Seismic Performance of Asymmetric Hospital Building Structures using Pushover Analysis Based on ATC-40 Guidelines

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Keywords: Structure of the building, ATC-40, Pushover Analysis.

Abstract. Hospital buildings play a vital role in public service delivery, especially during and after earthquake events. Therefore, ensuring seismic resistance in hospital building design is essential. The case study in this research is a five-story hospital building located on Jalan Diponegoro No. 50, Ponorogo, East Java, Indonesia. The building features an L-shaped floor plan without structural separation (dilatation) and utilizes reinforced concrete as its primary structural system. Constructed in 2018, it was originally designed under the guidance of SNI 2847:2002 and SNI 1726:2012. This study uses pushover analysis based on ATC-40 and updated seismic criteria in SNI 1726:2019 to evaluate the hospital building's structural performance. The findings of the analysis show that the structure satisfies the Immediate Occupancy performance level; however, to guarantee the best possible post-earthquake functionality, structural details upgrades are advised.

Introduction

Indonesia is categorized as a high seismic risk region due to its position at the convergence of four major tectonic plates. Therefore, seismic-resistant structural design is crucial, particularly for essential facilities such as hospitals [1]. The development of hospital infrastructure is a key priority in public facility management, especially in post-earthquake recovery efforts. As such, the design of earthquake-resistant hospital buildings is of utmost importance [2]. In structural planning, several factors must be considered, including strength, stability, comfort, and economic feasibility. Additionally, the location of the building is a critical factor, as it directly affects the intensity of seismic forces that may act upon the structure [3].

Construction codes and regulations continue to be updated periodically to ensure accurate, safe, and efficient structural design. These updates often include revisions to dimensional and reinforcement requirements for structural components in building systems [4]. For instance, current codes regulate both the reinforcement detailing in concrete structures and the determination of seismic loads acting on a building [5].

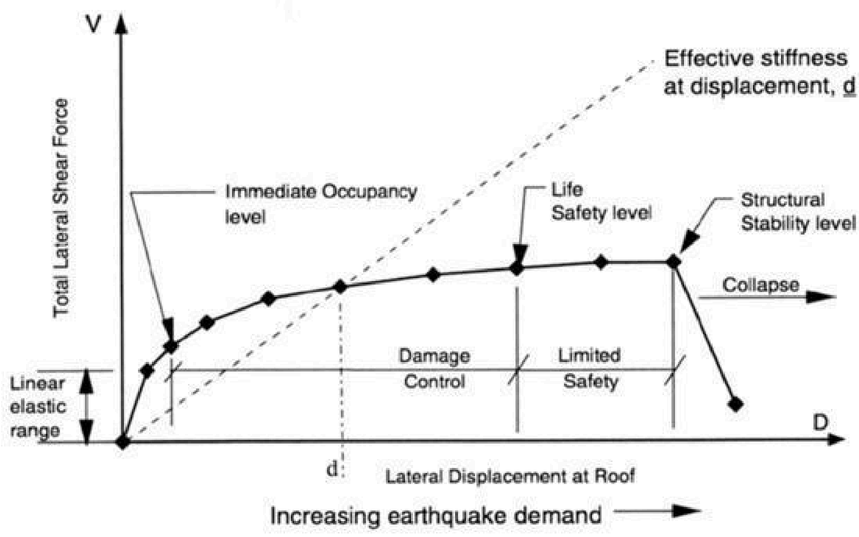
Structures with geometric irregularities, whether in vertical or horizontal configuration, are more vulnerable to earthquake damage compared to buildings with more regular forms [6]. Therefore, proper structural design is essential to ensure a building's safety, stability, and usability following seismic events. Indonesia is divided into six seismic zones, where Zone 1 represents the lowest seismic hazard and Zone 6 the highest [7]. The structural performance of irregular buildings differs from that of regular buildings under the same load intensity, particularly when evaluated in terms of displacement, drift, and reinforcement detailing [8].

Literature References

Buildings with a limited number of columns or walls on certain floors, or with unequal story heights, often exhibit a soft story condition, which tends to initiate structural damage or even collapse starting from the irregular level [9]. An earthquake is a sudden ground movement caused by the release of energy accumulated over a long period within the Earth's crust. As a result, earthquakes frequently lead to loss of life, material damage, and the destruction of infrastructure [10]. The increasing intensity of earthquakes is an important concern for infrastructure planners, particularly in building design. Structural planning for buildings in Indonesia must comply with current regulations and keep up with developments in seismic design standards [11].In the context of earthquake-resistant design, it is crucial to predict the formation mechanism of plastic hinges, as this allows engineers to determine the building's expected seismic performance level. This performance level reflects the degree of damage a structure may experience during a seismic event and is used to classify the safety and functionality of a building after an earthquake [12].

Basic Concept of Earthquakes. Seismic force is directly proportional to the mass of the structure and the ground acceleration at the building's location. According to Newton's Second Law, the magnitude of the seismic force is defined as $F = m \times a$, where m represents the mass of the structure and a denotes the ground acceleration during an earthquake [13]. The SNI 1726:2019 standard is the latest seismic design code in Indonesia, replacing SNI 1726:2012, which was considered inadequate due to the significant structural damage caused by past earthquakes in the country [14]. Structural performance refers to the ability of a building to respond to a design-level earthquake, and it is typically classified into different performance levels based on expected behavior under seismic loading [15].

Performance of Structures. The performance level, or degree of damage, is determined by the state of the structure and its structural elements [16]. The ability of a structure to react to an earthquake at the design level is known as structural performance. The degree of damage the structure sustains during an earthquake with a predetermined return duration can be used to assess this performance level[17]. As a result, the cost of repairing the building's damage is directly related to the structural system's performance level. Without sacrificing the building's occupants' safety, performance-based structural design usually aligns the planned performance with the building's function and purpose while taking economic considerations such possible earthquake repair costs into account [18]. To reduce the risk of structural collapse and resulting damage, as well as to prevent hazardous collisions between adjacent buildings or separated structural components, the ultimate performance limit of the building is defined by assessing the maximum inter-story



drift caused by seismic impact. This evaluation is conducted under the condition that the structure is at the verge of collapse[19] .

Nonlinear Static Analysis Concept (Pushover Analysis). By determining the maximum deformation forces that the structure encounters, pushover analysis is utilized to pinpoint the critical areas. These crucial regions are therefore given extra care to improve details and guarantee structural stability[17].

Fig. 1. Structural Performance Levels of a Building by ATC-40 [20]

Analysis Assessment Procedure. According to the Capacity Spectrum Method, the connection between the response spectrum curve and the capacity curve is known as the performance point (ATC-40, 1996). Information about the building's lifespan and effective damping caused by the development of plastic hinges can be found at the performance point. Other structural reactions, like interstory drift and the positioning of plastic hinges, can also be determined using this data [21]. The Capacity Spectrum Method graphically presents two curves referred to as spectra: the capacity spectrum, which shows the relationship between total base shear and lateral displacement (usually measured at the roof level) to determine the structural capacity [22]. Six performance levels are used to classify the structural performance of buildings. Level 3: Immediate Occupancy, Structural Stability, Life Safety, Limited Safety, Damage Control, and Non-Considered are the first six categories. The **Fig. 1** depicts these performance levels [23].
ATC-40 provides drift ratio limits used to evaluate structural performance. These drift ratio limits are presented in **Table 1**.

Table 1. ATC-40 Roof Drift Ratio Limits for Different Structural Performance Levels [20].

Parameter	Structural Performance Levels			
	Immediate occupancy	Damage control	Life safety	Structural stability
Maximum Total Drift	0,01	0,01-0,02	0,02	0,033-Vi/Pi
Maximum Inelastic Drift	0,005	0,005-0,015	Not limited	Not limited

Method

Muhammadiyah Hospital Ponorogo, which is situated at Jalan Diponegoro No. 50, Ponorogo Regency, serves as the case study for this investigation. The construction is a five-story reinforced concrete building with a letter "L"-like layout that lacks structural separation (dilatation).
Structural Elements. The data used consists of existing data obtained from the Hospital Development Planning Consultant, as presented in **Table 2.**

Tabel 2. Data of Structural Elements Used

Column	Beam
Main Column K1 600/600	Main Beam B1 700/400
Main Column K2 500/500	Secondary Beam B2 500/300
Main Column K3 400/400	Secondary Beam B3 600/300
Main Column K4 300/500	

Evaluation Stages. The data gathering phase of this study started with the building's technical drawings, loading data, and structural material specifications. The geometric arrangement and configuration of the structural elements were comprehended through the use of the drawings. According to SNI 1726:2019, Dead loads, live loads, and seismic loads were all included in the loading data, and the concrete and reinforcing steel quality criteria were included in the material data. Upon completion of data collection, structural modeling and evaluation were conducted using SAP2000 software to analyze the building system's behavior under seismic loading. he structure's ability to tolerate seismic forces gradually until failure was then assessed using a pushover analysis, a nonlinear static approach. After that, a performance review was conducted in accordance with SNI 1726:2019's seismic requirements and ATC-40 criteria. The development of conclusions on the building's structural performance level marked the end of this stage. Using SAP2000 software, structural modeling was done using the data from the structural elements.

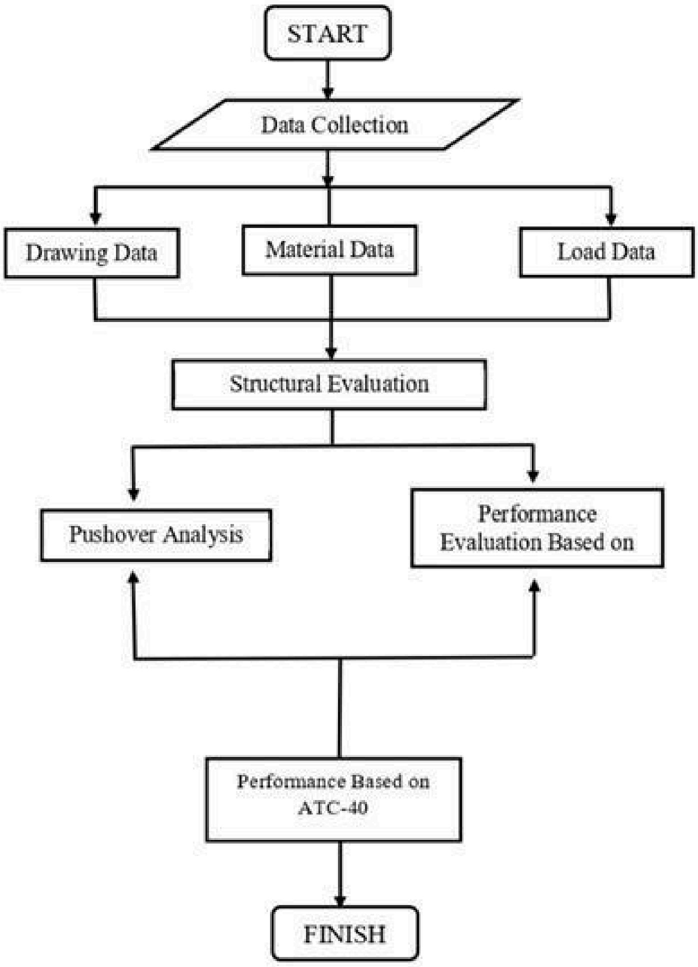


Fig. 2. Flow Chart Research

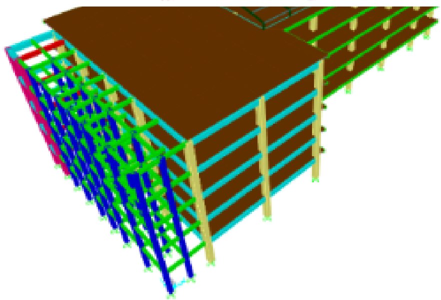


Fig. 3. 3D View of the Building

Result and Discussion

Structural Performance. The loading considered in the structural modeling includes dead loads, live loads, and seismic loads. In this structural analysis, dynamic earthquake loading was applied using the response spectrum method. The response spectrum function was defined based on the seismic hazard map corresponding to medium soil conditions (Site Class SD) at coordinates Longitude 111.461° and Latitude -7.866°.

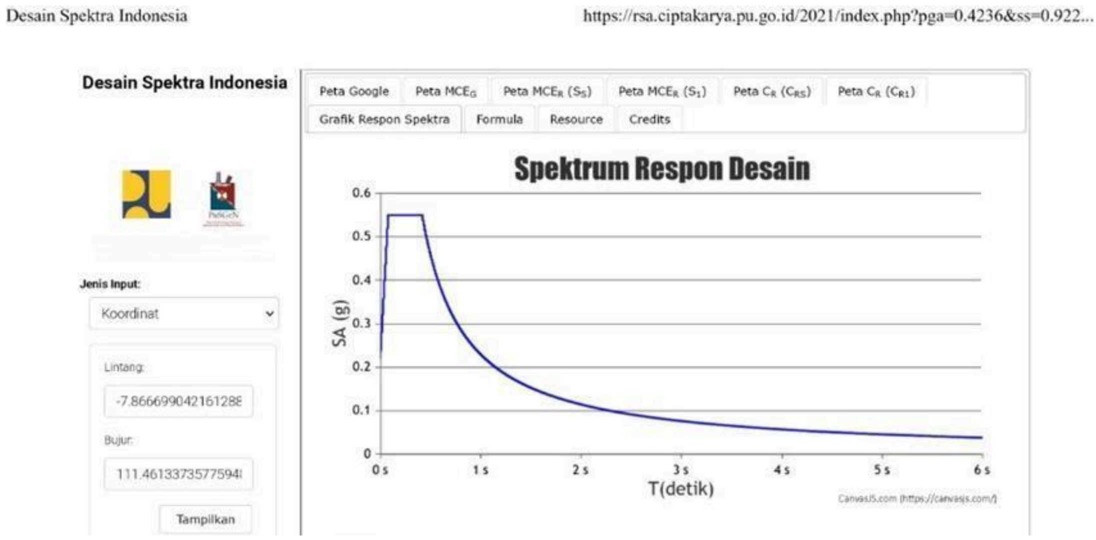


Fig. 4. Seismic parameters and the response spectrum function were obtained from RSA2021

Drift Analysis. According to SNI 1726:2019, calculations were made based on the displacement data to compare the structural displacement with the target displacement for hospital buildings. The findings were as follows:

Table 3. Structural Performance Limit Control due to Equivalent Static Earthquake Load in the X Direction

Story	h (mm)	*Δs Drift in the direction of X (mm)*	*Δs Inter-story Drift (mm)*	Drift Limit (mm)	*ΔM Drift in the direction of X (mm)*	*ΔM Inter-story Drift (mm)*	Drift Limit (mm)	Remar
5	19250	*38,84*	4,24	15,00	23,77	15,22	77,00	OK
4	15400	*34,60*	6,96	15,00	38,99	14,55	77,00	OK
3	11550	27,64	9,56	15,00	53,53	6,64	77,00	OK
2	7700	18,08	10,75	15,00	60,18	19,12	77,00	OK
1	3850	7,33	7,33	15,00	41,05	41,05	77,00	OK

Table 4. Structural Performance Limit Control due to Equivalent Static Earthquake Load in the Y Direction

Story	h (mm)	*Δs Drift in the direction of Y (mm)*	*Δs Inter-story Drift (mm)*	Drift Limit (mm)	*ΔM Drift in the direction of Y (mm)*	*ΔM Inter-story Drift (mm)*	Drift Limit (mm)	Remar
5	19250	40,69	4,69	15,00	26,25	16,05	77,00	OK
4	15400	36,00	7,55	15,00	42,31	13,06	77,00	OK
3	11550	28,44	9,89	15,00	55,36	5,90	77,00	OK
2	7700	18,56	10,94	15,00	61,26	18,60	77,00	OK
1	3850	7,62	7,62	15,00	42,66	42,66	77,00	OK

Pushover Analysis Results. the SAP2000 analysis shows that the base shear versus displacement curve in the X direction shows that the peak base shear was around ±4,628,763 N, and the largest displacement was about 49.23 mm. This number shows that the structure can endure large lateral forces before suffering from a considerable loss of stiffness. In the meantime, a peak base shear of roughly 7.9×10^6 N is visible in the base shear versus displacement curve in the Y direction.

Table 5. Pushover capacity curve in the X direction

LoadCase	Step	Displacement	BaseForce	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	BeyondE	Total
Text	Unitless	mm	N	Unitless	Unitless	Unitless	Unitless	Unitless	Unitless	Unitless	Unitless
PUSH X	0	0	0	3126	0	0	0	0	0	0	3126
PUSH X	1	5.4139	1051040.42	3102	24	0	0	0	0	0	3126
PUSH X	2	33.1922	6374142.72	2949	277	0	0	0	0	0	3126
PUSH X	3	43.1922	7625720,98	2841	285	0	0	0	0	0	3126
PUSH X	4	43.1927	7620798,36	2841	285	0	0	0	0	0	3126
PUSH X	5	43.1927	7621077,63	2841	285	0	0	0	0	0	3126

Table 6. Pushover capacity curve in the Y direction

LoadCase	Step	Displacement	BaseForce	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	BeyondE	Total
Text	Unitlees	mm	N	Unitless	Unitless	Unitless	Unitless	Unitless	Unitless	Unitless	Unitless
PUSH Y	0	0	0	3126	0	0	0	0	0	0	3126
PUSH Y	1	-0.079764	3044435.96	3122	4	0	0	0	0	0	3126
PUSH Y	2	-0.095525	3900879.54	3046	80	0	0	0	0	0	3126
PUSH Y	3	-0.095942	3935470.24	3038	88	0	0	0	0	0	3126
PUSH Y	4	-0.097031	4094368.16	3022	104	0	0	0	0	0	3126
PUSH Y	5	-0.097206	4208655.56	3010	116	0	0	0	0	0	3126
PUSH Y	6	-0.106972	7685538.85	2573	553	0	0	0	0	0	3126
PUSH Y	7	-0.126503	7411540.08	2569	557	0	0	1	0	0	3126
PUSH Y	8	-0.126527	7411870.24	2569	557	1	0	1	0	0	3126
PUSH Y	9	-0.188718	7760252.19	2543	582	17	0	1	0	0	3126
PUSH Y	10	-0.20104	7899128.8	2518	606	18	0	2	0	0	3126

The roof displacement was 43.192 mm in the X direction and 0.243 mm in the Y direction, as indicated in **Table 5** and **6**. Since the observed displacements are less than the displacement limit (control), which is 2% of the building height, or 2% × 19.25 m = 0.38 m, the displacement performance of the building can be deemed adequate.

Based on the pushover curves generated by SAP2000 in the X and Y axes, **Table 7** displays the pertinent data.

Table 7. Performance Point Values

Parameter	X Direction	Y Direction
Performance Point (V ; D)	4,337,763 ; 22.566	4,296,742 ; -0.097
Performance Point (S_a ; S_d)	0.09 ; 17.456	0.09 ; 16.656
Performance Point (T_{eff} ; B_{eff})	0.08 ; 0.051	0.862 ; 0.056

Level of Structural Performance The structural performance level is determined based on the drift ratio limits presented in **Table 1**.

Table 8. Level of Structural Performance

Parameter	X Direction	Y Direction	Structural Performance Level
Maximum Total Drift (D_t/H)	0.043/19.25 = 0.002	0.002/19.25 = 0.0001	Immediate Occupancy
Inelastic total drift maksimum ((D_t-D_1)/H)	(0.043 – 0.005) / 19.25 = 0.001	(.002-0.000079)/19,25 = 0.000099	Immediate Occupancy

As can be seen in **Table 8**, The hospital building's performance level is classified as Immediate Occupancy, which means that it has little to no structural or non-structural damage and is fully operational after an earthquake.

Conclusion

The analysis of the hospital building's performance indicates that the performance level in both the X and Y directions is below the operational level. This suggests that the building may continue to operate almost exactly as it did prior to the earthquake, with little chance of structural failure or casualties. Using the capacity spectrum method from ATC-40, the pushover analysis findings show a maximum total drift of 0.0001 m in the Y direction and 0.002 m in the X direction. The structural condition matches the Immediate Occupancy (IO) level in accordance with the ATC-40 performance standards. This indicates that the building can withstand a seismic event with very little structural or non-structural damage and still be fully operational. In other words, after experiencing a design-level earthquake, the building not only maintains its integrity but is also immediately safe for reoccupation and continued use, without the need for major repairs.

Recommendations

Based on the analysis results, it is recommended to conduct regular maintenance and periodic inspections of structural elements such as columns, beams, and joints. This is essential to ensure the building maintains optimal performance and to prevent functional decline due to minor damage. For similar structures located in seismic-prone areas, the implementation of comparable strengthening methods is advised to enhance shear capacity, reduce displacement, and improve structural stability and stiffness. These measures help minimize the risk of damage and provide greater assurance of occupant safety.

Further recommendations from this study include implementing retrofitting techniques for vulnerable structural components and considering the incorporation of separation joints (dilatations) in future design modifications. These measures aim to reduce torsional effects and enhance the overall seismic resilience of the building.

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