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Dynamic Behavior of a 5-Story Building with Variations of Structural Parameters Using Modal Analysis

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Abstract: Civil engineering structures in earthquake-prone regions should be designed to adopt the effect of an earthquake. The dynamic behavior of a building when an earthquake is shaking, depends on the variation of the parameters of the building structure, namely the mass, stiffness and damping value. The purpose of this study is to explore the effect of variations in the mass, the stiffness and the damping value to the dynamic behavior of a five-story building. The modal analysis method is applied to this study to calculate the modal parameters of the structure that are modal periods, modal damping ratios and modal participation factors. This study shows that variations in the mass and stiffness of the building have an influence on the modal periods, modal damping ratios and modal participation factors at various levels. The variation of damping values of building stories affects the modal damping ratios but does not affect the modal periods and modal participation factors.

Key words: Building structure, modal analysis, dynamic behavior, participation, damping ratios

INTRODUCTION

In earthquake-prone areas such as in most parts of Indonesia, civil engineering structures have to be designed to enable of accommodating the effect of an earthquake. It is a wise attitude for inhabitants in the areas to live in harmony with nature to reduce the risk of earthquake disaster. The dynamic behavior of a building, when an earthquake is shaking, depends on the variation of the parameters of the building structure that is its mass, stiffness and damping value. Various ways to study the dynamic behavior of buildings can be found today, for example using computer simulation (Arafat, 2015; Louzai and Abed, 2015; Nurhidayatullah, 2016; Poursha and Amini, 2015) or physical testing to full-scale structures (Caetano and Cunha, 2004). Dynamics behavior of the real building structures during earthquake shocks using recorded data on the structures has also been evaluated.

The purpose of this study is to determine the effect of variations in the mass, stiffness and damping of a five-story building to the dynamic behavior of the building. Using the shear building model and applying modal analysis method, modal parameters of the structure can be calculated. Dynamic behavior of the building was evaluated from the identified modal parameters, namely modal periods, modal damping ratios and modal participation factors.

MATERIALS AND METHODS

Building model and modal analysis: This study briefly explains the model of the studied building along with its structural parameters and the modal analysis method to calculate the modal parameters.

Building model: Structural parameters of a five-story building are mass (m) that is lumped to the floor, the stiffness of story (k) and damping value of story (c) that can be illustrated in Fig. 1. As the model reference, the standard model of the building has 100% values for all of m, k and c, meaning that:

$$m_1 = m_2 = m_3 = m_4 = m_5 = m \tag{1}$$

$$c_1 = c_2 = c_3 = c_4 = c_5 = c \tag{2}$$

$$k_1 = k_2 = k_3 = = k_4 = k_5 = k \tag{3}$$

Where:
m = 29.01 $kg.sec^2/cm$
c = 1422.72kg.sec/cm
k = 284544.01kg/cm as the standard parameters that are given the value of 100%

The variation of the structural parameter reduction can be seen in Table 1. Variation of the proportions of mass, stiffness and amping value of the studied

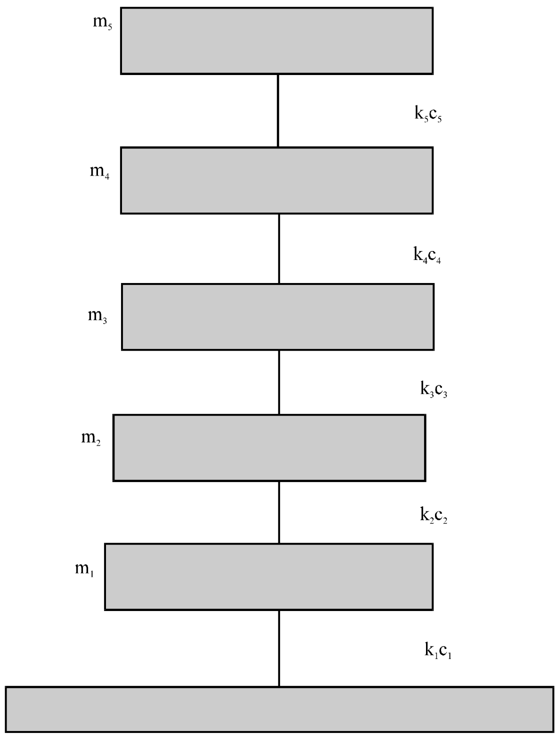

Fig. 1: Structural model of the studied building as a shear inverted pendulum

Table1: The reduction of consecutive structural parameters in Fig. 1 to form model variations with the reference of the mass of floor 3 as well as the stiffness and damping value of story 3

Models	m (%)	Model	k (%)	Model	c (%)
mp10	+10	kp10	+10	cp10	+10
mp05	+5	kp05	+5	cp05	+5
s000	0	s000	0	s000	0
mm05	-5	km05	-5	cm05	-5
mm10	-10	km10	-10	cm10	-10

Table 2: The reduction of consecutive mass (in%) whereas all stiffness and damping value are given 100% for k and c, respectively

Models	mm10	mm05	s000	mp05	mp10
m_1	80	90	100	110	120
m_2	90	95	100	105	110
m_3	100	100	100	100	100
m_4	110	105	100	95	90
m_5	120	110	100	90	80

Table 3: The reduction of consecutive stiffness (in%) whereas all mass and damping value are given 100% for m and c, respectively

Models	km10	km05	s000	kp05	kp10
k_1	80	90	100	110	120
k_2	90	95	100	105	110
k_3	100	100	100	100	100
k_4	110	105	100	95	90
k_5	120	110	100	90	80

structure can be seen in Table 2-4, respectively with the reference of Table 1. s000 in the tables is the standard model of the building structure.

Table 4: The reduction of consecutive damping value (in%) whereas all mass and stiffness are given 100% for m and k, respectively

Models	cm10	cm05	s000	cp05	cp10
c_1	80	90	100	110	120
c_2	90	95	100	105	110
c_3	100	100	100	100	100
c_4	110	105	100	95	90
c_5	120	110	100	90	80

Modal analysis: For the shear inverted pendulum model or the shear building model as shown in Fig. 1, the general equation of motion of the multi-story building can be written as:

$$M\,\ddot{u} + C\,\dot{u} + K\,u = -M\,1\ddot{u}_g \tag{4}$$

Where:
M = Matrix of mass
C = Matrix of damping value
K = Matrix of stiffness
1 = Unit vector

In Eq. 4, $\ddot{u}$, $\dot{u}$, u and $\ddot{u}_g$ are the vectors of acceleration, velocity, displacement and ground acceleration, respectively. Processed by using modal analysis operation (Vamvatsikos and Cornell, 2005), Eq. 4 leads to modal equations of motion. The modal equation of motion of a certain mode of vibration can be expressed as:

$$\ddot{u} + 2\zeta\omega\,\dot{u} + \omega^2\,u = -\Gamma\,\ddot{u}_g \tag{5}$$

Where:
ω = Modal naturalangular frequency
ζ = Modal damping ratio
Γ = Modal participation factor

The modal natural period, usually called as modal period, can be written as:

$$T = 2\pi/\omega \tag{6}$$

RESULTS AND DISCUSSION

Giving the data in Eq. 1-3 and applying modal analysis procedures using Eq. 4-5, the modal parameters are calculated in various given structural parameters and the results are discussed. The discussion is limited to vibration Modes 1 and 2 due to limited space. The discussion of higher modes of the building vibration is subjected to future publications.

Variation of mass: Referring to Table 2 with the explanations in Fig. 1 and Table 1, the modal natural periods, modal damping ratios and modal participation factors are obtained and presented in Table 5-7, respectively. The results in Table 5 are plotted in Fig. 2 where the modal natural periods are normalized to one of the standard model (s000, 100%).

Table 5: Modal natural period t (sec)

Models	Mode 1	2	3	4	5
mp10	0.669	0.240	0.153	0.120	0.103
mp05	0.684	0.240	0.153	0.119	0.104
s000	0.698	0.239	0.152	0.118	0.104
mm05	0.713	0.238	0.151	0.117	0.102
mm10	0.728	0.237	0.150	0.117	0.100

Table 6: Modal damping ratios of each model variation ξ (%)

Models	Mode 1	2	3	4	5
mp10	2.35	6.54	10.26	13.13	15.29
mp05	2.30	6.55	10.30	13.22	15.16
s000	2.25	6.57	10.35	13.30	15.17
mm05	2.20	6.60	10.41	13.38	15.35
mm10	2.16	6.63	10.48	13.45	15.70

Table 7: Modal participation factor of each model variation Γ

Models	Mode 1	2	3	4	5
mp10	2.182	-0.690	0.348	-0.164	0.038
mp05	2.138	-0.676	0.349	-0.181	0.059
s000	2.097	-0.660	0.348	-0.194	0.089
mm05	2.058	-0.643	0.344	-0.201	0.123
mm10	2.022	-0.622	0.337	-0.204	0.160

Figure 2 presents the relationship between reduction of the mass proportion (x-axis) and normalized natural periods of Mode 1 and 2 (y-axis). Focusing on Mode 1 as the proportion of mass are given smaller for the upper building, the period will shorten linearly as shown in the fitting curve that has $R_1 = 1$ for a linear equation. In the condition, the building will have higher frequency linearly. Since, Mode 1 dominates the vibration of the building as indicated in the figure and shown later in the discussion of the modal participation factors, giving greater masses for the upper stories will elongate the building period.

The phenomenon of Mode 2 is in contrary to that one of Mode 1. Figure 2 reveals that whenever the proportion of masses for the upper building is given smaller than the lower one, the modal period will be longer. The curve of the trend of Mode 2 best fits a cubic polynomial equation for having $R_2 = 1$. In the state of larger than the reduction of around 10%, Fig. 2 informs that the period of Mode 2 will start to shorten.

The calculated modal damping ratios are shown in Table 6. The results in the Table 6 are plotted in Fig. 3 where the modal damping ratios are normalized to one of the standard model (s000, 100%).

Figure 3 shows the relationship between reduction of the mass proportion (x-axis) and the normalized modal damping ratios of Mode 1 and 2 (y-axis). Focusing on Mode 1 as the proportion of mass become smaller to the upper building, the damping ratio will be larger in quadratic as shown in the fitted curve that has $R_1 = 1$ for a quadratic equation. It means that the modal motion will decay faster when the masses of lower floors are given larger proportion than one of the upper floors.

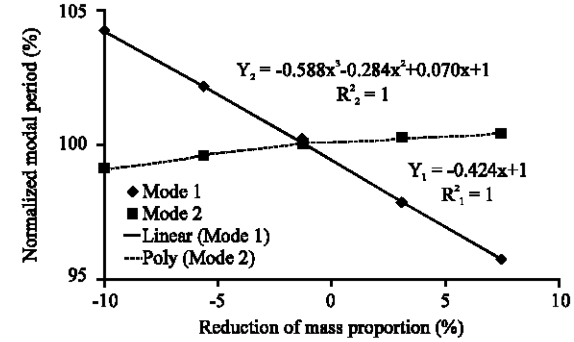

Fig. 2: Normalized modal natural periods of Mode 1 and 2

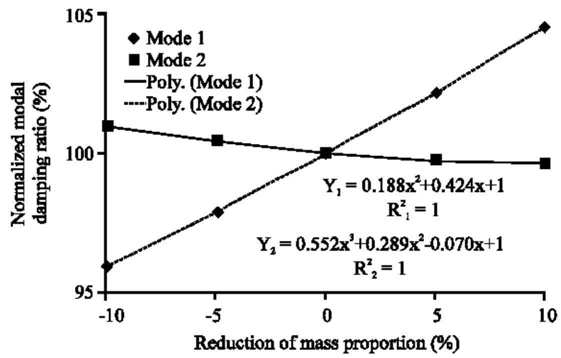

Fig. 3: Normalized modal damping ratios of Mode 1 and 2

Since, Mode 1 dominates the vibration of the building as indicated in the table and shown later in the discussion of the modal participation factors, giving greater masses to the upper stories will cause the building to longer vibrate.

The phenomenon of Mode 2 is different from one of Mode 2. Figure 3 reveals that if the proportion of upper masses of the building is smaller than the lower ones, the modal damping ratio will be smaller. Curve fitting of the trend for the phenomenon of Mode 2 is not linear. Setting the cubic polynomial equation is the best fit for having $R_2 = 1$. In the state of larger than the reduction of around 10%, the figure notifies that the damping ratio of Mode 2 will tend to increase.

The calculated modal participation factors are shown in Table 7. The results in the table are graphed in Fig. 4 where the modal participation factors are normalized to one of the standard model (s000, 100%).

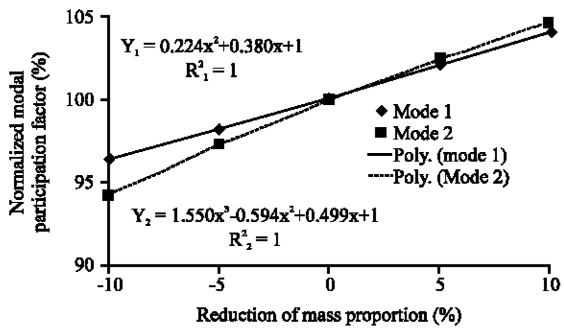

Fig. 4: Normalized modal participation factors of Mode 1 and 2

Figure 4 shows the relationship between reduction of the mass proportion (x-axis) and normalized modal participation factors of Mode 1 and 2 (y-axis). The figure reveals that as the proportion of mass are given smaller for the upper building, the participation factor of either Mode 1 and 2 will be larger non-linearly. It means that the motion will become more dominated by Mode 1 and 2 when the masses of upper floors are given smaller proportion that one of lower floors.

Variation of stiffness: Referring to Table 3 with the explanations in Fig. 1 and Table 1, the modal natural periods and the modal damping ratios are computed and shown in Table 8 and 9, respectively. The results in Table 8 are plotted in Fig. 5 where the modal natural periods are normalized to one of the standard model (s000, 100%).

Figure 5 shows the relationship between the reduction of the stiffness proportion and the normalized modal natural periods of Mode 1 and 2. Focusing on Mode 1 as the proportion of stiffness are given smaller for the upper building stories, the period will shorten cubically as shown in the fitting curve that has $R_1 = 1$ for a cubic equation. In that state, the building will have increasing frequency cubically. Vise a versa when the proportion stiffness is greater to the upper stories, the period will elongate. It means that the building will tend to have a lower frequency.

Since, Mode 1 dominates the vibration of the building as indicated in the figure and shown later in the discussion of the modal participation factors, giving greater stiffness for the upper stories will elongate the building period. In Fig. 5, the phenomenon of Mode 2 is not parallel to that one of Mode 1. Increasing the stiffness of upper stories will not always shorten the modal period.

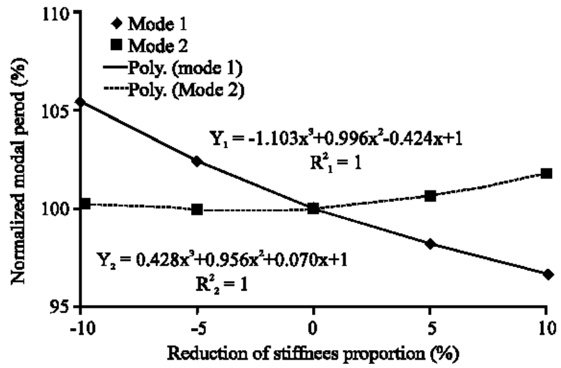

Fig. 5: Normalized modal natural periods of Mode 1 and 2

Table 8: Modal natural period t (sec)

	Mode				
Models	1	2	3	4	5
kp10	0.675	0.243	0.155	0.121	0.103
kp05	0.685	0.241	0.153	0.119	0.104
s000	0.698	0.239	0.152	0.118	0.104
km05	0.715	0.239	0.151	0.118	0.103
km10	0.736	0.240	0.152	0.118	0.101

Table 9: Modal damping ratios of each model variation ξ (%)

	Mode				
Models	1	2	3	4	5
kp10	2.21	6.81	10.82	13.82	14.73
kp05	2.22	6.64	10.50	13.50	15.09
s000	2.25	6.57	10.35	13.30	15.17
km05	2.31	6.59	10.38	13.33	14.91
km10	2.40	6.70	10.55	13.47	14.43

The calculated modal damping ratios are shown in Table 9. Graphically, the results in the table are shown in Figure 6 where the modal damping ratios are normalized to one of the standard model (s000, 100%).

Figure 6 illustrates the relationship between the reduction of the stiffness proportion and the normalized damping ratios of Mode 1 and 2.

Focusing on Mode 1 as the proportion of stiffness become smaller to the upper building, the damping ratio will be smaller cubically as shown in the fitted curve that has $R_1 = 1$ for a cubic equation. It means that the modal motion will decay longer when the stiffness of the upper stories is given smaller proportion than one of lower floors. Since, Mode 1 dominates the building vibration as indicated in the figure and shown later in the discussion of the modal participation factors, giving greater stiffness to the upper stories will cause the building to vibrate shorter.

It should be noted that the trend of damping ratios for the stiffness reduction above 10% seems to become larger. For Mode 2, giving larger or smaller proportion of stiffness will always increase its damping ratio.

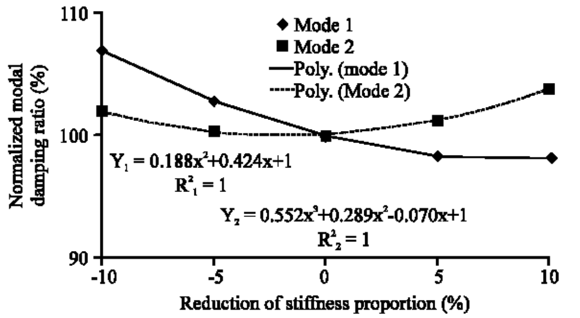

Fig. 6: Normalized modal damping ratios of Mode 1 and 2

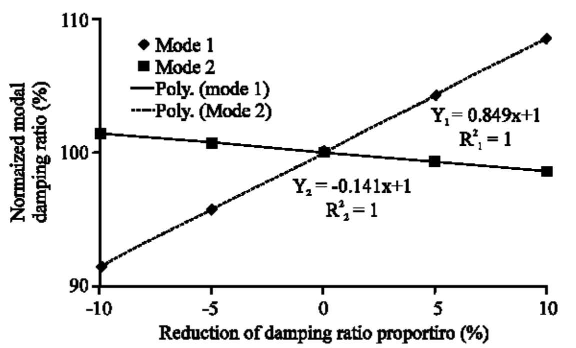

Fig. 7: Normalized modal damping ratios of Mode 1 and 2

Table 10: Modal damping ratios of each model variation ξ (%)

Models	Mode 1	2	3	4	5
cp10	2.44	6.48	10.13	12.98	14.79
cp05	2.35	6.52	10.24	13.14	14.98
s000	2.25	6.57	10.35	13.30	15.17
cm05	2.15	6.61	10.47	13.46	15.36
cm10	2.06	6.66	10.58	13.62	15.55

Variation of damping value: Referring to Table 4 with the explanations in Fig. 1 and Table 1, the modal periods and modal participation factors are not affected by the variation of damping values of the building story. However, the modal damping ratios are affected as indicated in Table 10. Graphically, the results in the table are plotted in Fig. 7 where the modal damping ratios are normalized to one of the standard model (s000, 100%).

Figure 7 shows the relationship between the reduction of the damping value proportion of the structure and the normalized damping ratios of Mode 1 and 2. Focusing on Mode 1 as the proportion of damping values is smaller to the upper building stories, the damping ratio will be larger linearly as indicated by the best-fitted curve that has $R_1 = 1$ for a linear equation. It means that the modal motion will decay faster when the damping values of upper stories are given smaller proportion than one of lower stories. This also means that when the damping values of lower building stories are given larger to that one of upper stories, the damping ratio of Mode 1 will become greater. Since, Mode 1 usually dominates the building vibration, giving greater damping values to the lower stories will cause the building to vibrate shorter. The trend of Mode 2 is in contrary to one of Mode 2.

CONCLUSION

The general conclusions of this study are: giving smaller proportion masses for upper building floors will tend to shorten the period, shorten the vibration and increase the domination of Mode 1 and 2 providing smaller proportion of stiffness for upper building stories will lead to shorten the period of Mode 1 and 3 setting greater proportion of damping values for lower building stories will tend to shorten the building vibration.

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