Comparison Of Structural Performance Of 20- Storey Building in Surakarta Using Response Spectrum and Linear Time History Method

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Abstract

Assessment of the performance of multi-storey building structures against earthquake loads is a crucial aspect in building planning in seismically prone areas, such as Indonesia. This study aims to compare the seismic response of a 20-story building structure using two linear dynamic analysis methods, namely the spectrum response method and linear time history. The structural model is analyzed based on the provisions of SNI1726:2019 by considering the response spectrum parameters according to the location conditions. Evaluation of structural performance is carried out based on the value of the deviation classified by the ATC-40 guidelines with further calculations to obtain the value of its performance level or perofrmance point. The results of this study show that the linear time histoy method produces a more conservative structural response than the spectrum response method, especially at the maximum deviation of the roof floor. Although the value of the deviation is greater, the resulting performance level remains the same, namely, Immediate Occupancy (IO). This is a reference for planners in choosing the optimal analysis approach in the design of high-rise buildings. Keywords: Response Spectrum Method, Linear Time History Method, ATC-40, Performance Levels

1. INTRODUCTION

The growth of urban areas in various regions of Indonesia and the world has encouraged the construction of high-rise buildings as a solution to land limitations. High-rise buildings not only reflect the development of construction technology, but also symbolize the economic and social progress of an area. The increasing number of high-rise buildings must be accompanied by careful structural design considerations, especially in earthquake-prone areas such as Indonesia. In this context, the structural safety aspect becomes a crucial factor in ensuring that the building can function optimally during and after an earthquake event. Thus, an analysis is needed to determine the structural performance of a high-rise building.

The dynamic analysis method is an approach to understand and take into account the response of structures to earthquake loads that are dynamic and change over time. These methods are also used to determine the performance of building structures. The two most commonly used methods in the practice of structural performance analysis are the spectrum response and linear time history methods. The spectrum response method uses spectral acceleration curves to calculate the response of a structure to a plan earthquake. In contrast, the linear time history method uses actual earthquake records as input, allowing for a more detailed simulation of a structure's response to seismic loading over time.

Various studies have shown that there are significant differences between the analysis results using the spectrum response method and the linear time history method. One study reported that the time history method produced greater values of maximum deviation and base shear force than the spectrum response method[1]. Similar findings were also reported by Rahman[6] who showed that the time history method is more sensitive to variations in earthquake input, so it can provide more conservative results in evaluating structural performance. Therefore, the selection of methods used in the planning and evaluation of multi-storey building structures should be based on the complexity of the project and the design objectives to be achieved.

This study aims to compare the structural performance of a 20-storey building against earthquake loads using two approaches, namely response spectrum and linear time history. The parameters evaluated include maximum deviation, inter-story deviation, and structural performance level. The results of this study are expected to provide important input for planners in determining the most appropriate dynamic analysis method for high-rise buildings in earthquake-prone areas, taking into account the level of safety and comfort of the resulting structure.

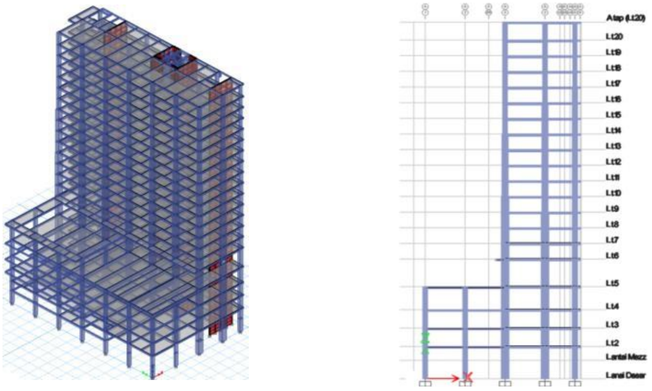
2. METHOD

2.1. Structure Modeling

This study modeled a 20-story building structure that functions as a hotel with building dimensions of 50,3 m long, 31,05 m wide, and 77,45 m high. There are varying heights between levels with configurations of 3 m, 3,4 m, 3,9 m, 4 m, 5 m, and 6 m. This building has a setback structural plan characteristic, where the area ratio of the plan above has less area than the floor below. The building under review has a typical plan from the 6th floor to the roof. The foundation is assumed to be wedged at the bottom level of the ground floor with a depth of -0.5m. Each floor slab and roof that has been modeled is input with live load, roof live load, and additional dead load in accordance with SNI 1727:2020 loading regulations. Meanwhile, the dead load of the structure is based on the materials used such as beams, columns, plates, and shear walls. The results of structural modeling can be seen in Figure 1 and Figure 2.

(a) (b)

Fig. 1. Plan: 5th Floor (a) and 6th Floor (b)



(a) (b)

Fig. 2. 3D (a) and X-direction section (b)

2.2. Response Spectrum Method

The response spectrum method represents the spectral of the maximum response of a single degree of freedom system to a specific plan earthquake. Earthquake response spectrum data consisting of acceleration, velocity, and spectral displacement can be calculated based on SNI 1726:2019[5]. The parameters that will be used in this method refer to the seismicity of Surakarta city with the values shown in Table 1.

Table 1: Spectrum Response Design Parameters

Parameter	**Value**
Site Class SD	SD
Design Category D	D
Short Period Spectral Acceleration, Ss 0.7974 g	0,7974 g
1 Second Period Spectral Acceleration, S1 0.3863 g	0,3863 g
Site Coefficient, Fa 1.18104	1,18104
Site Coefficient, Fv 1.9137	1,9137
Long Period, TL 20 s	20 s

After analyzing the seismicity with the spectrum response method in the structural analysis software according to the spectrum response design parameter table above, the seismic base shear force will be obtained. The seismic base shear force resulting from the spectrum response method analysis or dynamic base shear force will be compared to the results of the static base shear force. If the result of the dynamic base shear force is smaller than the static base shear force ($V_{Dynamic} < V_{Static}$), it is necessary to scale the base shear force so that the dynamic base shear force is greater than the static base shear force ($V_{Dynamic} > V_{Static}$). The calculation of base shear force scaling can be known by the following equation:

$$RS = \frac{g \times I_e}{R} \times \left(\frac{V}{V_t}\right) \qquad (1)$$

The scaling result from the calculation of equation (1) above, is the scale factor value to re-analyze seismicity with the spectrum response method so that the output dynamic base shear force is greater than the static base shear force ($V_{Dynamic} > V_{Static}$). After the basic shear force requirements are met, the lateral deviation will be analyzed to obtain the performance level value.

2.3. Linear Time History Method

The linear time history method is one of the most detailed dynamic analysis approaches for evaluating the response of structures to earthquakes. In this method, the structural response is calculated based on input data in the form of actual earthquake acceleration records as a function of time. Unlike the response spectrum method, which provides the maximum response from a one-degree-of-freedom analysis, time history allows direct evaluation of the response of a multi-degree-of-freedom structure over time. The main advantage of this method is its ability to capture earthquake effects more realistically, including cumulative effects, resonance, and mode interaction[4].

The location of the analyzed building is in Surakarta, which belongs to a zone that does not have much earthquake history. Based on SNI 1726-2019 for recording or simulating the time history of ground motion acceleration, three of several earthquake events with similar magnitude and distance of the earthquake source reviewed from the Indonesian deaggregation map must be selected. The reference for the selection of earthquake data records from the Indonesian deaggregation map can be seen in Table 2, and 3 earthquake records were obtained as in Table 3.

Tabel 2: Linear Time History Earthquake Record Data Reference

Source	**Magnitude**	**Distance (km)**
Benioff	6.8-7	120-150
Shallow Crustal	6.2-6.4	40-50
Megathrust	8.4-8.6	120-150

Tabel 3: Linear Time History Earthquake Record Data used

RSN	**Event**	**Location**	**Year**	**M**	**R (km)**	**Vs30 (m/s)**
4023521	Miyagioki	Japan	2003	7	148,24	338,1
326	Coalinga	California	1983	6,36	44,72	173,02
6001822	2844986	SouthAmerica	2010	8,81	124,48	304

Before analyzing the structure with the seismicity of the linear time history method, it is necessary to do spectral matching first. SNI 1726-2019 describes the range of matching periods between 0.8 Tlower to 1.2 Tupper with an apparent acceleration damping of 5%. Spectral matching is successful if the time history matching ratio value is below 10% of the target specrtum response. After spectral matching, the seismicity analysis of the linear time history method is carried out.

After analyzing the seismicity of the linear time history method, it is required that the dynamic base shear force is greater than the static base shear force (Vdynamic > Vstatic). The calculation of the base shear force scaling equation with the linear time history method refers to SNI 1726:2019 as follows:

$$V_I = \left(\frac{V_E I_e}{R}\right) \tag{2}$$

$$\eta = \left(\frac{V}{V_I}\right) \geq 1,0 \tag{3}$$

$$TH = \frac{g \times I_e}{R} \times \eta \tag{4}$$

In the linear time history method, the calculation of the scale factor for force scaling results is different from the spectrum response method. Equation (2) first finds the value of the inelastic base shear force (V_I). Then the value of the main scale factor (η) is sought by comparing the static shear force and the inelastic base shear force. After that, the scale factor value will be known in equation (4) and the analysis is carried out again until the output dynamic base shear force is greater than the static base shear force (Vdynamic > Vstatic).

2.4. Structure Performance

The ATC 40 (Applied Technology Council) Guidelines are an important reference in evaluating the performance of building structures against earthquake loads, particularly reinforced concrete and steel structures. This guideline provides a capcity spectrum method-based approach to determine the performance point or performance of a structure in the face of a plan earthquake. By integrating the plan earthquake response spectrum and time history, ATC 40 enables the identification of structural damage levels in a practical and efficient manner. Performance evaluation is crucial in the context of performance-based design, which is currently the main approach in earthquake engineering[3]. Capcity spectrum method based on ATC-40 is the analysis of structural performance from the calculation of actual structural displacement or drift. The performance level or performance point is determined from the maximum drift based on equation (5) and the maximum inelastic drift based on equation (6).

$$D = \frac{D_t}{H} \tag{5}$$

$$D = \frac{D_t}{H} \tag{6}$$

The maximum drift is obtained from the ratio of the maximum lateral deviation (D_t) to the total building height (H). Meanwhile, the maximum inelastic drift (D_{MI}) is defined as the ratio between the difference between the maximum lateral deviation (D_t) and the 1-second period deviation (D_1) to the building height. ATC-40 categorizes structural performance levels into three main categories, namely Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). Each of these levels describes the limit of the structure's ability to resist deformation due to earthquake lateral loads. IO indicates that the structure remains safe and can be occupied immediately after the earthquake, LS indicates that the structure is safe against casualties but requires repairs, while CP indicates that the structure is still standing but is approaching collapse (Fajri, 2022) Determination of the performance point is carried out using an earthquake response spectrum that has been designed with 5% damping, and adjusted to the soil type and seismic region. The spectrum is then plotted against the structural capacity curve to obtain the performance point.

Table 4: Performance Level of Building Structure Based on Displacement

	Performance Level			
Interstory Total Drift	***Immediate Occupancy***	***Damage Control***	***Life Safety***	***Structural Stability***
Maximum Total Drift	0,01	0,01 - 0,02	0,02	$0{,}33V_i/P_i$
Maximum inelastic drift	0,005	0,005 - 0,015	Unlimited	Unlimited

3. RESULTS AND DISCUSSION

3.1. Response Spectrum Method

Based on the response spectrum parameters in Table 2, the response spectrum graph for earthquake loading is obtained as shown in Figure 3.

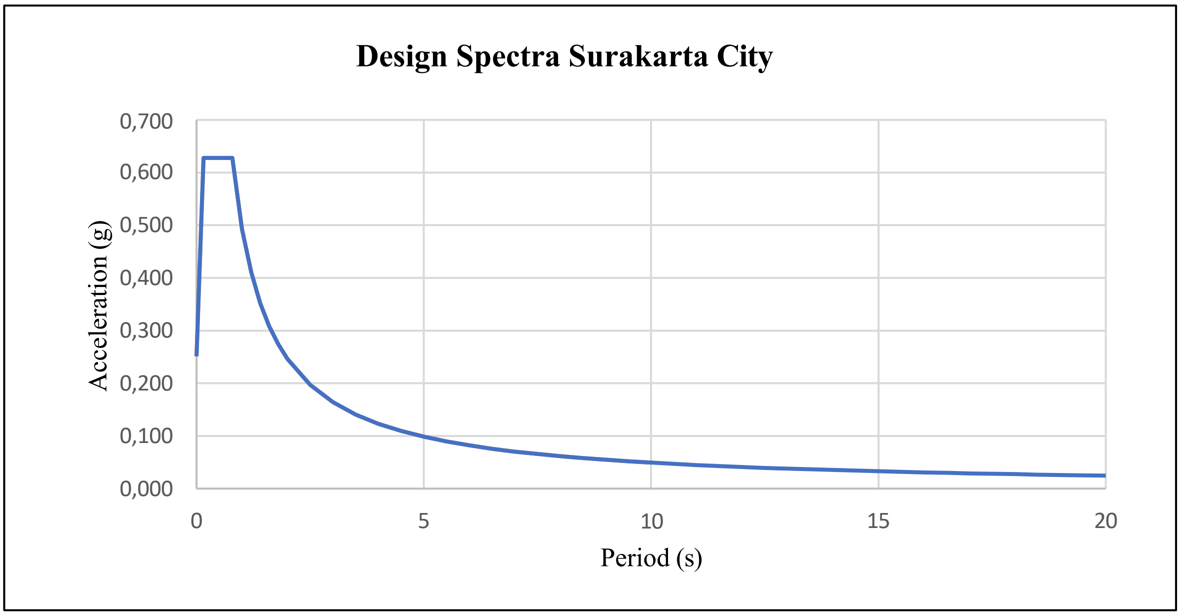


Fig. 3. Design Spectra Surakarta City

The results of the analysis with the earthquake loading spectrum response method obtained the base shear force values as shown in Table 5.

Table 5: Base Shear Force Output Before Scaling

Output Case	Case Type	Step Type	Step Number	FX (kN)	FY (kN)
Spec X	LinRespSpec	Max		3792,5198	566,7802
Spec Y	LinRespSpec	Max		566,7797	2895,0906
Static X	LinStatic	Step By Step	1	-6846,7855	0
Static X	LinStatic	Step By Step	2	-6846,7855	0
Static X	LinStatic	Step By Step	3	-6846,7855	0
Static Y	LinStatic	Step By Step	1	0	-6358,1666
Static Y	LinStatic	Step By Step	2	0	-6358,1666
Static Y	LinStatic	Step By Step	3	0	-6358,1666

In the Output Case "Spec X" and "Spec Y" the value of the base shear force is still too small compared to the static base shear force. Therefore, it is necessary to scale the base shear force according to equation (1) in both earthquake directions with the following calculation:

Scale the RS earthquake in the X-direction and Y-direction

axis X:

$$Scale - X = \frac{V}{V_{t-X}} = \frac{6845{,}54}{3792{,}149} = 1{,}805$$

axis Y:

$$Scale - Y = \frac{V}{V_{t-Y}} = \frac{6357{,}57}{2894{,}738} = 2{,}196$$

With the adjustment to the RS earthquake force through the earthquake scale, the values input to the RS-X and RY-Y loads need to be changed, among other things:

Load *RS-X*:

$$RS - X = \frac{g \times I_e}{R} \times \left(\frac{V}{V_{t-X}}\right) = \frac{9800 \times 1}{7} \times 1{,}805 = 2528{,}98\ mm/s^2$$

Load *RS-Y*:

$$RS - Y = \frac{g \times I_e}{R} \times \left(\frac{V}{V_{t-Y}}\right) = \frac{9800 \times 1}{7} \times 2{,}196 = 3076{,}84\ mm/s^2$$

After obtaining the latest scale factor, the seismicity of the response spectrum method was re-analyzed and the latest base shear force results are shown in Table 6.

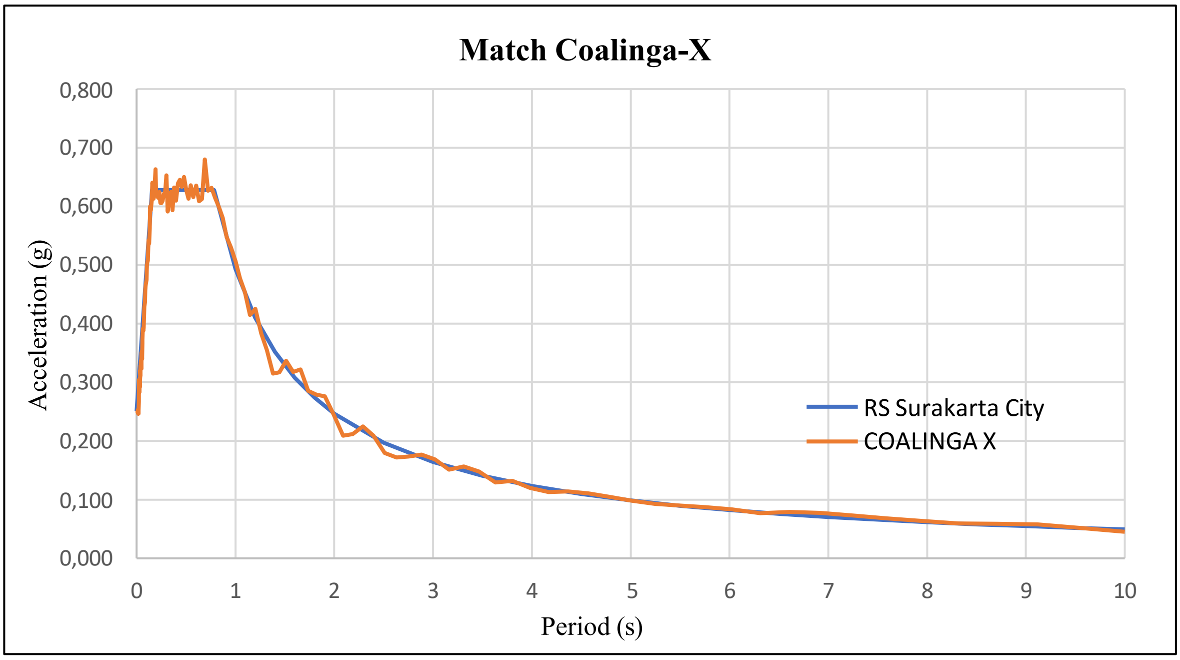
Table 6 : Base Shear Force Output After Scaling

Output Case	Case Type	Step Type	Step Number	FX (kN)	FY (kN)
Static X	LinStatic	Step By Step	1	-6846,7855	0
Static X	LinStatic	Step By Step	2	-6846,7855	0
Static X	LinStatic	Step By Step	3	-6846,7855	0
Static Y	LinStatic	Step By Step	1	0	-6358,1666
Static Y	LinStatic	Step By Step	2	0	-6358,1666
Static Y	LinStatic	Step By Step	3	0	-6358,1666
Scaled Spec X	LinRespSpec	Max		6846,2164	1023,1455
Scaled Spec Y	LinRespSpec	Max		1244,7914	6358,3501

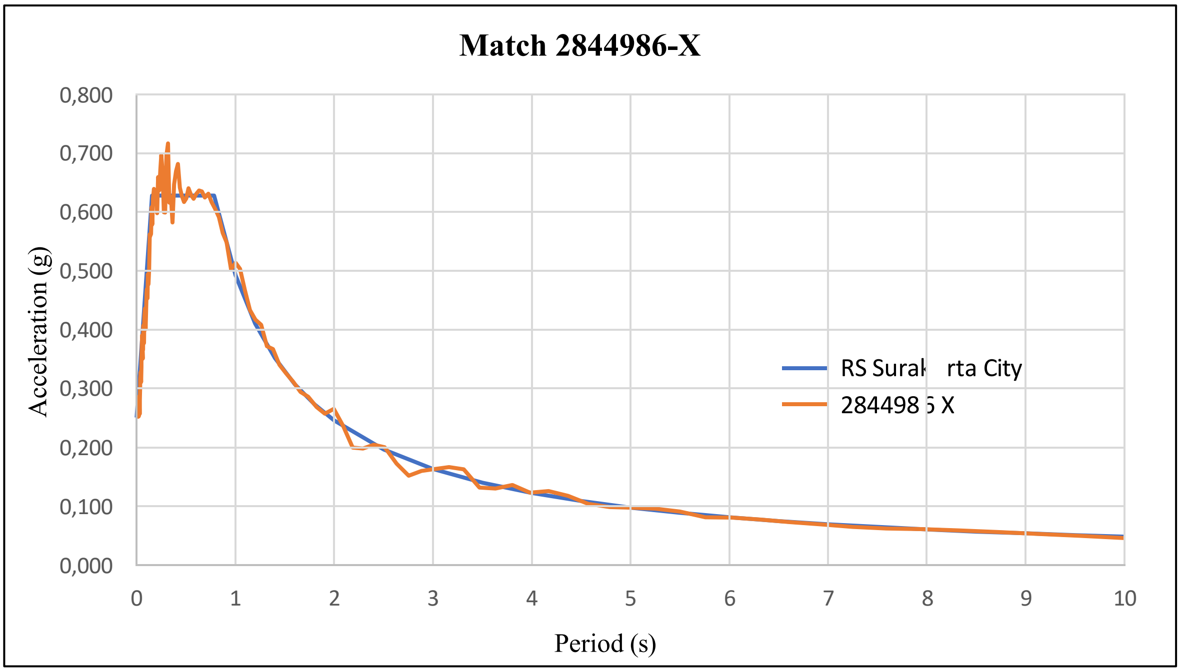
It can be seen that after scaling the base shear force, the value of the dynamic base shear force is greater than the static base shear force (V dynamic >V static). And the output of other analysis results such as deviation can be used for analysis of building

3.2. Linear Time History Method

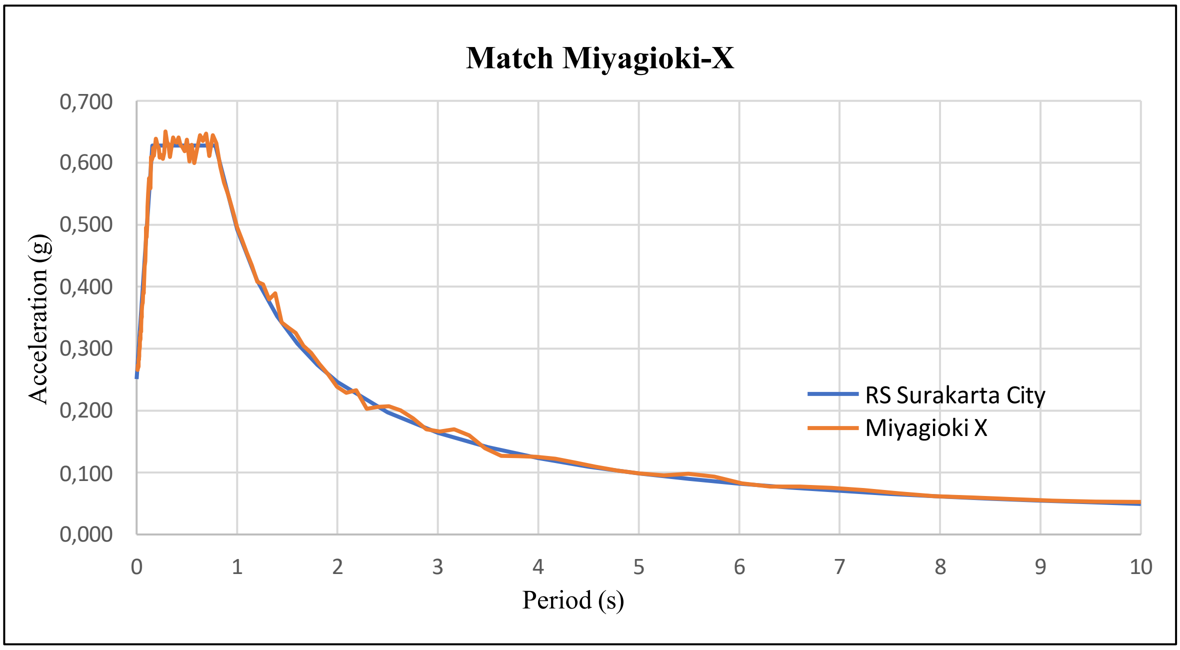
Each earthquake record as shown in Table 2 must first go through a spectral matching process. SNI 1726-2019 describes the matching period range between 0,8 Tlower to 1,2 Tupper with an apparent acceleration attenuation of 5%. Spectral matching is successful if the time history matching ratio value is less than 10% of the specrtum response target. The process was carried out using software assistance by inputting earthquake recordings and target spectral responses. Some spectral matching results from each time history earthquake record are shown in Figure 4.


Match Coalinga-X
Acceleration (g)
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
1
2
3
4
5
6
7
8
9
10
Period (s)
RS Surakarta City
COALINGA X

(a)


Match 2844986-X
Acceleration (g)
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
1
2
3
4
5
6
7
8
9
10
Period (s)
RS Surakarta City
2844986 X

(b)



(c)

Fig. 4. X-direction Spectral Matching: (a) Coalinga Earthquake, (b) 2844986 Earthquake, (c) Miyagioki Earthquake

After spectral matching, it was analyzed by seismicity linear time history method and the elastic base shear force was obtained as shown in Table 7.

Table 7 Elastic shear force (V_E) values of all ground motions

Load Case	V_E **(kN)**
Miyagioki X	19773,46
Miyagioki Y	20605,81
Coalinga X	24222,35
Coalinga Y	22773,72
2844986 X	20740,13
2844986 Y	22627,19

After obtaining the elastic shear force value, the inelastic shear force (VI) is calculated according to equation (2) with one of the earthquake records (GM) calculations as follows:

GM Coalinga-X:

$$V_{IX} = \left(\frac{V_{EX} I_e}{R_X}\right) = \left(\frac{24222{,}35\times 1}{7}\right) = 3460{,}3\ \text{kN}$$

in the same way calculated for all GMs in both directions. The results are shown in Table 8.

Table 8: Inelastic shear force (V_I) values of all ground motions

Ground Motion	V_I **(kN)**
Miyagioki X	2824,78
Miyagioki Y	2943,69
Coalinga X	3460,34
Coalinga Y	3253,39
2844986 X	2962,88
2844986 Y	3232,46

Determination of the scale factor (η) according to SNI 1726-2019 using formula (3). One of the calculations is as follows:

GM Coalinga-X:

$$\eta_X = \left(\frac{V_X}{V_{IX}}\right) = \left(\frac{6845{,}54}{3460{,}34}\right) = 1{,}98 \geq 1{,}0, \text{ sesuai syarat}$$

in the same way calculated for all GMs in both directions. The results are shown in Table 9.

Table 9: Scale factor (η) values of all ground motions

Ground Motion	η
Miyagioki X	2,42
Miyagioki Y	2,16
Coalinga X	1,98
Coalinga Y	1,95
2844986 X	2,31
2844986 Y	1,97

With the adjustment to the TH earthquake force, the values inputted in the TH-X and TH-Y loads for all earthquake records need to be changed. The calculation uses equation (4). One of the calculations is as follows:

GM Coalinga-X:

$$\text{Coalinga-X-X (100\%)} = \frac{g \times I_e}{R} \times \eta_X = \frac{9800 \times 1}{7} \times 1{,}98 = 2771{,}481\ mm/s^2$$

in the same way calculated for all GMs in both directions. The results are shown in Table 10.

Table 10: Time History Earthquake Load Scale Factor Value

Ground Motion	***Scale Factor (input ETABS)***
Miyagioki X	3395,046
Miyagioki Y	3025,672
Coalinga X	2771,481
Coalinga Y	2737,648
2844986 X	3236,807
2844986 Y	2755,376

Basically, the use of scale factor (η) in the time history method is to ensure that the base shear force generated by time history is not less than the base shear force obtained by equivalent static analysis. To confirm this, after inputting the latest scale factor, the latest shear force value from the time history method can be seen as in Table 11.

Table 11: Comparison of Time History and Statically Basic Shear Force

Ground Motion	***Base Shear (Time History) -kN***		***Base Shear (Static)- kN***	
	X	**Y**	**X**	**Y**
Miyagioki X	6850,19	-	6845,54	6357,57
Miyagioki Y	-	6361,88		
Coalinga X	6850,18	-		
Coalinga Y	-	6361,89		
2844986 X	6850,18	-		
2844986 Y	-	6361,88		

3.3. Comparison of Building Structure Performance

The comparison of the performance of the building structure is calculated from each maximum deviation of the roof floor due to the two earthquake loading methods, namely, the spectrum response method and the linear time history method. The results of the deviation of the two methods can be seen in Table 12 and Table 13.

Table 12: Displacement Value of Roof Floor

Load Case	**Displacement Value of Roof Floor (mm)**	
	Axis-X	**Axis-Y**
Response Spectrum	118,07	196,36
Miyagioki	167,90	177,29
Coalinga	127,35	164,91
2844986	157,96	209,72

Table 13: Displacement Value of Fist Floor

Load Case	**Displacement Value of Fist Floor (mm)**	
	Axis-X	**Axis-Y**
Response Spectrum	0,94	2,70
Miyagioki	1,31	2,23
Coalinga	0,85	2,38
2844986	1,17	2,84

The deviation described in the table above will be divided by the total height of the structure to obtain the ratio of maximum total drift and inelastic maximum drift. In Table 14 to Table 17, the analysis shows that the performance level based on the earthquake loading of the spectrum response method and the linear time history method is included in the Immediate Occupancy category.

Table 14 Maximum Drift X-Direction Structure Performance Level

Load Case	***Dt* (m)**	***H* (m)**	***Maksimum Total Drift***	**Performance Level**
	Axis-X			
Response Spectrum	0,1181	77,45	0,00152	*Immediate Occupancy*
Miyagioki	0,1679		0,00217	*Immediate Occupancy*
Coalinga	0,1274		0,00164	*Immediate Occupancy*
2844986	0,1580		0,00204	*Immediate Occupancy*

Table 15 Maximum Drift Y-Direction Structure Performance Level

Load Case	***Dt* (m)**	***H* (m)**	***Maksimum Total Drift***	**Performance Level**
	Axis-Y			
Response Spectrum	0,1964	77,45	0,00254	*Immediate Occupancy*
Miyagioki	0,1773		0,00229	*Immediate Occupancy*
Coalinga	0,1649		0,00213	*Immediate Occupancy*
2844986	0,2097		0,00271	*Immediate Occupancy*

Table 16 Maximum Inelastic Drift X-Direction Structure Performance Level

Load Case	***Dt* (m)**	***D1*(m)**	***H* (m)**	***Maksimum Inelastic Drift***	**Performance Level**
	Axis-X				
Response Spectrum	0,1181	0,0009	77,45	0,00151	*Immediate Occupancy*
Miyagioki	0,1679	0,0013		0,00215	*Immediate Occupancy*
Coalinga	0,1274	0,0009		0,00163	*Immediate Occupancy*
2844986	0,1580	0,0012		0,00202	*Immediate Occupancy*

Table 17 Maximum Inelastic Drift Y-Direction Structure Performance Level

Load Case	***Dt* (m)**	***D1*(m)**	***H* (m)**	***Maksimum Inelastic Drift***	**Performance Level**
	Axis-Y				
Response Spectrum	0,1964	0,0027	77,45	0,00250	*Immediate Occupancy*
Miyagioki	0,1773	0,0022		0,00226	*Immediate Occupancy*
Coalinga	0,1649	0,0024		0,00210	*Immediate Occupancy*
2844986	0,2097	0,0028		0,00267	*Immediate Occupancy*

In the maximum drift table results in both directions (Table 14 and Table 15), it is known that the maximum drift value of the spectrum response method is smaller than the value due to the linear time history method. However, the difference between the maximum drift values of the two earthquake loading methods is not so far and the performance level parameters are still at the Immediate Occupancy level.

4. CONCLUSION

The 20-storey building structure has been analyzed with two earthquake loading methods, namely, the spectrum response method and the linear time history method with 3 types of earthquakes (Miyagioki, Coalinga, 2844986). In both methods, the earthquake force is applied in two directions to the building structure. The maximum deviation of the roof floor generated from both methods, the linear time history method, is greater than the spectrum response method. However, the difference in the magnitude of the deviation value does not imply a different level of performance. However, both methods fall into the Immediate Occupancy category because the maximum total drift value is smaller than 0,01. Thus, the structure has the ability to withstand seismic activity without experiencing structural or non-structural damage.

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