SVA

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Simplified Vulnerabiltiy Analysis (SVA) Preliminary Design of the Frame Structure in the Architectural DesignProcess

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Abstract

Background: There is a need for a good cooperation between the architects and structural experts in creating of earthquake architecture. Through some ways in the design process, the architects can identify and evaluate the vulnerability of the building from earthquakes. Unfortunately, there is no available evaluation method, so the alternative is adopting SVA (Simplified Vulnerability Analysis) method, a limited engineering analysis based on the information from the architecture and structure drawings of the existing buildings. The Japan Building Disaster Prevention Association (JBDPA) and Matsutaro Seki developed the SVA, and then Seki adopted the SVA of JBDPA and adjusted it to the international earthquake regulation. In principle, the JBDPA and Seki SVA is a safe structure if the seismic structure index ≥ the seismic demand index. The modification of the JBDPA and Seki SVA in this research is that the seismic structure index consists of the column dimension index, column rigidity index, strong column/weak beam index, redundancy index, and structure ductility index. Meanwhile, the seismic demand index is the multiplication between seismic response index and the priority factors of building functions. **Methods**: It is a quantitative research with experimental research method. The modified SVA formulation was compared with the pushover analysis from other researchers. The results were then tabulated, graphed and compared. **Findings**: For a model with less than 10 floors, the vulnerability prediction between SVA and pushover analysis is relatively similar. While for a model with more than 10 floors, the vulnerability prediction between SVA and pushover analysis is relatively almost similar (within the range of prediction of pushover analysis) influenced by the height of the building. Thus, SVA procedure is more appropriate to evaluate the design vulnerability of low and middle rise building. **Applications**: The SVA procedure can be used to underlie the potential status of the selected buildings and subsequently there are a list of the buildings which needs more detailed vulnerability assessment conducted by the structural experts.

Keywords: Earthquake, Irregular, Architectural design, SVA, Simplified Vulnerability Analysis.

1. Introduction

Indonesia is an earthquake-prone area, so the buildings should have earthquake resistant constructions. In order to create an earthquake architecture[1] which is aesthetically appealing and structurally resistant to earthquake, it needs a good cooperation between architects and structural experts. The first step in creating the earthquake architecture, in the design process, is that the architects can identify and evaluate the vulnerability of the building towards the earthquakes[2].

Unfortunately, there is still no evaluation method available, so the alternative is adopting the

SVA (Simplified Vulnerability Analysis) method[3] which is a limited engineering analysis based on the information from architectural drawings and structures of the existing buildings. Some of the developers of SVA are The Japan Building Disaster Prevention Association (JBDPA)[4] and Matsutaro Seki[5]. Seki adopted the SVA of JBDPA and adapted it to international earthquake regulation. The purpose of the developing SVA is the structural verification of retrofitting hence the need for modification in the architectural design process when using it to identify and evaluate the vulnerability of buildings. The proposed purpose of SVA in this research is to build the procedures or methods which can be used by architects in evaluating the vulnerability of buildings to earthquakes during the architectural design process (on design development and detail engineering design/DED steps), and which are in accordance with the conditions in Indonesia. In the architectural design process, dimensional structural elements and building geometric forms can be controlled by this SVA. The research is limited to the dimension and type of structure commonly used in Indonesia (moment-resisting frame with 1 or 2-way floor system), the middle rise maximum height (± 10 floors), and the regular-category building's geometric form[6].

In principle, the SVA of JBDPA and Seki is a safe structure if the seismic structure index (I_S) ≥ the seismic demand index (I_{SO}). The lateral force resistant system is at least influenced by redundancy, column dimensions, column rigidity, strong column / weak beam and structural ductility[7]. The seismic structure index consists of the lateral force of the column defined as the ratio of the minimum column area and the design column area (I_{Ac-i}), redundancy is defined as the period of structural vibration (I_T), column rigidity is defined as the ratio of the height and width of the column (I_{C-i}), strong column/weak beam is defined as the ratio of the number of columns fulfilling the criteria of the strong column/weak beam and the total number of the columns (I_{SCWB-i}), and structural ductility adopts the Matsutaro Seki's procedures by including the ratio of response modification factor (R) and the over strength factor (Ω_0) - (R/Ω_0). The modification of SVA of JBDPA and Seki in this research is based on the explanation that the seismic structure index (I_S) is the multiplication of column dimension index (I_{Ac-i}), column rigidity index (I_{C-i}), strong column/weak beam index (I_{SCWB-i}), redundancy index (I_T), structure ductility index (R/Ω_0) , irregularity index (S_D) and time index (T).The limited geometric shapes are regular and considered as new buildings, so it is assumed that S_D=1 and T=1. On the other hand, the seismic demand index (I_{SO}) is the multiplication between seismic response index (I_{CS}) and the priority factors of building functions (I_e).The problem in the proposed procedures is to what extent the accuracy in evaluating and assessing the vulnerability of buildings in the design process. In order to find out the validity of building vulnerability assessment procedure in this design process, the procedures will be compared with the more detailed vulnerability assessment procedure from other researchers called the pushover analysis.

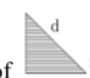
1.1. Seismic Structure Index (I_S)

In general, JBDPA and Seki define the formulation of the seismic structure index as follow:

$$I_S = E_0.S_D.T \tag{1}$$

In which, I_S = Seismic structure index; E_0 = Basic seismic structure index; S_D = Irregularity Index (regular building S_D=1); T = time index (new building T=1).The modification of the basic seismic structure index (E_0) is based on the concept that the resistance of the column in resisting the lateral load of the earthquake is defined into column dimension, influenced by column rigidity, forms strong column/weak beam, good structure ductility and the unity of the whole structural elements (redundancy). The formulation is as follow:

$$E_0 = \frac{n+1}{n+i}(I_{Ac-i}.I_{C-i}.I_{SCWB-i}.I_T).\frac{R}{\Omega_0}] \tag{2}$$

In which, n = the number of building levels the; i = The evaluated level(s). Where the first level is given number 1 and the followings are given n; $\frac{n+1}{n+i}$= the modification factor of level shear capacity. It follows the distribution of  [8]; I_{Ac-i} = column dimension index of the evaluated level; I_{C-i} = column type index of the evaluated level; I_{SCWB-i} = strong column/weak beam index of the evaluated level; I_T = structural vibration period index, $T_c \leq T_{max} \rightarrow I_T = 1$ and $T_c > T_{max} \rightarrow I_T = 0$; T_c = structural vibration period based on the software calculation (seconds); T_{max} = The maximally allowed structural vibration period (seconds) based on the article 7.8.2 of SNI 1726:2012[9] or on the formulation 25 of SNI 1726:2002[10]; R/Ω_0= structure ductility, R = The modification factor of moment-resisting frame (table 9 of SNI 1726:2012 or table 3 of SNI 1726:2002), Ω_0 = The overstrength factor of moment-resisting frame based on the table 9 of SNI 1726:2012 or the table 3 of SNI 1726:2002.

The concept of column lateral force (I_{Ac-i}) assumed as the ratio of design column area ($\sum A_C$) and minimum column area ($\sum A_{C\ min}$) is described follow:

$$I_{Ac-i} = \frac{\Sigma A_C}{\Sigma A_{C\min}} \tag{3}$$

In which, $\sum A_C$= total design column area (m^2); $\sum A_{C\ min}$= total minimum column area (m^2) 0.15% of the cumulative area of column load[11], in which the minimum column area is 0.09 m^2 or 0.3x0.3 m.

The concept of column rigidity (I_{C-i}) assumed as the ratio of the average of column types (N_Cx0.7-1.0) and total columns ($\sum N_C$) is described below:

$$I_{C-i} = \frac{(N_{C-a}x0.7) + (N_{C-b}x0.8) + (N_{C-c}x1.0)}{\Sigma N_C} \tag{4}$$

In which, N_{C-a}= total of column types –a (Table 1); N_{C-b}= total of column types–b (Table 1); N_{C-c}= total of column types-c (Table 1); index of column types of a, b & c (I) = 0.7, 0.8, 1.0 (Table 1); $\sum$NC= Total columns.

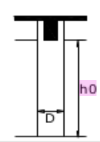
which is the ratio of the design and minimum lateral seismic loads. The design lateral seismic loads is based on the spectral responses of S_S and S_1, for those using SNI 1726:2012 or coefficients of Ca and Cv for those using SNI 1726:2002 in each building site; while the minimum lateral seismic loads is based on seismic zone division FEMA 155[13] which is a low seismic zone with S_S =0.25 g and S_1=0.1 g or zone 2A according to UBC 1997[14]. The concept of seismic demand index or lateral seismic load index (I_{SO}) is the multiplication of seismic response coefficient index (I_{CS}) and the priority factors of building function (I_e). Meanwhile, the seismic response index (I_{CS}) is the ratio of design seismic coefficient (C_S) and the minimum seismic coefficient (C_{Smin}).

$$I_{SO} = \frac{n+i}{2n-i+1}.(I_{CS}.Ie) \tag{6}$$

$$I_{CS} = \frac{C_S}{C_{S\min}} \tag{7}$$

In which, I_{SO} = seismic demand index; n = number

Table 1. Index of combined shear stress average and ductility index of structure elements (Source: processed from [4,5])

Types of Lateral Elements	Requirements		Index (I)
Columns	Clear Height/Column Depth; h0/D	Definition h0/D	
a). Slender columns	6≤h0/D	 	0.7
b). Normal columns	2<h0/D<6		0.8
c). Short columns	h0/D≤2		1.0

The concept of strong column/weak beam (I_{SCWB-i}) assumed as the ratio of the number of columns fulfilling the criteria of the strong column/weak beam (N_{SCWB}) and total columns ($\sum N_C$) is described below:

$$I_{SCWB-i} = \frac{N_{SCWB}}{\Sigma N_C} \tag{5}$$

In which, $\sum N_C$= total columns, N_{SCWB}= number of columns fulfilling the criteria of the Wp column ≥ 1.2xWp beam, Wp=plastic modulus, Wp=0.25xbxh^2, b&h= dimension of width and height of beam or column[12]. Height of beam =1/10 – 1/14xL, L= span.

1.2. Seismic Demand Index (I_{SO})

The concept of column lateral capacity (I_{Ac-i}), the ratio of the design column area and minimum column area, is also applied to the lateral seismic load (I_{SO}) concept,

of building levels; i = evaluated level(s), where the first level is given number 1 and the followings are given n; $\frac{n+i}{2n-i+1}$ = modification factor of seismic demand of the levels, following the distribution of 

[8]; C_S = Seismic response coefficient of the design based on the formulations 21-25 of SNI 1726:2012 or on the formulation 26 of SNI 1726:2002; C_{Smin} = minimum seismic response coefficient S_S=0.25g and S_1=0.1g based on FEMA 155 or zone 2A of UBC 1997; I_{CS} = seismic response coefficient index; I_e = the priority factors of building function based on the table 1 & 2 of SNI 1726:2012 or based on the table 1 of SNI 1726:2002.

Table 2. Recommendation for the evaluation of potential seismic vulnerability based on the seismic performance (source :modification of procedure[5])

Seismic vulnerability evaluation	Potential level of damage	Seismic performance-FEMA 273 (FEMA 273)[15]	
$I_S > I_{SO}$	Light Damage	<0.5%	IO (*Immediate Occupancy*)
$0.5I_{SO} \leq I_S \leq I_{SO}$	Moderate Damage	<1.5%	LS (*Life Safety*)
$I_S < 0.5I_{SO}$	Heavy Damage	<2.5%	CP (*Collapse Prevention*)

1.3. Seismic Structure Index (I_S) vs Seismic Demand Index (I_{SO})

The concept of ratio of seismic structure index (I_S) and seismic demand index (I_{SO}). Structure is safe if:

$$I_S \geq I_{SO} \quad (8)$$

In which, I_S = seismic structure index; I_{SO} = seismic demand index. For other ratios, evaluating the vulnerability of building structures can be done by comparing the seismic structure index towards the seismic demand index, and each level can be identified for its possible level of damage (table 2).

2. Research Method

This research is an experimental research. In order to verify the proposed procedure, it will be compared with the result of pushover analysis conducted by other researchers, so the result will be more objective. Although the proposed SVA procedure is to analyse the vulnerability of building with a middle rise maximum height (± 10 floors) but the validity limit of the observed model was determined up to 14 floors. The data of earthquake zones and structures were collected from the research[16–21] in table 3 and 4. The calculation steps are as follows:

a. capacity of each floor, based on the data from table 3 and 4 calculate the column dimension index - $I_{Ac\text{-}i}$ (formulation 3), calculate the column type index - $I_{C\text{-}i}$ (formulation 4) and calculate the strong column/weak beam index-$I_{SCWB\text{-}i}$ (formulation 5). Obtain a T_C and compare it to T_{max} specify the index of the structural vibration period (I_T) and obtain R and Ω_0 values from table 9 of SNI 1726:2012 or table 3 of SNI 1726:2002 calculate the structure ductility R/Ω_0. Multiply all values (formulation 2) so that the basic seismic index of structure (E_0) can be obtained. Multiply the basic seismic index of structure (E_0) with the irregularity index (S_D) for regular building S_D=1 so that the seismic capacity index of structure (I_S) can be obtained (formulation 2).

b. Calculate the modification factor of level seismic demand of each floor, based on the data from table 4, calculate the C_S and C_{Smin} values, and then input them to formulation 7 to obtain I_{CS} value. Obtain I_e value from table 1 and 2 of SNI 1726:2012 or table 1 of SNI 1726:2002 for the office function of I_e=1. Input the values of modification factor of seismic demand, I_{CS} and I_e to formulation 6 to obtain the seismic demand index (I_{SO}) value.

c. Compare the I_S and I_{SO} values based on the

Table 3. Data of building structure of the models (source : [16–21])

Model	Number of floors/levels (height-m)	Beam Dimension (cm)	Column Dimension (cm)	Building Dimension (m)	Module (m)
a	6 (3.5 m)	25X50	65X65 (1st-3rd floor), 55X55 (4th-6th floor)	18X18	6X6
b	14 (4 m)	40X80 (1st-4th floor), 40X70 (5th-9th floor), 30X60 (10th-14th floor)	80X80 (1st-5th floor), 70X70 (6th-10th floor)	30X30	5X5
c	10 (4 & 3.6 m)	40X60 (main beam), 30X60 (subsidiary beam)	80X80 1st-4th floor), 70X70 (5th-14th floor)	24X24	8X8
d	5 (4 m)	35X60	60X60	42X32	6X8
e	4 (4 & 3.5 m)	30X45 (1st-3rd floor), 30X40 (4th floor)	45X45	18X18	4.5X4.5
f	12 (4 m)	40x60	60X60	42X42	6X6

provisions in table 2 so that the level performance is possible to find. Then, compare the level performance of SVA results with the level performance of pushover analysis SAP2000/ETABS from the research[16–21].

The processes above are tabulated to describe the calculation and comparison.

Tabel 4. Earthquake zone data of the model (source : [16–21])

Model	Code	Earthquake Zone	Site Class	Structure system	Ie
a	SNI 1726-2002	Zone 6 Ca=0.35,Cv=0.54	Moderate Soil	Special moment-resisting frame	1
b	SNI 1726-2002	Zone 6 Ca=0.38,Cv=0.95	Soft Soil	Special moment-resisting frame	1
c	SNI 1726-2002	Zone 6 Ca=0.33,Cv=0.42	Hard Soil	Special moment-resisting frame	1
d	SNI 1726-2012	Banyumas Ss=0.7g,S1=0.25g	Hard Soil	Moderate moment-resisting frame	1
e	SNI 1726-2002	Ternate - Zone 4 Ca=0.28, Cv=0.42	Moderate Soil	Special moment-resisting frame	1
f	SNI 1726-2012	Bobong City Ss=1.355 g, S1=0.537 g	Moderate Soil	Special moment-resisting frame	1

3. Results and Discussion

The calculation result of formula 1 – 8 on model a – f can be seen in table 5 and 6 on column SVA. While the result of pushover analysis on model a – f can be seen in table 5 and 6 on column pushover analysis.

Table 5 and 6 showed the calculation result of SVA model a, b, d, and e on all floor are IO except rooftop. This means the dimension of column and beam, and the height and width of building ratio has been designed carefully ensuring rigidity, strength, and ductility on the event of earthquake and will only lead to light damage or IO (Immediate Occupancy). However, SVA of rooftop lead to LS (life Safety) / medium damage or CP

Table 5. Comparison performance level (IO, LS or CP) and drift ratio (%) between SVA and pushover analysis models a, b and c.

Floor	Model a		Model b		Model c	
	SVA	Pushover analysis[16]	SVA	Pushover analysis[17]	SVA	Pushover analysis[18]
1st	IO (0.5%)	IO (0.61%)	IO (0.5%)	IO-LS (0.85%)	CP (2.5%)	LS-CP (1.78%)
2nd	IO (0.5%)	IO (0.61%)	IO (0.5%)	IO-LS 0.85%)	CP (2.5%)	LS-CP (1.78%)
3rd	IO (0.5%)	IO (0.61%)	IO (0.5%)	IO-LS (0.85%)	CP (2.5%)	LS-CP (1.78%)
4th	IO (0.5%)	IO (0.61%)	IO (0.5%)	IO-LS (0.85%)	CP (2.5%)	LS-CP (1.78%)
5th	IO (0.5%)	IO (0.61%)	IO (0.5%)	IO-LS (0.85%)	CP (2.5%)	LS-CP (1.78%)
6th	-	-	IO (0.5%)	IO-LS (0.85%)	CP (2.5%)	LS-CP (1.78%)
7th	-	-	IO (0.5%)	IO-LS (0.85%)	CP (2.5%)	LS-CP (1.78%)
8th	-	-	IO (0.5%)	IO-LS (0.85%)	CP (2.5%)	LS-CP (1.78%)
9th	-	-	IO (0.5%)	IO-LS (0.85%)	CP (2.5%)	LS-CP (1.78%)
10th	-	-	IO (0.5%)	IO-LS (0.85%)	-	-
11th	-	-	IO (0.5%)	IO-LS (0.85%)	-	-
12th	-	-	IO (0.5%)	IO-LS (0.85%)	-	-
13th	-	-	IO (0.5%)	IO-LS (0.85%)	-	-
Rf	LS (1.5%)	IO (0.61%)	LS (1.5%)	IO-LS (0.85%)	CP (2.5%)	LS-CP (1.78%)

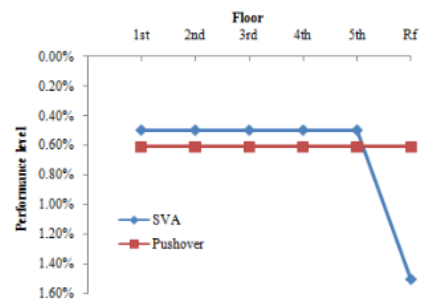
Table 6. Comparison performance level (IO, LS or CP) and drift ratio (%) between SVA and pushover analysis models d, e and f

Floor	Model d		Model e		Model f	
	SVA	Pushover analysis[19]	SVA	Pushover analysis[20]	SVA	Pushover analysis[21]
1st	IO (0.5%)	IO (0.31%)	IO (0.5%)	IO (0.6%)	LS (1.5%)	IO-LS (1.36%)
2nd	IO (0.5%)	IO (0.31%)	IO (0.5%)	IO (0.6%)	LS (1.5%)	IO-LS (1.36%)
3rd	IO (0.5%)	IO (0.31%)	IO (0.5%)	IO (0.6%)	LS (1.5%)	IO-LS (1.36%)
4th	IO (0.5%)	IO (0.31%)	-	-	LS (1.5%)	IO-LS (1.36%)
5th	-	-	-	-	LS (1.5%)	IO-LS (1.36%)
6th	-	-	-	-	LS (1.5%)	IO-LS (1.36%)
7th	-	-	-	-	LS (1.5%)	IO-LS (1.36%)
8th	-	-	-	-	LS (1.5%)	IO-LS (1.36%)
9th	-	-	-	-	LS (1.5%)	IO-LS (1.36%)
10th	-	-	-	-	LS (1.5%)	IO-LS (1.36%)
11th	-	-	-	-	LS (1.5%)	IO-LS (1.36%)
12th	-	-	-	-	-	-
13th	-	-	-	-	-	-
Rf	LS (1.5%)	IO (0.31%)	CP (2.5%)	IO (0.6%)	CP (2.5%)	IO-LS (1.36%)

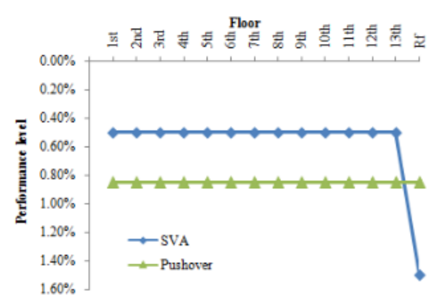
(Collapse Prevention) / heavy damage. It happens because strong column/weak beam is not constructed as the result of discontinued column which leads to the condition of column that weaker than the beam. However, this condition will not affect the mechanism of entire frame. It is important in detailing the column well to avoid critical strength degradation on plastic joint[22].
Model c in table 5 showed the SVA calculation report on all floors are CP. This is caused by the structure vibration period index (I_T)=0 since T_C=0.69 seconds > T_{max}=0.5 seconds which resulted in very flexible structure. In fact, the dimension of columns and beams has been designed very carefully but it should be combined with shear wall ensuring strength, ductility and rigidity. Rigid building (T_C<T_{max}) is a requirement for safety of architectural elements, comfort of residents, and prevention of structure damage. Architectural damage caused by flexible building such as broken glass on windows or door, and excessive vibration especially on upper floor lead into residents' anxiety[23]. Meanwhile, the structural damage occurred is the weakening of structure followed by the formation of plastic joint and lead to sudden collapse[24].

Model f on table 6 showed the SVA calculation result on all floor is LS except rooftop. This happens because the column and beams do not have good design. The building has sufficient rigidity and ductility but it has insufficient structural strength. This will lead into medium damage or LS in the event of strong earthquake. Column dimension is one of important parameters on lateral structure strength. Thus, Ersoy[11] proposed the minimal dimension of column is 0.15% of the cumulative area of column load or 0.3x0.3m. Rooftop SVA model f is CP because strong column/ weak beam are not constructed, as explained above.

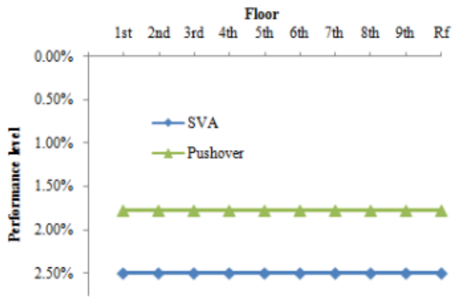
Figure 1. Comparison between between SVA and pushover analysis model a, b, c, d, e & f



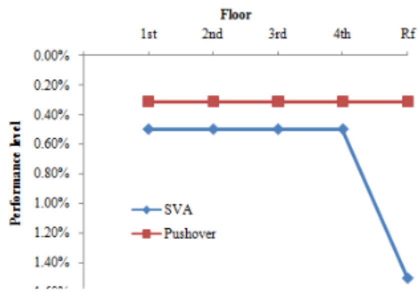
Model a



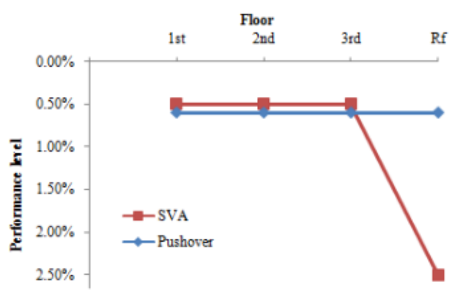
Model b



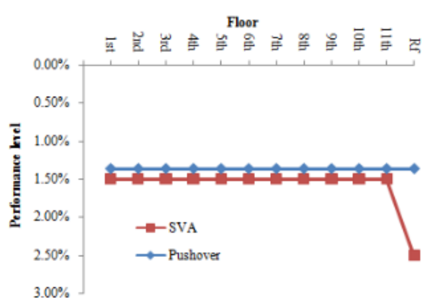
Model c



Model d



Model e



Model f

Table 5, 6, and figure 1 showed the comparison of SVA and pushover analysis on model a, b, c, d, e, and f. generally, it has similar pattern of flat linear except rooftop. The difference is on how the plastic joint formed. In SVA, the plastic joint will be formed when the column and beam dimension does not fulfill strong column / weak beam criteria which lead into LS or CP damage. However, in pushover analysis, the plastics joint occurs within column and beam is not only because of its dimension but also because its ratio and reinforcement detail[25].

Another difference is, on model with more than 10 floors, the vulnerability of SVA and pushover analysis is closely similar (within the pushover analysis range). On model with less than 10 floors, if column dimension - $I_{Ac\text{-}i}>1$, beam dimension 1/10-1/14*L, slender column - $I_C \geq 0.6$, strong column/weak beam – $I_{SCWB\text{-}i}=1$, structure vibration period – $I_T=1$ and ductility – $R/\Omega_0 = 1.7$ (moderate moment-resisting frame) or 2.7 (special moment-resisting frame) and width and height of building ratio < 2 then its vulnerability is close to IO or light damage. For model with more than 10 floors and having similar criteria, its vulnerability is almost LS or medium damage. This happens since a low building with relatively small mass and relatively big rigidity will result in short vibration time. However, a high building with conversely condition will result in long time vibration or flexible structure[26]. So, for a high rise building and considering its efficient design, the level of vulnerability is allowed until level CP or heavy damage[27]. But the proposed SVA is still in the design process and is still within the elastic limit so that the ideal and permitted vulnerability is IO.Thus, SVA is more appropriate on evaluating the vulnerability of multistory building with maximum ±10 floors or middle rise.

4. Conclusion

Based on the results of the research, there are some conclusions as follows:

a. The prediction on the proposed SVA procedure for model a (6 floors), d (5 floors), and e (4 floors) has a relatively similar result to which have been conducted by other researchers on the building models.
b. The prediction on the proposed SVA procedure for model b (14 floors), c (10 floors), and e (12 floors) has a relatively close result to which have been conducted by other researchers on the building models.

c. For the buildings with moment-resisting frame < 10 floors, the building performance is dominated by the dimensions of beam, column, and the ratio of height and width of the building, while for the buildings ≥ 10 floors, the building performance is dominated by the dimensions of beam, column and the height of building.

The purpose of the prediction on SVA procedure here does not look for exactly similar results to the more accurate results of the procedure analysis such as pushover analysis, but the result of SVA prediction is one level higher or lower than the accurate calculation is considered adequate because according to [3],the result of the SVA procedure can be used to underlie the potential status of the selected buildings and subsequently there are a list of the buildings which needs more detailed vulnerability assessment conducted by the structural experts.

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5. Acknowledgement

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