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Investigation of seismic resistant structures with various moment-resisting frame systems and pushover analysis

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Abstract
Earthquakes are a serious threat in the construction of multi-storey buildings in Indonesia, which are divided into several seismic design categories. The design of seismic-resistant buildings requires the management of plastic hinges to reduce seismic loads. The aspects of seismic-resistant structural design in Indonesia are regulated by SNI 1726:2019, SNI 1727:2020, and SNI 2847:2019. Intermediate Moment Resisting Frame System (IMRFS) and Special Moment Resisting Frame System (SMRFS) are used based on seismic category and earthquake intensity. Pushover analysis is used to analyze the structures behavior when exposed to seismic loads. This research designs seismic resistant structures with IMRFS and SMRFS at different locations with the aim of assessing structural performance and gaining reinforcement to the concrete ratio, which is relevant for the design and construction of multi-storey buildings in Indonesia. The results of this research are the structural performance levels, reinforcement volume, concrete volume, and the reinforcement to concrete volume ratio. Both IMRFS and SMRFS reached Immediate Occupancy to Life Safe performance levels after the earthquake because their monitored displacement was not significantly different. The structural failure modes of both systems meet the Strong Column–Weak Beam requirements. The distribution of plastic hinges also remains in the Immediate Occupancy category.

Keywords:
Deformation;
IMRFS;
Pushover Analysis;
Seismic Shear Force;
SMRFS;

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INTRODUCTION

Earthquakes are a serious threat in designing multi-storey buildings in Indonesia. Earthquake locations in Indonesia are divided into several seismic design categories, from A to F, based on the strength of the earthquake and the risk that occurs [1, 2, 3]. Therefore, earthquake strength must be considered in planning the multi-storey building [3]. In designing seismic-resistant buildings, the formation of plastic hinges must be managed to reduce the seismic load received by the structure. This aims to make the building survive and not collapse when an earthquake occurs [1, 2, 3, 4, 5, 6, 7].

The design aspects of seismic-resistant structures in multi-storey buildings in Indonesia are regulated in SNI 1726:2019, SNI 1727:2020, and SNI 2847:2019. Moment Resisting Frame Systems are used following the seismic design categories applicable to the specific area [8][9]. Special Moment Resisting Frame System (SMRFS) is often used for areas with seismic categories D, E, and F which have a full level of ductility [10]. On the other hand, the Intermediate Moment Resisting Frame System (IMRFS) is generally used in areas that are more prone to earthquakes with a B-C seismic design and a moderate level of ductility [11]. This shows that the treatment of seismic loads is different, even though the building structures have a similar layout. In IMRFS, the applied seismic loads tend to be greater than those applied in SMRFS, which is in line with SNI guideline 1726:2019 [12, 13, 14, 15]. In addition, SMRFS produces a more robust structure than using IMRFS [16, 17, 18, 19, 20, 21]. With a good understanding of how these systems behave in different seismic situations, building designers can design stronger and safer buildings [18, 20, 23, 24]. The level of the structural performance of multi-storey buildings can be investigated using the pushover analysis method [14, 15, 25].

Pushover analysis is used to evaluate the behavior and performance of a structure when exposed to seismic loads or other lateral loads [13, 26, 27]. This method aims to investigate the extent of a building's ability to withstand lateral loads, such as those that occur in earthquakes, and how deformation occurs during this process [13][27].

A comparison of seismic performance evaluation of earthquake-resistant buildings using structures with the same dimensions between the SMRFS, IMRFS, and OMRFS methods shows different seismic loads [12]. The analysis showed that SMRFS required more shear reinforcement but had smaller flexural reinforcement compared to IMRFS [12]. The distribution of plastic hinges for both methods remained in the Immediate Occupancy (IO) category until a transition of 0.85 cm, but SRMFS did not meet ductility requirements [12].

In Indonesia, high earthquake risk poses a significant challenge for designing multi-storey buildings [1, 2, 3]. While building codes mandate different levels of earthquake resistance based on location, the current practice employs two distinct structural systems: SMRFS for high-risk zones and IMRFS for moderate-risk zones [22]. This research aims to address the knowledge gap regarding the comparative effectiveness of these two systems by analyzing their structural performance, component detailing, and reinforcement needs in their respective optimal locations [26]. By comparing these aspects, this research seeks to provide valuable insights for selecting the most efficient and resilient design approach for earthquake-resistant multi-storey buildings in Indonesia.

METHOD

Research Process

Figure 1 shows the process of conducting the research. The process starts with modeling the buildings with IMRFS and SMRFS and lasts until the structural performance and failure models are analyzed with pushover analysis.

Research Object

Figure 2 shows the building layout configuration with a beam span size of 5 m using Autodesk Revit. The 8-story building was designed using Autodesk Revit and analyzed using ETABS as in Figure 3.

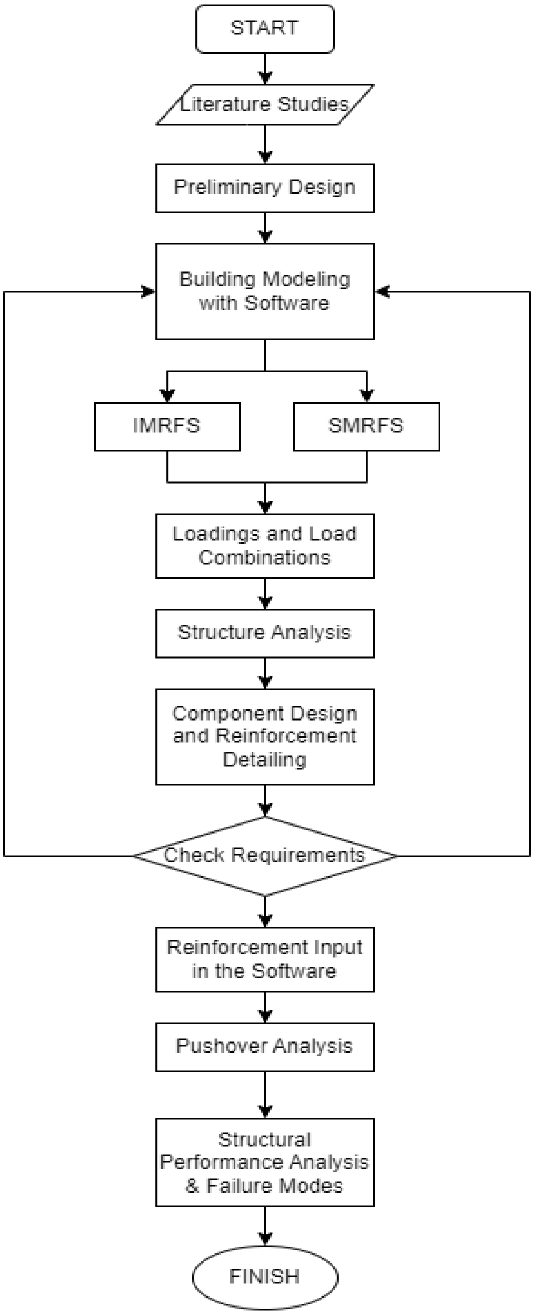

Figure 1. Research Process

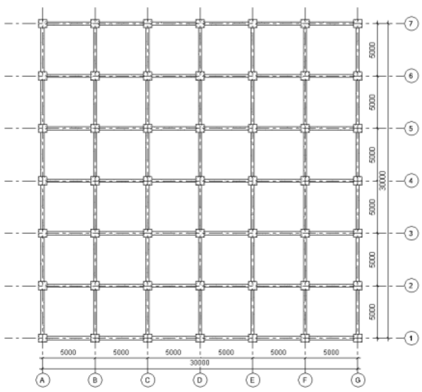

Figure 2. Building Layout

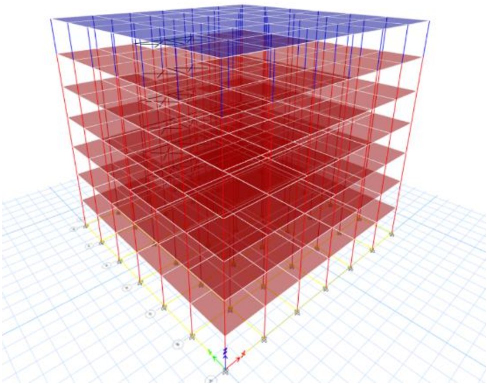

Figure 3. Structure Modeling

General Structural Data

Table 1 displays general structural data for research based on the preliminary design of the latest regulations.

Building Loading Calculations

SNI 1727:2020 is an Indonesian national standard (SNI) that specifies the minimum design loads and associated criteria for buildings and other structures. SNI 1727:2020 is based on the American Society of Civil Engineers (ASCE) 7-16 standard.

Seismic Loading Data

The seismic loading parameters used for modeling are shown in Table 2 in accordance with SNI 1727:2020. Figure 4 shows a graph of the spectrum response graph with SMRFS in Jakarta, 2023. Figure 5 shows a graph of the spectrum response graph with IMRFS in Jakarta, 2023.

Table 1. General Structural Data

General Data	SMRFS	IMRFS
Location	Lebak Bulus, Cilandak, South Jakarta	Bukit Dangas, Tanjung Pinggir, Sekupang, Batam
Number of Floors	8	8
Floor's Height	4 m	4 m
Purpose of the Building	Office	Office
Quality of Beam	f'_c = 30 MPa	f'_c = 30 MPa
Quality of Steel Reinforcement	f_y Main Reinforcement = 420MPa f_y stirrup = 420MPa	f_y Main Reinforcement = 420MPa f_y stirrup = 420MPa
Preliminary	-Column K1: 800mm.800mm -Beam B1: 300mm.500mm - Beam B2: 300mm.600mm -Slab: 12.5mm	- Column K1: 800mm.800mm - Beam B1: 250mm.450mm - Beam B2: 300mm.500mm -Slab: 12.5mm

Table 2. Seismic Loading Parameters

Parameters	SMRFS	IMRFS
Risk Category	II	II
Priority Factors for Earthquake (I_e)	1	1
Soil Condition	C	C
KDS	D	B
S_S	0.891 g	0.079 g
S_1	0.431 g	0.123 g
Fa	1.2	1.3
Fv	1.5	1.5
S_{MS}	0.962	0.103
S_{M1}	0.647	0.185
S_{DS}	0.642	0.069
S_{D1}	0.431	0.123
T_0	0.134	0.358
T_S	0.672	1.792
T_L	20	12
R	8	5
Ω_0	3	3
C_d	5.5	4.5

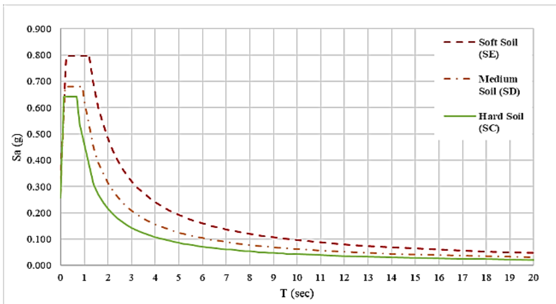

Figure 4. Response Spectrum in Jakarta

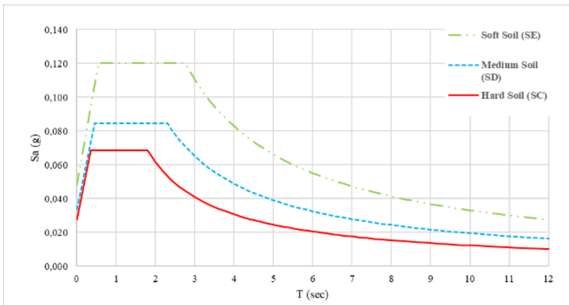

Figure 5. Response Spectrum in Batam

Structural Analysis

After inputting the material information data used and determining the preliminary design, the next step is to carry out a structural analysis. The results of structural analysis using ETABS provide information regarding internal forces, displacements, and failure modes in the form of plastic hinge points that appear [27, 28, 29, 30].

Reinforcement Detailing

To find out how the reinforcement is distributed to each structural component, a detailed process is carried out on beams, columns, slabs, and shear walls. The process aims to obtain detailed information regarding the distribution of reinforcement in each structural component [32][33]. Reinforcement detailing must comply with the building standards and codes to ensure structural safety following SNI 2847:2019. Proper detailing will help avoid structural failure, increase the structure's resistance to loads, and ensure that the structure can function as designed.

Structural Performance Analysis

Structural performance theory refers to the ability of a structure to withstand the loads acting on the structure without experiencing damage or failure. The level of structural performance is a measure of the structure's ability to withstand the load. The performance level of a structure is determined based on the displacement targets experienced with the specified displacement targets in Figure 6.

Performance evaluation in the Federation Emergency Management Agency (FEMA) 273/356 regulates the level of performance of a building as follows:

1. S-1 Immediate Occupancy (IO)
   The level of performance is considered adequate if, although there is damage after an earthquake, the damage is not significant and it is still possible to safely re-occupy [24].
2. S-2 Damage Control (DC)
   As a range or transition between the structural performance levels of Life Safety (S-3) and Immediate Occupancy (S-1). This performance level aims to reduce repair time and still allow the structure to survive an earthquake with a very low risk of loss of life [24].
3. S-3 Life Safety (LS)
   The condition of damage that occurs to building structures after an earthquake occurs, but does not result in a safety hazard because no large debris falls around the building [24].
4. S-4 Limited Safety
   The severity of structural damage falls between the Life Safety (S-3) and Collapse Prevention (S-5) structural performance level ranges [24].
5. S-5 Collapse Prevention (CP)
   a condition where after an earthquake occurs, the building is damaged and is at risk of partial or complete collapse, but is still able to support its gravitational load through all gravity load-bearing components [24].

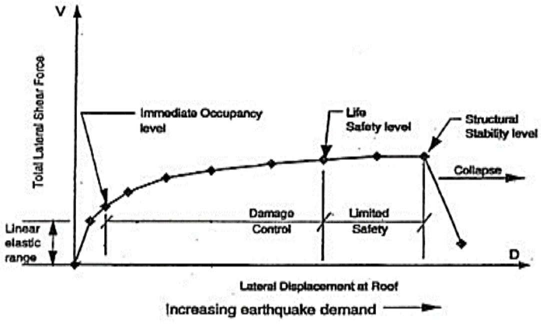

Figure 6. Capacity Curve [23]

Pushover Analysis

Pushover analysis or static thrust load analysis is a non-linear analysis technique used to identify the collapse behavior of a building in an earthquake [13]. This analysis process involves applying a static lateral load pattern to the structure and gradually increasing the multiplier factor until it reaches the target lateral displacement from a reference point. This reference point is usually chosen at the highest point of the building, or more precisely at the center of mass of the roof. In this way, pushover analysis can help estimate the capacity of a structure to withstand earthquakes and ensure that the structure is strong and safe.

Failure Modes

Building structures receive seismic loads at certain levels or conditions, plastic hinges or permanent damage will occur to the beams and columns in the structure. Plastic joints occur when structural elements can no longer withstand internal forces. To design a building, it is necessary to pay attention to design principles with the concept of strong columns-weak beams [18].

RESULTS AND DISCUSSION

The results of the structural analysis are internal forces that are used for structural component design calculations, as well as displacement and pushover analysis.

Design Detailing of Column Component

Table 3 shows the results of detailing column components for IMRFS and SMRFS according to the internal force calculations issued from ETABS, following SNI 2847:2019.

Table 3. Detailing of Column Component

	Columns of SMRFS	Columns of IMRFS
Dimension	800.800	800.800
Longitudinal Reinforcement	20D22	20D22
End-Span Stirrup	3D13-120	4D13-100
Mid-Span Stirrup	2D13-100	2D13-100

Design Detailing of Beam Component

Table 4 shows the results of detailing beam components for IMRFS according to the internal force calculations issued from ETABS, following SNI 2847:2019. Table 5 shows the results of detailing beam components for SMRFS according to the internal force calculations issued from ETABS.

Reinforcement to Concrete Ratio

Results of concrete volume and reinforcement weight are produced from Autodesk Revit (Figure 7). Calculations using BIM to minimize errors in calculating the volume to be used. The resulting concrete volume will be compared with the weight of the reinforcement to produce a ratio of reinforcement weight to concrete volume.

Table 6 and Table 7 show the ratio of reinforcement weight to concrete volume for buildings using the IMRFS and SMRF methods. Concrete volume and reinforcement weight are generated from QTO Revit which has been modeled separately.

Table 4. Detailing of Beam Component IMRFS

Dimension	Beam B1 250.450	Beam B2 300.500
End-Span Longitudinal Above	4 D16	4 D16
End-Span Longitudinal Middle	2 D13	2 D13
End-Span Longitudinal Below	2 D16	3 D16
Mid-Span Longitudinal Above	2 D16	3 D16
Mid-Span Longitudinal Middle	2 D13	2 D13
Mid-Span Longitudinal Below	3 D16	3 D16
End-Span Stirrup	2D10-50	3D10-100
Mid-Span Stirrup	2D10-75	2D10-150

Table 5. Detailing of Beam Component IMRFS

Dimension	Beam B1 250.450	Beam B2 300.500
End-Span Longitudinal Above	4 D19	3 D19
End-Span Longitudinal Middle	2 D19	2 D19
End-Span Longitudinal Below	3 D19	3 D19
Mid-Span Longitudinal Above	2 D19	2 D19
Mid-Span Longitudinal Middle	2 D19	2 D19
Mid-Span Longitudinal Below	2 D19	2 D19
End-Span Stirrup	3D10-75	3D10-100
Mid-Span Stirrup	2D10-150	2D10-150

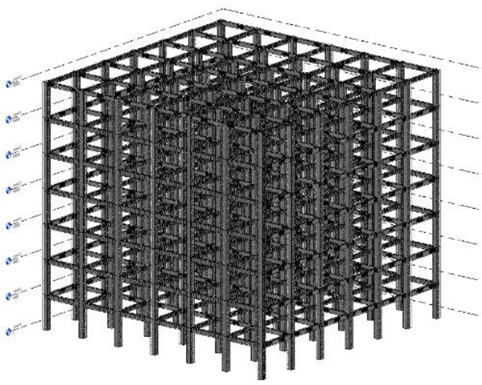

Figure 7. Design Building by Using Revit

Table 6. The ratio of Reinforcement Weight to Concrete Volume in IMRFS

Data	Element		
	Beam B1	Beam B2	Column
Concrete Volume (m^3)	209.79	90,72	878,08
Reinforcement Weight (kg)	51681.92	16716,78	131612,53
The ratio of Reinforcement Weight to Concrete Volume (Kg/m^3)	246,350	184,268	149,887

Table 7. The ratio of Reinforcement Weight to Concrete Volume in SMRFS

Data	Element		
	Beam B1	Beam B2	Column
Concrete Volume (m^3)	279.72	108.84	878.08
Reinforcement Weight (kg)	66115.26	20068.18	153978.82
The ratio of Reinforcement Weight to Concrete Volume (Kg/m^3)	236.362	184.382	175.359

IMRFS Structure Performance Levels

The level of structural performance is determined by comparing the monitored displacement with the overall height of the building structure. Figure 8 and Figure 9 show that the monitored displacement that occurs in the IMRFS building is 539 mm, and the overall building height is 28,000 mm. The ratio that occurs in the IMRFS building is 0.01925 which shows that the IMRFS building has a structural performance level between Immediate Occupancy to Life Safety, and damage control with a ratio of 0.01-0.02.

IMRFS Failure Modes

The failure modes in the IMRFS building were obtained from the results of running a pushover analysis with 60 steps in the x-direction and 60 steps in the y-direction which were given until the structure failed. In both directions, plastic hinges appeared at step 42 in the beam with Immediate Occupancy performance (Figure 10 and Figure 12) and it eventually collapsed at step 58 (Figure 11 and Figure 13).

The IMRFS building exhibits a structural performance level between Immediate Occupancy to Life Safety, with a ratio indicating damage control. The observed failure modes, including the appearance of plastic hinges and eventual collapse during the pushover analysis, underscore significant vulnerabilities in the building's structural integrity.

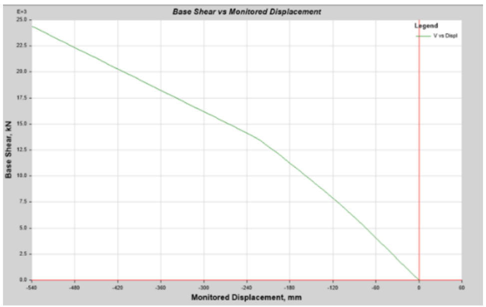

Figure 8. IMRFS X–Direction Failure Curve

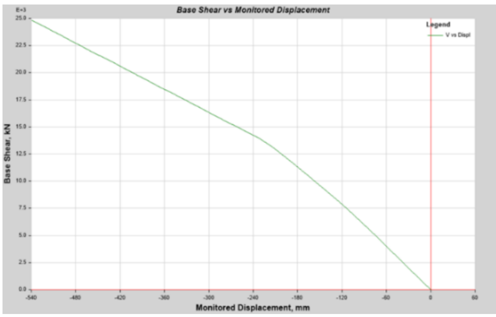

Figure 9. IMRFS Y–Direction Failure Curve

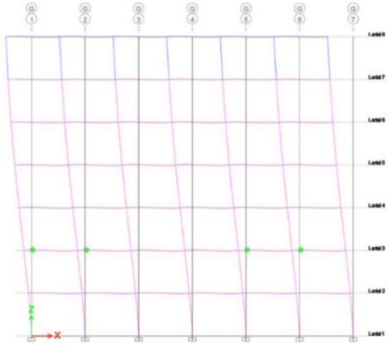

Figure 10. Plastic Hinges at Step 42 in the X-Direction of IMRFS

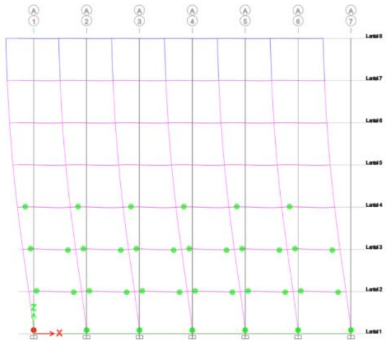

Figure 11. Plastic Hinges at Step 58 in the X-Direction of IMRFS

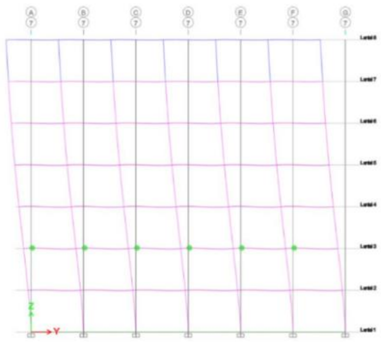

Figure 12. Plastic Hinges at Step 42 in the Y-Direction of IMRFS

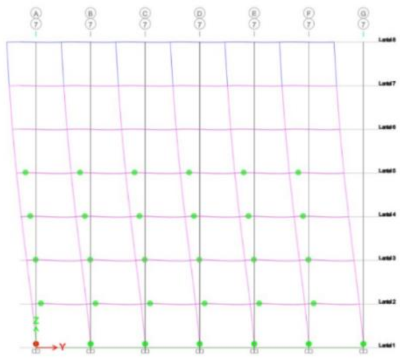

Figure 13. Plastic Hinges at Step 58 in the Y-Direction of IMRFS

Immediate action is recommended to ensure occupant safety, which may include structural strengthening, retrofitting, and regular maintenance. This analysis emphasizes the importance of proactive measures to mitigate the risks associated with seismic events and prevent potentially catastrophic failures.

SMRFS Structure Performance Levels

The results obtained a comparison curve between base shear and monitored displacement. Figure 14 and Figure 15 show that the monitored displacement that occurs in the SMRFS building is 504 mm, and the overall building height is 28,000 mm. The ratio that occurs in the SMRFS building is 0.018 which shows that the SMRFS building has a structural performance level damage control with a ratio of 0.01-0.02.

SMRFS Failure Modes

In Figure 16, the x-direction plastic hinges appear in step 33 which is located at the end of the 3rd floor beam. The plastic hinges in the column appear in step 56 as shown in Figure 17. In Figure 18, the y-direction plastic hinges appear in step 46. In Figure 19, plastic hinges appear in step 58 which are located on the beam and column simultaneously. Plastic joints that appear in green indicate that their performance level is Immediate Occupancy.

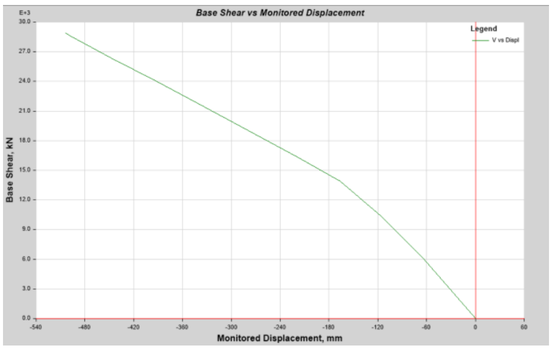

Figure 14. SMRFS X–Direction Failure Curve

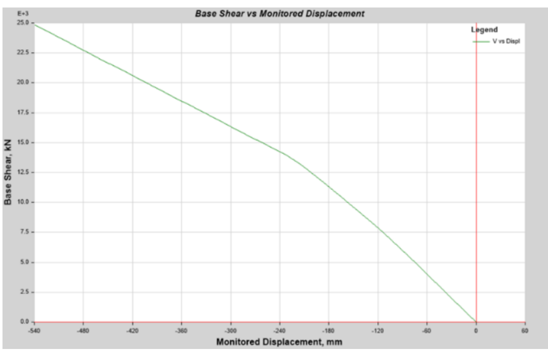

Figure 15. SMRFS Y–Direction Failure Curve

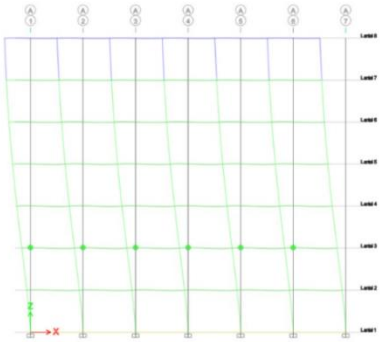

Figure 16. Plastic Hinges at Step 34 in the X-Direction of SMRFS

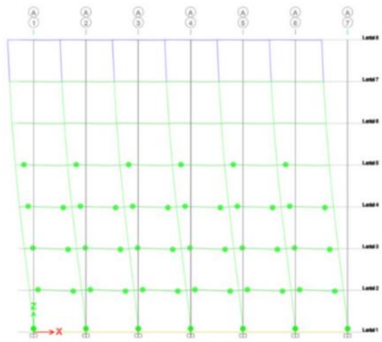

Figure 17. Plastic Hinges at Step 56 in the X-Direction of SMRFS

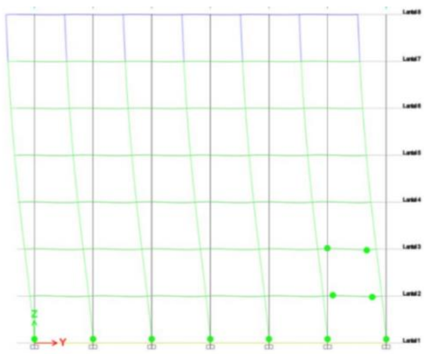

Figure 18. Plastic Hinges at Step 46 in the Y-Direction of SMRFS

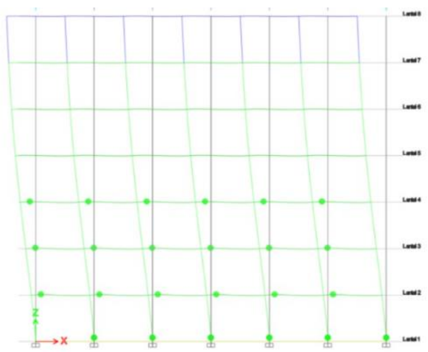

Figure 19. Plastic Hinges at Step 58 in the Y-Direction of SMRFS

The SMRFS building has a structural performance level of damage control with its ratio indicating a moderate level of damage. Plastic hinges were observed in the x-direction (at the end of the 3rd-floor beam), the y-direction (on both beam and column), and the column itself. Despite these plastic hinges, the building remains in a state of Immediate Occupancy, allowing for immediate evacuation after an earthquake. This action can be proposed since the damage situation is known [34]. It is recommended that the building undergoes continued monitoring and consideration of mitigation measures to prevent further structural degradation [35]. This analysis highlights the importance of proactive measures to maintain the safety of occupants and prevent potential risks associated with seismic events.

Another finding shows that the SMRFS building required more shear reinforcement but had smaller flexural reinforcement compared to the IMRFS building [12]. The analysis also revealed that the distribution of plastic hinges for both methods remained within the Immediate Occupancy category until a transition of 0.85 cm. However, SMRFS did not meet the ductility requirements for this event [12].

The failure to meet ductility requirements in the SRMFS structure is suspected to be due to using the same dimensions as the IMRFS method. It should be noted that for the SRMFS structure, slimmer dimensions should be employed to meet ductility requirements within the SMRFS method [36].

Based on the non-linear pushover analysis, both of the IMRFS and SMRFS building structures achieved performance levels ranging from Immediate Occupancy to Life Safety. The ductility of both structures also meets the requirements outlined by the Indonesian National Standard.

CONCLUSION

The two building structures, IMRFS and SMRFS, are in the performance level of Immediate Occupancy to Life Safety, based on the non-linear pushover analysis. This is the condition where the building structures, after experiencing an earthquake, remain strong and almost in the same condition as before the earthquake. This condition can be determined from the resulting monitored displacement that does not show much difference. The structural failure patterns that occurred in both buildings met the Strong Column–Weak Beam requirements. The distribution of plastic hinges for both structures is still in the Immediate Occupancy category. In the IMRFS building, the ratio of reinforcement weight to concrete volume for beam element B1 was 246.350 kg/m^3; beam B2 of 184.268 kg/m^3; and column of 149.887 kg/m^3. In the SRPMK building, the ratio of reinforcement weight to concrete volume for beam element B1 was 236.350 kg/m^3; beam B2 of 184.384 kg/m^3; and column of 175.359 kg/m^3.

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REFERENCES

[1] K. S. Pribadi *et al.*, "Learning from past earthquake disasters: The need for knowledge management system to enhance infrastructure resilience in Indonesia," *International Journal of Disaster Risk Reduction*, vol. 64, Oct. 2021, doi: 10.1016/j.ijdrr.2021.102424.

[2] R. Faizah and R. Amaliah, "Comparative Study of Indonesian Spectra Response Parameters for Buildings According To 2012 and 2019 Seismic Codes," *International Journal of Integrated Engineering*, vol. 13, no. 3, pp. 168–175, 2021, doi: 10.30880/ijie.2021.13.03.020.

[3] A. H. Prathama, M. Teguh, and F. Saleh, "Response analysis of a multi-story building structure with a variety of horizontal irregularities and shear wall geometries," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Dec. 2021. doi: 10.1088/1755-1315/933/1/012008.

[4] M. Irsyam *et al.*, "Development of the 2017 national seismic hazard maps of Indonesia," *Earthquake Spectra*, vol. 36, no. 1_suppl, pp. 112–136, Oct. 2020, doi: 10.1177/8755293020951206.

[5] F. Monika, A. Pujianto, and H. Prayuda, "Vulnerability Assessment of Infrastructure Building, Permanent Resident and Evacuation Route Vulnerability Assessment of Infrastructure Building, Permanent Resident and Evacuation Route In Merapi Volcano Area, Indonesia," *Indonesia Article in International Journal of Earth Sciences and Engineering*, vol. 12, no. 01, pp. 157–163, 2019, doi: 10.21276/ijee.2019.12.0303.

[6] I. W. Sengara and F. Aldiamar, "Assessment on earthquake resistance spectral design load criteria for buildings and infrastructures in Indonesia," in *E3S Web of Conferences*, EDP Sciences, Dec. 2021. doi: 10.1051/e3sconf/202133107009.

[7] M. Husni Rizal, J.-P. Metaxian, and M. Husni RIZAL, "Structure of Merapi-Merbabu complex, Central Java, Indonesia, modeled from body wave tomography," 2020. [Online].

Available: https://www.researchgate.net/publication/343721961
[8] Badan Standardisasi Nasional Indonesia, *SNI 1726:2019 Tata cara perencanaan ketahanan gempa untuk struktur bangunan gedung dan nongedung* . 2019.
[9] Badan Standardisasi Nasional, *SNI 2847:2019 Persyaratan Beton Struktural untuk Bangunan Gedung*. 2019.
[10] S. W. Han and C. S. Lee, "Cyclic behavior of RC OMF beam-corner column joints under unidirectional and bidirectional loadings," *Eng Struct*, vol. 224, p. 111304, Dec. 2020, doi: 10.1016/j.engstruct.2020.111304.
[11] H. S. Aji, A. Rosyidah, and J. Saputra, "The effect of variation of shear walls placement on the response of building structure using the Direct Displacement-Based Design method," *SINERGI*, vol. 26, no. 2, p. 201, Jun. 2022, doi: 10.22441/sinergi.2022.2.009.
[12] A. Louzai and A. Abed, "Concentric versus eccentric strut models in the seismic response of masonry infilled reinforced concrete frame structures using nonlinear dynamic analysis," *Natural Hazards*, vol. 106, no. 3, pp. 2111–2137, Apr. 2021, doi: 10.1007/s11069-021-04532-z.
[13] T. J. Sullivan, "Simplified Pushover Analysis of Moment Resisting Frame Structures," *Journal of Earthquake Engineering*, vol. 25, no. 4, pp. 621–648, 2021, doi: 10.1080/13632469.2018.1528911.
[14] B. Ganjavi, "Effects of soil-structure interaction and lateral design load pattern on performance-based plastic design of steel moment resisting frames," *Structural Design of Tall and Special Buildings*, vol. 28, no. 11, 2019, doi: 10.1002/tal.1624.
[15] A. Sadeghi, "Probabilistic seismic analysis of steel moment-resisting frame structure including a damaged column," *Structures*, vol. 33, pp. 187–200, 2021, doi: 10.1016/j.istruc.2021.03.065.
[16] B. T. Pham, D. D. Nguyen, Q. A. T. Bui, M. D. Nguyen, T. T. Vu, and I. Prakash, "Estimation of ultimate bearing capacity of bored piles using machine learning models," *Vietnam Journal of Earth Sciences*, vol. 44, no. 4, Sep. 2022, doi: 10.15625/2615-9783/17177.
[17] G. Ghayoumian and A. R. Emami, "A multi-direction pushover procedure for seismic response assessment of low-to-medium-rise modern reinforced concrete buildings with special dual system having torsional irregularity," *Structures*, vol. 28, pp. 1077–1107, Dec. 2020, doi: 10.1016/j.istruc.2020.09.031.
[18] N. Khurram, M. F. Tahir, U. Akmal, M. I. U. Hassan, and U. U. Sahar, "Design and Cost Comparison of High-Rise Building Structural Systems Using Performance-Based Design," Online, 2022.
[19] J. Propika, "Building Structure Analysis with and without Direct Foundation Modelling using Reinforced Concrete Special Moment Resisting Frame," *J Phys Conf Ser*, vol. 2117, no. 1, 2021, doi: 10.1088/1742-6596/2117/1/012012.
[20] A. S. Thakur, "Analytical Investigation of Moment Resisting Frame Structure—A Case Study on Performance-Based Capacity Spectrum Method," *Lecture Notes in Civil Engineering*, vol. 196, pp. 735–745, 2022, doi: 10.1007/978-981-16-6557-8_60.
[21] S. F. Fathizadeh, "Considering soil–structure interaction effects on performance-based design optimization of moment-resisting steel frames by an engineered cluster-based genetic algorithm," *Engineering Optimization*, vol. 53, no. 3, pp. 440–460, 2021, doi: 10.1080/0305215X.2020.1739278.
[22] Badan Standariisasi Nasional Indonesia, *SNI 1727:2020 Beban Desain Minimum dan Kriteria terkait untuk Bangunan Gedung dan Struktur Lain*. 2020.
[23] ATC-40, "Seismic Evaluation and Retrofit of Concrete Buildings [S]. Applied Technology Council." 1996.
[24] FEMA 356, *Pre-Standard and Commentary for the Seismic Rehabilitation*. Federal Emergency Management …, 2000.
[25] H. Jarrahi, "Soil-structure interaction effects on the seismic performance of steel moment-resisting frames equipped with optimal rotational friction dampers," *Structures*, vol. 43, pp. 449–464, 2022, doi: 10.1016/j.istruc.2022.05.118.
[26] A. Rosyidah and I. Luthfiyanti, "Structural Performance of 1 Way And 2 Way Setback With The Soft First Story Using DDBD," 2022.
[27] Ayuddin and K. R. Bindhu, "Application of Capacity Spectrum Method (CSM) for non-symmetrical reinforced concrete high-rise buildings as a tool for seismic design," *SINERGI*, vol. 27, no. 3, pp. 405–414, 2023, doi: 10.22441/sinergi.2023.3.011.
[28] H. Jiang, "Seismic Performance of High-rise Moment-resisting RC Frame Structures with Vertical Setback," *International Journal of High-Rise Buildings*, vol. 9, no. 4, pp. 307-314, 2020, doi: 10.21022/ijhrb.2020.9.4.307
[29] M. S. Khan, A. Basit, and N. Ahmad, "A simplified model for inelastic seismic analysis of RC frame have shear hinge in beam-column joints," *Structures*, vol. 29, pp. 771–

784, Feb. 2021, doi: 10.1016/j.istruc. 2020.11.072.

[30] H. Elsanadedy, “Assessment of progressive collapse potential of special moment resisting RC frames – Experimental and FE study,” *Eng Fail Anal*, vol. 105, pp. 896–918, 2019, doi: 10.1016/j.engfailanal.2019.07.045.

[31] A. Sharma, R. K Tripathi, and G. Bhat, “Comparative performance evaluation of RC frame structures using direct displacement-based design method and force-based design method,” *Asian Journal of Civil Engineering*, vol. 21, no. 3, pp. 381–394, Apr. 2020, doi: 10.1007/s42107-019-00198-y.

[32] V. N*, R. Kannan M*, and K. L, “Seismic Analysis of Multi-Storey Irregular Building with Different Structural Systems,” *International Journal of Recent Technology and Engineering (IJRTE)*, vol. 8, no. 6, pp. 3146–3155, Mar. 2020, doi: 10.35940/ijrte.F8813.038620.

[33] A. M. Iswidyantara & A. E. Husin, “Key success factors analysis for improving cost performance of green retrofit infrastructure on the jetty project,” *SINERGI*, vol. 27, no. 1, pp. 89-100, 2023, doi: 10.22441/sinergi.2023.1. 011

[34] K. Trevlopoulos, P. Guéguen, A. Helmstetter, and F. Cotton, “Earthquake risk in reinforced concrete buildings during aftershock sequences based on period elongation and operational earthquake forecasting,” *Structural Safety*, vol. 84, 2020, doi: 10.1016/j.strusafe.2020.101922.

[35] F. Kiakojouri, V. De Biagi, B. Chiaia, and M. R. Sheidaii, “Progressive collapse of framed building structures: Current knowledge and future prospects,” *Engineering Structures*, vol. 206, 2020. doi: 10.1016/j.engstruct.2019. 110061.

[36] S. N. Iravani, “Comparison of Seismic Behavior Factors for Reinforced Concrete (RC) Special Moment Resisting Frames (SMRFs) in Iran in Low-, Mid-, and High-Rise Buildings based on Iranian Seismic Standard 2800 and ASCE," *Journal of Economics and Administrative Sciences,* vol. 5, 2022.