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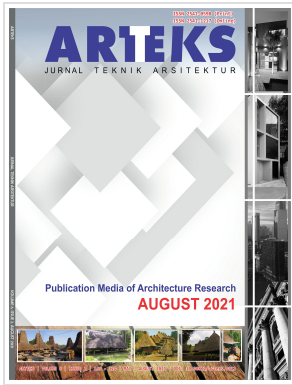
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## Identifying geometric configuration of earthquake-resistant buildings

Livian Teddy\*<sup></sup>, Johannes Adiyanto<sup></sup>, Husnul Hidayat<sup></sup>

Department Architecture, Faculty of Engineering, Universitas Sriwijaya  
Jl. Palembang-Prabumulih KM. 32, Indrajaya, Indonesia



ARTICLE INFO	ABSTRACT	CrossMark
<p><i>Article history:</i> Received December 18, 2020 Received in revised form Dec. 31, 2021 Accepted March 14, 2021 Available online August 01, 2021</p> <p><i>Keywords:</i> Architecture Earthquake Geometry configuration Guidance Simulation</p> <p><b>*Corresponding author:</b> Livian Teddy Department Architecture, Faculty of Engineering, Universitas Sriwijaya, Indonesia Email: <a href="mailto:livianteddy@gmail.com">livianteddy@gmail.com</a> ORCID: <a href="https://orcid.org/0000-0002-0275-598X">https://orcid.org/0000-0002-0275-598X</a></p>	<p>Indonesia is an earthquake-prone area because it is located at the world's most active tectonic plates and hundreds of local faults. Obviously, there have been many earthquake victims caused by collapsed buildings, hence the need for earthquake-resistant construction. However, there is not much guidance for architects to design earthquake-resistant buildings. This research proposes guidance for architects on how to design building forms relatively able to resist earthquakes. The simulation experiment method involving 32 building models in various forms was employed. The experimental results were then analyzed with modal analysis in ETABS and SVA for architectural design. Based on the analysis report, some guidelines were proposed: 1). Avoid buildings that are too slender, use the slenderness ratio <math>H/D \leq 2</math>, 2). Avoid soft stories where the ratio of the top column height (<math>h</math>) to the bottom column height (<math>h1</math>) <math>\leq 0.8</math>, 3). Use symmetrical shapes with 1 or 2 axes and avoid shapes with random compositions, 4). Use the additive and subtractive mass transformation <math>\leq 15\%</math>, 5). Strengthen the structural elements, install shear walls, or use dilatation to minimize potential torsional irregularities and non-parallel system irregularities of L, T, U, +, and Z forms 6). Avoid using non-axial asymmetrical forms.</p>	

### Introduction

According to the 2016 earthquake catalog published by PUSGEN (Tim Pusat Studi Gempa Nasional 2017), from 1900 – 2016, there were 50.000 earthquakes with a magnitude of  $M_w > 5$  in Indonesia. These earthquakes were caused by subduction earthquakes as a result of the movement of some tectonic plates like the Indo-Australian plate, the Eurasian plate, the Pacific plate, the Philippine Sea plate, and the movement of local faults such as the Great Sumatra fault (the Semangko fault), the Lembang fault and etc. From earthquakes occurring in 2004 - 2010 only, more than 250.000 people had died. Most of the victims died because the buildings fell on them, hence the need for earthquake-resistant buildings

(Kementerian Pekerjaan Umum dan Perumahan Rakyat 2010).

Designing earthquake-resistant buildings certainly needs effective collaboration between architects and structural engineers (Arnold and Stewart 2000; Hoedajanto and Riyansyah 2015). Many codes and guides are related to this type of buildings, but only a few are made for architects (Özmen and Ünay 2007). This study strives to give a small contribution to architects in the form of guidance in designing geometric configurations of earthquake-resistant buildings. This research involved 32 building models with basic and complex geometric forms as the configurations. Simulations were then conducted using ETABS dan SVA for architectural design to comprehend the deformation behavior of each model as a result of earthquake loads. After

conducting simulations, the strengths and weaknesses of each model were compiled as the guidance for architects to design earthquake-resistant buildings.

## Method

The quantitative method with the experimental simulation was used in this research. There were 32 models for simulation, and they were assumed as the representation of the basic geometric forms (models 0 to 3), the subtractive and additive transformation forms (models 04, 11, 13, 18, 21, 23 B, 25), the composition of the basic forms (models 05, 06, 07, 08, 09, 10, 12, 19, 20, 22, 24, 26, 26B, 26C, 27, 27C, 27E), and organic/curved forms (models 14, 15). In addition, the strong earthquake zone ( $SS = 1.5$  and  $S1 = 0.6$ ), the soft ground site class, and the office buildings were also simulated in this research.

The structural system which was used is the moment resisting frame. The height of the building model was 10 floors except for models 13 to 15, which were only 7 floors. The height between floors was 4 m, except for the column of the first floor in model 16 and model 17 (6 m). The beam dimension was 0.25x0.4 m, except for model 11 (using beam combination 0.25x0.4 m and 0.25x1.0 m), model 15 (using beam combination 0.3x0.6 m and 0.25x0.5 m), model 26 (using beam combination 0.25x0.4 m and 0.25x0.5 m), and both model 26B and 26C (0.25x0.5 m). The column dimension, moreover, was 0.6x0.6 m, except for model 3 and model 14 (0.6 m in diameter), model 16 (0.65 m in diameter), and several models; namely 26, 26B, 26C, 27, 27C and 27E; that combined column dimension of 0.6x0.6 m and diameter of 0.6 m. The thickness of the floor plate for the simulation was 0.12 m where the concrete quality of the beam/column/floor plate was K-300, the quality of the main reinforcing steel was  $F_y = 4000$  Kg/cm<sup>2</sup>, and the quality of stirrup steel was  $F_y = 2400$  Kg/cm<sup>2</sup>. The assumption of the dead load, in addition, was 400 Kg/m<sup>2</sup> while the assumption of the live load was 250 Kg/m<sup>2</sup> (office buildings function).

The aforementioned data were input to ETABS (in which the modal analysis and eccentricity analysis were conducted) and to Simplified Vulnerability Analysis (SVA) for Architectural Design. The results obtained from

the modal analyses were Period (T), Shape Mode Translation (Ux, Uy) and Rotation (Rz), Participating Mass Ratio (Sum Ux, Sum Uy) while outputs from the eccentricity analysis were centers of mass and rigidity. The results from SVA analyses were vertical/horizontal irregularities.

By comparing the fundamental period of the building model (T) and the maximum fundamental period (Tmax), the structure's stiffness can be seen (Budiono and Supriatna 2011). If  $T < T_{max}$  then the structure is stiff and if  $T > T_{max}$  then the structure is flexible. The Tmax is based on the earthquake zones in Indonesia which are categorized as "high".

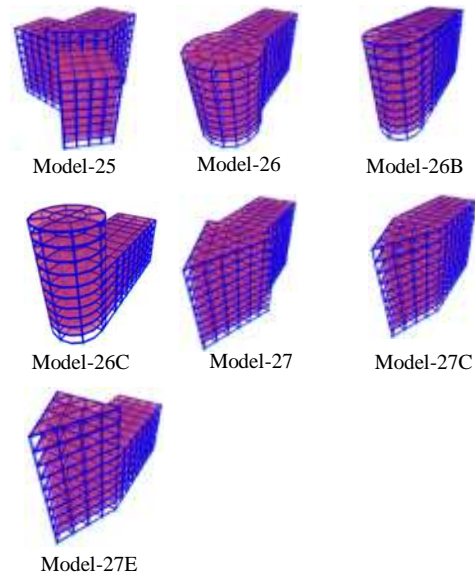
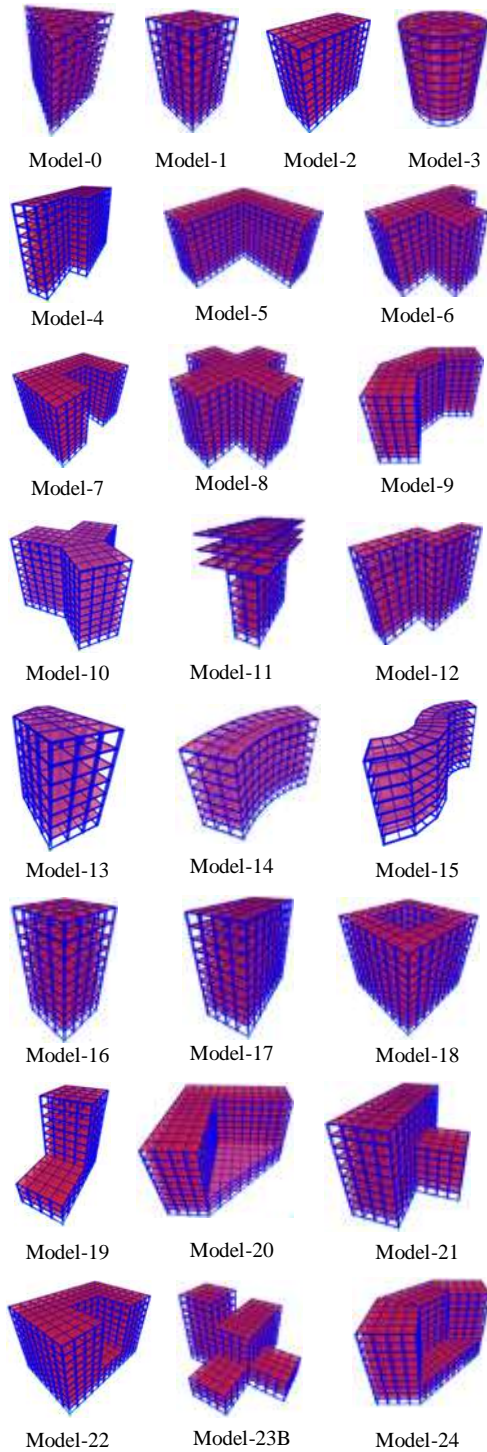
Ux, Uy, and Rz are used to assess the level of irregularity. Buildings with dominant translation in mode 1 and mode 2 (Ux and Uy) and rotation in mode 3 (Rz) can be categorized as regular (Murty et al. 2012).

Sum Ux and Sum Uy are the sums of the contributions each mode towards -x and -y axes in the modal analysis. To ensure its accuracy, this method relied on the part participating in the total building mass called Participating Mass Ratio (Hanna et al. 2017). According to the latest earthquake regulations, SNI 1726: 2019, the mass participation ratio must reach 100% (Badan Standarisasi Nasional 2019). One of the reasons why the mode calculation of one building model cannot reach 100% is its complexity and/or irregularity. The more complex and/or the more irregular a building is, the more modes needed and the more difficult the calculation mode to reach 100 %.

Eccentricity occurs in buildings where the centers of mass and rigidity do not coincide or are eccentric so that it can cause torsion in the building when an earthquake lateral force occurs (Tjokrodinuljo 1997).

Based on FEMA 451B (FEMA 2007) and Simplified Vulnerability Analysis (SVA) for Architectural Design (Teddy et al. 2018), there are two criteria of buildings' geometric configurations, regular and irregular. Irregular configurations, particularly, have two categories namely, horizontal structural irregularities and vertical structural irregularities. Horizontal structural irregularities comprises of Torsional irregularity, Re-entrant Corner (setback) Irregularity, Diaphragm Discontinuity Irregularity, Out of Plane Offsets Irregularity, and Nonparallel Systems Irregularity. Vertical structural irregularities, on the other hand,

consists of Stiffness (Soft Story) Irregularity, Weight (Mass) Irregularity, Vertical Geometric Irregularity, In-Plane Discontinuity Irregularity, and Strength (Weak Story) Irregularity.

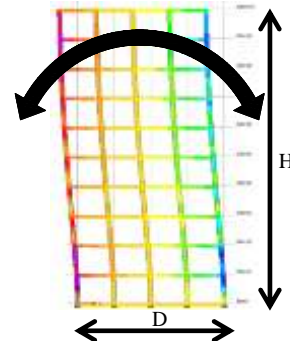


**Figure 1.** The 32 building models

## Result and discussion

### Period (T)

From [table 1](#), it can be seen that there are no significant differences between the building's fundamental period (T) and the building's maximum period (Tmax) except for model -11. This condition means that the other building models are still stiff enough while the model-11 is relatively slender ( $H/D=4$ ) so that it will not be so stiff. Nathan Madutujuh (Madutujuh 2020) proposes the ideal comparison  $H/D \leq 2$  that can reduce over-turning effects, especially in tall buildings.



**Figure 2.** The ideal comparison between height (H) and width (D) of a tall building  $H/D \leq 2$  to reduce the possibility of over-turning due to an earthquake  
 Source: (Madutujuh 2020)

Shape mode translation (Ux, Uy), rotation (Rz) and eccentricity

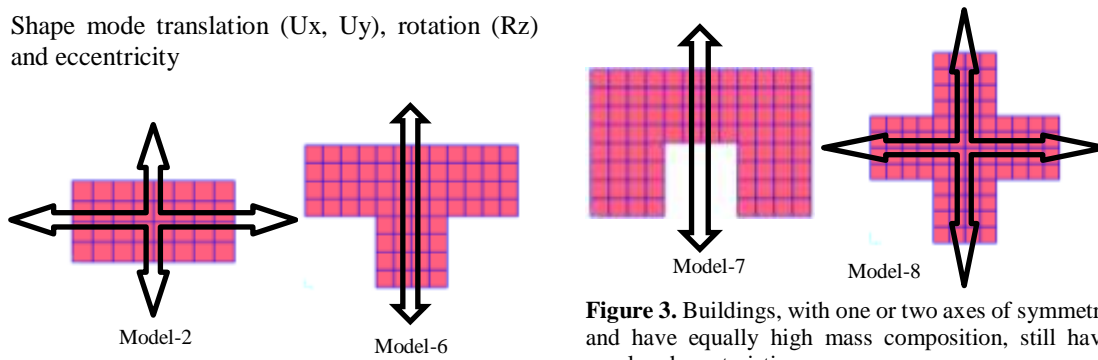


Figure 3. Buildings, with one or two axes of symmetry and have equally high mass composition, still have regular characteristics

Table 1. The results of analysis of modal analysis, eccentricity and SVA of architectural design 32 building models

Model	n floors	Period -T (dtk)		Tmax. (Sec.)	H/D	L/D	mode 1	mode 2	mode 3	Sum Uy (100%) mode -n	Sum Ux (100%) mode -n	eccentricity	Irregularity
		mode 1	mode 2										
0	10	1.853 (x)	1.830 (y)	1.80	1.3	1.0	0.953 (Ux)	1.000 (Uy)	0.953 (Rz)	27	26	no	non paralel
1	10	1.886 (y)	1.886 (x)	1.80	2.0	1.0	0.824 (Uy)	0.824 (Ux)	1.000 (Rz)	24	23	no	-
2	10	1.935 (y)	1.865 (x)	1.80	2.0	2.0	1.000 (Uy)	1.000 (Ux)	1.000 (Rz)	23	24	no	-
3	10	1.889 (y)	1.889 (x)	1.80	1.3	1.0	0.564 (Uy)	0.564 (Ux)	1.000 (Rz)	30	30	no	non paralel
4	10	1.954 (y)	1.844 (x)	1.80	2.0	3.0	0.990 (Uy)	0.824 (Ux)	0.816 (Rz)	26	27	no	re-entrant
5	10	1.921 (xy)	1.908 (xy)	1.80	2.0	3.0	0.418 (Uy,Ux)	0.500 (Uy,Ux)	0.835 (Rz)	28	28	no	re-entrant
6	10	1.924 (y)	1.890 (x)	1.80	2.0	3.0	1.000 (Uy)	0.970 (Ux)	0.970 (Rz)	27	26	no	re-entrant
7	10	1.909 (x)	1.908 (y)	1.80	2.0	1.5	0.987 (Ux)	1.000 (Uy)	0.987 (Rz)	29	28	no	re-entrant
8	10	1.907 (x)	1.907 (y)	1.80	2.0	3.0	0.993 (Ux)	0.993 (Uy)	1.000 (Rz)	25	26	no	re-entrant
9	10	1.891 (y)	1.857 (x)	1.80	2.0	3.8	1.000 (Uy)	0.600 (Ux)	0.600 (Rz)	35	34	no	non paralel
10	10	1.907 (x)	1.878 (y)	1.80	2.0	2.6	0.998 (Ux)	1.000 (Uy)	0.998 (Rz)	26	27	no	re-entrant, non paralel
11	10	2.827 (rz)	2.611 (y)	1.80	4.0	3.0	1.000 (Rz)	1.000 (Uy)	1.000 (Ux)	25	24	no	setback, massa
12	10	1.942 (y)	1.818 (rz)	1.80	2.0	5.0	1.000 (Uy)	1.000 (Rz)	1.000 (Ux)	27	28	no	re-entrant
13	7	1.306 (y)	1.241 (x)	1.31	1.9	2.0	0.952 (Uy)	0.953 (Ux)	0.995 (Rz)	19	19	no	non paralel
14	7	1.304 (y)	1.219 (rz)	1.31	1.4	3.2	1.000 (Uy)	0.915 (Rz)	0.915 (Ux)	20	19	no	non paralel
15	7	1.141 (rz)	1.097 (y)	1.31	2.8	5.4	0.496 (Rz)	0.525 (Uy)	0.814 (Ux)	44	44	no	non paralel
16	10	2.028 (y)	2.028 (x)	1.80	2.1	1.0	0.545 (Uy)	0.545 (Ux)	1.000 (Rz)	23	23	no	soft story
17	10	2.080 (y)	2.007 (x)	1.80	2.1	2.0	1.000 (Uy)	1.000 (Ux)	1.000 (Rz)	24	25	no	soft story
18	10	1.879 (x)	1.879 (y)	1.80	1.0	1.0	0.961 (Ux)	0.961 (Uy)	1.000 (Rz)	24	24	no	diaphragm
19	10	1.816 (y)	1.647 (x)	1.80	2.0	2.0	0.936 (Uy)	1.000 (Ux)	0.937 (Rz)	26	25	yes	torsional, setback
20	10	1.833 (rz)	1.797 (xy)	1.80	1.6	3.0	0.360 (Rz)	0.500 (Ux,Uy)	0.640 (Rz)	27	27	no	re-entrant, setback
21	10	1.832 (x)	1.777 (y)	1.80	2.0	3.0	0.657 (Ux)	1.000 (Uy)	0.645 (Rz)	26	25	yes	torsional, re-entrant, setback
22	10	1.858 (x)	1.853 (y)	1.80	1.6	1.5	0.825 (Ux)	1.000 (Uy)	0.825 (Rz)	26	25	no	re-entrant, setback
23B	10	1.562 (x)	1.385 (y)	1.80	2.0	3.0	0.814 (Ux)	0.989 (Uy)	0.588 (Rz)	28	28	yes	torsional, re-entrant, setback
24	10	1.741 (rz)	1.723 (y)	1.80	1.6	3.8	0.539 (Rz)	1.000 (Uy)	0.538 (Ux)	33	34	yes	torsional, non paralel, setback
25	10	1.797 (x)	1.732 (y)	1.80	2.0	2.6	0.734 (Ux)	0.857 (Uy)	0.778 (Rz)	28	27	yes	torsional, re-entrant, non paralel, setback
26	10	1.947 (y)	1.726 (x)	1.80	2.0	3.3	0.645 (Uy)	1.000 (Ux)	0.645 (Rz)	29	30	no	non paralel
26B	10	1.683 (y)	1.565 (rz)	1.80	2.0	3.0	0.924 (Uy)	0.924 (Rz)	1.000 (Ux)	34	35	no	non paralel
26C	10	1.460 (y)	1.151 (x)	1.80	2.0	3.0	0.795 (Uy)	1.000 (Ux)	0.534 (Uy)	34	35	yes	torsional, non paralel, setback
27	10	1.936 (y)	1.841 (x)	1.80	2.0	3.5	0.986 (Uy)	1.000 (Ux)	0.986 (Rz)	28	26	no	non paralel
27C	10	1.955 (y)	1.840 (x)	1.80	2.0	3.0	0.994 (Uy)	1.000 (Ux)	0.994 (Rz)	27	26	no	non paralel
27E	10	1.643 (y)	1.303 (x)	1.80	2.0	3.0	0.780 (Uy)	1.000 (Ux)	0.582 (Uy)	28	26	yes	torsional, non paralel, setback

According to FEMA 451B and SVA for Architectural Design, it is only models -1 and -2 that have regular geometric configuration categories. However, from 10 irregular categories based on FEMA 451B, SNI 1726:2019 only disallows buildings with torsional, soft story, and weak story irregularities. Thus, a building model

is categorized as relatively regular if the models -1 and the model -2 are dominant translation (Ux and Uy), the model-3 is dominant rotation (Rz), the eccentricity is not excessive, and there is no soft story/weak story. Of 32 models, only 16 of them that can be included in the category, namely models -0, 1, 2, 3, 4, 6, 7, 8, 9, 10, 13, 18,



22, 26, 27, and 27C. From these 16 models, furthermore, 14 of them are categorized as symmetrical building models with one or two axes (model -0, 1, 2, 3, 6, 7, 8, 9, 10, 18, 22, 26, 27 and 27C) and have equally high mass composition. In addition, the other two models categorized as relatively regular are models -4 and -13. These two models are not symmetrically formed by the subtractive transformation, which is not dominant ( $\leq 15\%$ ). Therefore, their deformation behavior is still dominated by their two-axial symmetrical intact mass.



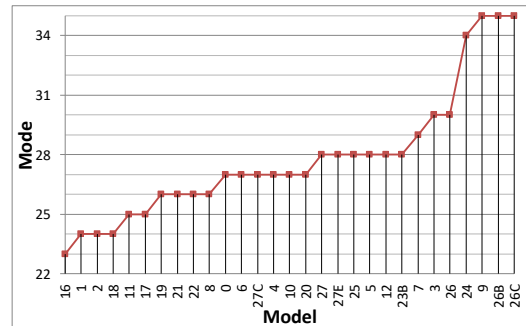
**Figure 4.** Buildings with subtractive results 10% - 15% in which their intact mass deformation behavior is symmetrical rectangles with two axes

From all previously mentioned 32 models, most of them still have irregularities (see table 1) like torsional irregularities, re-entrant corner irregularities, diaphragm discontinuity irregularities, non-parallel system irregularities, soft story irregularities, weight (mass) irregularities, and vertical geometric irregularities. Irregularities definitely will cause torsion and concentrations of tension on some parts of buildings (Arnold 2006), but these potential problems can be reduced by using shear walls/core walls and strengthening structures where the concentrations of tension occur.

#### The mass participation ratio

The number of maximum modes needed to conduct modal analyses of building models is  $10 \times$  the floor number (N) (Madutujuh 2020). It is after the analyses have been done that the exact number of modes needed to reach 100% mass participation is known. In addition, the geometric configuration, both vertical and horizontal, can also influence the number of modes. Table 1 and figure 5 shows two 7-floor-building models with relatively simple geometric configurations, model -13 (from the subtractive result) and model -14 (having one-axial symmetrical form), only needs mode 19 and mode 20 to reach 100% mass participation. Furthermore, to reach a more complex model like model -15 which has non-parallel system irregularities, it needs mode 44.

For the 10-floor-building model, increasing the number of modes is started by simple models with mode 23 - 25 (models -16, 1, 2, 18, 11, 17). The next levels are firstly dominated by models having two and one axes of symmetry with mode 26 and 27 (models 19, 21, 22, 8, 0, 6, 27C, 10); and then by non-symmetrical models with mode 28 (models 25, 5, 12, 23B). For the last level, models are dominated by non-parallel system irregularities with mode 29 - 35 (model -3, 26, 24, 9, 26B, 26C). The 7-floor-model, model -15, also has non-parallel system irregularities with mode 44. The number of these modes is even beyond the maximum number of modes for the 10-floor-building. This condition proves that the more irregular a building is, the more difficult the building reaches 100% mass participation, hence not recommended structure.



**Figure 5.** The increasing number of mass participation modes reaching 100% based on the buildings' irregularity level

#### Guidance

From the geometric configuration analyses described above, the guidance in the form-finding process of architectural design is proposed (Goldsmith 2014), and from this guidance, the buildings' geometric configurations relatively resistant to earthquakes are obtained, namely:

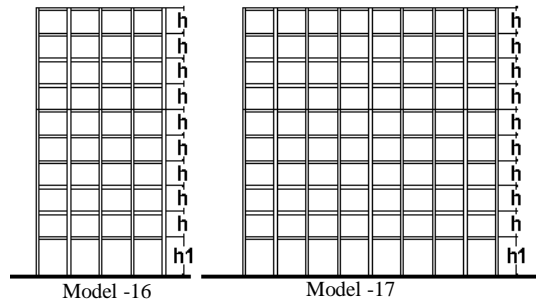
- 1). The comparison between the buildings' height and width.

For the moment resisting frame, limit the buildings' height (H) and width (D) by applying the ratio  $H/D \leq 2$ . If  $H/D > 2$ , combine it with shear walls and/or core walls.

- 2). The use of buildings having different heights between floors.

The configuration of stiffness irregularities is sudden diminishing of lateral stiffness in one building/soft story. Such condition usually happens in any building's level if the ratio of the column height of the upper level (h) to the column

height of the level below ( $h_1$ ) is  $\leq 0.8$  (FEMA 2007) (figure 6).

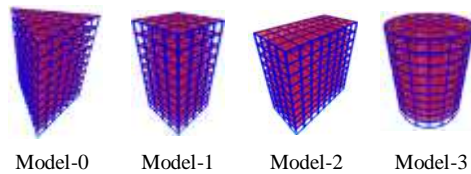


**Figure 6.** Geometric configuration with the ratio of the column height of the upper level ( $h$ ) to the column height of the level below ( $h_1$ ) is  $\leq 0.8$  can cause a soft story

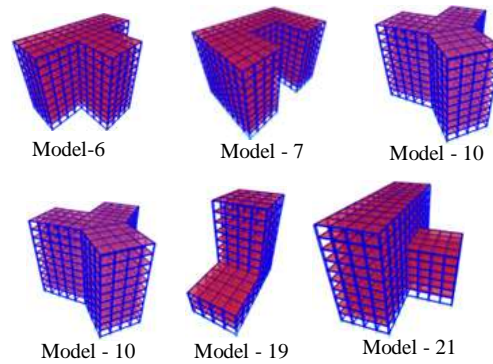
Avoid the geometric configurations that contain soft story especially in strong earthquake zones because soft story is the major cause of the damaged and collapsed building every time a strong earthquake happens in Indonesia (Boen 2006; 2007a; 2007b).

3). The use geometric configurations of one or two axes of symmetry and the same height.

Though aesthetically monotonous, the basic or primary forms like triangular tubes, square boxes, rectangular boxes, and cylindrical tubes are the regular forms that offer very effective resistance to earthquakes (figure 7).



**Figure 7.** Geometric configuration with basic forms like triangular tube, square box, rectangular box, and cylindrical tube that have good resistance to earthquakes

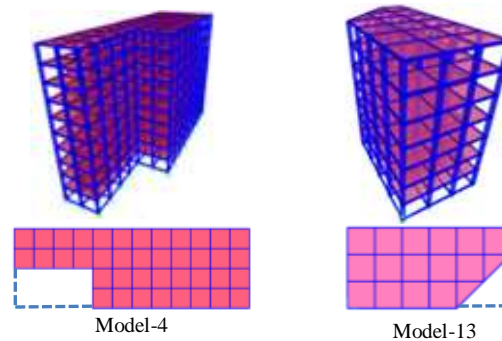


**Figure 8.** Geometric configurations in one axis of symmetry and in the same height still have relatively regular deformation behavior towards earthquakes

Geometric configurations that have one axis of symmetry and the same heights still have relatively regular deformation behavior towards earthquakes and interesting composition in connection with the aesthetic (figure 8).

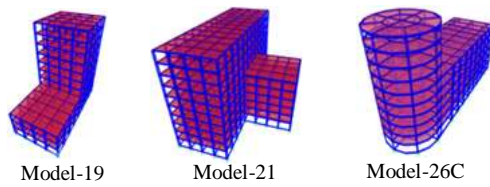
4). The use of additive and subtractive transformation mass.

The geometric configuration; created through additive or subtractive processes,  $\leq 15\%$  from basic forms; evidently offers relatively effective resistance to earthquakes, and its basic or primary form, as well as its variation, is quite aesthetically interesting (figure 9).



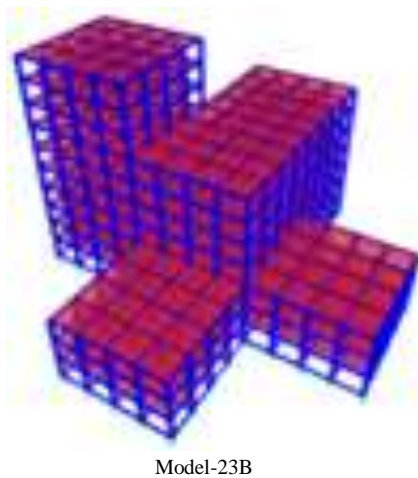
**Figure 9.** Geometric configurations with subtractive mass forms  $\leq 15\%$  are still influenced by the deformation behavior of their intact masses

5). The use of transformation and composition forms that have different heights.



**Figure 10.** Torsion occurring in geometric configurations with one axis of symmetry mass composition and having different heights can be reduced with shear walls or core walls

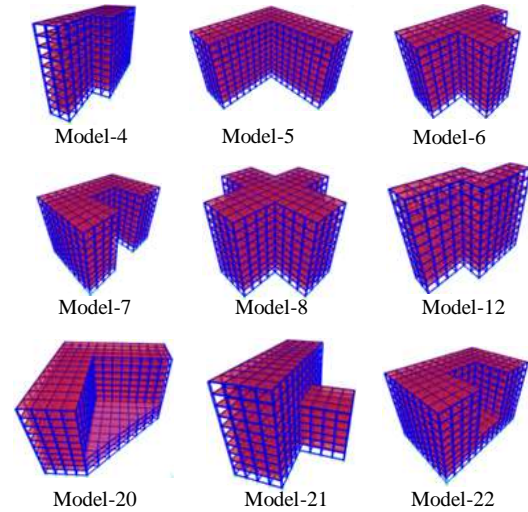
Apparently, the occurrence of torsion is more sensitive in the vertical mass composition changes than in the horizontal ones (figure 10). However, if the mass is still symmetrical (1 axis minimum), the behavior deformation can still be anticipated in several ways such as using shear walls or core walls for the higher mass to reduce potential torsion.



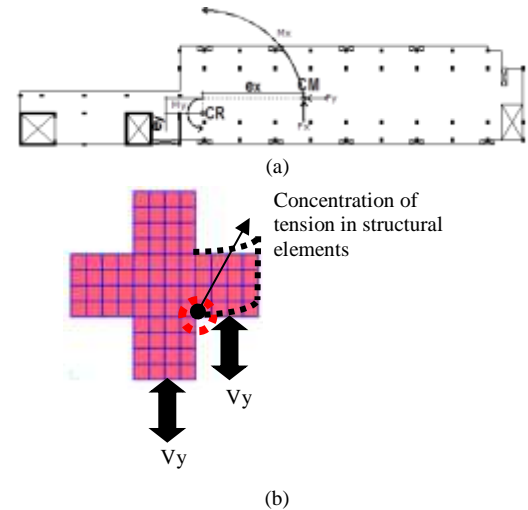
**Figure 11.** A geometric configuration with random mass composition will also create random deformation behavior

Though it is challenging, building construction having random mass composition or transformation should be avoided since such construction may also cause random deformation behavior which obviously cannot be predicted or anticipated (figure 11).

6). The use of L, T, U, +, and Z forms.



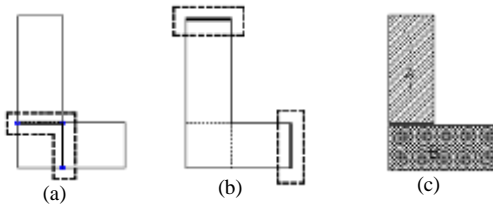
**Figure 12.** Geometric configurations of L, T, U, +, Z have potential torsional and re-entrant corner irregularities



**Figure 13.** (a). Eccentricity ( $e_x$ ,  $e_y$ ) between Center of Mass (CM) and Center of rigidity (CR) that can cause torsion to buildings, (b). The difference between deformation and tension concentration in the + mass form as a result of an earthquake ( $V_y$ )

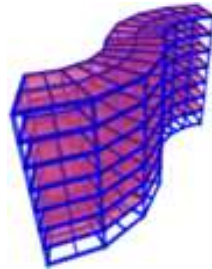
The L, T, U, +, and Z forms (figure 12) have potential torsional irregularities (figure 13a) and re-entrant corner irregularities (figure 13b). To minimize the irregularities, some methods can be applied like strengthening areas where the concentration of tension force as a result of earthquakes is likely to occur (figure 14a), reducing potential torsion by installing shear walls at the tips of the wings (figure 14b), or using

dilatation to separate the irregular building masses (figure 14c) (adaptation from Duggal (2007)).



**Figure 14.** (a). Strengthen the places where the concentration of tension force potentially occurs, (b). Use shear walls to reduce the potential torsion or, (c). Conduct dilatation to separate the building mass

7). The use of non-axial asymmetrical mass form.



Model-15

**Figure 15.** The organic forms that have potential torsional and non-parallel system irregularities tend to have random deformation behavior

The organic geometric configurations are non-axial asymmetrical forms that potentially have both torsional irregularities and non-parallel system irregularities. If the configurations are complex, it will be difficult to predict buildings' ability to respond to earthquakes. Therefore, although they are architecturally attractive, the organic forms are not recommended forms in strong earthquake zones because they are less resistant to earthquakes (LI 2019).

## Conclusion

Actually, there is no prohibition on designing any kind of building forms in architecture. However, an architect must understand the risks of building damage due to earthquakes and the additional costs for anticipating such disasters. Therefore, "simple is secure" is better than "simple is bore" when it is related to designing buildings in earthquake-prone areas.

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#### Author(s) contribution

**Livian Teddy** contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

**Johannes Adiyanto** contribute to methodology, supervision, and validation.

**Husnul Hidayat** contribute to methodology, supervision, and validation.

