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Research Article

The Effect of Building Irregularities on the Structural Performance of Air Traffic Control Towers in High Seismic Zones

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Abstract: This study examines the seismic performance of slender Air Traffic Control (ATC) towers in high-hazard regions (PGA > 0.4g), where vertical taper, torsional eccentricity, and top-heavy cab mass can significantly increase drift, base shear, and collapse risk relative to conventional buildings. Existing studies often rely on linear procedures and outdated provisions, leading to underestimation of nonlinear behaviour and limited guidance for ATC towers designed to SNI 1726:2019. The research aims to quantify these irregularity effects and formulate design recommendations that satisfy Immediate Occupancy, Life Safety, and Collapse Prevention performance targets. The methodology couples response spectrum analysis, using a site-specific Padang spectrum consistent with SNI 1726:2019 and ASCE 7-16, with nonlinear pushover analysis interpreted through FEMA/ATC performance-based criteria. A parametric study is performed on three cab configurations—small, medium, and large—modelled as 5%, 15%, and 25% mass ratios at the tower head, while keeping a 10 m × 10 m hybrid core–frame shaft constant. Results indicate that larger cab mass produces systematic but moderate increases in global displacement, story drift, and base shear, while plastic hinges localize primarily in the upper stories and cab-support region, yielding performance levels from Immediate Occupancy to Collapse Prevention. Overall, the tower meets code drift limits and acceptable performance if local strengthening is provided around the shaft–cab interface, offering a calibrated reference for top-heavy ATC tower design in Indonesian high-seismic settings and identifying priorities for future time-history and soil–structure interaction studies.

Keywords: ATC Tower; Mass Irregularity; Nonlinear Pushover Analysis; Response Spectrum Analysis; Seismic Performance.

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1. Introduction

Managing flights is the main responsibility of the Air Traffic Control (ATC) Tower as it is an important structure found at all airports. Since it is important, it has to be operational after an earthquake to provide services and safeguard the safety of the aviation industry. The ATC towers are built like skyscrapers, and the structure is not like normal buildings. These structures use a mix of steel shear and concrete. Because of the slim and unique geometry, towers behave differently during an earthquake than ordinary buildings.

Research has documented that earthquakes can cause damage to buildings that are not regularly shaped in design and structure, and horizontally and/or vertically may suffer from increased base shear, lateral displacement, floor drift, and increased torsion. This leads to a reduction in earthquake resistance of buildings. This is particularly important for the ATC tower. Irregularities in the floor plan, tower, and the arrangement of the shear core walls along with mass and stiffness distribution at varying heights has the potential to reduce the towers earthquake response. This is especially important for ATC towers in high seismic zones where it is necessary to ensure that ATC towers are safe and functional.

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When looking into how irregular buildings hold up in an earthquake, building scientists usually do response spectrum analysis, nonlinear time-history analysis (NTHA), and pushover analysis. Response spectrum analysis is the most common analysis that is done to determine engineering requirements and how far floors are displaced in an irregular structure. The problem with this analysis is that it is based on elastic structure response and cannot measure post-elastic response. This can be an issue for tall post-elastic structures located in high earthquake risk zones (Khatiwada et al., 2023; Tohho et al., 2024). NTHA is used when nonlinear response is needed, however, NTHA requires representative earthquake information, complex 3D models, and a significant amount of computing power (Du et al., 2024; Khatiwada et al., 2023; Mokarram et al., 2025; Valente, 2021). NTHA is also the greatest expense, no other response systems cause more expense, and for most systems, a pushover analysis is sufficient. Irregular structures can be analyzed by using pushover analysis to determine their performance points and capacity curves. While pushover analyses are the most efficient of all the analyses, they are still complex and numerous structures can be overly large to be analyzed through this method (Aşıkoğlu et al., 2020; Kuria & Kegyes-Brassai, 2024; Oyguc, 2022). This is especially true of systems that have a dominate torsional structural response and complex 3D behavior. Thus, especially for the ATC tower, which is a tall structure that is likely to be impacted by torsional systems, is analysis method is an important decision.

Research about irregular structures proves that plan and vertical irregularities tend to promote higher values of drift and base shear forces, as well as increasing the collapse risk. The ATC tower is, however, structurally worse because the torsional effects and the uneven stiffness distribution worsen the structural performance. The ATC tower is often perceived as just another building, ignoring its unique seismic performance (Aşıkoğlu et al., 2020; Aslani & Tehrani, 2025; Xiao et al., 2023). Other studies of tall buildings have found that geometric modifications, specifically those involving shear walls and mass-stiffness eccentricity, contribute to an increase in drift, internal forces, and collapse potential; yet, ATC towers have been the subject of very little research, particularly in assessing vertical irregularities, mass-stiffness distribution, and the seismic response (Hussain et al., 2024; Kimsan, 2024; Sarvade et al., 2022). This research void underlines the necessity of targeted ATC towers studies to investigate the impact of inclusions on displacement, torsion, capacity and damage concepts.

This study intends to conduct dynamic evaluations of the ATC tower using the most recent earthquake-resistant design code (SNI 1726:2019) and applicable standards for the irregularity parameters. Other studies have concluded that updating the analysis to reflect current seismic design codes creates a different perspective regarding the safety of the structures (Fadzilah et al., 2021; Putri et al., 2022; Zachari & Turuallo, 2020). valuations that do not account for the geometric configuration and mass-stiffness distribution may ignore excessive drift, along with high base shear, and critical zone deformation, which are important factors in high seismic risk zones (Fadzilah et al., 2021; Putri et al., 2022). This is why modeling ATC towers using different types of irregularities is a dynamic approach that the authors plan to conduct along with the dynamic response spectrum method and some other selected nonlinear analysis techniques to evaluate the inelastic response (Abdullah et al., 2025; Fadzilah et al., 2021; Ilham, 2021; Putri et al., 2022; Turu'allo & Anggara, 2023).

Using the proposed methodology, response parameters such as peak displacement, inter-floor drift ratio, base shear force, and plastic hinge occurrences can be measured quantitatively and assessed relative to different configurations of irregularity. It is anticipated that the results will help to achieve further clarity concerning the extent to which shape and stiffness distribution influences the seismic performance of ATC towers in high seismic zones (Abdullah et al., 2025; Fadzilah et al., 2021; Ilham, 2021; Putri et al., 2022; Turu'allo & Anggara, 2023). Previous research indicates that dynamic analysis and performance assessment based on the IO/Life Safety/Collapse Prevention methodology is suitable in evaluating whether the structure is within acceptable displacement and base shear force limits (Budi Asmara et al., 2021; Fadzilah et al., 2021; Putri et al., 2022; Setianto et al., 2025). Nevertheless, this methodology is yet to be applied to slender ATC towers, which is what this research aims to do, adapting a contemporary dynamic evaluation methodology in line with modern seismic code provisions.

This study intends to begin addressing this issue by identifying particular geometric and structural irregularities with ATC towers. The study also intends to analyze how such irregularities influence critical seismic responses such as inter-floor drift, peak displacement, torsion and base shear, and to recommend positive design solutions for ATC towers situated in seismic risk zones (Aslani & Tehrani, 2025; Mahi et al., 2025). The study intends to enable the design of ATC towers to be further refined in order to enhance safety in high seismic zones, as well as to assist in the planning and evaluation of ATC tower structures in such zones.

2. Preliminaries or Related Work or Literature Review

2.1. Overview State of The Art

Building irregularities, both vertical and torsional, greatly increase the risk for high-rise buildings in highly seismic regions (PGA > 0.4g), like Indonesia, Japan, and California, leading to heighten- ed inter-story drift, base shear, and collapse potential, particularly in lower stories (Aslani & Tehrani, 2025; Kumar et al., 2022; Patel & Khatri, 2023; Satheesh et al., 2020; Zain et al., 2025). For the ATC tower studies, linear/pushover analyses show a concentration of nonlinear damage that is underestimated (Sarvade et al., 2022). Hexagonal and octagonal shapes are noted to reduce drift, yet increase shear (Sarvade et al., 2022). Research, particularly in the Indonesian context, integrating SNI 1726:2019 and explicit torsional and vertical irregularities is sparse, indicating the need for more recent updates on non-linear performance assessments.

2.2. Comparative Review

Table 1. Comparative Review.

Author	Object	Parameter	Methods	Results	Gaps
Aslani & Tehrani	RC dual buildings	Vertical geometric irregularity ini wall height; stiffness variation along elevation	Nonlinear THA; collapse capacity	Vertical irregularities in the lower floor significantly increase drift, shear, and the probability of collapse.	Not ATC; does not model mass–stiffness eccentricity and streamlined shape; not based on SNI 1726:2019
Patel & Khatri	11-story MRF Building	Vertical irregularity (stiffness, mass, geometry)	Response Spectrum (NBC 105:2020)	Vertical geometric irregularities have the greatest influence on displacements and internal forces.	Linier analysis without pushover and performance building.
Mahi et al	Regular vs plan irregular RC Buildings	Plan irregularity; torsional irregularity	SAP 2000; RSA; and THA review	Irregular structures exhibit larger displacement and drift	No pushover analysis; no vertical irregularities
Amrutkar et al	ATC Tower square/ pentagonal/ hexagonal/ octagonal	Plan shape irregularity (different polygons)	Linear THA (SAP 2000); Indian Code	Hexagonal / octagonal shapes provide the smallest drift and displacement, but the largest base shear.	Doesn't discuss about mass/stiffness eccentricity, vertical taper, or nonlinear performance
Proposed Study	**Irregular ATC** Towes in **Indonesia high seismic zone**	**Vertical irregularity**; **torsional irregularity**; mass irregularity (**top heavy cab**)	**RSA** (SNI 1726:2019); **Nonlinier Pushover** Analysis	Displacement; Story drift ratio; base shear; and performance buildings.	Focus on ATC slender / tapered top heavy, multi irregularities, and nonlinear performance evaluation.

2.3. Research Gap and Contribution

Literature review reveals prior studies underestimate drift and shear risks in irregular structures due to symmetric RC building models, linear analysis, and pre-SNI 1726:2019 codes

(Aslani & Tehrani, 2025; Kumar et al., 2022; Patel & Khatri, 2023; Satheesh et al., 2020; Zain et al., 2025). For slender, top-heavy ATC towers, this gap widens from limited combined vertical and torsional irregularity modeling caused by mass-stiffness eccentricity. This research fills the void through multi-irregularity modeling and explicit nonlinear performance evaluation (pushover/THA) using SNI 1726:2019 design spectra, yielding IO/LS/CP performance maps for ATC planning and retrofitting in Indonesia's high seismic zones.

3. Proposed Method

This study employs a systematic modeling and dynamic analysis framework to quantify the impact of building irregularities—specifically vertical taper, torsional eccentricity, and top-heavy mass distribution—on the seismic performance of Air Traffic Control (ATC) towers in high seismic zones, as illustrated in Figure 1.

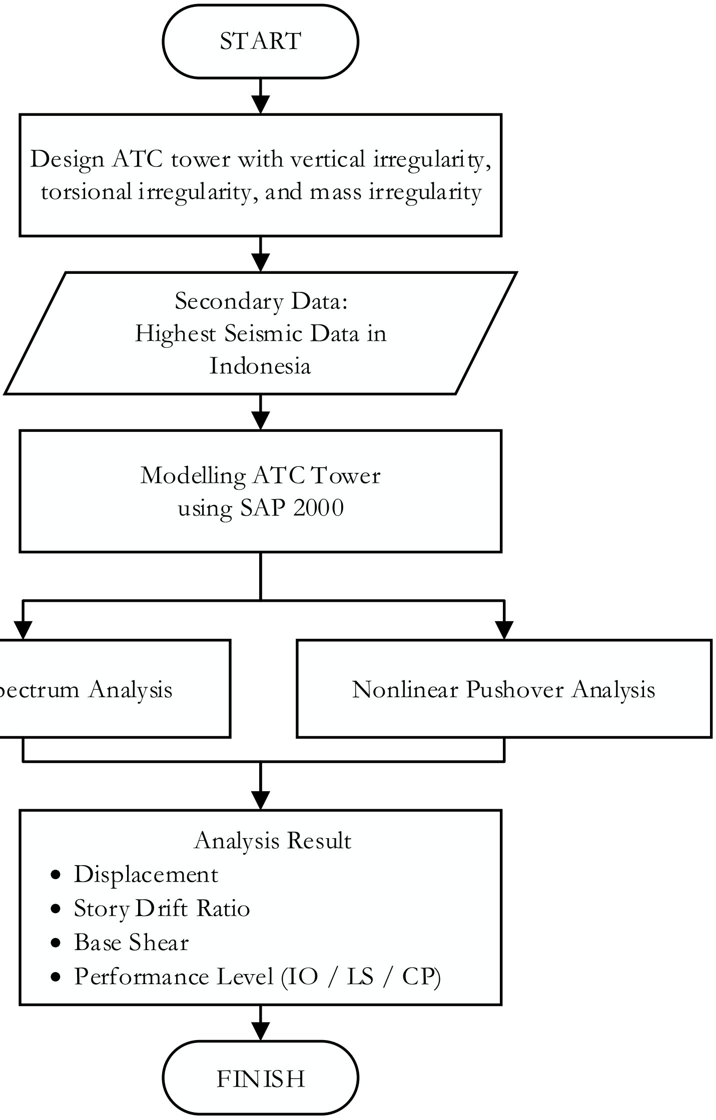
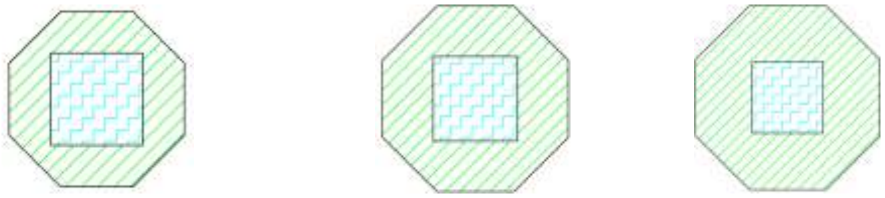


Figure 1. Methodology Flowchart.

4. Results and Discussion

4.1. Design Air Trafic Control Tower

The Air Traffic Control (ATC) tower investigated in this study is conceived as a prototype for an international-class airport, with its geometric and functional configuration tailored to typical conditions of major Indonesian airports, namely relatively flat runways and limited surrounding vertical obstructions. The tower is designed with a total height of 70 m from ground level to the cab floor, providing a controller eye level considered adequate to ensure direct line-of-sight coverage of all primary operational areas, including runways, taxiways, and aprons within a conventional international airport layout. The shaft is idealized as a square plan structure measuring 10 m × 10 m, accommodating the vertical core, vertical circulation (stairs and elevator), and building services, while simultaneously acting as the primary lateral-load-resisting system through a combination of shear walls and moment-resisting frames. The cab is located at the top of the shaft and is configured as an octagonal volume with a height of 5 m, providing unobstructed 360° visibility together with sufficient space for air traffic controller workstations, communication and navigation equipment, and ancillary operational areas. To enable a systematic and quantifiable assessment of top-heavy effects, the study maintains identical shaft geometry and structural system in all scenarios, and varies only the size and mass of the cab. On this basis, three top-heavy cab configurations are defin **Model A, Model B, and Model C** each representing a different severity level of concentrated mass at the tower head while preserving the same global ATC tower configuration that can see in figure 2. Its representing typical equipment loading variations in high seismic zones, to systematically evaluate mass irregularity effects under SNI 1726:2019 provisions.



(a)
Model A Small Cab
5% Mass Ratio

(b)
Model B Medium Cab
15% Mass Ratio

(c)
Model C Large Cab
25% Mass Ratio

Figure 2. Layout of Air Trafic Control Tower.

4.2. Dataset about Response Spectrum in High Seismic Zone in Indonesia

Indonesia seismic hazard maps 2021 shows the **western Sumatra** and **southern Java** regions as the highest values of S_1 and Ss, which represent the highest peaks of spectral accelerations and are hence the most critical areas in the country concerning the seismic design parameters of SNI 1726:2019. This research analyzes **Padang** as a representative case: it is located on the west side of Sumatra, which is extremely close to the critical subduction zone and highly active earthquakes due to the intense movements of tectonic plates.

The following presents seismic data for the Padang,West Sumatra and assuming soft soil conditions in the surrounding area under the most critical (worst-case) scenario:

a. Ss = 1.1245 g
b. S1 = 0.5737 g
c. PGA = 0.7172 g
d. TL = 20 s

4.3. Computational Setup

4.3.1. Modelling ATC Tower using SAP 2000

The structural modeling of the Air Traffic Control (ATC) tower was conducted using SAP 2000, a dedicated software environment for the analysis and design of building structures. The adopted material characteristics, encompassing the specified concrete and steel grades, along with the prescribed gravity and seismic load cases and their associated load combinations, are comprehensively documented in the accompanying table 2 to ensure methodological transparency and facilitate reproducibility of the numerical investigation.

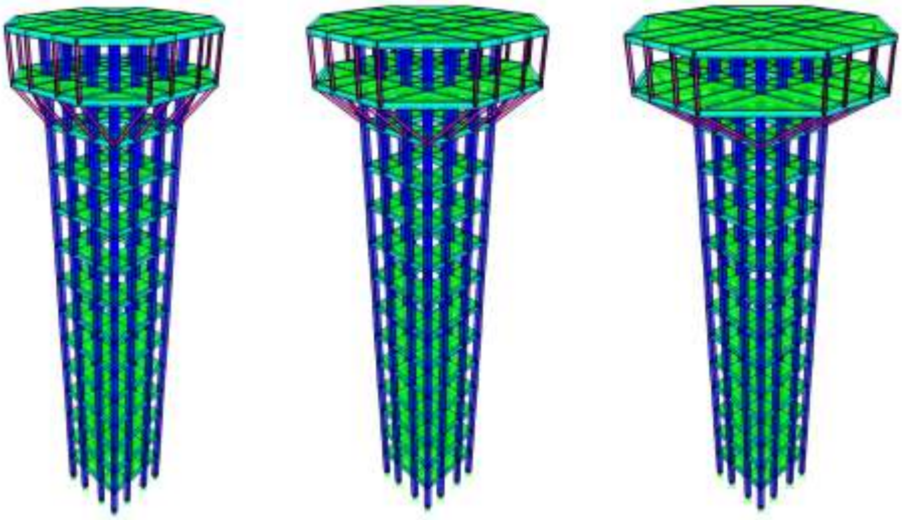
Table 2. Characteristic Material.

Material	Characteristic
Steel	BJ 37
Concrete (Beam and Slab)	fc’ = 30 MPa
Concrete (Column)	fc’ = 35 MPa
Rebar	BJTD 40

The structural configuration of the ATC tower, as idealized and analyzed in SAP2000, is illustrated in Figure 3. This figure presents the three-dimensional model, including the shaft, cab, and lateral-load-resisting system, which forms the basis for all subsequent response spectrum and nonlinear analyses reported in this study.

4.3.2. Modelling Response Spectrum Analysis in SAP 2000

The site-specific design response spectrum adopted in this study was developed in accordance with the provisions of ASCE 7-16 and subsequently implemented in SAP 2000 as a modal response spectrum function. The spectrum is defined for a damping ratio of 5%, with short-period spectral acceleration Ss and S_1 spectral acceleration previously obtained in Section 4.2, that shown in figure 4.

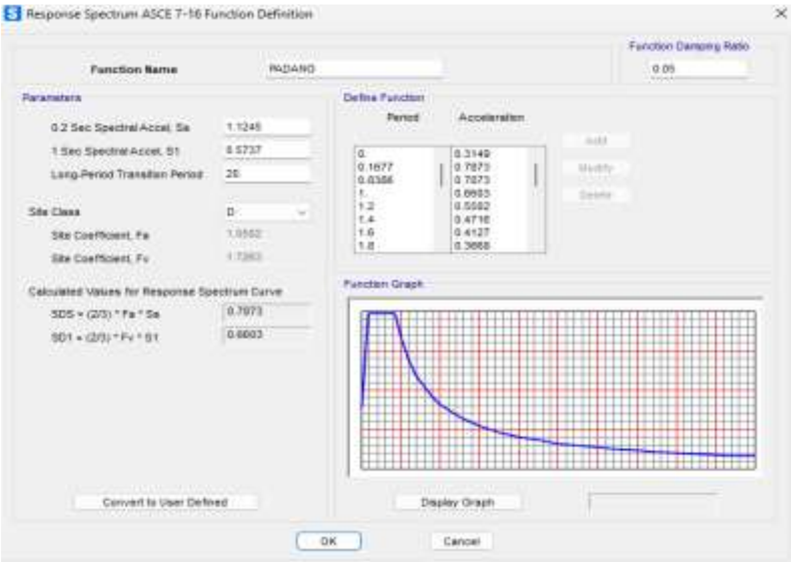


(a)
Model A

(b)
Model B

(c)
Model C

Figure 3. Modelling ATC Tower in SAP 2000.



Response Spectrum ASCE 7-16 Function Definition

Function Name: PADANG

Function Damping Ratio: 0.05

Parameters

0.2 Sec Spectral Accel, Ss: 1.1245
1 Sec Spectral Accel, S1: 0.5737
Long-Period Transition Period: 20

Site Class: D
Site Coefficient, Fa: 1.0502
Site Coefficient, Fv: 1.7263

Calculated Values for Response Spectrum Curve
SDS = (2/3) * Fa * Ss: 0.7873
SD1 = (2/3) * Fv * S1: 0.6603

Define Function

Period	Acceleration
0.	0.3149
0.1677	0.7873
0.8386	0.7873
1.	0.6603
1.2	0.5502
1.4	0.4716
1.6	0.4127
1.8	0.3668

Figure 4. Modelling Response Spectrum in SAP 2000.

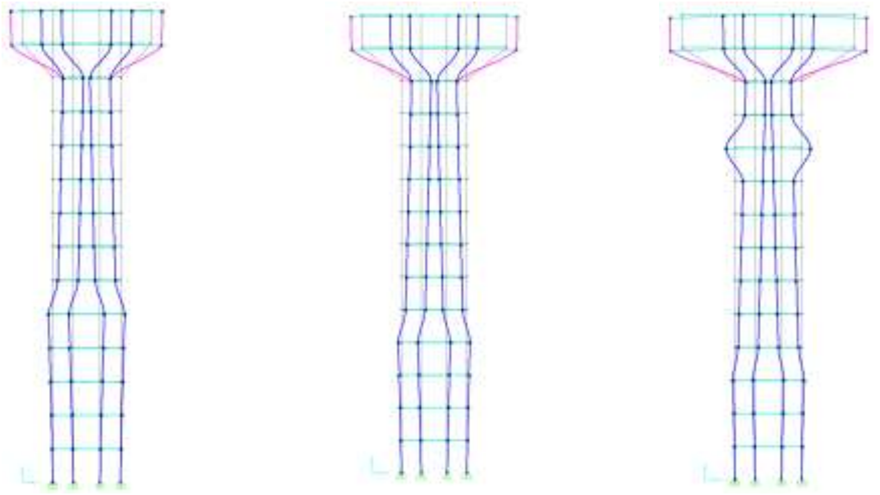
4.3.3. Modelling Nonlinear Pushover Analysis in SAP 2000

The nonlinear static pushover analysis conducted in this study follows established performance-based seismic evaluation procedures as outlined in the FEMA and ATC guidelines for building structures. In this approach, the modeled ATC tower is subjected to a monotonically increasing lateral load pattern, applied in the horizontal direction while maintaining the constant gravity loads, until a target displacement or significant strength degradation is reached. The lateral load vector is defined to be proportional to the fundamental mode shape, so that the pushover curve obtained from the analysis can be interpreted consistently with the equivalent single-degree-of-freedom idealization adopted in FEMA and ATC procedures.

4.4. Response Spectrum Analysis

4.4.1. Deformation

The deformation pattern corresponding to the critical load combination of 0.9D + 1E, representing the simultaneous action of reduced dead load and design seismic effects, is illustrated in Figure 6. This figure shows the displaced shape of the ATC tower under the governing seismic load case and highlights the maximum lateral deflections and overall deformation profile along the height of the structure.



(a)
Model A

(b)
Model B

(c)
Model C

Figure 5. Deformation.

4.4.2. Displacement

The displacement demands obtained from the response spectrum analysis in SAP2000 are summarized in Table 3 and Figure 6, which reports the calculated lateral displacements at the control points of the ATC tower for the considered seismic loading cases.

Table 3. Displacement Output.

Story	**Model A**		**Model B**		**Model C**	
	δ_x (mm)	δ_y (mm)	δ_x (mm)	δ_y (mm)	δ_x (mm)	δ_y (mm)
14	84.41	84.51	86.79	86.88	89.71	89.82
13	80.14	80.24	82.25	82.39	84.81	85.02
12	75.32	75.24	77.19	77.04	79.48	79.20
11	69.72	69.70	71.26	71.23	73.13	73.09
10	63.71	63.69	64.99	64.97	66.55	66.51
9	57.39	57.37	58.45	58.42	59.72	59.69
8	50.83	50.81	51.69	51.66	52.72	52.69
7	44.08	44.06	44.77	44.75	45.59	45.56
6	37.20	37.18	37.73	37.72	38.37	38.34
5	30.24	30.23	30.64	30.63	31.11	31.09
4	23.26	23.25	23.55	23.54	23.88	23.86
3	16.35	16.35	16.54	16.53	16.75	16.74
2	9.66	9.65	9.76	9.76	9.87	9.87
1	3.59	3.59	3.62	3.62	3.66	3.66

4.4.3. Story Drift Ratio

The inelastic story drift values, calculated from the displacement results reported in Table 3 using Equation (1) in accordance with the SNI 1726:2019, are presented in Table 4.

Table 4. Story Drift Ratio.

$$\Delta = \frac{\delta . C_d}{I_e} \tag{1}$$

Story	Model A		Model B		Model C	
	Δ_x (mm)	Δ_y (mm)	Δ_x (mm)	Δ_y (mm)	Δ_x (mm)	Δ_y (mm)
14	23.50	23.46	24.98	24.75	26.99	26.39
13	26.48	27.49	27.82	29.41	29.30	31.97
12	30.82	30.51	32.60	31.94	34.91	33.63
11	33.05	33.05	34.47	34.45	36.22	36.18
10	34.77	34.76	36.01	36.00	37.53	37.52
9	36.10	36.09	37.19	37.17	38.52	38.50
8	37.11	37.10	38.06	38.05	39.24	39.22
7	37.84	37.83	38.68	38.66	39.71	39.68
6	38.28	38.27	39.01	39.00	39.91	39.89
5	38.37	38.36	39.01	38.99	39.78	39.76
4	38.00	37.98	38.55	38.53	39.21	39.18
3	36.82	36.80	37.28	37.26	37.82	37.79
2	33.40	33.38	33.76	33.74	34.17	34.15
1	19.73	19.72	19.92	19.92	20.13	20.12

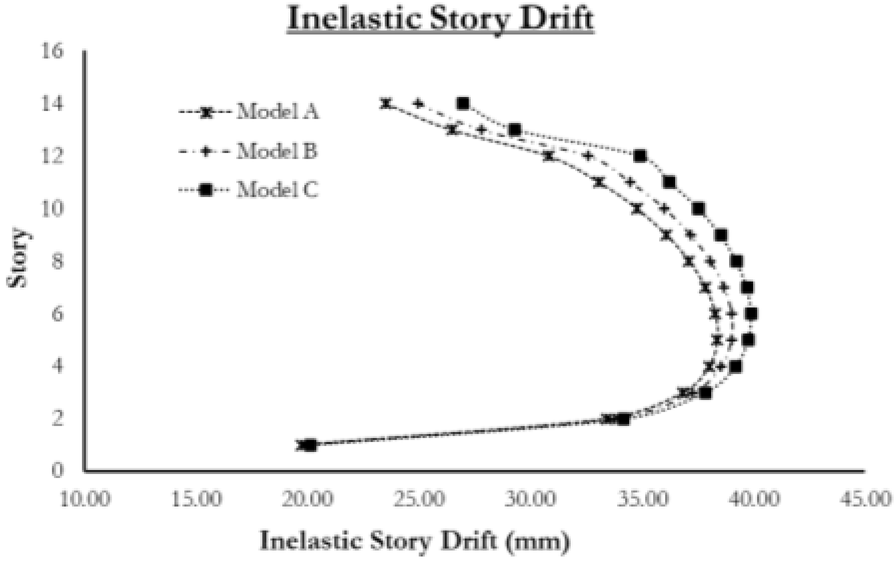


Figure 6. Inelastic Story Drift.

4.4.4. Base Shear

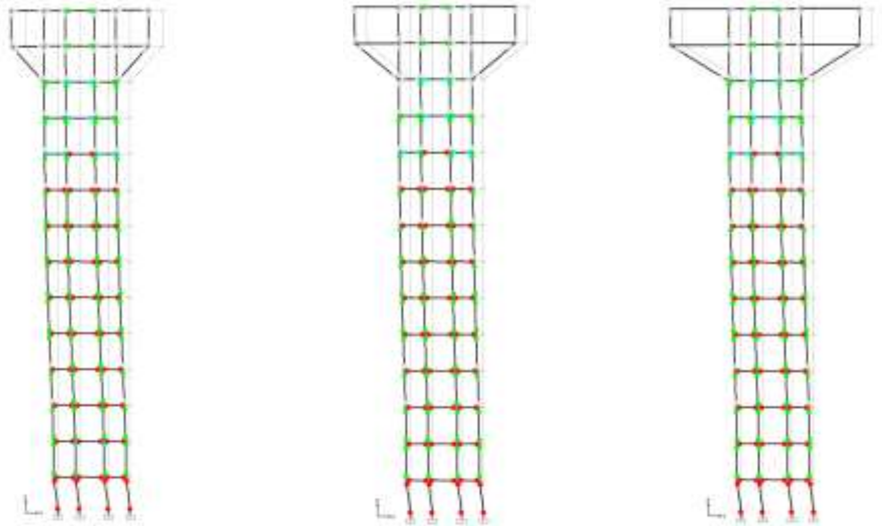
The global seismic response of the ATC tower was quantified in terms of base reactions obtained from the response spectrum analysis carried out in SAP2000. In this procedure, the three-dimensional structural model was subjected to the site-specific design response spectrum defined in accordance with ASCE 7-16. These base reaction values, which are subsequently summarized in Table 3, provide a consistent measure of the overall seismic demand on the tower and form the primary basis for checking the adequacy of the foundation design as well as for comparing the seismic demand among the different top-heavy cab configurations investigated in this study.

Table 5. Base Shear Reaction.

Model	Base Shear (kN)
Model A	1273.69
Model B	1284.72
Model C	1296.19

4.5. Nonlinear Pushover Analysis

The pushover analysis output provides a detailed representation of the structural performance of the ATC tower under progressively increasing lateral loads, explicitly capturing its behavior in the nonlinear range. In this output, each structural element or hinge location is assigned to a performance category, so that the global and local damage states can be visualized consistently with performance-based seismic design practice. As illustrated in Figure 7 and 8, the distribution of performance points allows the behavior of the structure to be interpreted across several damage levels. Points classified as Immediate Occupancy (IO) are shown in green and correspond to regions that remain essentially elastic, with negligible damage, indicating that the structure can be re-occupied almost immediately after the seismic event. Points in the Life Safety (LS) range, indicated in blue, denote areas where inelastic deformations and damage have occurred but overall stability and life safety are maintained, and no partial or global collapse is expected. Points reaching the Collapse Prevention (CP) level, shown in red, identify zones that have experienced significant damage and are in a critical condition, yet still retain sufficient residual strength and deformation capacity to prevent total collapse.

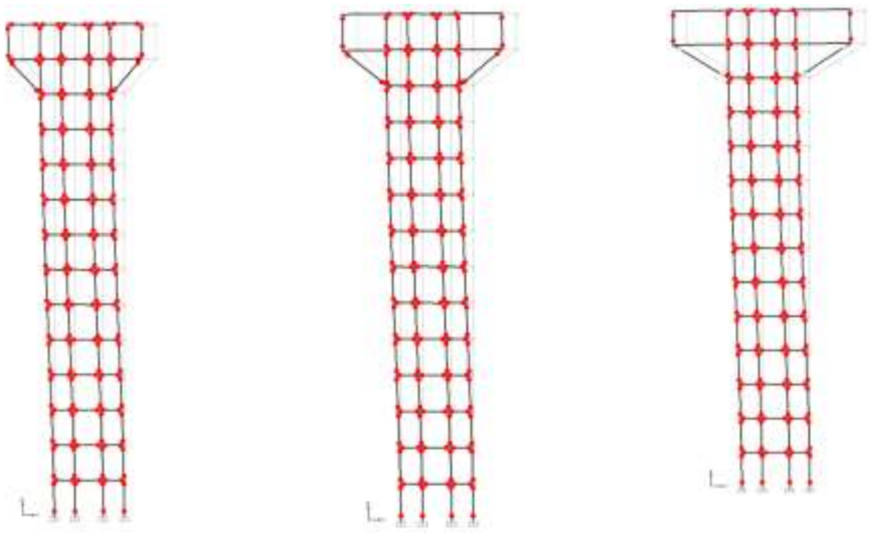


(a)
Model A

(b)
Model B

(c)
Model C

Figure 7. Performance Point of Structure in Push – X.



(a)
Model A

(b)
Model B

(c)
Model C

Figure 8. Performance Point of Structure in Push – Y.

The overall distribution of IO, LS, and CP points in Figure 6 therefore describes how the structure responds to increasing lateral demand, and this interpretation can be further substantiated by examining the corresponding capacity curve or force–displacement report, which relate base shear to roof displacement and provide a quantitative measure of the global nonlinear response.

4.6. Discussion

The discussion highlights how the adopted top-heavy cab configurations influence the seismic performance of the 70 m ATC tower in a high-hazard Indonesian context. The response spectrum results indicate that lateral displacements increase systematically from Model A to Model C, in line with the progressive increase in cab mass and plan dimension; however, the increase in drift demand remains relatively modest, reflecting the effectiveness of the hybrid core–frame system and the regularity of the 10 m × 10 m shaft in controlling global deformations under the Padang-type spectrum. The elastic story drifts derived from these displacements and amplified in accordance with SNI 1726:2019 stay within the code-specified limits for all three models, confirming that the tower retains an acceptable deformation-controlled performance despite the pronounced mass irregularity at the top. The base shear reactions also show a clear yet limited escalation with cab size, with Model C developing the largest base shear but only marginally higher than Models A and B, which suggests that the additional seismic demand due to the heavier cab is primarily expressed in local member forces and deformation patterns near the shaft–cab transition rather than in a dramatic increase of global base forces. This trend is consistent with the nonlinear pushover outcomes, where the distribution of IO, LS, and CP hinges demonstrates that plasticity concentrates mainly in the upper stories and cab-support region, while the lower shaft remains predominantly in the IO range, indicating adequate reserve strength and stiffness in the primary lateral-force-resisting system. Overall, the combined response spectrum and pushover analyses show that, for the considered geometry and material properties, the ATC tower can safely accommodate realistic variations in top-heavy cab configuration typical of international airports in Indonesia, although careful detailing and local strengthening around the cab interface become increasingly critical as the mass ratio approaches that of Model C.

5. Comparison

Comparison with state-of-the-art approaches constitutes an essential component of this research, as it enables a more measurable articulation of the scientific contribution relative to existing knowledge. By juxtaposing the proposed ATC tower models—particularly the systematic variation of top-heavy cab mass ratios and their seismic implications under SNI-based response spectrum and pushover analyses—with contemporary studies on tall, core–frame, and mass-irregular structures, the authors can demonstrate how this work extends current understanding of performance-based design for critical airport infrastructure in high-seismic regions. This comparative perspective may be presented either as a concise, dedicated subsection or integrated within Section 4 (Results and Discussion), for example by summarizing key similarities and differences in modeling assumptions, seismic demand parameters, drift and performance-point criteria, as well as practical design recommendations for top-heavy towers. Through such an integrated discussion, the novelty of the present study—namely, its focus on realistic ATC prototypes, Indonesian seismic code provisions, and explicit mass-irregularity scenarios—can be highlighted in a clear and technically grounded manner.

6. Conclusions

This study has examined the seismic performance of a 70 m top-heavy Air Traffic Control (ATC) tower representative of international-class Indonesian airports, by systematically varying the cab mass while keeping the shaft geometry and structural system constant. The main findings show that increasing the cab mass ratio from 5% (Model A) to 15% (Model B) and 25% (Model C) produces a consistent but moderate increase in global displacement, story drift, and base shear, whereas the most pronounced effects appear locally in the shaft–cab transition region where inelastic demands and hinge concentrations are highest. These results confirm the initial hypothesis that mass irregularity at the tower head is a governing parameter for performance, but also demonstrate that a well-proportioned hybrid core–frame system, designed in accordance with SNI 1726:2019 and evaluated through response spectrum and pushover analysis, can maintain drifts within allowable limits and achieve Life Safety to Collapse Prevention performance levels even in high-seismic zones. The research contributes to current knowledge by providing a code-consistent, quantitatively calibrated reference model for ATC towers in Indonesia, clarifying how different realistic cab configurations influence displacement, drift, base shear, and nonlinear damage patterns, and by translating these findings into practical recommendations on acceptable cab mass ratios and the need for local strengthening near the cab interface. Nonetheless, the study is limited to one tower height, a single site condition (Padang-type high hazard, soft soil), and simplified representation of nonstructural components and soil–structure interaction. Future work should extend the parametric space to include different tower heights, alternative lateral systems, explicit SSI modelling, and nonlinear time-history analyses using site-specific ground motions, so that the robustness of the conclusions can be further validated and refined for broader application in performance-based design of critical airport control facilities.

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