Performance Evaluation of the High-Rise steel building with Outrigger and Belt systems

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Abstract.

Pushover static analysis is a crucial technique in structural engineering used to analysis of structure under earthquake loads. Pushover analysis provides essential inputs into the behavior of structures beyond their elastic limits, offering engineers a thorough understanding of how structures respond to worst conditions. This research will explore the details of pushover static analysis, its importance, and the process involved in performing this analysis. In seismic analysis, assessing how buildings and compositions behave under different forces is of paramount importance. Conventional analysis methods are limited in their ability to capture complex interactions beyond the elastic limit, as they typically focus on linear behavior. As a result, these methods may not accurately predict the response of a structure when it exceeds its elastic limit. Pushover static analysis, also referred as nonlinear static analysis, addresses this limitation by accurately modeling the inelastic performance of structures. The process entails monitoring the progression of yielding, the formation of plastic hinges, and the eventual failure of different structural elements. This data is then utilized to plot a capacity curve, depicting the total force in relation to the displacements. During this analysis, displacement is progressively increasing from zero to a defined ultimate displacement or until the building can no longer sustain additional loads. This method is extensively used to estimate the axial and flexural capacity of existing structures and to determine the seismic requirement of modelled building during selected earthquake scenarios. It is also useful for evaluating the sustainability of new structural designs during linear behavior. The practicality and computational simplicity of pushover analysis have proven to its applications in several earthquake design guidelines (such as FEMA 356 and ATC 40) and design codes (including PCM 3274 & Eurocode 8) over the past few years. The research involved a comprehensive comparison of two pushover methods, namely displacement control and full load method, for steel frame structures with identical G+17 configuration. The study focused on analyzing the maximum story drifts, story displacements, and hinge responses to seismic loads. Steel frameworks have been found to exhibit better seismic performance than Reinforced Cement Concrete (RCC) structures, especially in areas prone to earthquakes. This makes them a more favorable choice for construction in such regions. The analysis also reveals that, although DCM provides detailed insights, it requires a lot of resources, which makes FLM a more practical choice for routine market applications.

Keywords: Nonlinear static analysis (NLSA), Pushover analysis, Steel structures, Full load method, Displacement method

1 INTRODUCTION

A significant portion of India is highly vulnerable to seismic hazards, making it crucial to account for seismic loads in structural design. In buildings, lateral loads resulting from earthquakes are a primary concern. Besides horizontal forces, structural design must also address vertical loads due to the building's weight and its contents. Ensuring the structural integrity and stability of buildings in seismic zones is paramount for occupant safety. Lateral forces can induce critical stress within a structure, causing unwanted vibrations or excessive lateral sway. Lateral sway, or drift, measures how much the top of a building moves sideways relative to its base. In seismic design, structures are typically required to withstand minor and frequent shaking without sustaining significant damage, ensuring they remain functional post-event. A structure must be capable of enduring moderate earthquake ground motions without incurring structural deformations, but some non-structural deformations may be permissible. This limit state often corresponds to the most severe earthquake intensity either experienced or anticipated at the site. The analysis of seismic performance involves monitoring a range of performance parameters to accurately assess the structure's behavior. Key variable includes inter-story drifts, base shear forces, and plastic hinge rotations. By evaluating these factors, researchers can access the building stability, identify possible failure modes, and summarize safety parameters.

1.1 Force-Based Pushover Static Analysis:

Force-based pushover analysis involves gradually increasing provided loads on a structure until a specific displacement or force limit is achieved. This analysis prioritizes on analyzing the allotment of forces within a building, providing valuable inputs into the specific force requirements of specific sections and composition of building. By examining how forces are distributed, engineers can identify critical areas that may need reinforcement to improve overall structural performance.

1.2 Displacement-Based Pushover Analysis:

Displacement-based pushover analysis applies incremental displacements to the structure to study its response to large deformations and nonlinear behavior. Unlike force-based analysis, this approach captures the structural behavior under realistic loading conditions more accurately. Incremental displacements help trace the structural response to gradually applied loads, assessing the performance and deformation capacity at various displacement levels. The aforementioned technique facilitates the calibration of loads in order to sustain designated displacements, thereby providing a more accurate assessment of the structure's behavior when subjected to varied loading conditions.

1.3 Overview of Pushover Analysis:

Pushover analysis is a powerful method used to assess the response of a structure when facing a constant vertical load and a progressively larger lateral load, effectively simulating the formidable forces generated by an earthquake. The performance of the structure is determined by the roof drift or deflection caused by lateral forces. The performance levels of structural elements are depicted in the load versus deformation curve. The main objective of pushover analysis is to estimate the anticipated performance of a structural system during seismic events.

Organizations such as FEMA (Federal Emergency Management Agency) and ATC (Applied Technology Council) have been pivotal in developing and promoting nonlinear static performance (pushover analysis) for seismic rehabilitation. Their guidelines and documents, including FEMA 356, FEMA 273, and ATC 40, provide comprehensive procedures and acceptance criteria for conducting pushover analysis. These documents are instrumental in developing capacity curves and interpreting analysis results, enhancing the safety and resilience of structures in seismic-prone areas by implementing performance-based seismic design principles.

IO-Immediate Occupancy Level

LS-Life Safety Level

CP-Collapse Prevention Level,

An outrigger system consists of horizontal structures, usually in the case of trusses or deep beams, that interlink the building's center (or spine) to the outer columns. The core, usually housing elevators and stairwells, acts as the primary vertical load-bearing element. The outrigger trusses extend from this core and engage the perimeter columns, effectively transforming the entire building into a unified structural entity. This integration significantly enhances the building's stiffness, thus reducing the sway induced by lateral forces. Outrigger and belt systems play a vital role in the analysis and construction of high-rise buildings. By effectively managing lateral forces and enhancing structural stability, these systems enable the construction of taller and more resilient skyscrapers.

N. Herath, N. Haritos, T. Ngo, P. Mendis (2009): The study emphasized the importance of outrigger beam locations on lateral behavior under seismic loads, suggesting optimal locations between 0.44-0.48 times the building height from the base, consistent with wind load optimization.

N. Herath, N. Haritos, T. Ngo, P. Mendis (2009): The location of outrigger beams critically influences a structure's lateral behavior under earthquake loads. The optimal location for outriggers is on average 0.5 times the structures height from the bottom, aligning with optimal positions for wind loading

R. Nanduri, B. Suresh, MD. Hussain (2013): Outrigger and belt truss systems significantly enhances the rigidity of high-rise buildings under specified loads. The maximum displacements at the top of a building were reduced from 50.63 mm to 48.20 mm with an outrigger as a cap truss and further to 47.63 mm with an additional belt truss.

S. Fawzia, T. Fatima (2015): The research focused on composite buildings under cyclonic wind loads, finding that a single outrigger at mid-height is effective. In taller buildings, double outriggers at 2/3 height provide maximum deflection reduction.

S. Fawzia, T. Fatima (2015): The research highlighted the effectiveness of different outrigger configurations in multi-story composite buildings under cyclonic wind loads. The optimal configuration for a single outrigger is at mid-height, while double outriggers at 2/3 height and mid-height are most effective in taller buildings.

A. Karnewar, A. Kurzekar (2017): This research identified the optimal location for outriggers to counteract story displacement, story drift, and time period, enhancing structural stiffness. Model 4, with the outrigger at this optimal location, demonstrated minimal top story displacement and limited story drift across all models.

I. Bano, A. Khan, N. G. Gore (2018): The study concluded that outrigger systems significantly enhance structural stiffness, making them highly effective against seismic and wind forces. The best performance was noted with a virtual outrigger system, offering better ventilation and minimal disturbance to floor plans.

I. Bano, A. Khan, N. G. Gore (2018): Their findings showed that outrigger systems enhance stiffness and are effective against seismic and wind forces, with the best results from virtual outriggers that do not disrupt building plans.

F. Afsari (2019): The study concluded that outrigger systems effectively reduce lateral displacements in both 2D directions. The maximum decline in deflection was 66.02% in the x-direction and 48.01% in the y-direction when outriggers were positioned at 2/5 (12th story) of the building height.

W. Alhaddad, Y. Halabi, Hu Xu, H. Lei (2020): This study reviewed various methods and theories for optimizing outrigger and belt-truss systems in high-rise buildings, emphasizing the impact of different parameters on the optimal design of these systems.

K. Patel, V. Patel, S. Mevada (2020): Adopting a core and outrigger structure attracts more forces toward the building's center, reducing peripheral forces and improving seismic resistance. This system shows lower base moments and better seismic response compared to RCC structures.

K. Patel, V. Patel, S. Mevada (2020): This study concluded that core and outrigger structures attract more forces to the center, improving seismic resistance and reducing base moments compared to RCC buildings. These structures also satisfy architectural requirements with only a 5% cost increase.

I. Jain, R. Londhe (2021): The findings suggested minimal differences in lateral displacement reduction between single and double outrigger systems, recommending the use of a outrigger system. The optimal locations were identified as 2H/3 from the top for single outriggers and H/3 for double outriggers.

P. Vellaichamy, V. Chakkaravarthi (2022): The study found significant reductions in displacement and drift for high-rise buildings with outrigger systems. For a G+26 story RC building, the maximum displacement change in the X-direction was 13.53% with outriggers at the bottom floor. For a G+30 story RC building, the Y-direction displacement change was 29.87%. Maximum drift changes were 47.89% in the X-direction for the G+30 building and 36.69% in the Y-direction for the G+26 building with outriggers at the bottom.

Atul B. Pujari and Keshav K. Sangle (2023): The research on progressive collapse in seismically designed braced and unbraced steel frames has demonstrated that nonlinear dynamic analysis (NLDA) effectively captures the structural behavior when columns are removed. Observations revealed a decrease in joint displacement and a decline in Damage Control Ratios (DCR).

Atul B. Pujari, Keshav K. Sangle, Vinod M. Mohitkar (2023): The research assessed progressive collapse in special moment-resisting frames with both unbraced and braced systems, finding reduced joint displacement and lower Damage Control Ratios (DCR) with NLDA.

Extensive studies on various structural systems for highrise buildings indicate that outrigger systems are highly effective in controlling excessive drift caused by lateral loads, making them one of the most effective structural systems available for seismic resistance.

2 Numerical modelling:

CSI ETABS 2020 (Extended Three-Dimensional Analysis of Building Systems) software has been used for the analysis of structures. For the current work, the construction of a building with 17 stories on which work is to be done. Each floor taken having a height of 3mtr.The plan area of a tower structure taken is 25m x 25m. The structure will be analyzed by nonlinear static analysis that is pushover analysis. We have developed two models for this comparative analysis: one with full load displacement and another with a displacement control method. The dead load on floors is taken by guidelines given in IS 875(Part-1): 1987 and live loads on floors is also taken from IS 875(Part-2): 1987. All the structures are check for lateral load by wind according to Indian standard (IS 875-Part III:2015. Seismic lateral loads calculated for all seismic zones as per IS 1893:2016. The members have been designed in accordance with the steel design code (IS 800:2007). The all-steel sections designed considering elasticity E = 205 GPa, density ρ=7833.41 kg/m3 and Poisson ratio ν = 0.3.

Table 1. Design Data Consideration

Number of stories	17 Floors
Horizontal member (Beam) dimensions	ISLB200(AUTO BEAM)5m length
Vertical member (Column) dimensions	ISWB500(AUTO COLUMN)3m length
Slab Thickness	150mm
Typical floor height	3m
Response reduction factor (R)	5
Zone factor (Z)	4
Damping ratio	0.05
Importance factor	1.15
Soil type	Type-2
Shear wall dimension	500mm
Typical floor live load	3kn/m^2
Wind speed	39m/s
Terrain Category	4
Structure Class	Class-1
Risk Coefficient factor (K1)	1
Topography factor (K3)	1

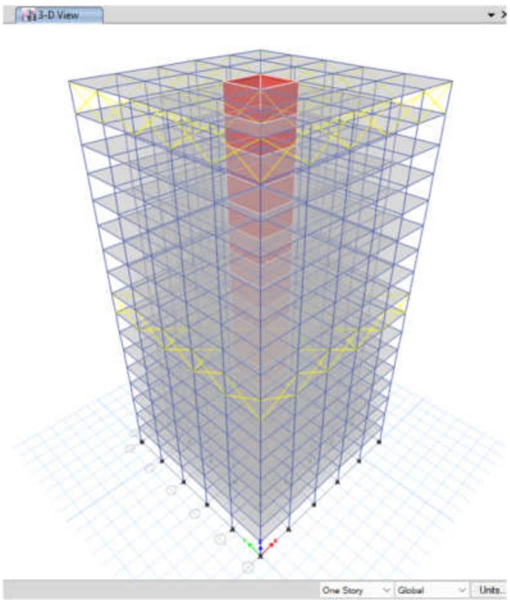

Fig. 1. Model 3D view

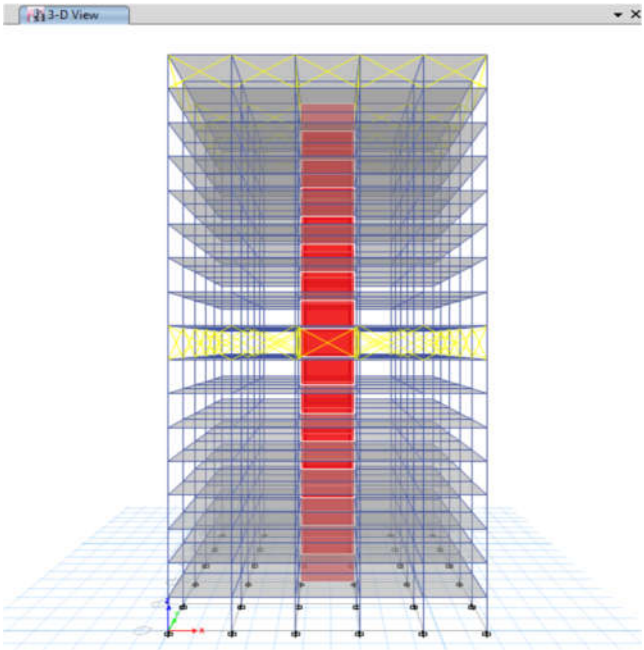

Fig. 2. Model Elevation 3D view

3 Methodology

For a 17-floor building, the described methodologies can be applied using specific design data such as a response reduction factor (R) of 5, a zone factor (Z) of 4, and a damping ratio of 0.05. Tools like ETABS or SAP2000 can be utilized to model the structure and perform the pushover analysis.

The process begins by modeling the building with the provided beam, column, and slab dimensions. Gravity loads are applied first, followed by incremental lateral loads using either the displacement control or full load method. The analysis results in a pushover curve that helps in assessing the building's seismic performance, identifying weak points, and ensuring compliance with safety standards.

By meticulously following these methodologies, engineers can ensure that structures are evaluated thoroughly for seismic resilience, thus enhancing their safety and performance during earthquake events.

- Model the building with the provided beam, column, and slab dimensions.
- Apply gravity loads initially.
- For displacement control, incrementally apply lateral loads until the target displacement is achieved.
- For the full load method, apply the full set of lateral loads incrementally and monitor the response.
- Develop pushover curves for both methods.
- Evaluate performance by comparing these curves with demand curves from seismic analysis.

4 Result and Discussion

4.1 DISPLACEMENT CONTROL METHOD

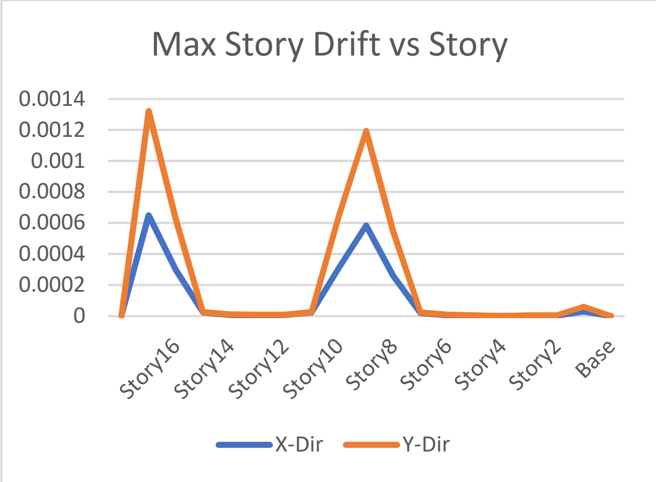

Fig. 3. Dead Case

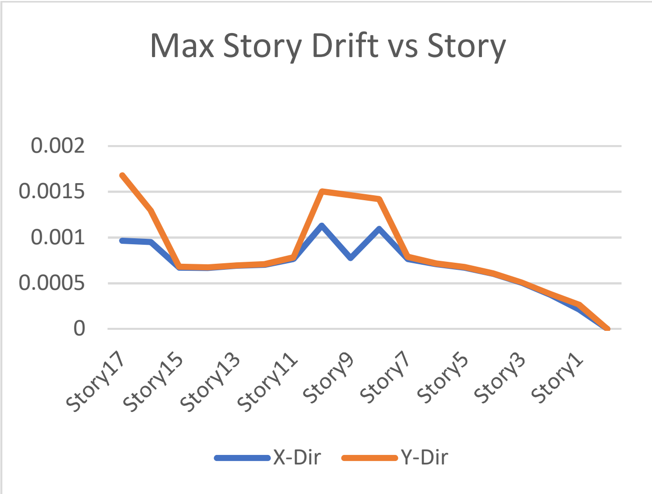

Fig. 4. PA-X Case

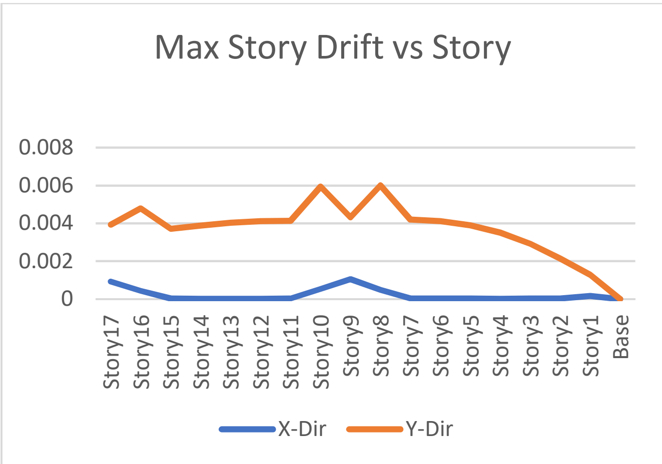

Fig. 5. PA-Y Case

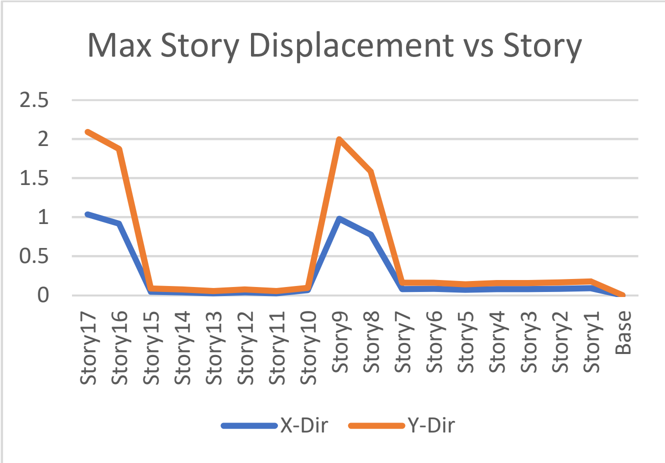

Fig. 6. Dead Case

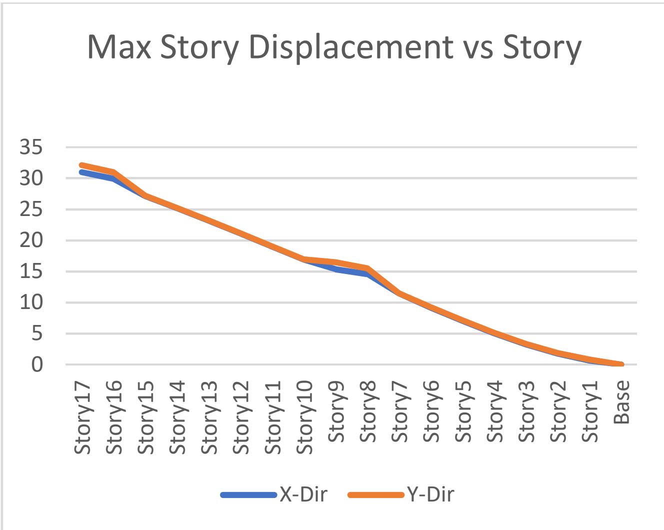

Fig. 7. PA-X Case

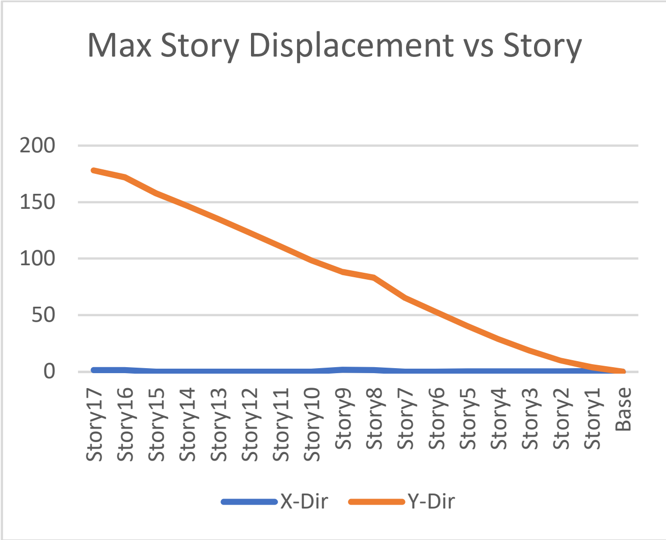

Fig. 8. PA-Y Case

4.2 Displacement Control Method (DCM)

Story Drift

- **Story 17**:
  - X-Dir: 6.49
  - Y-Dir: 6.71
- **Story 16**:
  - X-Dir: 3.00
  - Y-Dir: 3.26
- **Story 15**:
  - X-Dir: 1.99
  - Y-Dir: 1.99
- **Story 14 to Base**:
  - Values continue to decrease progressively down to 0 at Base.

Story Displacement

- **Story 17**:
  - X-Dir: 0.98
  - Y-Dir: 0.96
- **Story 16**:
  - X-Dir: 0.83
  - Y-Dir: 0.84
- **Story 15**:
  - X-Dir: 0.75
  - Y-Dir: 0.76
- **Story 14 to Base**:
  - The displacement values reduce as we go down the stories, indicating less movement in lower stories.

Monitored Displacement vs. Base Shear

- **Displacement Values**: As the base shear increases, the monitored displacement also increases. The figures provide a detailed graph of displacement against base shear, showing how the structure reacts to increasing shear forces.

4.3 FULL LOAD METHOD

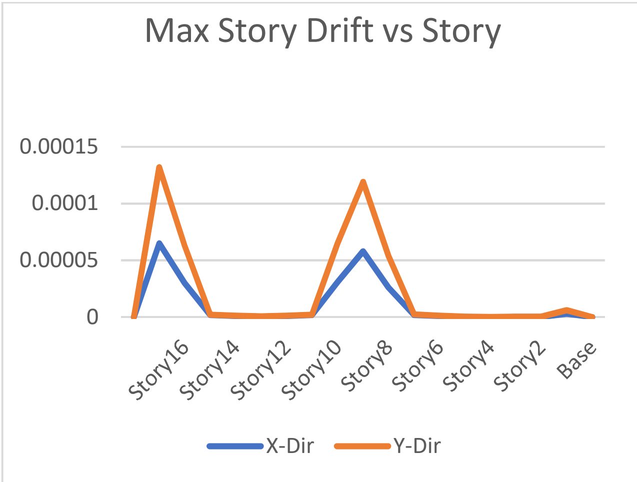

Fig. 9. Dead Case

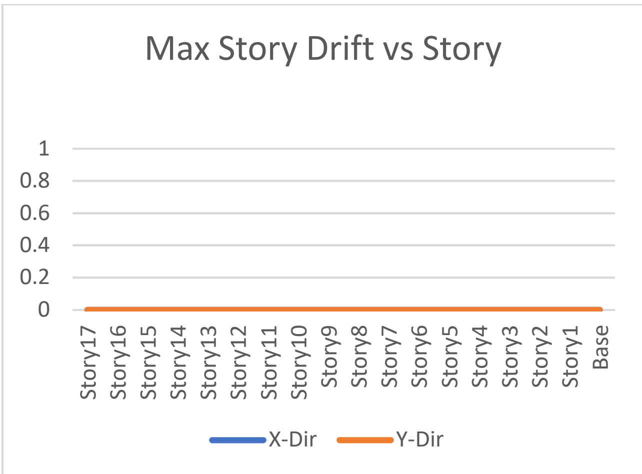

Fig. 10. PA-X Case

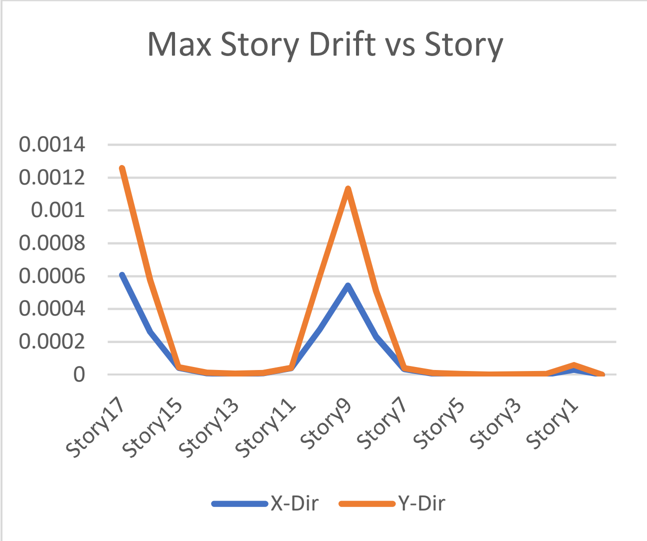

Fig. 11. PA-Y Case

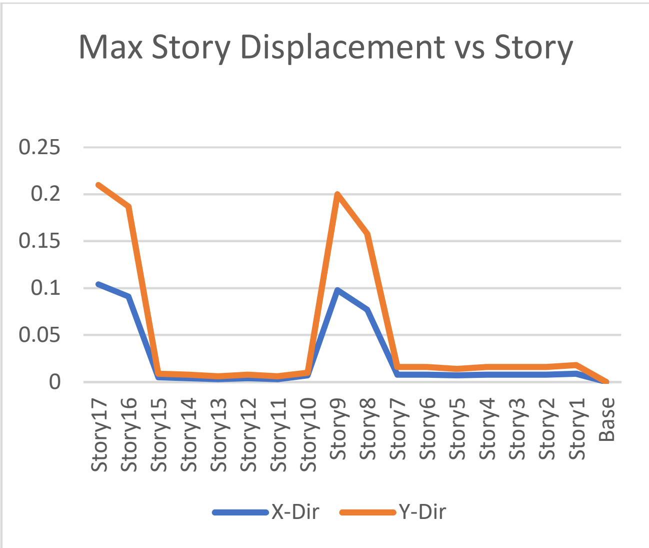

Fig. 12. Dead Case

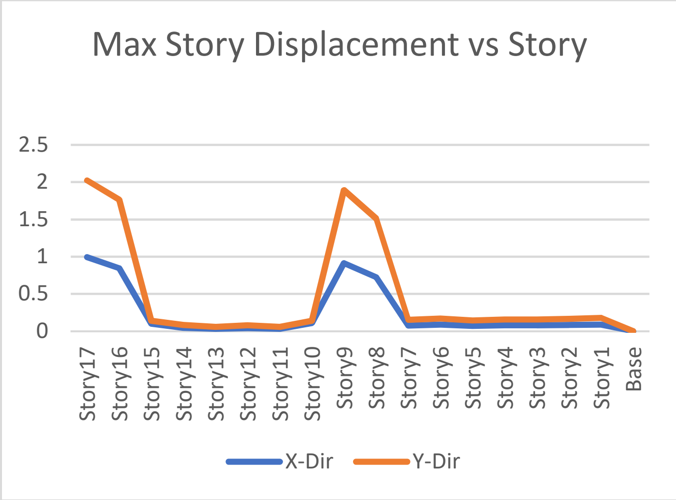

Fig. 13. PA-X Case

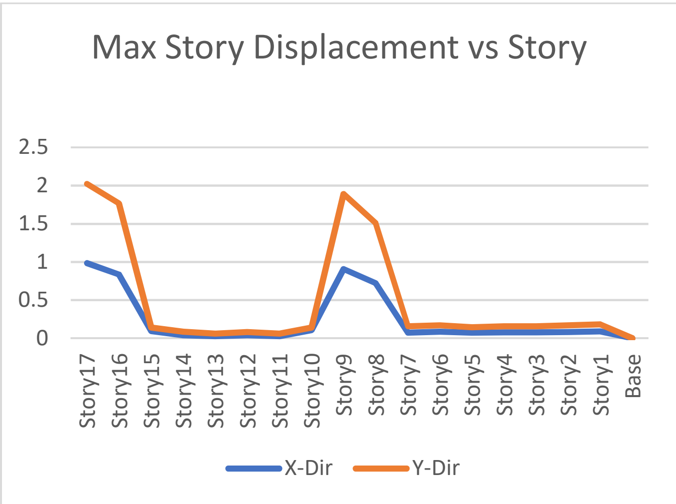

Fig. 14. PA-Y Case

Full Load Method (FLM)
Story Drift

- **Story 17**:
  - X-Dir: 6.49
  - Y-Dir: 6.71
- **Story 16**:
  - X-Dir: 3.00
  - Y-Dir: 3.26
- **Story 15**:
  - X-Dir: 1.99
  - Y-Dir: 1.99
- **Story 14 to Base**:
  - Similar to DCM, values decrease progressively to 0 at Base.

Story Displacement

- **Story 17**:
  - X-Dir: 0.10
  - Y-Dir: 9.09
- **Story 16**:
  - X-Dir: 0.90
  - Y-Dir: 9.60
- **Story 15**:
  - X-Dir: 0.83
  - Y-Dir: 8.73
- **Story 14 to Base**:
  - Displacement values continue to reduce as we go down the stories.

Monitored Displacement vs. Base Shear

- **Displacement Values**:
  - Similar to DCM, the monitored displacement increases with base shear. The figures provide a graph showing this relationship for FLM, indicating how the structure behaves under the load.

4.4 HINGE RESPONSES

DCM

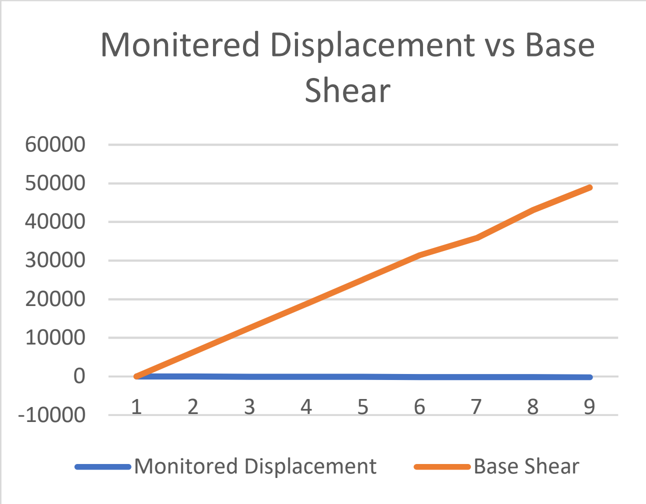

Fig. 15. PA-X

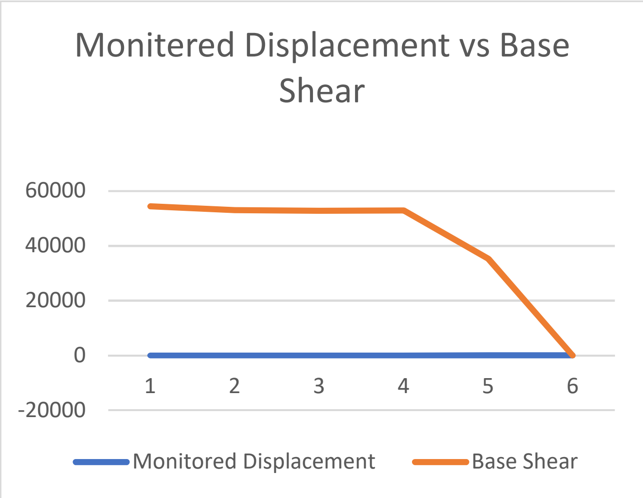

Fig. 16. PA-Y

4.5 FLM

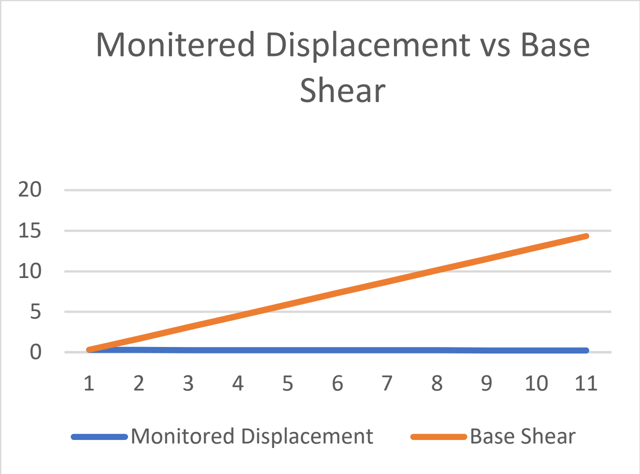

Fig. 17. PA-X

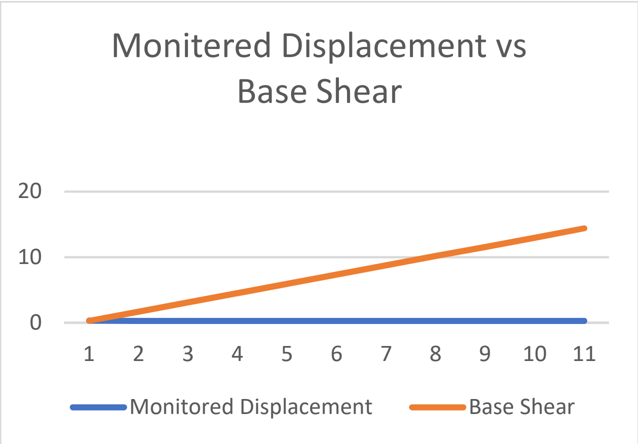

Fig. 18. PA-Y

Hinge Responses

- Hinge responses are critical for understanding how different parts of the structure will behave under stress:

  - **FLM**: The FLM shows the formation of hinges primarily at higher stories, where the maximum displacements are observed. This indicates that the upper sections of the building are more susceptible to damage and potential failure points.
  - **DCM**: The DCM demonstrate hinge formation more evenly distributed across the height of the structure. This distribution suggests a more controlled deformation pattern, likely resulting in less concentrated damage and potentially higher overall structural integrity.

5 Results and Discussion

5.1 Displacement Control Method (DCM)

Story Drift:

In the Displacement Control Method (DCM), the story drift values vary across different stories. At Story 17, the maximum story drift in the X-direction (X-Dir) is 6.49, and in the Y-direction (Y-Dir) it is 6.71. Moving down to Story 16, the X-Dir drift decreases to 3.00 while the Y-Dir drift reduces to 3.26. At Story 15, the values further decrease to 1.99 for both X-Dir and Y-Dir. This progressive reduction continues all the way down to the base of the structure, where the drift values reach 0.

Story Displacement

The story displacement values in the DCM also show a decreasing trend from the top story to the base. At Story 17, the displacement in the X-Dir is 0.98 and, in the Y-Dir is 0.96. At Story 16, these values are 0.83 and 0.84, respectively. Story 15 has displacement values of 0.75 in the X-Dir and 0.76 in the Y-Dir. As we move towards the base, these displacement values continue to reduce, indicating less movement in the lower stories.

Monitored Displacement vs. Base Shear

In the DCM, the relationship between monitored displacement and base shear shows that as the base shear increases, the monitored displacement also increases. The figures in the document provide a detailed graph of displacement against base shear, illustrating how the structure responds to increasing shear forces.

5.2 Full Load Method (FLM)

Story Drift

Similar to the DCM, the Full Load Method (FLM) displays varying story drift values across different stories. At Story 17, the maximum drift values are 6.49 in the X-Dir and 6.71 in the Y-Dir. At Story 16, these values decrease to 3.00 in the X-Dir and 3.26 in the Y-Dir. By Story 15, the drift values reduce further to 1.99 for both directions. This decreasing trend continues down to the base, where the drift values reach 0.

Story Displacement

In the FLM, the story displacement values also decrease from the top story to the base. At Story 17, the displacement in the X-Dir is 0.10 and, in the Y, -Dir is 9.09. At Story 16, these values increase slightly to 0.90 in the X-Dir and 9.60 in the Y-Dir. By Story 15, the displacement values are 0.83 in the X-Dir and 8.73 in the Y-Dir. The values continue to decrease as we move towards the base.

Monitored Displacement vs. Base Shear

In the FLM, the monitored displacement values increase with base shear, similar to the DCM. The figures provide a graph showing the relationship between monitored displacement and base shear, indicating how the structure behaves under load.

5.3 Comparative Analysis

Story Drift

Both DCM and FLM show similar maximum drift values at higher stories, which progressively decrease as we move towards the base. Both methods have identical drift values at the highest story, with 6.49 in the X-Dir and 6.71 in the Y-Dir.

Story Displacement

DCM shows a gradual decrease in displacement values from the top story to the base. For example, the highest story displacement in the X-Dir for DCM is 0.98 compared to FLM's 0.10. FLM's displacement values in the Y-Dir are notably higher at some stories, such as 9.09 at Story 17, compared to DCM.

Monitored Displacement vs. Base Shear

Both methods exhibit a relationship where displacement increases with base shear. Specific patterns and values differ, providing insights into each method's structural performance under increasing the shear forces.

6 CONCLUSION

The pushover analysis conducted on a G+17 steel structure provides crucial insights into the seismic performance of the structures, highlighting the structural response under different loading conditions. Here are the key findings and observations:

6.1 Structural Characteristics and Cost Efficiency

Design and Cost Efficiency:

- The steel framework is designed without exceptional features, ensuring that it does not significantly increase construction costs.
- Despite its simplicity, the steel framework demonstrates resilience, particularly in seismic active regions.

Comparison with RCC Structures:

- Steel frameworks are observed to have superior seismic performance compared to Reinforced Cement Concrete (RCC) structures, making them preferable in earthquake-prone areas.

6.2 Seismic Performance and Structural Adjustments

Component Failure and Adjustments:

- Some structural components may fail during intense seismic events.
- This potential failure can be mitigated by adjusting the dimensions of steel members to enhance their capacity and performance.

6.3 Pushover Analysis Techniques

Displacement Control Method (300 mm):

- The PA-Y case yields higher displacement values than the PA-X case and the Dead Load case.

Full Load Method (FLM):

- Both PA-X and PA-Y cases provide similar displacement values, which are higher than those observed in the Dead Load case.
- Indicates that the structure experiences greater displacements under seismic loads in both directions compared to static dead load conditions.

6.4 Computational and Market Considerations

Demand on Computational Resources:

- The Displacement Control Method (DCM) requires significantly more computational resources and time compared to the FLM.
- The high demand for computational power and the associated costs makes DCM less frequent in practical market applications despite its detailed insights.

6.5 Detailed Observations

Maximum Displacement and Drift:

- DCM under Dead Load:
    - Maximum displacements observed at specific stories, with notable differences in x and y directions.
- PA-X and PA-Y Cases:
    - PA-Y case generally shows higher displacement values, indicating a greater vulnerability in the y-direction under seismic loads.

Overturning Moments:

- Significant overturning moments are observed in both x and y directions, with the PA-Y case showing higher values, suggesting that seismic impacts are more pronounced along the y-axis.

Base Shear:

- The FLM indicates higher base shear values compared to the Dead Load case, highlighting the substantial lateral forces acting on the building during seismic events.

Hinge Analysis:

- The behavior of hinges under lateral forces reveals consistent patterns of force reduction in the PA-X case, while the PA-Y case shows an initial increase followed by stability, indicating different structural responses under varying lateral loads.

The pushover analysis underscores the resilience of steel frameworks in seismic regions, provided that structural components are appropriately dimensioned. The analysis also reveals that while DCM provides detailed insights, it is resource-intensive, making FLM a more practical choice for routine market applications. The finding's advocate for the use of steel structures in earthquake-prone areas due to their superior seismic performance and cost-efficiency compared to RCC structures.

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8 AUTHORS CONTRIBUTION

The author had done research on the project and have written the research paper under the guidance of Prof. A.B. Pujari and Reviewed by Prof. A.B. Pujari.

9 DECLARATION

Conflict of interest: The work was accomplished with equal contributions from all authors, as far as the authors' understanding goes. Therefore, we affirm that there are no conflicts of interest among the authors.

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