of flat slab buildings with conventional RC frame buildings [11]. The Conventional RC Frame Buildings exhibited less story displacement, story drift and base shear, indicating that they have higher resistance to seismic forces. In FEMA, the guidelines for pushover analysis have been developed with emphasis on limitations and assumptions associated with the method [12]. Fajfar also contributed to the understanding of pushover analysis, indicating its applicability to RC frame structures [13]. He showed that pushover analysis could reasonably replicate the order of damage and failure of a building in lateral displacement. The study by Thakkar et al. came out with a conclusion that typical RC frame buildings have relatively better seismic performance than flat slab systems with or without drops. Flat slab buildings, especially those without drops exhibit greater story displacements and drifts making them susceptible to larger seismic forces [14]. The study by Shahrooz and Moehle investigates the seismic performance of reinforced concrete (RC) frames, focusing on the drift capacity, strength, and overstrength of the structures [15]. Further, their test results showed that the overstrength observed in the reinforced concrete moment-resisting frames was significant; overstrength was largely attributed to the contribution of the floor slab to the beam negative moment strength.

However, there has not been a full, side-by-side comparison of how these benefits affect the overall behavior of the system when compared to other types of structures, like flat slabs, in real-world earthquake situations. Even though there is abundant research on these systems there are few direct comparative studies performed with modern analysis techniques like pushover analysis. This study aims to bridge that gap by providing a systematic comparison of flat slab to RC frame performance in the context of seismic response, that will provide guidance to engineers in the design of earthquake resilient structures.

2. Materials and Methods

For the performance evaluation purposes Rajshahi is selected as the site and seismic demand for Rajshahi has been estimated as per guideline of BNBC-2020. Structural performances of a 10 (TEN) story building of height around 100 feet have been investigated. This height range has been selected because of the fact that buildings with this height range are very common in Rajshahi city now a days. The performances of the buildings as evaluated through pushover analysis that have been presented through capacity curves and capacity spectrums.

It has been proposed to follow the following methodology in Figure 1:

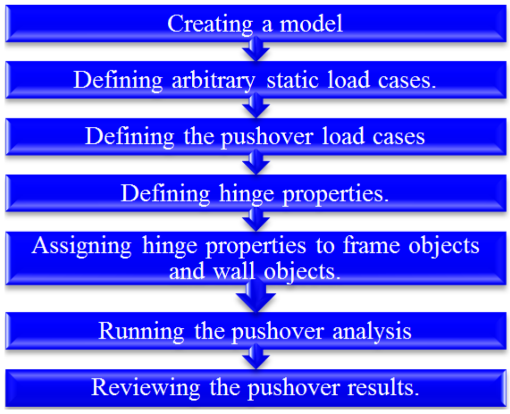

Figure 1. *Chart of Methodology.*

2.1. Creating a Model

Both flat slab and conventional RC framed structures are designed by using AutoCAD 2022 and ETABS 19 software for analysis. The plan of building for both buildings are same. The plan is shown in Figure 2:

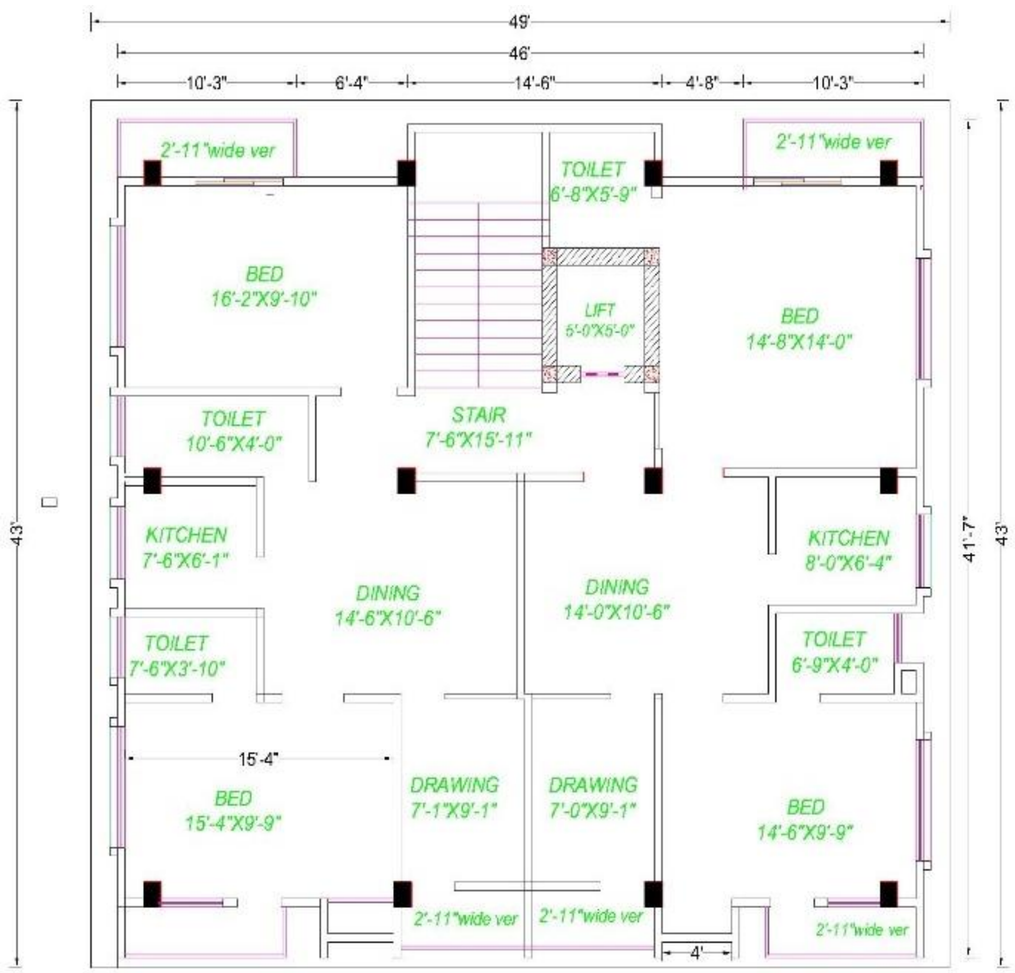

Figure 2. *Layout of plan of Flat slab and conventional RC framed structures.*

2.2. Materials

The materials used in the study would likely focus on various structural elements, analysis tools, and testing methodologies relevant to seismic performance. Here's an outline of materials and resources that may be relevant:

Structural Materials

Concrete: Concrete is the primary material for both flat slab and reinforced concrete (RC) frame structures. Concrete properties, such as, compressive strength of 3000 psi modulus of elasticity 57000×√ (3000) = 3122019, and shear modulus of 1300841, will be fundamental in evaluating seismic performance.

Steel Reinforcement:

The reinforcing steel used in both flat slabs and RC frames are used as main rebar and stirrup bar.

For main Rebar:

Minimum yield strength, f_y= 60000 psi

Minimum tensile strength, f_u= 90000 psi

Modulus of elasticity =29000000 psi

For stirrup bar:

Minimum yield strength, f_y= 40000 psi

Minimum tensile strength, f_u= 60000 psi

Modulus of elasticity = 29000000 psi

The sample size that is used in this research are flat slab structure and a RC framed structure. The specifications of these models are,

i. Flat slab structure

Slab thickness is 8 in

Column size is 24 in × 24 in

Drop panel size is 48 in (square)

Dead load (additional) is given as 0.139 psi.

Live Load is applied as 0.694 psi.

ii. RC framed structure

Slab thickness is 5 in

Column sizes are 15 in × 18 in, 20 in × 15 in, 25 in × 20 in

Beam size: Grade Beam Size is 12 in × 15 in

Floor Beam Size is 12 in × 15 in

Dead load (additional) is applied according to BNBC 2020.

Live Load is applied according to BNBC 2020.

2.3. Defining Arbitrary Static Load Cases

During this step, the pushover load cases are created to represent the increasing structural response subjected to lateral loads that simulates the effect of seismic loading. Nonlinear pushover analysis is the way to investigate how the structure will respond under gradually increasing lateral forces imposed on the structure until the building reaches a defined limit state or until a predetermined target displacement is reached. This is necessary for evaluating the structures seismic response and enables the application of the structural characteristics, quantifying how much the structure can withstand the forces and energy associated with earthquakes. The pushover analysis uses a series of pushover load cases; those load cases are used to incrementally apply lateral forces (or displacements) on the structure to see how it behaves progressing from elastic to plastic behavior. For pushover analysis, pushover load cases are defined in both direction for e.g. X direction and Y direction, such as PA_X and PA_Y.

1. Pushover Load Case in the X Direction

The pushover load case in the X direction is applied to assess the seismic performance of the structure due to lateral forces applied horizontally along the X-axis. Realistic seismic behavior can be simulated by distributing the load in the form of uniform, triangular, or modal shapes. The X direction pushover curve will give a good indication of the structure's lateral loading response in the X direction. Key results include:

Base Shear vs. Displacement graph

Plastic hinge formation at various levels.

Lateral loading displacement profile of the structure identifying the displacement at different points.

2. Pushover Load Case in the Y Direction

The pushover load case in the Y direction is applied to assess the seismic performance of the structure due to lateral forces applied horizontally along the Y-axis. Realistic seismic behavior can be simulated by distributing the load in the form of uniform, triangular, or modal shapes. The Y direction pushover curve will give a good indication of the structure's lateral loading response in the Y direction. Key results include:

Base Shear vs. Displacement graph

Plastic hinge formation at various levels.

Lateral loading displacement profile of the structure identifying the displacement at different points in Y axis.

2.4. Defining Hinge Properties

Hinge properties are assigned in columns and beams of the structural systems. In flat slab system, hinges are assigned only in columns following relative distance from the end about 0.1 and 0.9 of their length. P-M2-M3 property is used for defining the degree of freedom of the hinges. Shear Reinforcement ratio is taken from the current design.

In RC slab system, Hinges are assigned in both columns and beams following the relative distance from the ends about 0.1 and 0.9 of their length. Other properties are same as flat slab hinges.

The P-M2-M3 hinge represents an advanced nonlinear hinge model which includes axial force (P) and bending moments along two orthogonal axes (M2 and M3). The P-M2-M3 hinge proves especially beneficial for precisely simulating structural elements such as columns during seismic loading which facilitates enhanced pushover analysis by better representing their inelastic behavior.

2.5. Assigning Hinge Properties to Frame Objects and Wall Objects

Accurate modeling of structural responses under lateral loads during Non-Linear Pushover Analysis in ETABS requires proper assignment of hinge properties to frame elements like beams and columns as well as wall objects to account for inelastic deformations and failure modes. Hinge properties are designated at the ends of the frame elements. The yielding and ultimate capacity of materials serve as critical parameters to characterize hinge properties like yield moment, ultimate moment, and ductility. Defining structural elements' inelastic behavior through plastic hinges allows engineers to simulate accurate building reactions to lateral forces which helps them evaluate seismic performance and confirm design compliance with safety and performance standards. The prediction of damage and failure modes through this technique proves essential for structural design and evaluation processes.

2.6. Running the Pushover Analysis by Selecting a Static Nonlinear Load Case on the Set Load Cases to Run Form

Before starting the pushover analysis, the nonlinear static load cases must be defined. The load case represents the structure's seismic loading by modeling the progressive buildup of lateral forces. The Set Load Cases to Run from ETABS permits the definition of nonlinear load cases through the specification of load type, application direction, and load magnitude parameters.

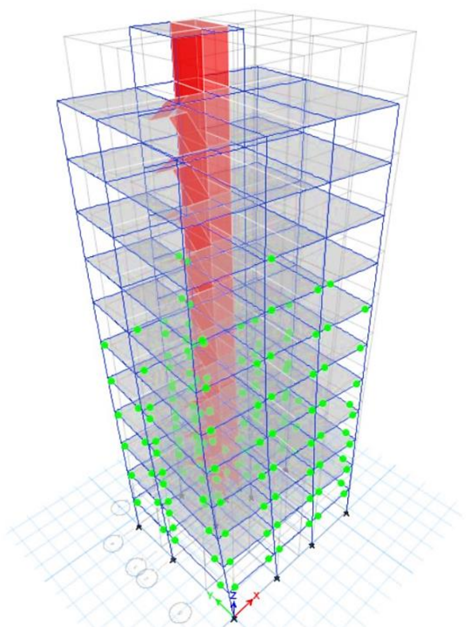

Figure 3. *Displacement and development of plastic hinge in X direction of structures.*

After defining the nonlinear static load case, the pushover analysis can be proceeded to start through the Set Load Cases to Run form. The form provides selection of appropriate load cases to run which guarantees the pushover load case runs correctly.

The nonlinear load cases that are used in this experiment is:

1. Nonlinear dead load
2. Pushover at X direction (PA_X)
3. Pushover at Y direction (PA_Y)

ETABS monitors the accumulation of nonlinearity in the structure during the analysis phase. Plastic hinge develops on the critical location of the structure like beam-column occupied for beam-column joints or base-column. The software detects the hinges to evaluate the energy dissipation capacity and the overall structural behavior for escalating lateral loads.

The simulations are portraited as Figure 3 and Figure 4.

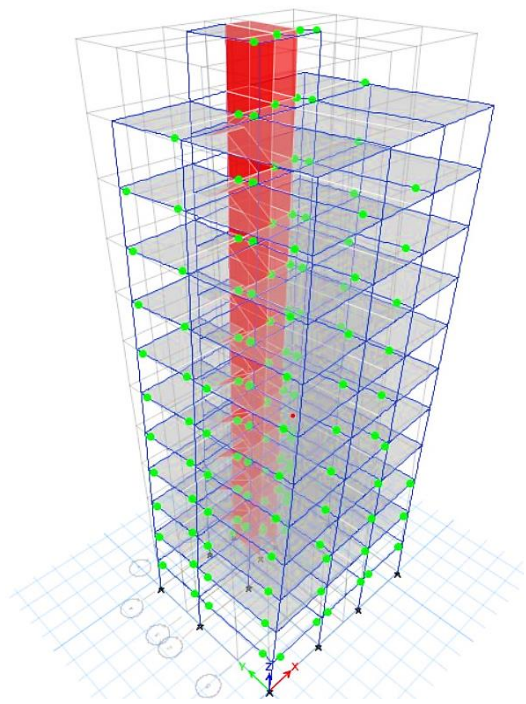

Figure 4. *Displacement and development of plastic hinge in Y direction of structures.*

2.7. Reviewing the Pushover Results

The pushover analysis works in three phases.

Phase 1: Linear Elastic Behavior

During this phase, the structure remains elastic and undergoes deformations without permanent damage. The responses to the applied lateral loads are proportional in the case of flat slab and RC frame structures.

Phase 2: Yielding and Formation of Plastic Hinges

As the lateral load increases, some materials in some sections yield and plastic hinges are formed. This phase is the beginning of the non-linear behavior, and some parts of the structure start undergoing plastic deformation, which signifies that they have reached their limit state.

Phase 3: Nonlinear Behavior and Failure

The final phase occurs as the applied load is increased further, additional plastic hinges form, thus redistributing internal forces. When the strength of the structure is surpassed, failure mechanisms will develop in the structure that typically leads to the collapse or large deformations of the structure.

Phase Diagrams of Pushover Analysis are shown in Figure 5:

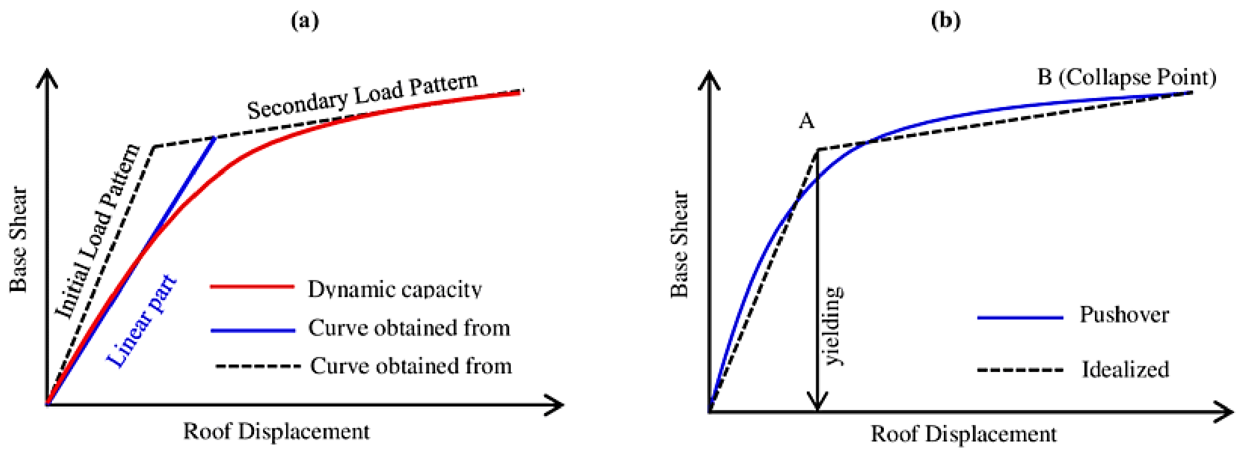

Figure 5. Typical diagram of Pushover Analysis [8].

The diagrams in Figure 5 can be explained as,

Part (a) - Dynamic Capacity and Load Patterns

Initial Load Pattern (Dashed Line): The structure shows its initial elastic behavior in this stage by demonstrating a linear relationship between base shear and roof displacement. This section demonstrates Hooke's Law by showing that structural deformation remains proportional to the applied load.

Linear Part (Red Line): The linear curve section shows the structure's dynamic capacity which deforms without exhibiting substantial non-linear behavior. The structure demonstrates elastic behavior until this threshold so that it returns to its initial shape once the load is removed.

Secondary Load Pattern (Blue Line): The structure displays this curve once it goes beyond its elastic limit. Permanent deformation in the structure causes non-linear behavior to become more visible. The diagram reveals that structural stiffness diminishes in response to growing damage or displacement.

Part (b) - Pushover and Collapse

Pushover Curve (Blue Line): The curve demonstrates how the structure continues to deform under rising lateral loads until reaching its ultimate load capacity followed by structural collapse. The "yielding" point is defined as the location where the curve first shows substantial deviation from its expected straight-line shape.

Idealized Curve (Dashed Line): The dashed line illustrates an idealized representation of the pushover curve. The response is represented as a smooth continuous trajectory. Point A indicates yielding because it marks the beginning of permanent deformation in the structure while point B shows the ultimate failure as the structure collapses under load.

Figure 6 illustrates how SF moment (shear force moment in kN-M) interacts with tension force while displaying lateral deformation (θ or Δ) on the X-axis and SF moment on the Y-axis. Here's a breakdown of the key components:

Point A represents the unloaded state.

AB (Linear range from unloaded state to effective yield): This area represents where the structure maintains elastic behavior while showing a linear response when loads are applied.

B to C (Inelastic range with linear response of reduced stiffness): The structure enters a phase of plastic deformation where yielding occurs while maintaining partial stiffness.

Immediate Occupancy (I.O.): The structure maintains usability without substantial safety issues.

Life Safety (L.S.): The structure remains able to bear loads without collapsing.

Collapse Prevention (C.P.): Although the structure faces risk it retains enough strength to avoid complete collapse.

Residual Strength (C): The structure has experienced major deformation and yet maintains some degree of strength.

D to E (Ultimate Deformation): The structure has reached its ultimate load limit which results in failure when further load is applied. Residual deformation (DE) describes the long-lasting shape changes that exist after the load gets removed.

CD and DE: Demonstrate how the load resistance decreases alongside the permanent deformation that occurs after failure.

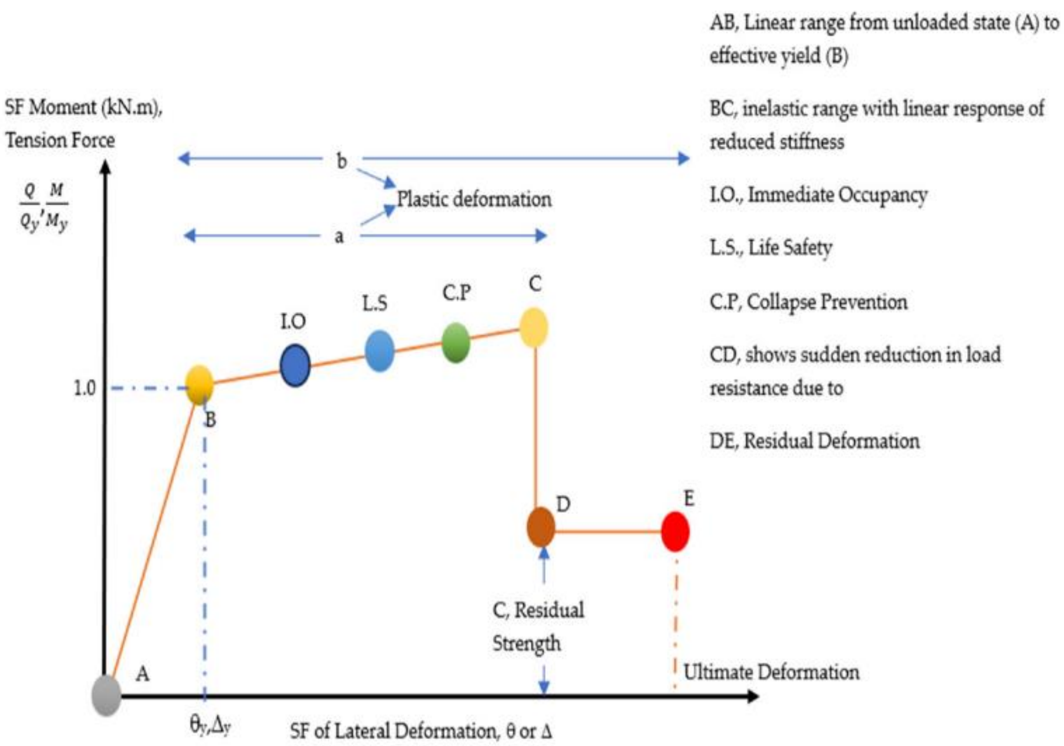

Figure 6. Different phases of Pushover curve the diagram [9].

3. Results & Discussion

3.1. Maximum Story Displacement Due to Pushover Loads

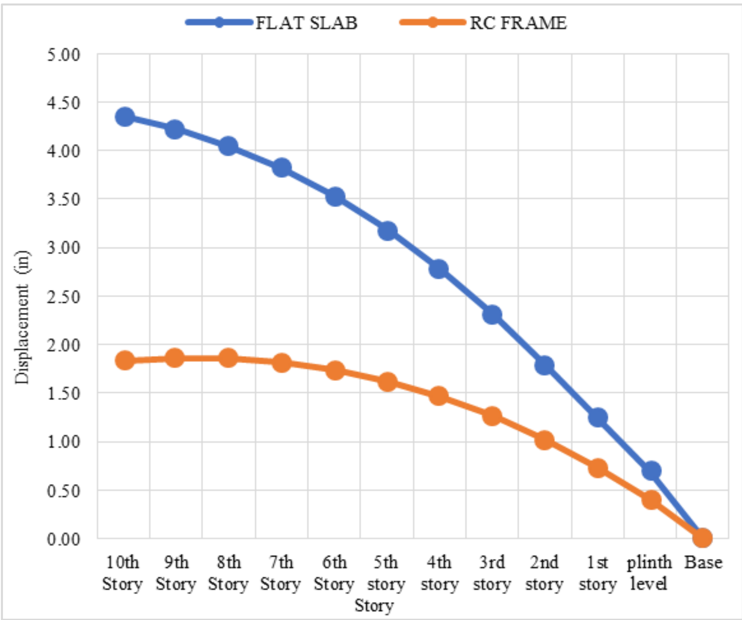

Figure 7. Comparison of maximum displacement: Flat Slab and RC Frame Structure in X direction.

Maximum story displacement is a fundamental parameter in evaluating the overall lateral response of a building during seismic events. It is known as the maximum horizontal displacement recorded at a particular story of the building during a lateral load, and it is a vital measure of the deformation behavior of the building. Maximum story displacements for both flat slab and RC frame structures from the pushover analysis are shown and discussed in this section.

From Figures 7 and 8, the Flat Slab shows more displacement than the RC Slab at the higher floors, then it is said to be more flexible or more prone to displacement in both directions. If minimizing displacement in the both direction is a priority for stability or structural integrity, then the RC Slab would be the best option at higher elevations.

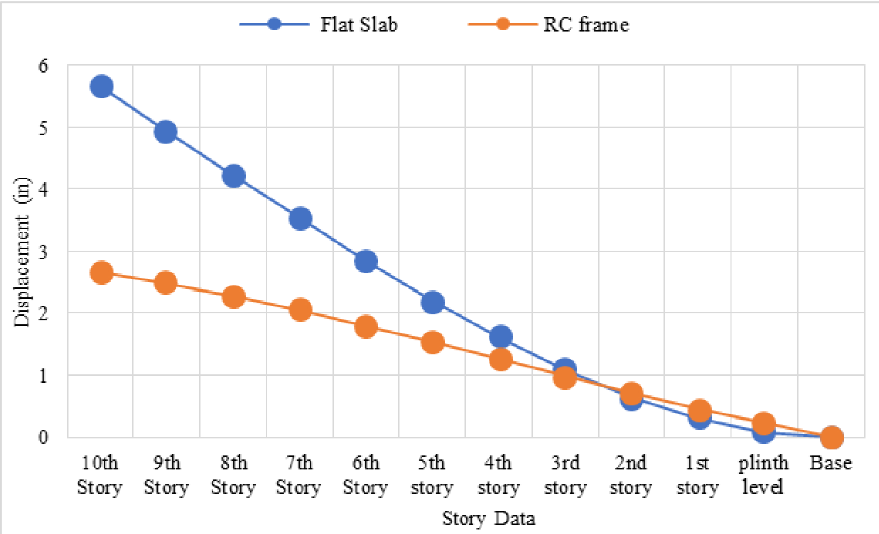

Figure 8. Comparison of maximum displacement: Flat Slab and RC Frame Structure in Y direction.

3.2. Maximum Story Drift Due to Pushover Load

The maximum story drift refers to the largest relative displacement between two consecutive floors within the building under pushover loads. This displacement is important since the drift in building element shows the indication for possible damage of structural elements, non-structural element failure and ultimately collapse of the structure.

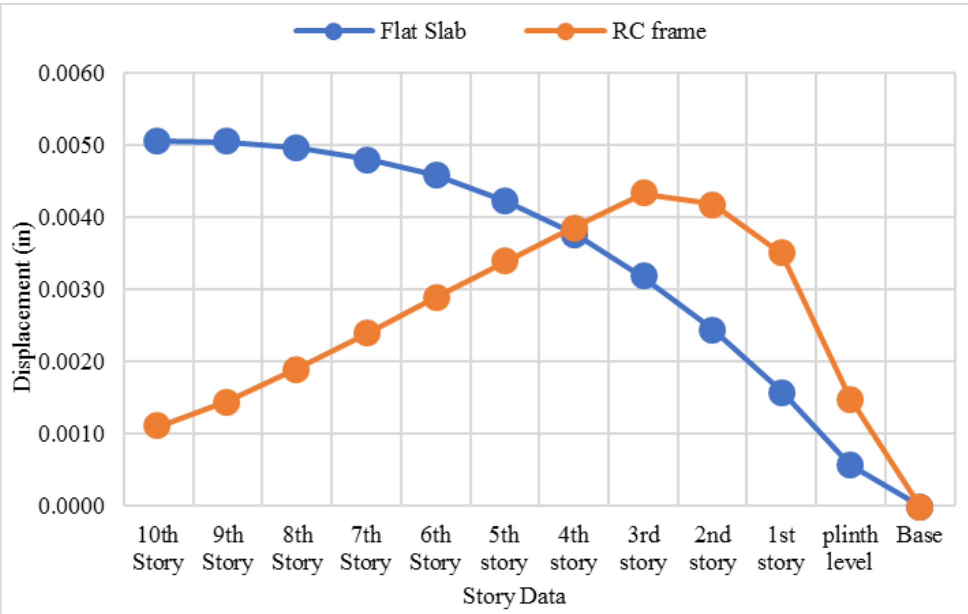

Figure 9. Comparison of maximum story drift: RC Frame Structure and Flat Slab in X direction.

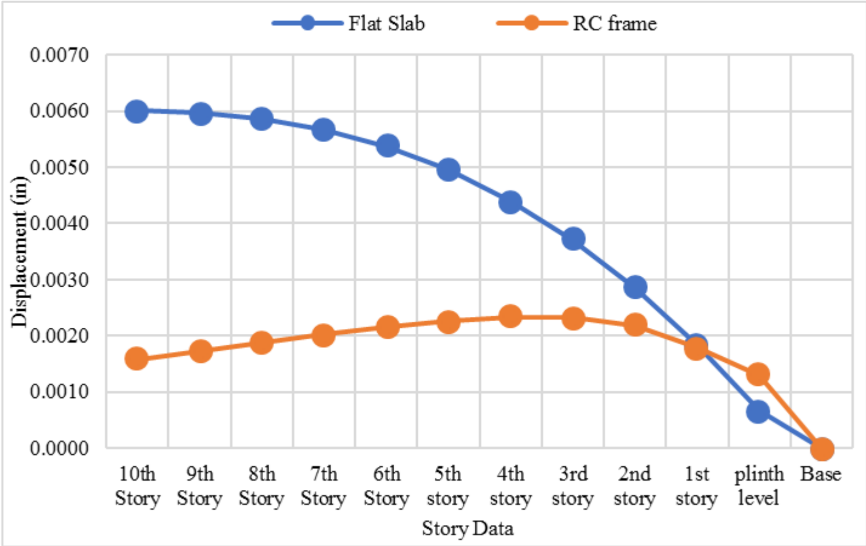

Figure 10. Comparison of maximum story drift: RC Frame Structure and Flat Slab in Y direction.

The variation of story drift with respect to story height is presented in this Figures 9 and 10. The increase in story drift for flat slab is gradual with respect to the elevation. It begins from zero and grows linearly with height of the building The drift remains minimal but consistently increasing until about 100 feet of height in the structure. The RC Frame story drift shows little change at the lower levels but then it rises rapidly after a certain point. The drift starts to take on a more substantial form around 30-40 feet and only continues this exponential growth as the elevation gains.

The studies consistently shows that flat slab structures are 25-50% more flexible than conventional RC frame buildings leading to increased susceptibility to seismic loading. In flat slab building, the value of displacement can be up to 44% higher compared to conventional RC frame buildings.

3.3. Pushover Analysis

Pushover analysis is an effective way to evaluate the behavior of a structure subjected to an earthquake by simulating their response to progressively increasing lateral loads. With this, it can evaluate the lateral force resisting capacity of the structure and give an idea about possible weak points and predict the modes of failure well in advance of any major damage. Pushover results are evaluated based on critical parameters such as, base shear and displacement, plastic hinge formation and the overall ductility of the structure.

3.3.1. Pushover Analysis in X Direction

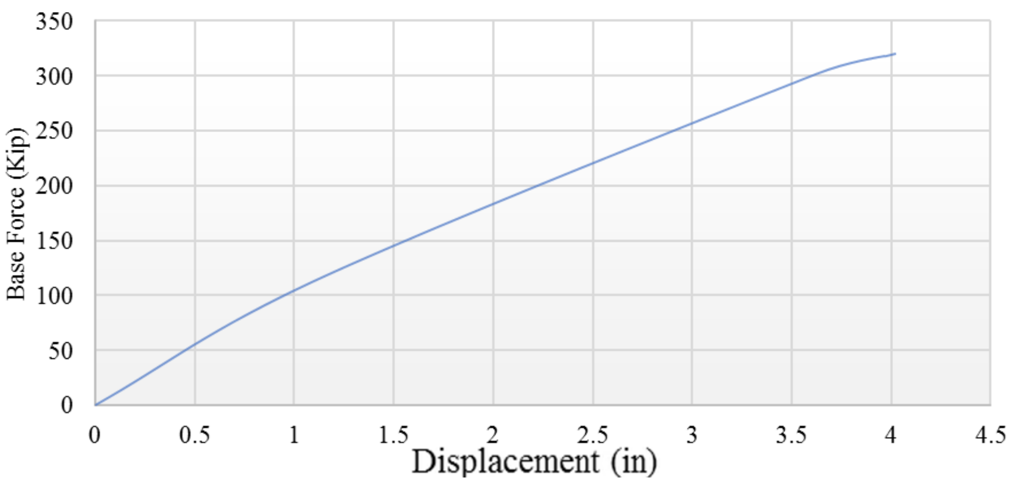

Figure 11. Base Shear with respect to displacement of RC framed Structure in X direction.

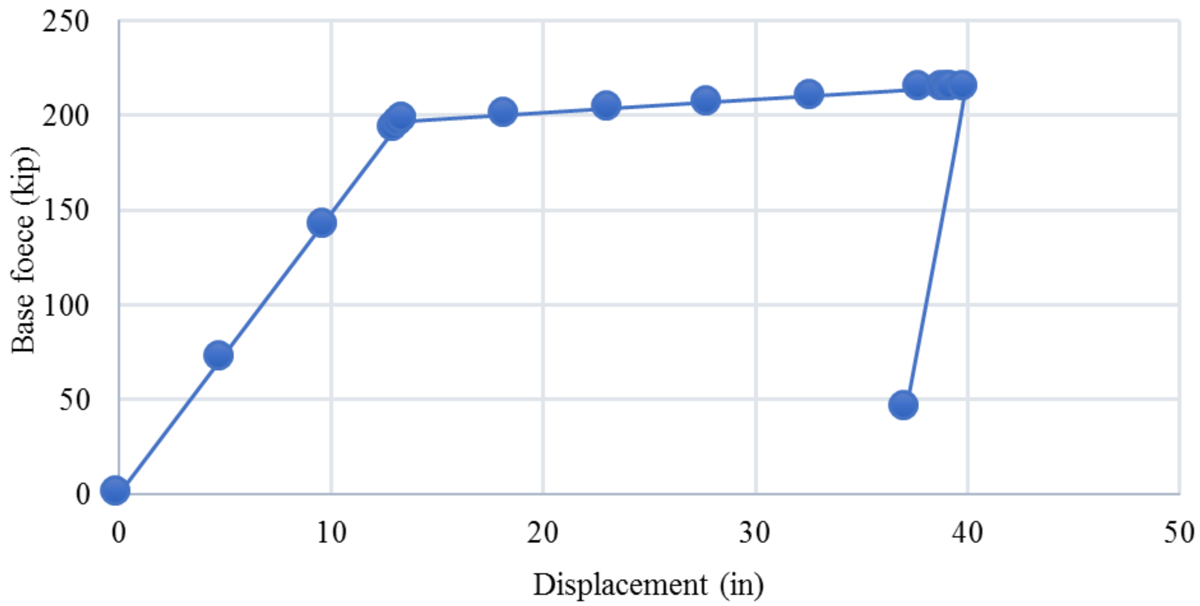

Figure 12. *Base Shear with respect to displacement of Flat Slab Structure in X direction.*

From the Figure 13, the graph of RC frame structure is showing base shear against displacement indicates a very high initial slope of base shear against very low displacement. it achieves around 320 KIP of base shear at almost 13 inches of displacement. it exhibits higher initial stiffness and lower ultimate displacement capacity.

Flat slab structure shows a gradual linear increasing base shear with displacement. It arrives at around 210 KIP of base shear at 40+ inches of displacement. It provides much lower stiffness but considerably larger displacement.

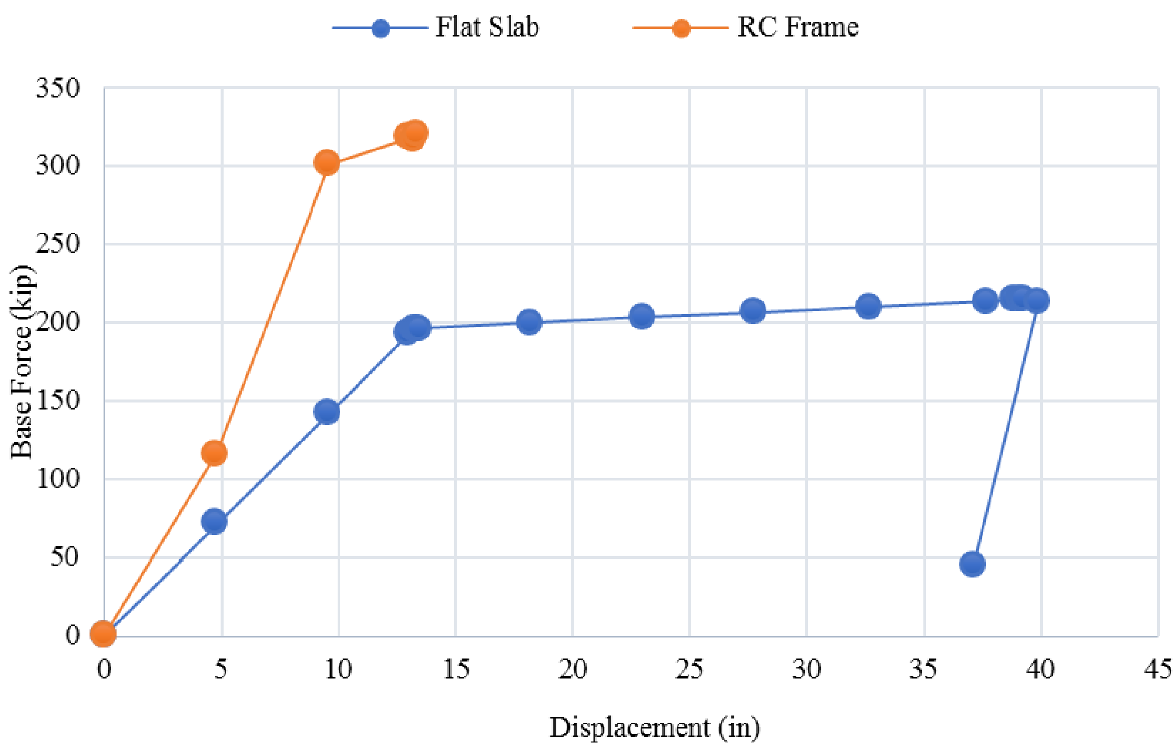

Figure 13. *Comparison of base Shear with respect to displacement of Flat slab structure and RC Framed Structure in X direction.*

3.3.2. Pushover Analysis in Y Direction

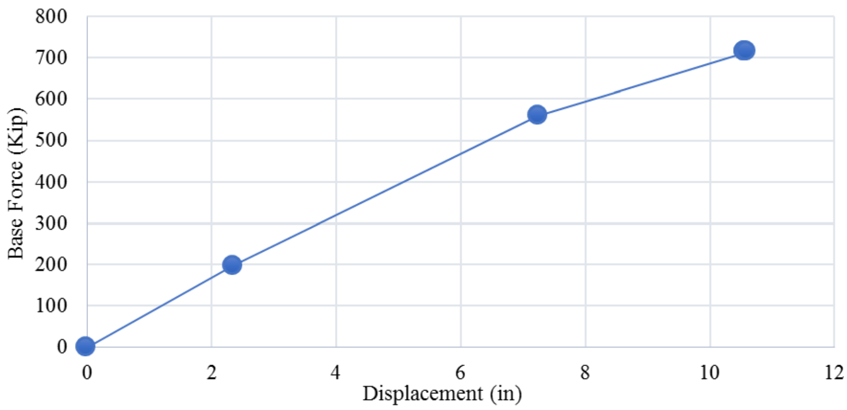

Figure 14. Base Shear with respect to displacement of RC Frame structure in Y Direction.

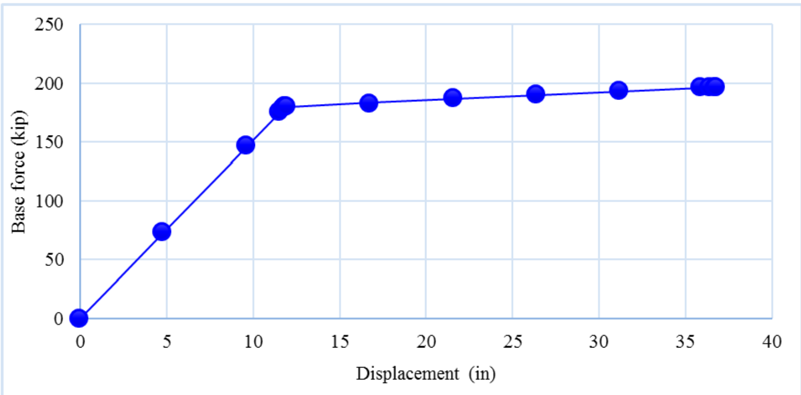

Figure 15. Base Shear with respect to Displacement of Flat Slab Structure in Y Direction.

From Figure 16, in RC frame structure, the base shear increases steeply with minimum displacement. At around 11 inches of displacement, it attains a base shear of about 720 KIP. it suggests both the greater initial stiffness and the lower ultimate displacement capacity.

The flat slab structure shows a gradual linear increase in base shear with displacement. it shows a base shear of around 200 KIP at 37 inches of displacement. it shows less stiffness but much larger amount of the deformation capacity.

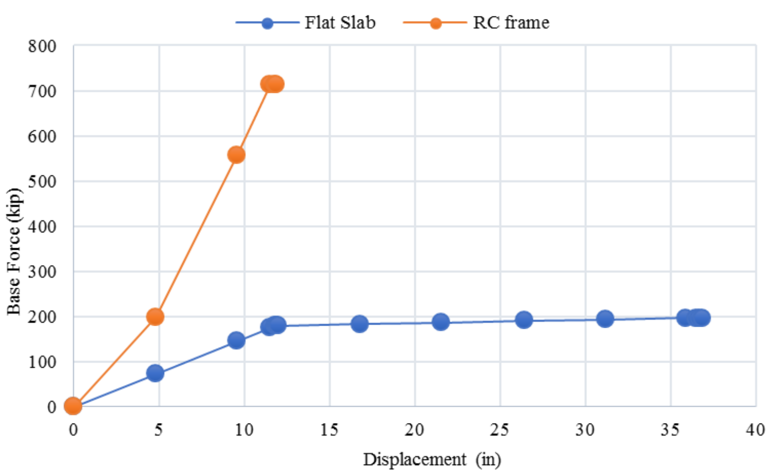

Figure 16. Comparison of Base Shear with respect to displacement of Flat slab structure and RC Framed Structure in Y direction.

This comparison shows that flat slab structures have benefits for construction and architecture, but their poor lateral performance than conventional slab-based RC framed structure in the Y direction means that careful design is needed and often requires extra structural elements.

3.4. Comparison of Performance Point at X Direction

A performance point is a cornerstone of ASCE 41-13's nonlinear static procedure (NSP). The performance point in the context of Pushover analysis, as defined in the ASCE 41-13 (American Society of Civil Engineers 41-13) code, represents the point where the structure's seismic demand (usually represented by the applied lateral force) intersects the structure's capacity (represented by the pushover curve). In other words, it is the location on the performance level of a structure during an earthquake at a given level of seismic hazard.

From Figures 17 and 18, the pushover curve of the RC moment-resisting frame structure has a sharp initial slope, resulting in a short effective period. It meets demand curves at a low drift of ≈5.4 in, demonstrating significant initial stiffness and rapid strength mobilization.

The flat slat slab structure without deep beams and rigid links presents a slight incline. Roof drift demands do not cross capacity until ≈24 inches of displacement, indicating very low lateral stiffness and a much greater period.

The RC framed structure supports ≈300 kip at the performance point, ≈1.7× that of the flat slab, ≈180 kip. Thus, for the same hazard level, the frame offers materially higher lateral strength.

For flat slab, meeting demand at much larger the displacement means the flat slab must undergo large inelastic deformations. Component ductility and punching-shear checks will be critical.

Determining performance point in ASCE 41-13 CODE Procedure in X direction:

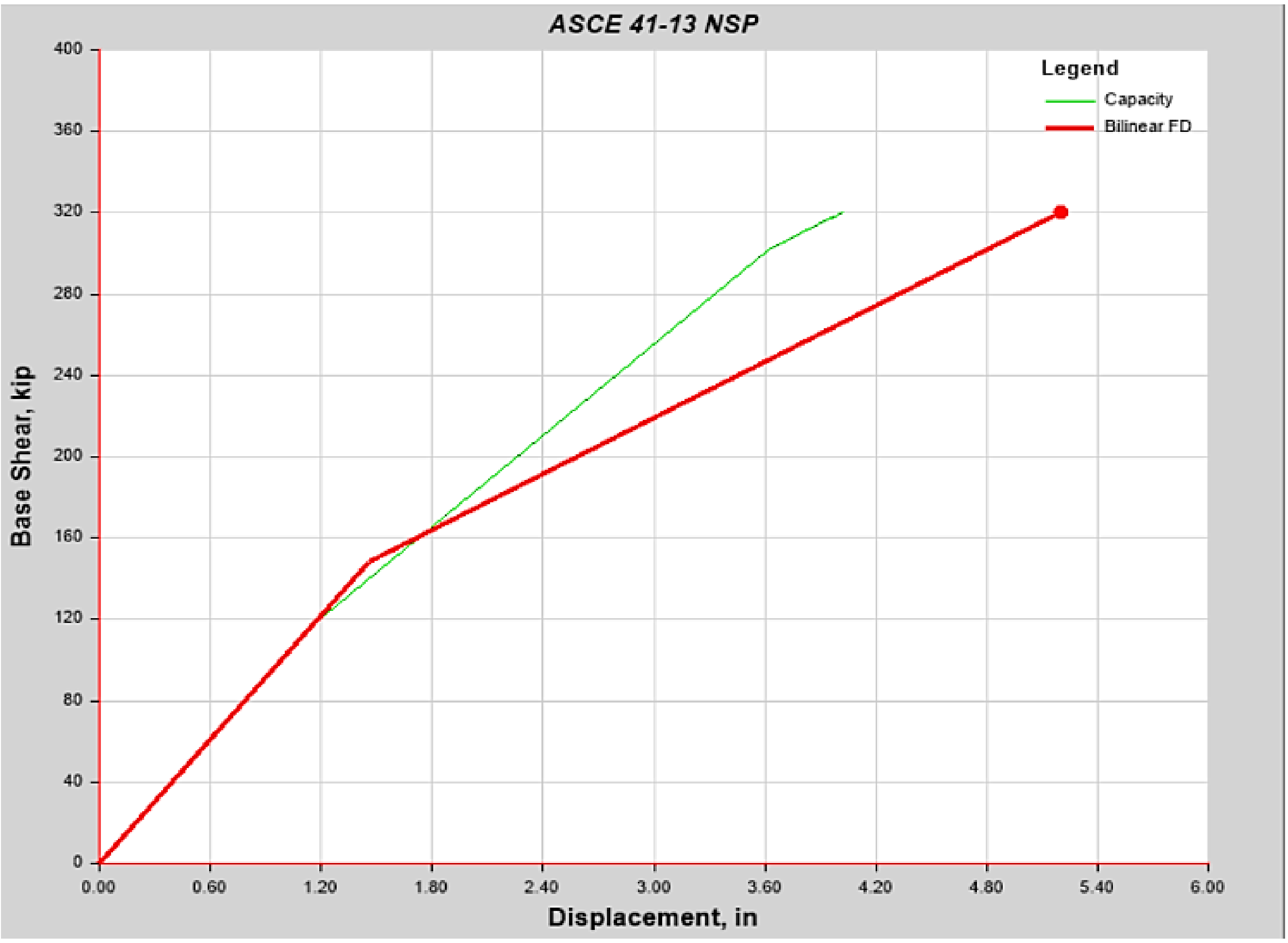

Figure 17. *Nonlinear static pushover curve (by ASCE 41-13) for RC frame structure at X direction.*

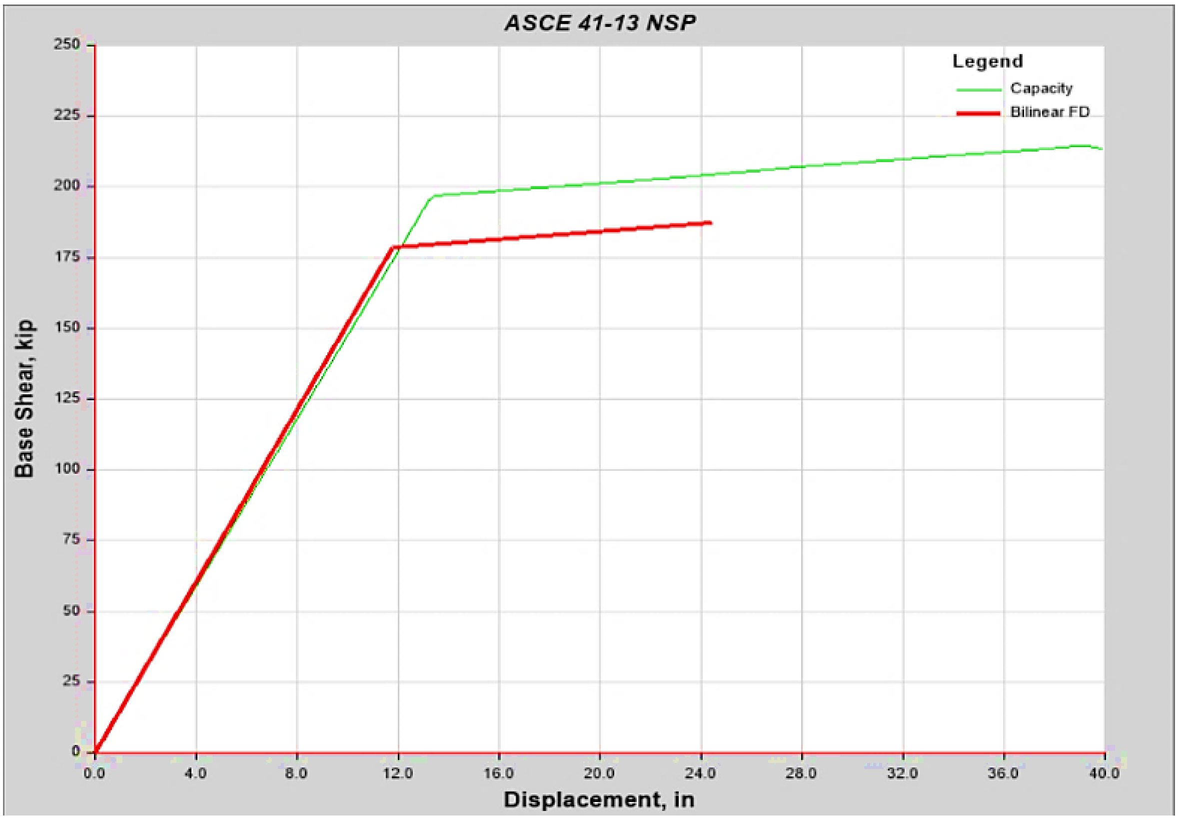

Figure 18. Nonlinear static pushover curve (by ASCE 41-13) for Flat Slab structure at X direction.

3.5. Comparison of Performance Point at Y Direction

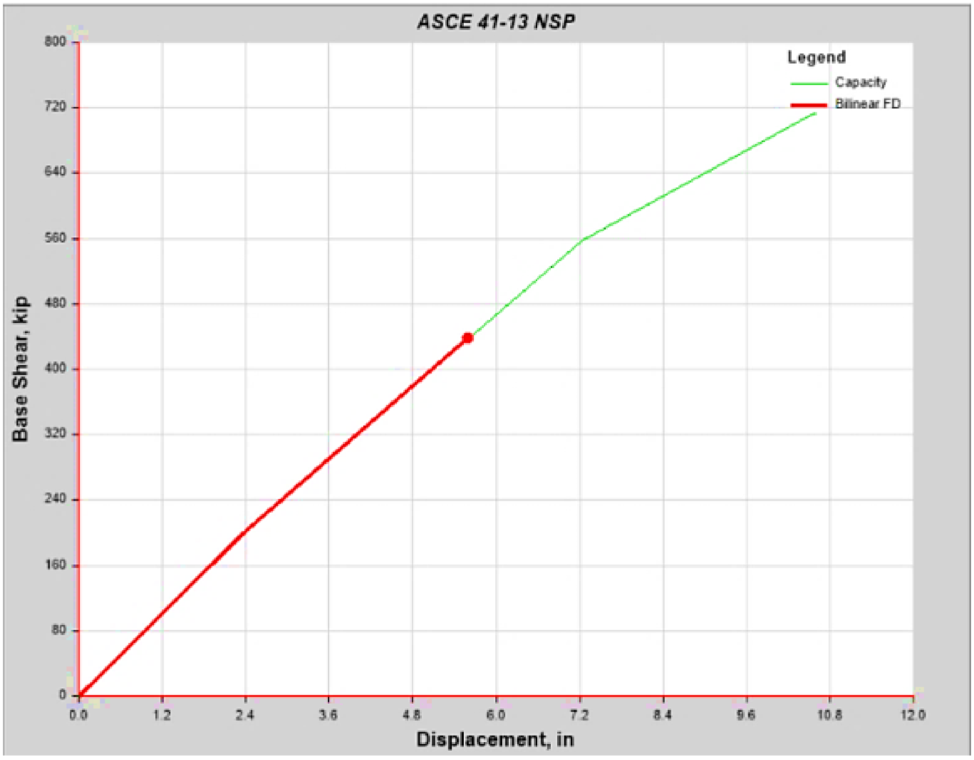

Figure 19. Nonlinear static pushover curve (by ASCE 41-13) for RC frame structure at Y direction.

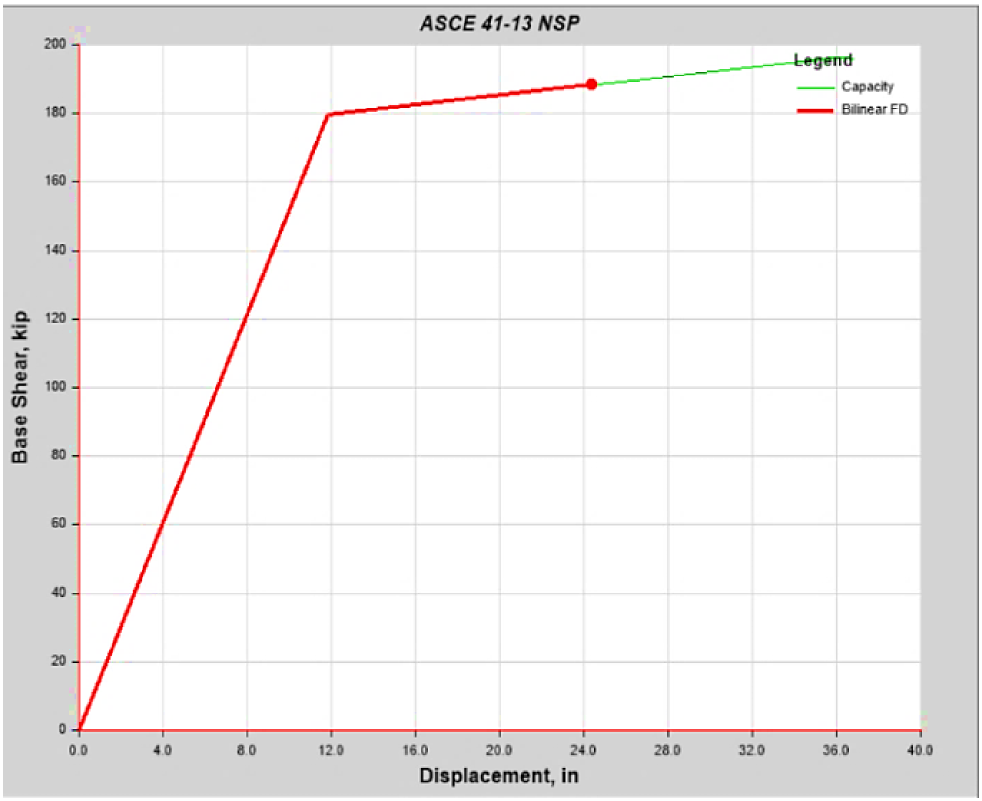

Figure 20. *Nonlinear static pushover curve (by ASCE 41-13) for Flat Slab structure at Y direction.*

From Figures 19 and 20, The performance point for the RC framed structure is located at approximately 4.5 inches of displacement with a base shear of about 400 kip. This means that the RC frame system can carry up to 480 kips of seismic force at 6 inches of displacement. It, however, hits the performance point at 4.5 inches of displacement. This indicates that this structure will be moderately deformed (displaced) in an earthquake but will remain well within safe limits as it does not exceed its capacity at this displacement.

The flat slab structure performance point occurs at a displacement of about 5.5 inch and base shear of about 100 kip. This implies that the flat slab structure is less seismically resistant than the RC frame one and reaches its performance point at a significantly lower base shear.

Compared with the one of RC frame, its total capacity of flat slab system is lower, and the performance point appears earlier on the curve (in terms of displacement and base shear). This may suggest that flat slab system is more susceptible to failure under seismic load, or less capable to provide large displacement capacity in comparison to equivalent RC frame system.

4. Conclusions

4.1. Research Summary

The main outcome of this study is a considerable variation in lateral displacement response between the two structural systems. When the same loads were applied, RC frame constructions always showed 30–50% less lateral movement than flat slab systems.

1) The study found that flat slab buildings are 25% to 50% more flexible than regular RC frame buildings, directly contributing to increased seismic vulnerability. The lack of deep beams in flat slab structures, which drastically lowers lateral stiffness, is the cause of this greater flexibility.
2) The comparative analysis revealed marked differences in base shear capacity results demonstrate that RC frames exhibit higher initial stiffness and superior load-carrying capacity with lower ultimate displacement demands than flat slab structures.
3) The ASCE 41-13 performance point analysis indicated that reinforced concrete frame structures have roughly 1.7 times greater lateral strength than flat slab systems, indicating superior seismic behavior.
4) Due to the increased flexibility and lower lateral stiffness of flat slab system as compared to similar RC frame systems, flat slab systems require additional lateral force-resisting elements (such as shear walls or bracing systems) in order to meet the necessary seismic performance criteria.
5) For the RC frame structure, the performance point occurs at a high base shear and relatively low displacement, which indicates that the structure is more rigid and has higher margins of safety against ground shaking. Flat slab performance point location indicates

larger displacements and smaller base shear, which means those slabs could provide a structural failure for larger earthquake without an enhancement due to additional lateral force-resisting elements.

4.2. Limitations

While this research provides valuable insights into the comparative seismic performance of flat slab and RC frame structures, certain limitations must be acknowledged:

1) The study has mostly focused on pushover analysis, which sometimes simplifies the true nature of a building's seismic response. Dynamic time-history analysis might provide us a better picture of how the real earthquake reaction works.
2) Standard material models were used in the investigation, which might not adequately represent the complicated behavior of reinforced concrete under extreme loading condition.
3) The study fails to account for the actual interaction behaviour between the soils and foundation, which could potentially impact the overall seismic response of the structures.
4) The study is predicated on standard building configurations; it might not accurately represent the performance of complex or irregular structural systems.

4.3. Future Scope of the Work

Based on the findings and limitations of this study, several areas for future research are recommended:

1) Dynamic time-history analysis should be used in the future which captures the seismic response more accurately.
2) Large or small fatigue test specimens could be valuable for verifying analytical results and could provide information on real failure modes and dynamic response details.
3) Hybrid structural systems, which can merge flat slab advantages with RC frame benefits should be investigated to provide new design solutions.
4) The impact of soil-structure interaction on the relative seismic performance of flat slab and RC frame structures in various soil conditions should be studied in future works.

Abbreviations

BNBC	Bangladesh National Building Code
ETABS	Extended Three-Dimensional Analysis of Building System
PA	Pushover Analysis
RC	Reinforced Concrete
psi	Pound per Square inch
ksi	Kilo-pound per Square Inch
ATC	Applied Technology Council
ASCE	American Society of Civil Engineers
in	inch

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Author Contributions

Md. Atiqur Rahman: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Md. Sohel Rana: Supervision, Validation

Nafisa Anjum: Resources

Fahmida Islam: Resources

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Data Availability Statement

The data available from the corresponding author can be provided for verification purposes. This publication has also included references to the data that support the findings of this investigation.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

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