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Comparative study of sinus earthquake forces and ground motion on structure behavioural response using linear time history analysis method

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ABSTRACT

This study aimed to calculate the design earthquake with a harmonic sine wave approach at a frequency of 1.5 Hz; 2.5 Hz; 3.5 Hz; 4;5 Hz, as well as Loma Prieta, Northridge, and Kobe ground motion. In addition, a structural response review was also carried out based on a comparison of the effects of the ground motion and sine wave earthquake forces. This study used an experimental method of modelling an apartment building with a scale of 1: 50. The case study was located in Mantrijeron, Yogyakarta, which has a seismic category in the medium-size class. The analysis phase began with material definition, element dimension estimation, modelling by analysis software, loading estimation, structural analysis, and comparison of structural responses based on the deviation. The results indicate that the building model could withstand dynamic loads from harmonic waves up to a frequency of 5.5 Hz for one minute of vibration. The most significant deviation is shown at a frequency of 4.5 Hz with an x-axis direction of 0.110 and a y-direction of 0.160. The structural response resulting from ground motion loading shows that the highest deviation occurred due to the influence of the Kobe earthquake, with a deviation of 0.063 in the x-axis direction and 0.054 in the y-axis direction. Based on these results, the effect of harmonic sine waves is greater than the ground motion loading on the response of the building structure, so it is used as an experimental loading through a vibrating table with the actual residual deviation results showing a value of 0.9 mm in the y-axis direction. The difference in structural response results could be caused by the supports and connections modelling in planning through analysis software which could not precisely represent the actual implementation of the building model.

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1. Introduction

Earthquake-tectonic events that vibrate the earth's surface consequently release energy suddenly caused by the movement of plates in the layers of the earth's crust or the existence of fault lines [1]. One area that has vulnerability to the earthquake is the Special Region of Yogyakarta. An earthquake hit Yogyakarta in 2006, with an earthquake magnitude of 6.2 which resulted in thousands of buildings and residents' houses collapsing and being damaged. The incident also recorded more than 5,700 people dying, and thousands more were injured [2]. Other impacts were the occurrence of landslides, ground cracks in Bantul and Prambanan, and liquefaction at Prambanan.

The damaged building structures caused most of the material losses and casualties. Tectonic earthquakes are closely related to the resilience of building and non-building structures. Earthquakes cause buildings to vibrate, so building materials are usually rigid. Neither could adjust in response to an earthquake [3]. Material limitations at the time of wobble cause the structure to get damaged. Damage to the structure has the potential to cause losses and risks to the safety of building occupants.

Proper building management and planning are required to minimize the impact of the earthquake. This aims to create a building that can absorb earthquakes up to a certain strength level without causing significant damage, or if the building collapses due to overload, the structure does not cause instantaneous collapse [3]. That condition is needed for the anticipation of the earthquake. So, inhabitants have a chance to save themselves and can release the casualties from the earthquake.

There are two methods for planning earthquake-resistant buildings, namely static equivalent analysis and dynamic analysis [1]. Equivalent static analysis is a technical analysis by approaching earthquake loads as static loads in the horizontal direction (x and y) that can be used for the analysis of simple buildings, by placing the earthquake load position on a mass structure. The dynamic analysis method consists of various analyses including response spectrum and linear time history analysis. The second analysis owns different complexity depending on the selection of location earthquake, a long transfer latency period (TL), and map simplification elastic range of response spectrum from ground motion with flexible design spectrum based on SNI 1726:2019.

Planning earthquake-resistant buildings in a region with an elevated vulnerability level, like Yogyakarta, needs to be done with the linear time history analysis method. Time history response analysis uses at least three adjusted ground motions from response spectrums data at the location to be reviewed [4]. The ground motions used were three earthquakes that have occurred in the world with a magnitude greater than 6.5, namely Loma Prieta, Kobe, and Northridge. The data selection referred to an earthquake of similar magnitude to the one in Yogyakarta in 2006. However, it happened at different frequencies so that it could be used for a simulation with more extensive earthquake plans. In addition, earthquake loading was also carried out with a periodic sine wave approach pattern at frequencies of 1.5 Hz; 2.5 Hz; 3.5 Hz; 4.5 Hz; and 5.5 Hz. The purpose of comparing the two loading approaches was to determine the structural response based on each floor's elastic deviation and distortion.

The principle of earthquake-resistant building planning is the resilience of the building structure to earthquake movements at a certain level [1]. Planning is required to accurately estimate the earthquake load. In the classroom learning process, students can practice by testing the shaking of the table to evaluate the seismic performance of the planning results. The expected result is to know the response of the building structure to variations in the earthquake plan by the location under review. The structural response due to these possible earthquake load variations will be used as a reference in justifying the planned earthquake load in the planning of full-scale buildings and model-scale buildings for experimental activities.

2. Method

This research uses an experimental method with a building model scale of 1:50 with variations in time history loads based on sine waves and ground motion to determine its effect on structural response. An experimental method was also used to evaluate seismic performance through testing table shakes with optimum earthquake loads based on a comparison of results.

2.1 Data Collection

The study used a building model with a scale of 1:50 as shown in Fig. 1, with the technical data including location: Yogyakarta, latitudes: -7.817779, longitude: 110.35995, function: apartment of 8 floors or 56 m. Material quality data includes concrete quality following mortar specifications and steel reinforcement quality. For a moment-bearing frame system, concrete compressive strength specifications require at least 21 MPa [2].

Fig. 1. Structural building model

In dynamic factor testing, material scale is essential, especially when comparing model-scale buildings and full-scale buildings because the strength of the material will increase as the element size decreases and the frequency load increases. However, the sign of a specific increase in strength could not be obtained accurately [5]. In this case, the material properties were directly defined on the building model with a scale of 1:50. So, the material used for the construction process can follow the material determined in the plan. Data on concrete and reinforcement materials used are presented in Table 1 and Table 2.

Table 1. The property of concrete and reinforcement

Property	Mortars	Main Reinforcement	Shift Reinforcement
Water-cement ratio	0.48	-	-
Planned Compressive Strength (MPa)	25	-	-
Realized Compressive Strength (MPa)	25.8	-	-
Diameter (mm)	-	1	0.6
Tensile Strength (MPa)	-	210	210
Breaking Strength (MPa)	-	340	340

Table 2. Concrete mix composition data

Material	Requirement per m ^{3} concrete (kg/m^3)
Water	26.4
Cement	41.25
Sand	165
Superplasticizers	6.1875
Fly Ash	13.75

The data used for earthquake load are ground motion recordings of Loma Prieta, Northridge, and Kobe, following the spectrum response design at the case study location [6]. The comparative data used were earthquake load with a 1.5 Hz; 2.5 Hz; 3.5 Hz; 4.5 Hz; and 5.5 Hz sine wave frequency method with 10 mm amplitude and 60 seconds of vibration duration. The loading data used in the analysis of the building model is dead load, which is the weight of the building structure, a live load of 1 kg per square meter floor, and dynamic load due to the influence of earthquake loads.

2.2 Data Analysis

The building structure was modelled in three dimensions as an open frame. Beam and column elements are defined as reinforced concrete materials with joints between elements at joints because these are rigid and can withstand moments [7]. Plate elements on each floor are defined as rigid diaphragm characteristics so that they can move together during earthquake shaking.

Figure 2. Modelling of Building Structure

Determination of material specifications used as input data in software analysis requires input data from specific gravity, elastic modulus, Poisson's ratio, yield point, tensile strength, and other properties based on the type of material used. The loading of building structures was carried out by considering static and dynamic loads. Static loads consist of dead loads and live loads. Meanwhile, dynamic loads are obtained from earthquakes based on response spectra and time histories that follow the selected case study.

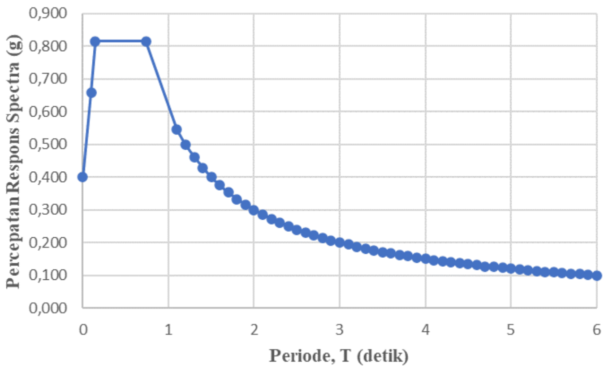

Fig. 3. Spectrum response design

The determination of the earthquake response spectrum was used for dynamic load input in structural modelling. The earthquake response spectrum was obtained from the Puskim (Centre for Research and Development of Housing and Settlements) website with the input coordinates of the case study location used [6].

Table 4. *Spectrum response* parameters design

Parameter	Value	Parameter	Value
PGA(g)	0.516	T_0 (second)	0.150
S_S (g)	1.198	TS (second)	0.770
S1 (g)	0.526	SDS (g)	0.810
Fa	1.021	S_{D1} (g)	0.620
Fv	1.379	CR_S	0.000
TL (second)	6.000	CR_1	0.900

Time history analysis is a method of dynamically induced ground motion loading based on event records that approximate seismotectonic earthquake conditions to the case study site under review [1]. The selection of ground motion data is done through trial and error to get the closest value to the target by looking at the shape and vulnerable value of the response spectrum [11]. Research shows this dynamic loading through scaling response spectrum location review with earthquake load based on ground motion and sine waves. Scaling stages of earthquake burden are presented in Fig. 3 and Fig. 4.

The entire period calculation was carried out by comparing the results of a manual calculation based on SNI 1726: 2019 with the calculation results by the structural analysis software. The fundamental period value will be used in seismic fundamental force calculations. Calculation results mark period structure (Tcrack) in analysis software as big 0.06398 to x direction. The value was furthermore controlled with the calculation of the minimum and maximum period of specified buildings based on Equation (1) and Equation (2).

$$\begin{aligned} Ta &= C_t \; x \; h_n^x \qquad (1) \\ &= 0.0466 \; x \; 0.56^{0.9} \\ &= 0.0277 \text{ seconds} \end{aligned}$$

Based on the results of the previous analysis, the SD1 value was 0.62 > 0.4. Therefore, a Cu value of 1.4 was obtained, and the calculation of the maximum fundamental period value (Ta max) is shown in Equation (2).

$$\begin{aligned} Ta\,(\max) &= Cu \text{ x } Ta \qquad (2) \\ &= 1.4 \text{ x } 0.0277 \\ &= 0.039 \text{ seconds} \end{aligned}$$

In scaling stages of a history time of ground motion with response spectrum, components from land motion must match 0.8 T lower up to 1.2 Tuppers [6].

a. T_{lower} is for period shakes at 90% participation mass actual has fulfilled in each orthogonal two-way response.

b. T_{upper} is for higher significant value between two-period values of fundamental vibration.

In the case of shape mode 8, for the x-axis = 0.9318 (93.18%) and y-axis = 0.9272 (92.72%) with a period of 0.01 seconds, so mark the T as T lower. T_{upper} calculation was done on modes 1 and 2 because of the mark. This represents the orthogonal direction of the structure direction x- and y-axes. The most significant value shown in mode-1 is 0.064, so the entire period used is cu x Ta, which is 0.039. Scaling process of T_{lower} and T_{upper} on planning is within the range as shown by Equation (3).

$$0.8\ T_{lower} \leq \text{scale} \leq 1.2\ T_{upper} \tag{3}$$

$$0.8 \text{ x } 0.01 \leq \text{scale} \leq 1.2 \text{ x } 0.039$$

$$0.08 \leq \text{scale} \leq 0.0468$$

Yield parameters calculation was used for input to ground motion in match software. Value range $0.8T_{lower} - 1.2T_{upper}$ should not be less than 10% and more than 10% [6]. Furthermore, scaling of ground motion and sine wave are performed according to Fig. 4 and Fig. 5.

Table 5. Modal participating ratio

Mode	Period	Sum UX	Sum UY
1	0.064	0.7868	0.00003326
2	0.061	0.7868	0.7684
3	0.049	0.7871	0.7702
4	0.02	0.8911	0.7702
5	0.019	0.8911	0.8829
6	0.015	0.8911	0.8833
7	0.011	0.9318	0.8833
8	0.01	0.9318	0.9272
9	0.008	0.9318	0.9272
10	0.007	0.9558	0.9272
11	0.006	0.9558	0.9533
12	0.005	0.9559	0.9533
If > 9 0 % OK		OK	OK

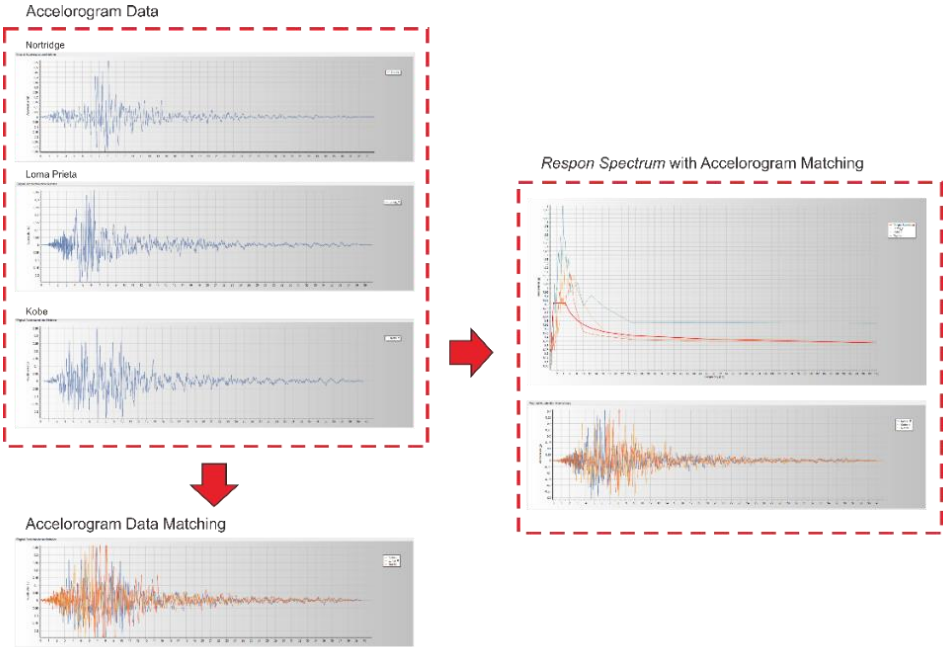

Fig. 4. Scaling of ground motion

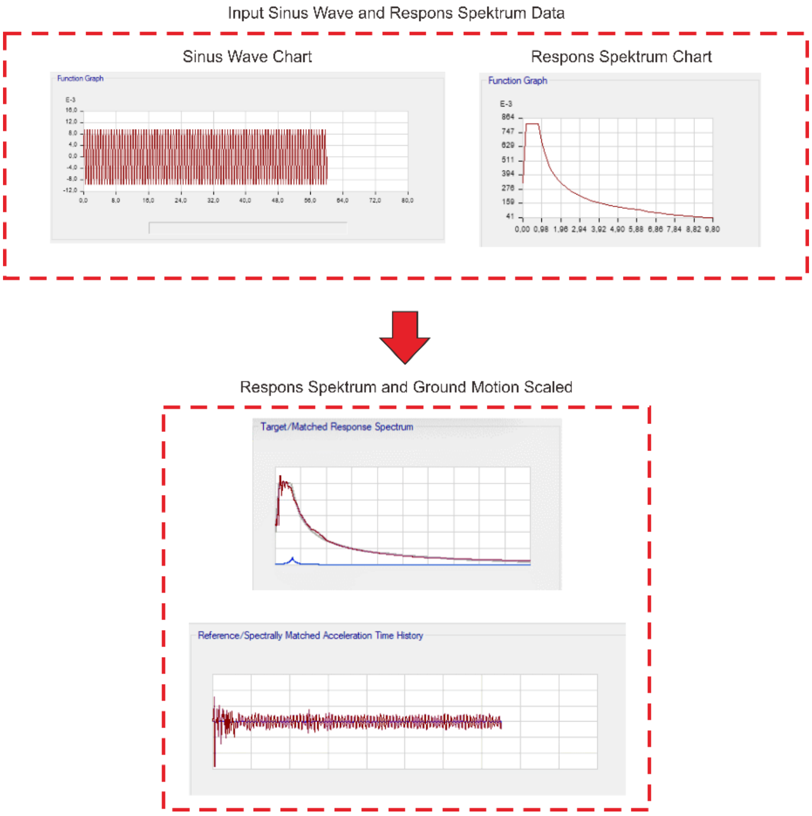

Fig. 5. Scaling of sine wave

Modeling with analysis software was conducted to know the forces acting on the structure, the reactions at each joint, and the structure capacities in withholding planned load. Forces analysis in structure aims to know the structure response reviewed on each element [8].

3. Results and Discussion

3.1. Response of Ground Motion Structure

3.1.1 Basic Shear Force

The shear force base review needed to know the comparison between dynamic and static as shown in Table 6. For Scaling the shear force, a history time method is also needed, like case method response spectrum performed if combination response for shear force base dynamic results analysis variance (Vt) is less of 100 % of shear force calculated basis (V) through method static equivalent [6].

Table 6. Shear force base loading of ground motion

Load Case	Dynamic Vex (kN)	Dynamic Vey (kN)	Static
Loma Prieta X	0.735	0.225	
Loma Prieta Y	0.221	0.751	
Kobe X	1,301	0.362	0.022
Kobe Y	0.391	1.208	
Northridge X	1.275	0.320	
Northridge Y	0.384	1,062	

3.1.2. Elastic Deviation of Ground Motion

Based on the analysis of the result indicated in Fig. 6, the deviation of elasticity increases along the increased amount of floor, so the most significant mark is on floor eight. The reason for this is due to the shear force load distribution that increases significantly with the number of floors in the building structure. The height of the building and the weight of the structure due to the earthquake are directly proportional to the shear force load distribution that occurs in the building, causing the eighth floor to have the maximum displacement at each ground motion loading [9].

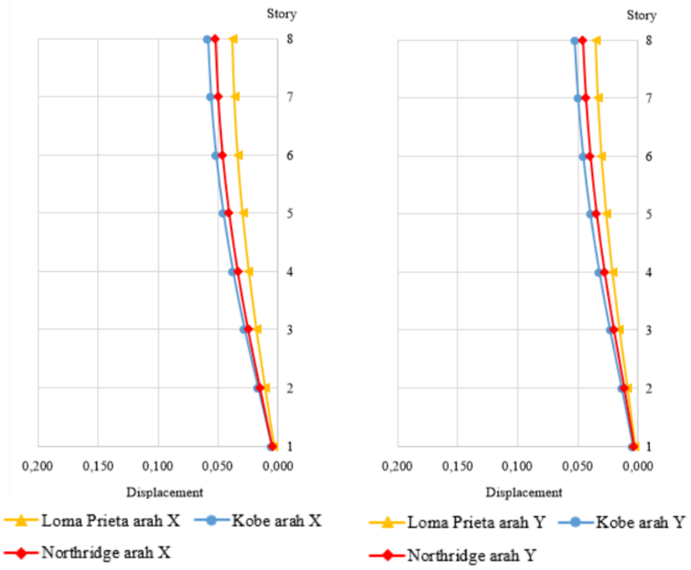

Fig. 6. Comparison of elastic deviation in the x-axis and y-axis directions

3.1.3. Story Drift due to Ground Motion

If reviewed from the deviation between the floor (story drift) direction x-axis (strong axis) and the y-axis (weak axis) as shown in Fig.7, the third ground motion owns marks a safe detour following allowable deviation. The deviation value between floors that most significantly loads the Kobe ground motion is shown on the third floor in the x-direction of 0.063, with a more significant value compared to the y-direction of 0.054. The deviation between floors in the Loma Prieta ground motion is the largest, shown on the third floor at 0.040 in the x-direction and 0.036 in the y-direction. Whereas in the Northridge ground motion, the deviation value between floors most significantly happened on floor three with a value of 0.056 to the direction x-axis and 0.047 to the direction y-axis. A review of the structural response based on the base shear force, elastic deviation, and inter-story deviation shows that the greatest consequences are due to the Kobe ground motion.

Based on the analysis results, it is known that the structural response of the building is also affected by the earthquake frequency level. At the low frequencies exhibited by the Kobe earthquake, the structural response of buildings is relatively high compared to earthquakes with other influence forces. The condition occurs in tall structures because they have a large enough fundamental period or low-frequency vibration that if subjected to earthquake forces at low frequencies, the structural response will be even greater [10].

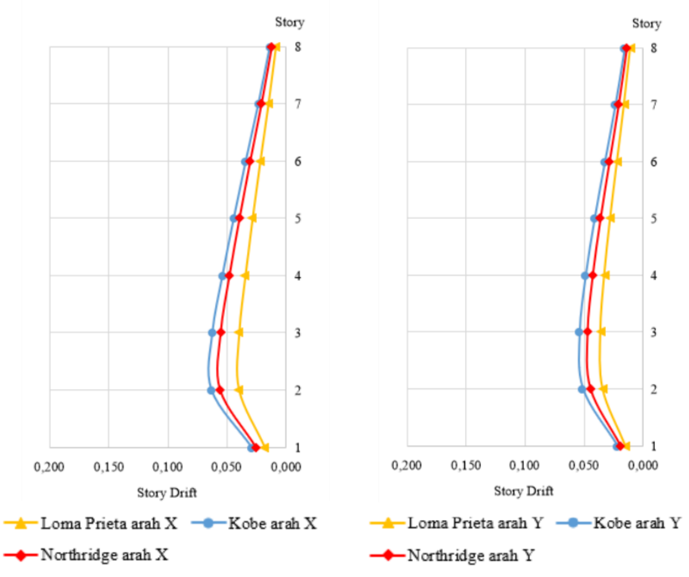

Fig. 7. Comparison of deviation between the floor (*story drift*) in the X-axis and Y-axis directions

3.2. Structural Response of Sine Wave Loading

3.2.1 Basic Shear Force of Sine Wave Loading

Table 7. Sinus shear force base loading

Load Case	Dynamic Vex (kN)	Dynamic Vey (kN)	static
1.5 Hz X	1.184	0.382	
1.5 Hz Y	0.358	1.279	
2.5 Hz X	1.357	0.305	
2.5 Hz Y	1.015	3.378	
3.5 Hz X	3.384	1.013	0.022
3.5 Hz Y	0.278	0.877	
4.5 Hz X	0.938	0.218	
4.5 Hz Y	0.284	0.737	
5.5 Hz X	0.881	0.263	
5.5 Hz Y	0.264	0.877	

Based on the data in Table 7, the base shear force value has fulfilled the ratio between dynamic and static marks. The shear forces that occur have met the combined response requirements for the base shear force resulting from the variance analysis (Vt) of more than 100% of the calculated shear force (V) through the equivalent static method [6].

3.2.2 Elastic Deviation of Sine Wave Loading

Based on the results of the sine wave loading analysis as shown in Fig.8, it can be seen that the structural response in terms of the elastic deviation mark is increasing at the top floor. The increase in elastic deviation due to sine wave loading is greater than that of ground motion. This condition occurs because the dynamic load shear force distribution will increase with the increase in the number of floors in the building structure so that the structure becomes heavier. The building height and weight of the seismic structure are directly proportional to the dynamic load shear force distribution in the building, causing the eighth floor to have the maximum displacement value [9]

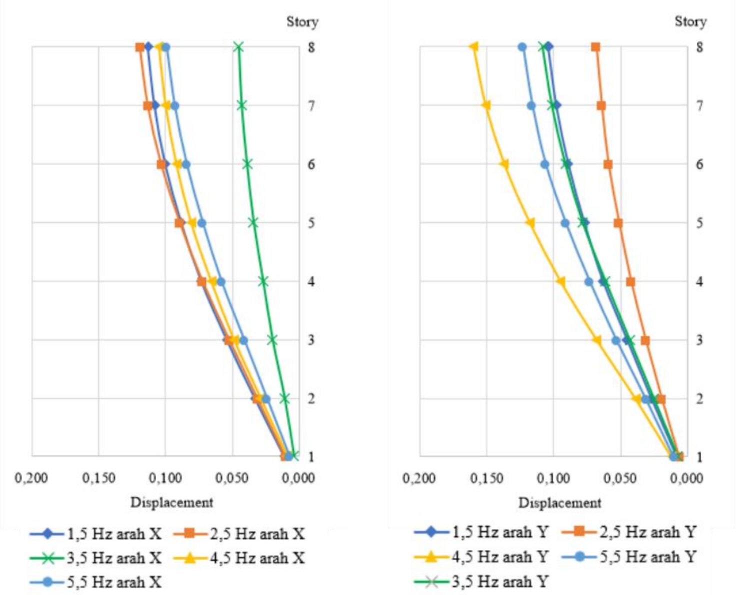

Fig. 8. Comparison of elastic deviation of the sine wave in the x-axis direction

3.2.3 Sine Wave of Deviation Between Floor (*Story Drift*)

The value of the structural response in terms of the deviation between floors (story drift) in the direction of the x-axis and y-axis in Fig.9 shows that the deviation at all frequencies is still below the allowable deviation limit, so the structure is in a safe condition. At frequencies of 1.5 Hz and 2.5 Hz, the deviation value in the x-axis direction is greater than that in the y-axis direction.

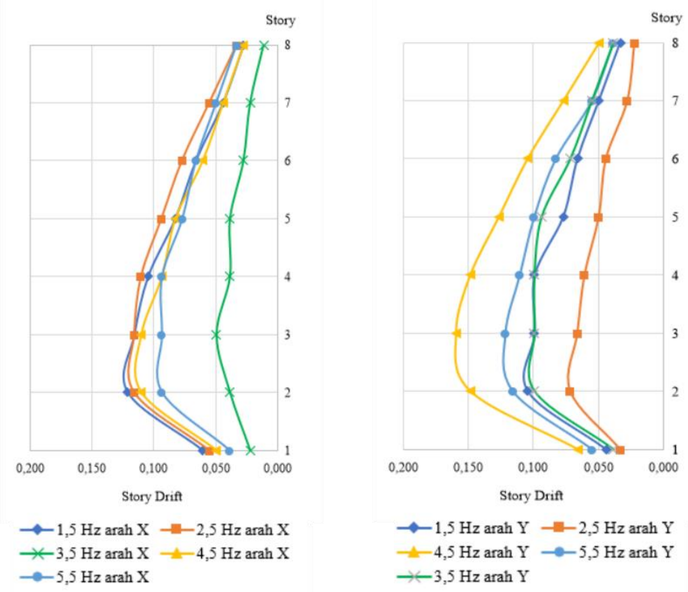

Fig. 9. Comparison of the deviation between floors (story drift) of sine waves in the x and y-axis directions

The largest inter-floor deviation value for the 1.5 Hz sine wave is shown on the second floor with an x-direction of 0.121, which is more significant than the y-direction of 0.022. The deviation between floors at a frequency of 2.5 Hz is shown on the second floor at 0.116 in the x-direction and 0.072 in the y-direction. A frequency of 3.5 Hz is shown to mark the y-direction by 0.099 greater than the x-direction by 0.007. The deviation between floors at a frequency of 4.5 Hz shows the most significant sign at the third floor, with a y-direction of 0.160 mm and an x-direction of 0.110 mm. Meanwhile, at a frequency of 5.5 Hz, the most significant inter-floor deviation value occurs at the third floor with a value of 0.121 mm for the y-axis direction and 0.094 for the x-axis direction.

3.3 Comparison of Structural Response between Sine Wave Loading and Ground Motion

Based on the results of structural modelling analysis, the sine wave loading method has more significant structural response results for both x-axis and y-axis directions compared to ground motion. The results of the structural response review based on the deviation between floors due to sine wave loading show the most significant value occurs at a frequency of 4.5 Hz. This has the following hypothesis: comparison of structural responses in terms of static shear force, elastic deviation, and inter-story deviation due to sine wave loading shows greater values than the results of ground motion loading. The conditions that occur due to sine waves are harmonic waves that have a uniform loading pattern at a certain time span, in contrast to loading due to ground motion which has a fluctuating loading pattern. [9]. The following is a comparison of the deviation mark between the sine wave and ground motion presented in Fig. 10 and Fig. 11.

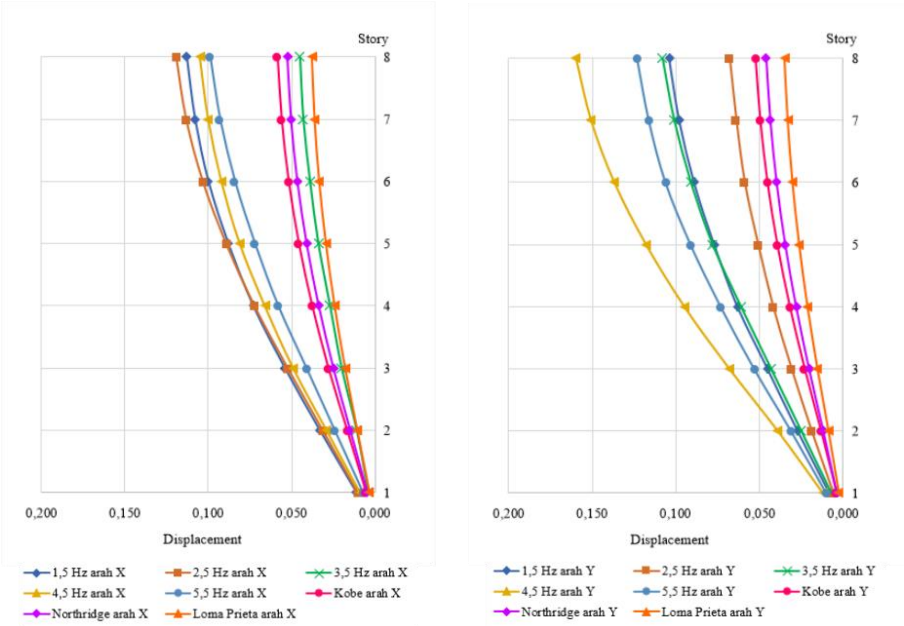

Fig. 10. Comparison of deviation of elasticity in the direction of the x-axis and y-axis

Based on the results of the comparison of the structural response viewed through the deviation between floors, the ground motion loading results taken from the earthquake recordings show lower marks. Because the time history loading method with ground motion is more recommended to be used in actual building structure planning calculations.

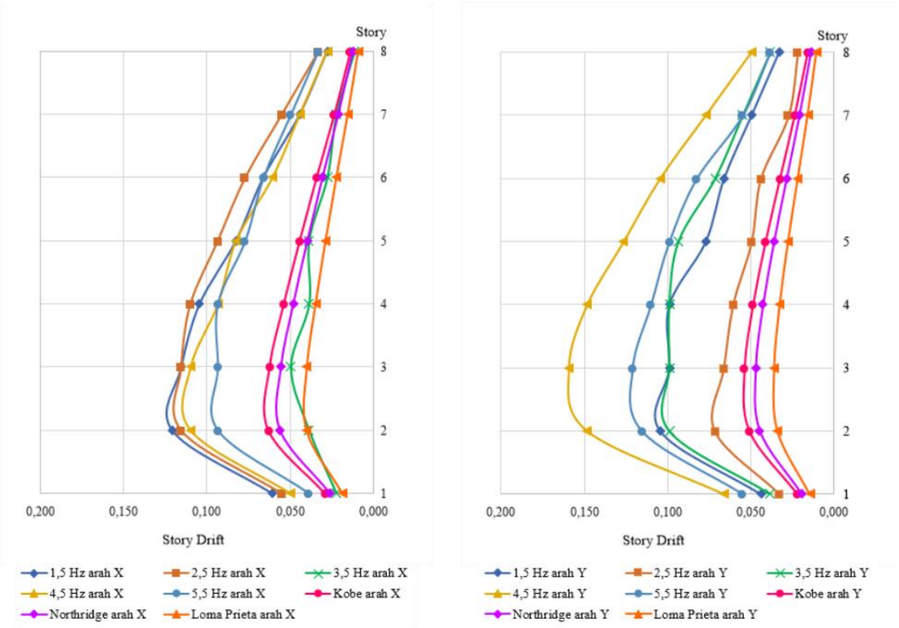

Fig. 11. Comparison of the deviation between floors (story drift) in the x and y-axis directions

The transient sine wave loading method can be used in experimental activities that perform physical testing through vibrating tables. The waves used in engine drives are of the sine or cosine type with a certain frequency and period. This loading approach is more likely to be used in physical testing simulations because the earthquake movement patterns can be modelled and controlled with the help of machines. In a case different from ground motion loading, earthquakes with fluctuating forces are complicated to implement in motion machines. Therefore, experiments can be conducted by testing an eight-story building model with a sine wave approach at a frequency step. An illustration of the test layout is provided in Fig. 12.

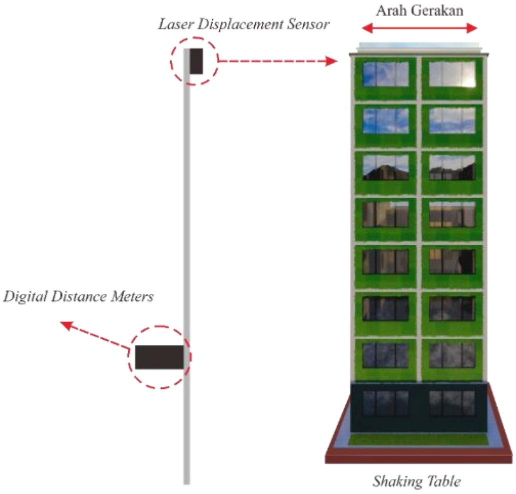

Fig. 12. Building layout test

Testing of the experimental building model was carried out in the direction of the weak Y axis which showed that the building can withstand up to 5.5 Hz frequency loading which corresponds to the plan load on the sine wave approach. The residual deviation or the actual residual deviation of the measurement results of the Installed Digital Distance Meter in the direction of the same weak Y axis on the top floor of the building is presented in Table 8.

Table 8. Recapitulation of residual deviation in the y-axis direction

Frequency	Deviation (mm)
1.5Hz	0.9
2.5Hz	0.5
3.5 Hz	0.7
4.5Hz	0
5.5Hz	0.8

When viewed from the results of the plan deviation, there is a considerable difference between the plan deviation and the residual deviation of the vibrating table test results. The maximum elastic deviation caused by the most significant sine loading was 0.160 mm in the y-direction, while the actual residual deviation showed a mark of 0.9 mm. Based on this data, the results of the No test values can be accurate according to what was planned. However, deviations still occur. No limit deviation was exceeded to ensure the building was safe until the highest frequency testing. The comparison graph of the deviation of the elasticity simulation test results through the vibrating table and the drift plan with the sine wave approach reviewed on the top floor model building is presented in Fig. 13.

The difference in results in the experiment presented in Fig. 13 is due to several factors, namely the use of materials, modelling in planning, and accuracy in the building fabrication process that differs between planning and implementation. One of the most influential parts of the results of this study is that the modelling support and connection in planning through software no analysis can represent the conditions in the implementation of the building model.

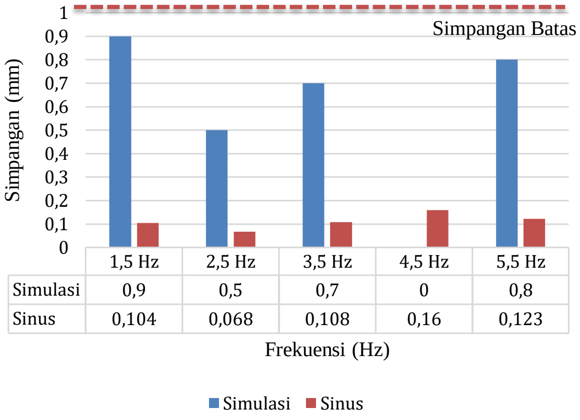

Fig. 13. Comparison of elastic deviation testing and sine

In the structure of the analysis software used, the connection system at each join could not be modelled in detail to match the implementation. Therefore, defining the parameters and planning characteristics of intermediate materials with different implementations, so that the resulting structural response is also different. The system connection column-beam used plate metal iron, as shown in Fig. 14. In the planning, the iron material as the connection was not modelled so parameters that affect the structural response such as Poisson's ratio could not be taken into account in the analysis. The Poisson ratio has an effect with a value proportional to the change in frequency.

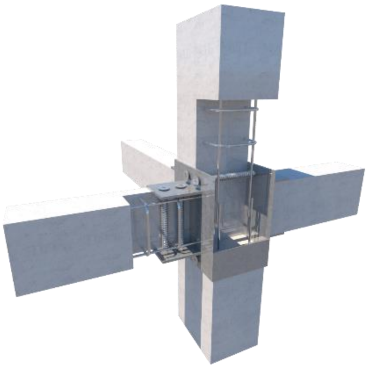

Fig. 14. Detail connection of beams building

It is also important to increase the damping due to vibration variations from frequency loading table shocks so as to minimise displacement. Therefore, a more detailed analysis is needed through modelling using the Finite Element method on the system connection and making a material parameter approach that matches the implementation to obtain accurate values.

4. Conclusion

Based on the results of the research and discussion, some conclusions can be drawn as follows :

a. The structural response results of the building model with ground motion loading, shown by incorporating the Kobe earthquake at a low frequency with deviation values of 0.063 in the x-axis direction and 0.054 in the y-axis direction.
b. The maximum deviation due to sine wave occurs at a frequency of 4.5 Hz with a value of 0.110 in one direction -x-axis and 0.160 mm in the same direction -y-axis.
c. Based on the model analysis results, the structural response value due to sine wave loading is greater than that of ground motion. Therefore, in the experimental simulation activity, the building model was tested with a sine wave because it can represent the motion pattern of the testing machine and the conditions can be controlled.
d. The earthquake scale model building can withstand earthquake loads at a finite sine wave frequency of 5.5 Hz. The maximum elastic deviation caused by the largest sine loading in the weak y-axis is 0.160, while the actual residual deviation results show 0.9 mm. This condition is due to the modeling support and connections in the planning through software that can not represent the actual conditions according to the implementation of the building model.

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