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STRUCTURAL REVIEW OF HORIZONTALLY IRREGULAR BUILDINGS USING PUSHOVER AND TIME HISTORY ANALYSIS

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ABSTRAK

Kota Padang, Ibu Kota Sumatera Barat merupakan salah satu daerah rawan gempa karena terletak di antara dua lempeng aktif dunia. Pada bangunan tahan gempa, geometri denah struktur bangunan sangat berpengaruh dalam merespon gaya gempa. Bangunan beraturan, sederhana, dan simetris akan mempunyai respon lebih baik terhadap gempa dibandingkan dengan bangunan yang tidak beraturan. Tujuan penelitian ini untuk mengevaluasi kapasitas struktur gedung tinjauan akibat pengaruh gaya gempa, termasuk mekanisme keruntuhan yang terjadi. Analisis ini dilakukan dengan metode pushover nonlinier menggunakan software Etabs untuk menghitung performance based design dengan parameter output hasil didasarkan dengan standar Applied Technology Council-40 (ATC-40), FEMA 356 & FEMA 440. Dari hasil penelitian diperoleh gaya geser maksimum yang dapat diterima struktur adalah 18344.6041 kN dengan displacement 291,435 mm akibat Push-X, dan 18611.7226 kN dengan nilai displacement 190.459 mm akibat Push-Y. Displacement yang terjadi masih dibawah displacement izin yaitu 2%xH yaitu 442 mm. Didapat maksimum total drift 0.013 arah X, 0.010 arah Y serta maksimum In-elastic drift 0.011 arah X & 0.006 arah Y, sehingga berdasarkan Drift Limitation parameter level kinerja, struktur gedung tinjauan termasuk dalam level Damage Control (DC). Dari masing-masing tinjauan gempa riwayat waktu didapatkan Hasil Analisis Nonlinear Time History Northridge 1994 dengan Drift Maksimum 2.45 %. Riwayat Gempa Kobe 1995 7.598 %, Riwayat Gempa Chichi 5.757 % dan Penskalaan Riwayat Gempa Padang 2.174 %.

Kata kunci : kapasitas struktur, struktur tidak beraturan, pushover, THA, FEMA 356, FEMA 440

ABSTRACT

Padang City, the capital of West Sumatra, is one of the earthquake-prone regions in Indonesia due to its location between two of the world's active tectonic plates. In earthquake-resistant buildings, the geometry of the structural layout plays a crucial role in how the building responds to seismic forces. Regular, simple, and symmetrical structures tend to perform better during earthquakes compared to irregular ones. The purpose of the research is to evaluate the building's structural capacity under seismic loads, including identifying potential failure mechanisms. The analysis was carried out using the nonlinear pushover method with ETABS software to perform a performance-based design evaluation. The output parameters and structural performance assessment were based on the standards of the Applied Technology Council ATC-40, FEMA 356, and FEMA 440 guidelines. Based on the results, the maximum shear force the structure can withstand is 18,344.6041 kN with a displacement of 291.435 mm under Push-X, and 18,611.7226 kN with a displacement of 190.459 mm under Push-Y. These displacement values remain below the allowable limit of 2% of the building height (H), which is 442 mm. The analysis also revealed a maximum total drift of 0.013 in the X-direction and 0.010 in the Y-direction, while the maximum inelastic drift was 0.011 in the X-direction and 0.006 in the Y-direction. According to Drift Limitation performance parameters, the structure falls under the Damage Control (DC) performance level. Further nonlinear Time History analysis using different earthquake records showed the following maximum drift values Northridge 1994 Earthquake 2.45%, Kobe 1995 Earthquake 7.598%, Chichi Earthquake 5.757%, Scaled Padang Earthquake Record 2.174%. These results demonstrate how different earthquake events affect the performance of an irregular building and

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highlight the importance of conducting detailed seismic evaluations in earthquake-prone regions such as Padang.

Keyword : structural capacity, irregular structure, pushover, time history analysis (THA), FEMA 356, FEMA 440

1. INTRODUCTION

The development of multi-story buildings has significantly accelerated in recent years, including the construction of hotels, office complexes, hospitals, and other facilities. In order to meet architectural aesthetics and accommodate limited land availability, building designs have increasingly moved away from traditional square or symmetrical layouts, adopting irregular structural forms. These irregular designs pose challenges in terms of structural integrity and seismic resistance, making earthquake-resistant design a critical consideration, especially in earthquake-prone areas.

Padang City, the capital of West Sumatra Province, is located along the western coast of Sumatra Island. Geographically, this region is highly susceptible to seismic activity due to its position between two active tectonic plates. A major earthquake struck Padang on September 30, 2009, with a magnitude of approximately 7.9 on the Richter scale, causing significant structural failures, total collapse of buildings, and extensive damage throughout the city [1].

Seismic design codes and standards are established to accommodate the varied responses of different building structures under earthquake loading. The seismic response of a building is strongly influenced by its geometry. Buildings with regular, simple, and symmetrical forms generally perform better during seismic events compared to irregular ones [2].

Irregular buildings, particularly those with horizontal irregularities, are more susceptible to torsion and eccentric behavior due to the discrepancy between the center of mass and center of rigidity. These conditions can lead to larger internal forces and reduced structural performance [3].

To evaluate seismic performance, nonlinear static pushover analysis is commonly used, in accordance with Indonesian standards SNI 1726:2019, SNI 2847:2019, and SNI 1727:2020. Pushover analysis simulates the effect of seismic forces as gradually increasing static lateral loads applied at the center of mass of each floor. These loads are increased until the structure yields, forming plastic hinges, and continues until it reaches post-elastic deformation and potential collapse [4].

Based on these considerations, this study aims to analyze the structural performance of an existing horizontally irregular building located in Padang City using both nonlinear pushover and time history analysis. The main objectives are to determine the maximum displacement and base shear capacity of the structure and to evaluate structural drift and overall performance under real earthquake records.

2. LITERATURE REVIEW

Horizontally irregular buildings, which exhibit plan asymmetry, re-entrant corners, non-uniform stiffness or mass distribution, and structural discontinuities, tend to experience complex seismic behavior dominated by torsion, drift concentration, and higher-mode effects. According to SNI 1726:2019, buildings are classified as regular or irregular based on their horizontal and vertical configurations, since the seismic response of irregular structures differs substantially from that of regular ones. As emphasized by Schodek [5], seismic forces are inertial and directly related to mass; an asymmetrical mass distribution can induce torsional moments that may lead to collapse, whereas symmetric structures are less affected and thus more desirable in seismic design. To evaluate seismic performance, pushover analysis has been widely applied as a nonlinear static procedure capable of estimating maximum base shear, performance levels, and collapse mechanisms under gradually increasing lateral loads, producing capacity curves that relate base shear to displacement. This method, central to performance-based seismic design, is supported by guidelines such as ATC-40 (1996), FEMA 356, and FEMA 440

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[6]-[8], which further classify performance levels into Immediate Occupancy (IO), Damage Control (DC), Life Safety (LS), and Structural Stability (SS), each associated with drift ratio limits that define seismic capacity. However, while conventional pushover analysis is computationally efficient, it is limited in capturing higher-mode and torsional effects in irregular buildings. To address this, improved methods such as multi-mode pushover, modal pushover, and bidirectional pushover analysis have been developed, offering better accuracy in representing torsional demand and redistribution effects [9]. Comparative studies highlight that pushover analysis may underestimate or misrepresent demands in irregular structures, whereas nonlinear time-history analysis (NTHA) provides more reliable results by explicitly capturing dynamic response, torsional behavior, and ground-motion variability [10], [11]. Consequently, a combined approach is often recommended, using enhanced pushover analysis for preliminary evaluation of capacity and weak zones, followed by NTHA for final verification of critical or highly irregular structures to ensure seismic safety.

3. METHOD

The analysis in this study is conducted based on the following standards and guidelines:

1. **SNI 1726:2019** – *Code for Seismic Resistance Design of Buildings and Non-Building Structures* (Tata Cara Perencanaan Ketahanan Gempa untuk Struktur Gedung dan Non-Gedung) [12];
2. **SNI 2847:2019** – *Requirements for Structural Concrete for Buildings* (Persyaratan Beton Struktural untuk Bangunan Gedung) [13];
3. **SNI 1727:2020** – *Minimum Load Requirements for the Design of Buildings and Other Structures* (Beban Minimum untuk Perancangan Bangunan Gedung dan Struktur Lain) [4];
4. **ATC-40**, **FEMA 356**, and **FEMA 440** – International guidelines used for nonlinear static analysis (pushover) and performance-based seismic evaluation of buildings [6]–[8].

Following this, data collection was carried out to obtain the necessary input parameters for the analysis. The calculation stages included: structural modeling in ETABS, input of structural and material data, execution of nonlinear pushover analysis, and interpretation of the resulting structural performance outputs such as base shear, displacement, and plastic hinge formation. The results were then evaluated to determine the structural capacity and seismic performance level according to the referenced standards.

3.1 Building Data

In this study, the building selected for analysis is the Fave Hotel, located in Padang City, West Sumatra, at coordinates Latitude: -0.9455437° and Longitude: 100.353717°. The building's key characteristics are as follows (Figure 1-3).

a. Function: Hotel
b. Number of Stories: 6 Floors
c. Total Height: 25.20 meters
   Structural Height: 22.10 meters
d. Building Length: 54.00 meters
e. Building Width: 16.30 meters
f. Structural Materials: Reinforced Concrete
   Material Type: Concrete
   - Concrete Strength (f'c): 30 MPa
   - Modulus of Elasticity (Ec): 4700 $\sqrt{f'c}$ MPa
   - Unit Weight (λc): 2400 kg/m³
   - Poisson's Ratio (νc): 0.2

   Material Type: Steel
   - Longitudinal Reinforcement Yield Strength (Fy): 400 MPa
   - Transverse Reinforcement Yield Strength (Fy): 240 MPa
   - Modulus of Elasticity (Es): 200,000 MPa
   - Poisson's Ratio (νs): 0.3

g. Structural Element Dimensions:
   - Column 1: 500 mm × 800 mm
   - Column 2: 300 mm × 700 mm
   - Beam 1: 350 mm × 700 mm
   - Beam 2: 250 mm × 500 mm
   - Beam 3: 350 mm × 600 mm
   - Floor Slab Thickness: 150 mm
   - Roof Slab Thickness: 120 mm

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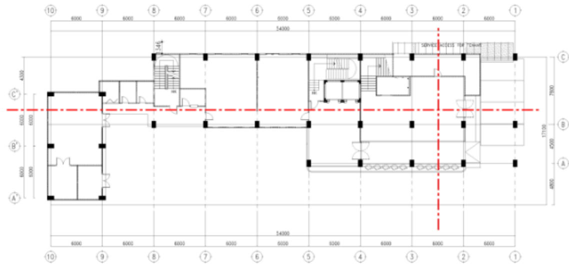

Figure 1. Existing Typical Floor Plan

Figure 2. Left Elevation

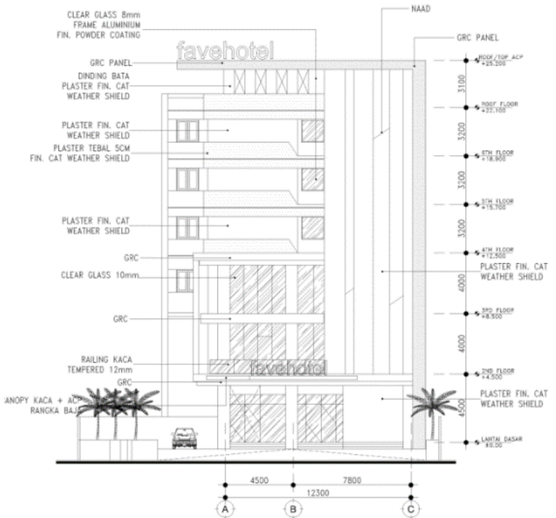

Figure 3. Front Elevation

3.2 Loading Assumptions

The structural load assumptions in this study were determined based on the functional use of the building and standard design practices as defined in relevant codes and guidelines. The considered loads include Dead Load, which consists of the self-weight of structural elements such as beams, slabs, and columns; Superimposed Dead Load (SIDL), representing additional permanent loads such as flooring and partitions; Live Load, which varies depending on the building's occupancy type; and Roof Live Load, which accounts for maintenance or limited-access loading on the roof. These loading conditions were defined in accordance with common structural engineering standards [14].

In addition to gravity-related loading, nonlinear static (pushover) load cases were defined to simulate the building's seismic response. These include the Gravity Load Case, consisting of a combination of dead and live loads under typical service conditions, and two lateral seismic load cases: Pushover X (lateral force in the global X-direction) and Pushover Y (lateral force in the global Y-direction). These pushover scenarios were modeled to evaluate the inelastic behavior of the structure under earthquake loading, following established methodologies in performance-based seismic evaluation [15], [16].

3.3 Structural Modeling & Analysis

The modeling and analysis were carried out using ETABS v16.2 software (Figure 4 and 5). The structure modeled is an existing building consisting of six floors.

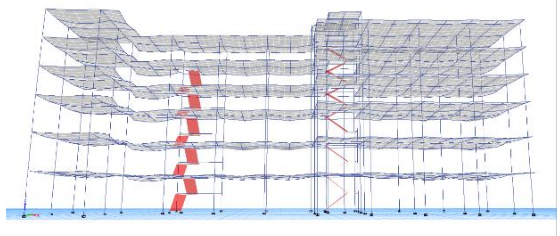

Figure 4. 3D Structural Modeling Using Software

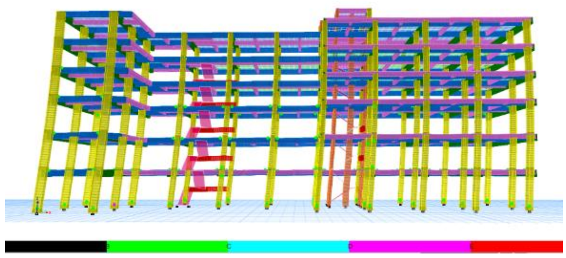

Figure 5. Longitudinal Perspective

This study presents a nonlinear static (pushover) analysis of an existing six-story reinforced concrete building using ETABS v16.2.1. The structural model was developed

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based on as-built data, with structural elements such as beams, columns, and floor slabs modeled and assigned appropriate material properties and cross-sectional definitions. Structural loads, including dead load, live load, and additional imposed loads, were applied according to relevant codes and assumptions. Key modeling considerations included meshing of floor slabs, diaphragm definition, rigid zone factors, end offsets, boundary conditions, and mass source definition.

Pushover analysis was performed using three primary load cases: GRAVITY (100% dead load and 25% live load), PUSH-X, and PUSH-Y, the latter two involving lateral loads in the X and Y directions, respectively. Displacement control was set at 2% of the total building height (504 mm). Plastic hinges were defined at the ends of all primary beams and columns to simulate potential yielding.

The results of the analysis were evaluated using the Capacity Spectrum Method as proposed in ATC-40 [5], and the Displacement Coefficient Method in FEMA 356 and FEMA 440 [6], [7]. The analysis produced capacity curves illustrating the relationship between base shear and roof displacement, and showing the distribution of plastic hinges throughout the structure. These results provide valuable insights into the seismic performance and nonlinear behavior of the existing building.

4. Results and Discussion

The pushover analysis results obtained from ETABS v16.2 software include the Capacity Curve and the yielding scheme, which illustrates the distribution of plastic hinges formed in the structure. At the Performance Point, the maximum base shear and maximum displacement are identified. These results are derived from the pushover analysis runs under three load cases: Nonlinear Gravity Case, Nonlinear Pushover Case in the X-direction, and Nonlinear Pushover Case in the Y-direction.

The maximum drift values are obtained from the earthquake load analysis using Nonlinear Time History Analysis.

4.1 Capacity Curve

The Capacity Curve represents the relationship between Base Shear and the Monitored Displacement (roof displacement) that occurs until the structure reaches collapse. This curve illustrates how the structure behaves from initial elastic response to inelastic deformation leading to failure. The Capacity Curves showing the relation between base shear and roof displacement can be seen in Figures 6 and 7 below.

Figure 6 illustrates the capacity curve for the structure under a nonlinear static pushover analysis in the X direction. The curve represents the relationship between base shear (kN) and monitored displacement (mm), capturing the structure’s ability to resist lateral loads before significant inelastic deformation occurs. As shown, the curve initially rises linearly, indicating elastic behavior, until approximately 150 mm of displacement. Beyond this point, the slope gradually decreases, reflecting a transition into the nonlinear range where stiffness begins to degrade. The curve reaches a peak base shear of approximately 17,600 kN at around 298 mm displacement, marking the structure's ultimate lateral load capacity. The overall trend of the curve is typical of a ductile structure with a gradual softening response, suggesting that the building can undergo considerable lateral deformation before failure. This capacity curve serves as a crucial input for performance-based seismic design and fragility assessment, allowing for the identification of damage thresholds and comparison with seismic demand spectra.

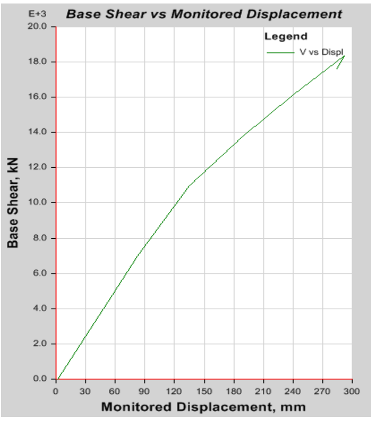

Figure 6. Capacity Curve Push X

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The figure 7 illustrates the relationship between Base Shear (kN) and Monitored Displacement (mm) for a structural system. As observed, the base shear increases progressively with displacement, indicating a nonlinear response behavior. Initially, the curve rises steeply, reflecting a stiffer response at lower displacements. As displacement continues to increase, the slope of the curve gradually decreases, suggesting stiffness degradation and a shift toward nonlinear structural performance. The maximum monitored displacement reaches approximately 180 mm, corresponding to a base shear capacity of nearly 19 kN. This trend highlights the structural system's resistance to lateral loading and provides valuable insight into its strength and ductility characteristics.

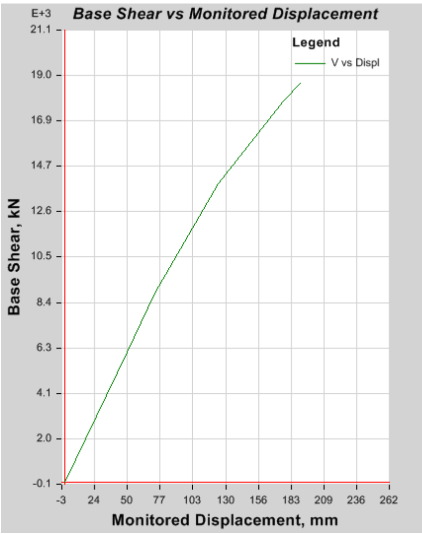

Figure 7. Capacity Curve Push Y

4.2 Maximum Drift

The results of the Time History Analysis are presented as curves depicting the relationship between time and structural displacement under a given seismic excitation. The maximum drift value is a critical parameter, representing the tangent of the structure's inclination, calculated by dividing the maximum displacement by the building height. In this study, the maximum drift induced by the earthquake is used to determine the fragility curves. The following are the results of the nonlinear Time History Analysis for each ground motion considered.

Table 1. Northridge Earthquake '1994

Scalling Factors	PGA Scalled (g)	Maximum Drift (%)
0.25	0.31	0.316
0.50	0.62	0.632
0.75	0.92	0.944
1.00	1.23	1.251
1.25	1.54	1.551
1.50	1.85	1.853
1.75	2.15	2.152
2.00	2.46	2.450

Table 2. Kobe Earthquake '1995

Scalling Factors	PGA Scalled (g)	Maximum Drift (%)
0.25	0.14	0.955
0.50	0.29	1.893
0.75	0.43	2.828
1.00	0.57	3.774
1.25	0.71	4.726
1.50	0.86	5.682
1.75	1.00	6.639
2.00	1.14	7.598

Table 3. Chi-chi Earthquake '1999

Scalling Factors	PGA Scalled (g)	Maximum Drift (%)
0.25	0.13	0.726
0.50	0.27	1.441
0.75	0.40	2.152
1.00	0.53	2.872
1.25	0.66	3.596
1.50	0.80	4.317
1.75	0.93	5.036
2.00	1.06	5.757

Table 4. Padang Earthquake '2009

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Scalling Factors	PGA Scalled (g)	Maximum Drift (%)
0.25	0.18	0.273
0.50	0.36	0.546
0.75	0.54	0.820
1.00	0.72	1.096
1.25	0.90	1.369
1.50	1.08	1.639
1.75	1.26	1.907
2.00	1.44	2.174

A key output of this analysis is the maximum drift, which quantifies the extent of lateral deformation by expressing the ratio of maximum displacement to the total height of the structure—essentially reflecting the inclination or "lean" of the building during an earthquake. This parameter is critical for evaluating structural performance and is used as the basis for constructing fragility curves [14], which assess the probability of reaching or exceeding various damage states.

For the Northridge 1994 earthquake (Table 1), the maximum drift increased from 0.316% at a scaled PGA of 0.31g to 2.450% at 2.46g. In contrast, the Kobe 1995 earthquake (Table 2) induced more severe drift, rising from 0.955% at 0.14g to a substantial 7.598% at 1.14g, indicating a more damaging motion profile even at lower PGA values. Similarly, the Chi-Chi 1999 earthquake (Table 3) showed a progressive increase in drift, from 0.726% at 0.13g to 5.757% at 1.06g. The Padang 2009 earthquake (Table 4), however, resulted in lower drift values overall, ranging from 0.273% at 0.18g to 2.174% at 1.44g. These results emphasize the influence of different ground motions on structural behavior and highlight the necessity of ground motion-specific analysis when developing fragility functions [16].

5 CONCLUSION

Based on the analysis and evaluation of the Fave Hotel building structure in Padang City, West Sumatra—which falls under the category of irregular structures—the following conclusions can be drawn. The pushover analysis using ETABS software revealed that the maximum base shear the structure can resist in the X-direction is 18,344.6041 kN, with a corresponding displacement of 291.44 mm (0.29 m). In the Y-direction, the structure was able to resist a slightly higher base shear of 18,611.7226 kN, with a lower displacement of 190.459 mm (0.19 m). These results indicate differing stiffness and capacity along the two principal axes of the structure, which is typical of irregular building behavior.

Furthermore, the nonlinear time history analysis using several earthquake records produced varying maximum drift values. The Northridge 1994 earthquake resulted in a maximum drift of 2.45%, while the Kobe 1995 record produced a significantly higher drift of 7.598%. The Chi-Chi 1999 earthquake resulted in 5.757%, and the scaled Padang earthquake record produced a drift of 2.174%. These results provide insights into the building's dynamic response and highlight the importance of considering multiple ground motion scenarios in performance-based seismic evaluations.

It is recommended that further assessment be conducted to determine whether retrofitting is necessary, particularly considering the high drift values observed in some earthquake scenarios. Additionally, adopting performance-based design approaches and incorporating damping or energy dissipation systems could enhance the seismic resilience of similar irregular structures in seismic-prone regions.

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