IOP Conference Series: Earth and Environmental Science

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## Preface



## Structural Engineering and Materials

## Building Science and Technology

## Construction Management



## Architecture and Urban Development

D Tjandra, H Sugiharto, J Buntoro and P S Wulandari

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# Preface

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# Preface

The Proceeding contains papers based on invited keynote speeches and oral presentations at the International Conference on **Digital & Empathic Architecture & Civil Engineering (DEACE 2021)** and International Student Workshop. The event was organized by the Faculty of Civil Engineering & Planning, **Petra Christian University (PCU), Surabaya, Indonesia** on **August 20th-21st, 2021** for the international conference and August 12th-21st, 2021 for the workshop as a series of events celebrating the 60th Anniversary of Petra Christian University.

The event covered several topics: 'Structural Engineering and Materials', 'Building Science and Technology', 'Construction Management', and 'Architecture and Urban Development'. DEACE presented a theme: "Digital and Empathic Engagement in the New Era for Architecture and Civil Engineering". Digital engagement can revolutionize approach to design and engineering while supporting opportunities to accommodate the implementation of advanced technology. While empathic engagement reflects not only on effectively design and build infrastructure to meet safety and other regulatory requirements, but also understanding customer essential needs. DEACE aimed to gather researchers, scholars, and practitioners all over the world to share and exchange their knowledge and breakthrough in the fields of Architecture and Civil Engineering especially toward the new era.

As the event was approaching and there was no sign of the Covid-19 pandemic slowing down earlier that year, it was decided not to postpone the event but to hold it virtually instead. The conference started with plenary sessions with four keynote speakers, and followed by parallel sessions in two rooms with four sessions. Each keynote speech took 45 minutes and 30 minutes for presentation and discussion, respectively. While speakers in parallel sessions were given 15 minutes and 5 minutes for presentation and discussion. The were 30 presenters out of 159 participants in total, consist of both academicians and professionals. They came from Indonesia as well as some other countries such as China, Taiwan, Germany, Japan and Australia. Zoom video conferencing application was used in the event which served the event very well.

Editor of DEACE 2021,
**Dr. Antoni Antoni**
**Dr. Pamuda Pudjisuryadi**

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# Welcome Speech

On behalf of the organizing committee, we would like to extend our warmest welcome to you to the Digital & Empathic Architecture & Civil Engineering (DEACE) International Conference.

DEACE International Conference and International Student Workshop on Bamboo Gridshell Computational Design are Virtual Events being held by the Faculty of Civil Engineering & Planning as a series of events celebrating the 60$^{th}$ Anniversary Petra Christian University, "The Rock Turns Diamond!"

DEACE aims to gather researchers, scholars, and practitioners all over the world to share and exchange their knowledge and breakthrough in the fields of Architecture and Civil Engineering especially toward the new era.

We would like to thank all keynote speakers, workshop speakers, scientific committee, session chairs, authors/presenters, participants, sponsors, conference & workshop coordinators, and everybody who has all contributed to this conference with great efforts for months.

We do hope that you enjoy your attendance at the DEACE 2021!

The chair of DEACE 2021,
**Dr. Rudy Setiawan**

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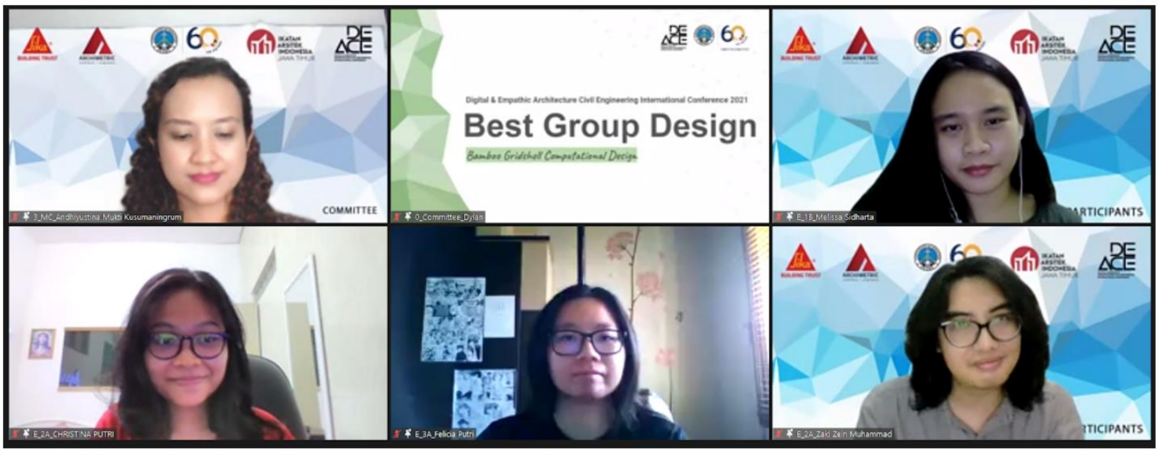

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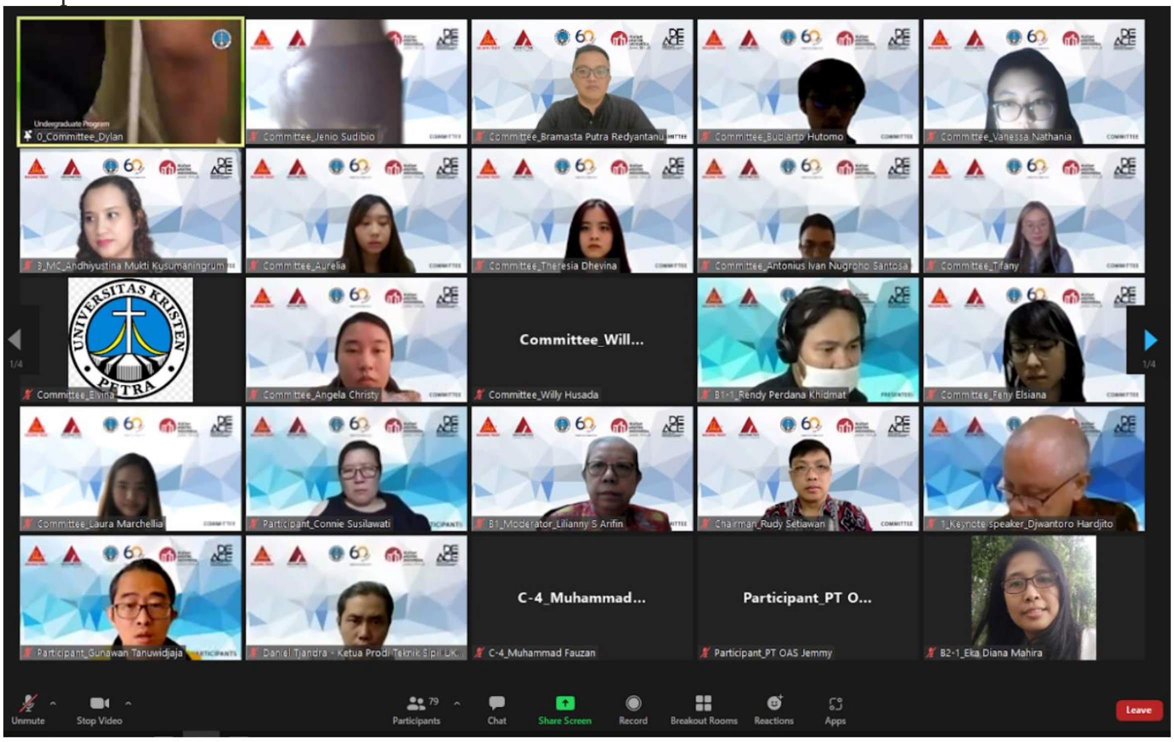


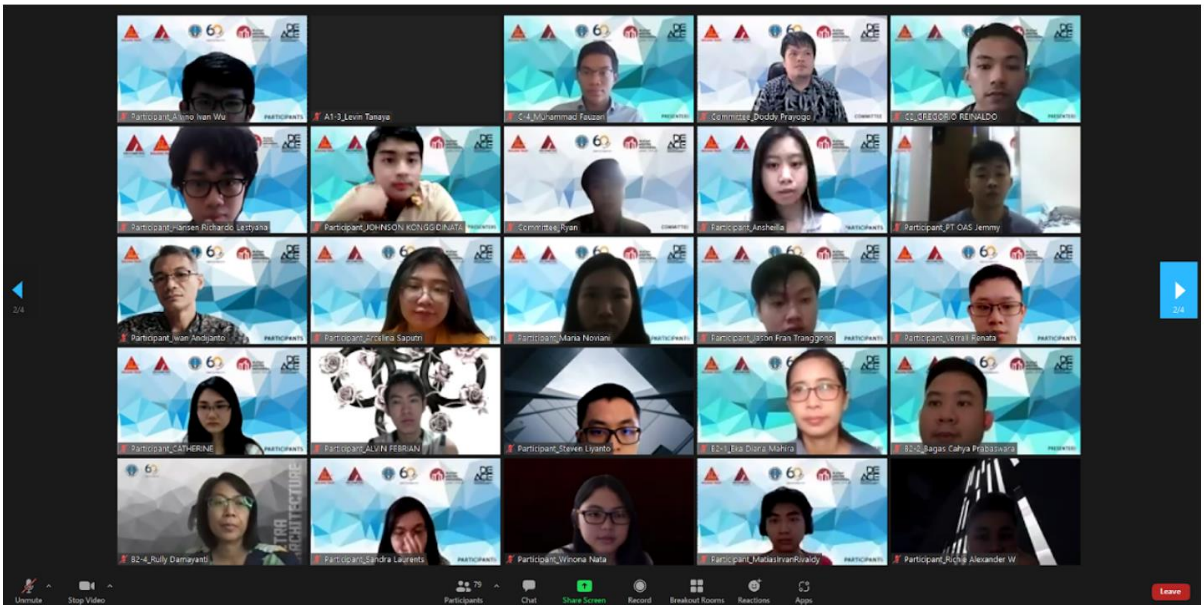

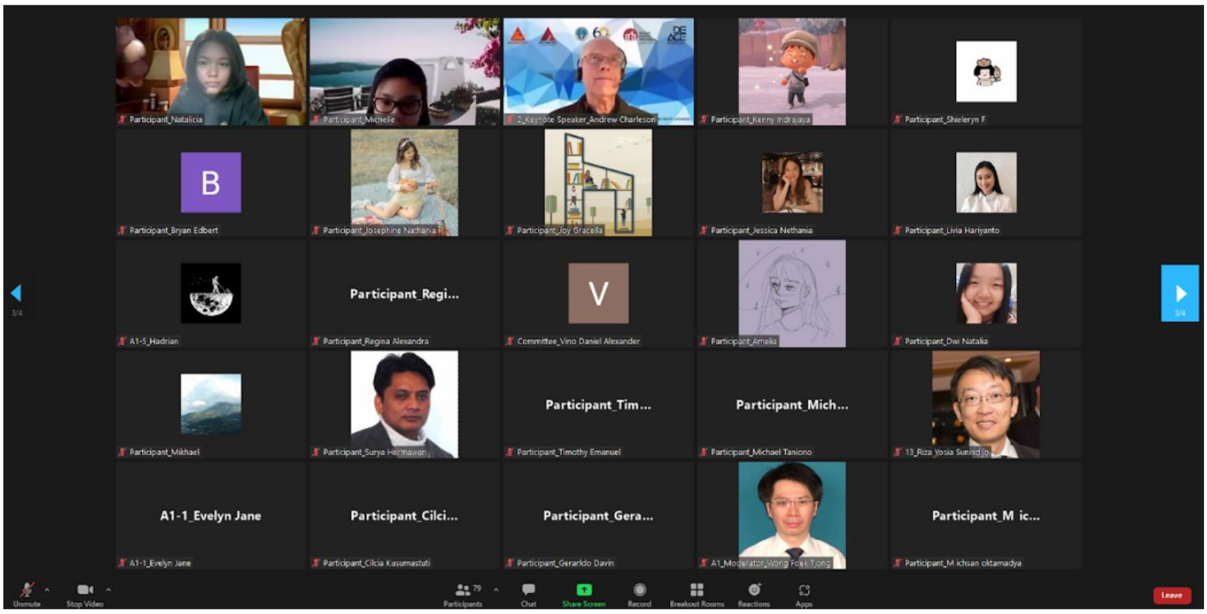
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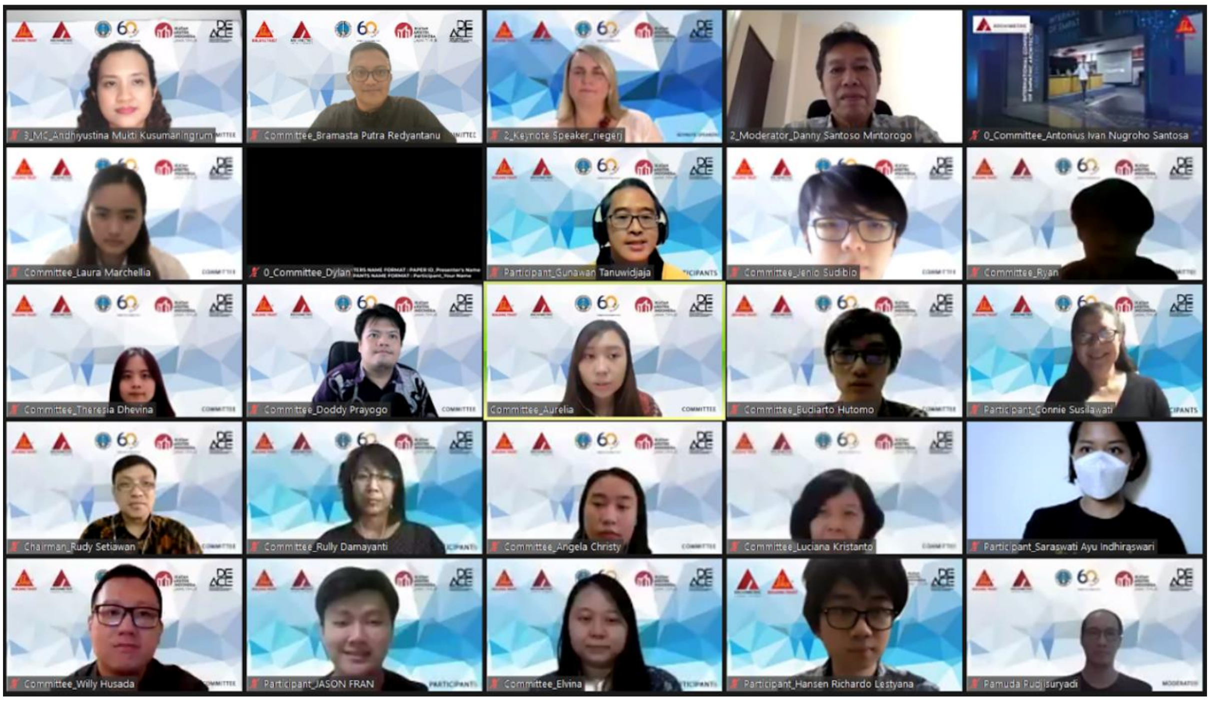
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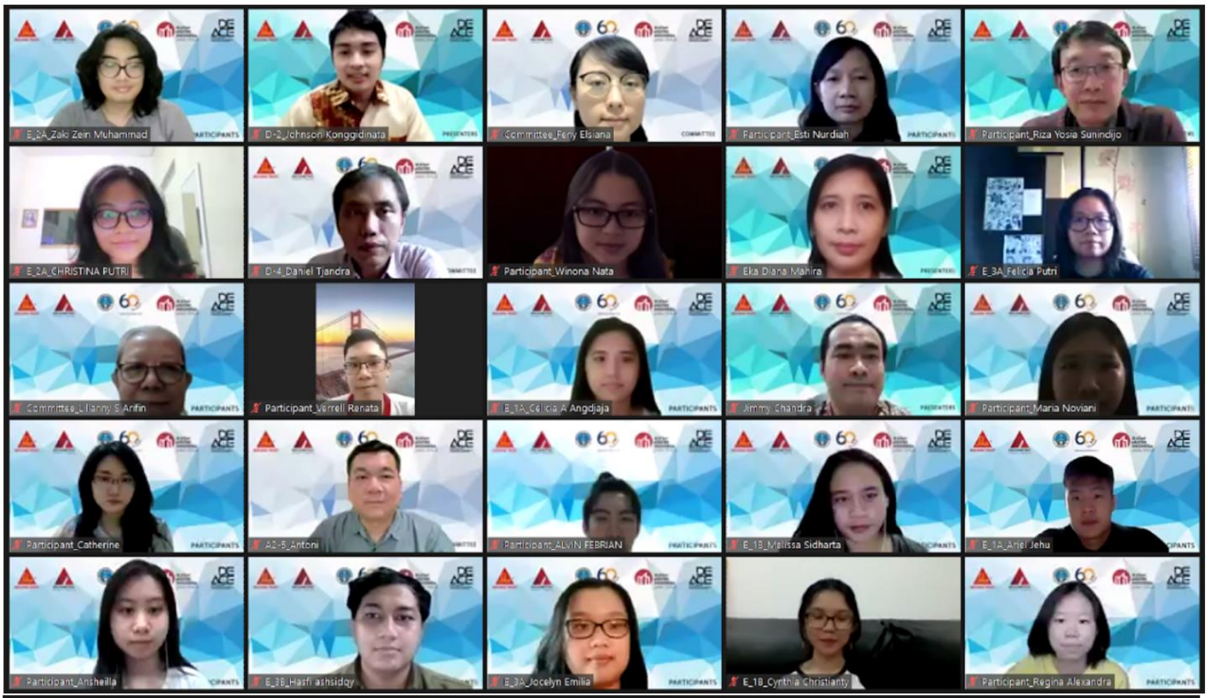
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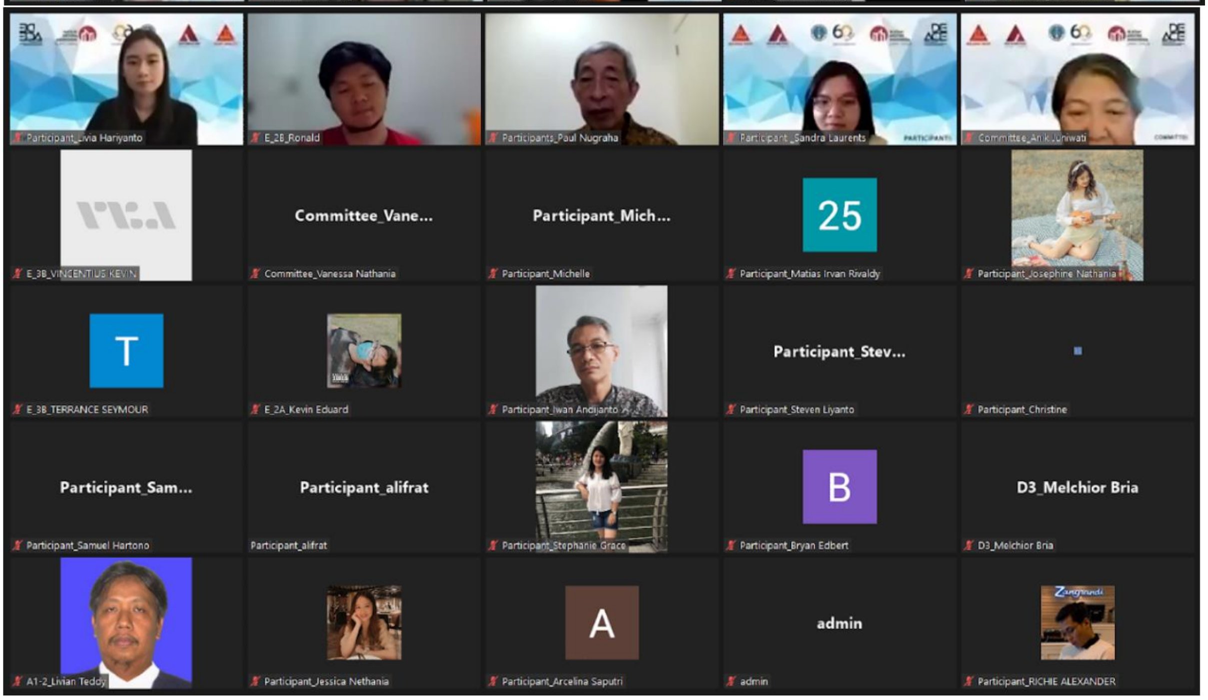
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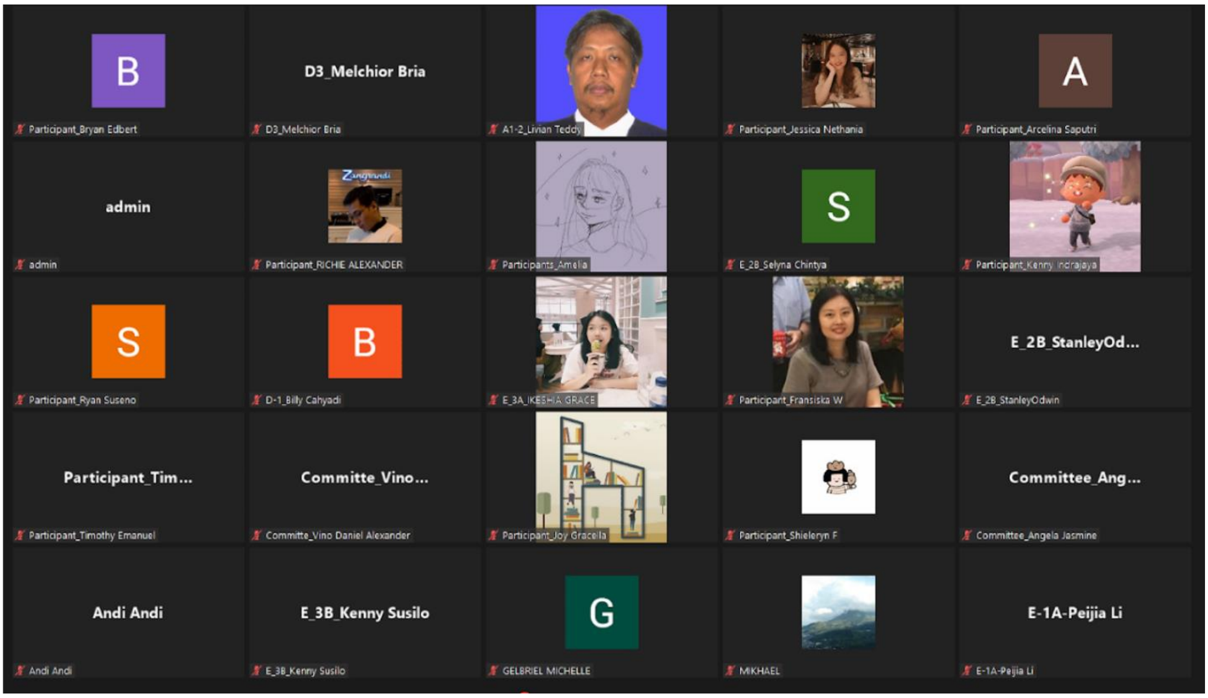
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International Student Workshop

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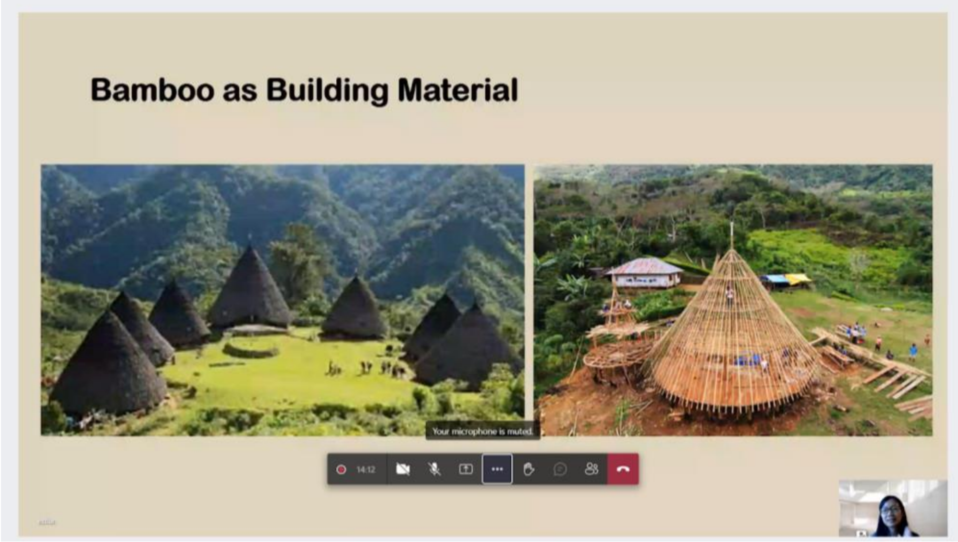


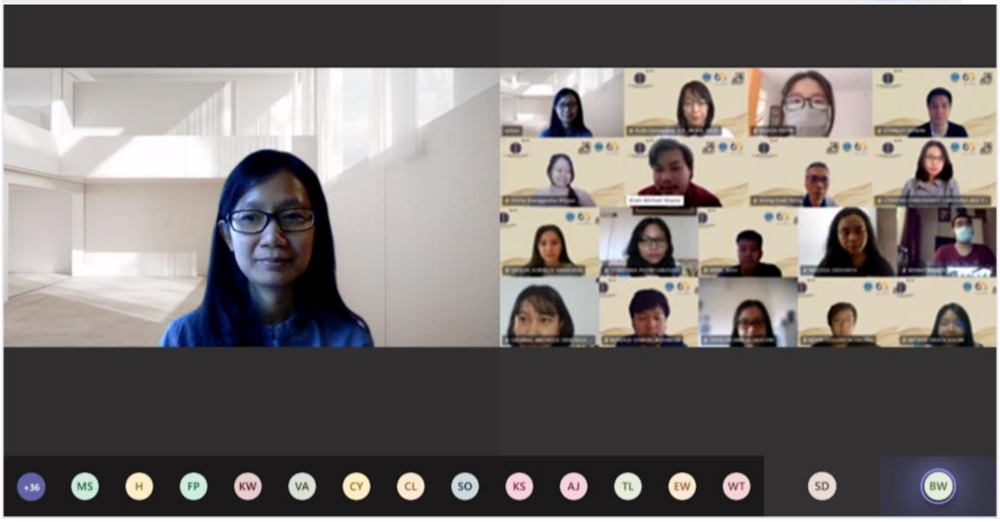

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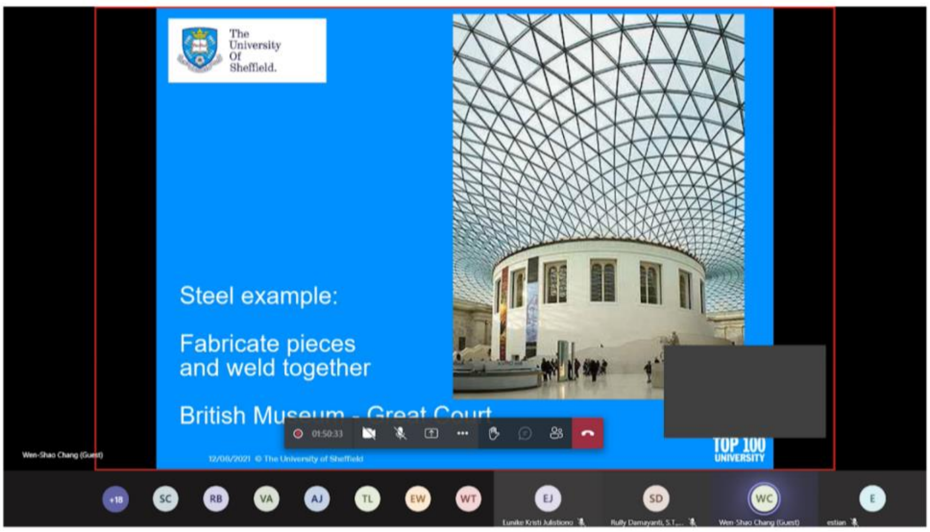

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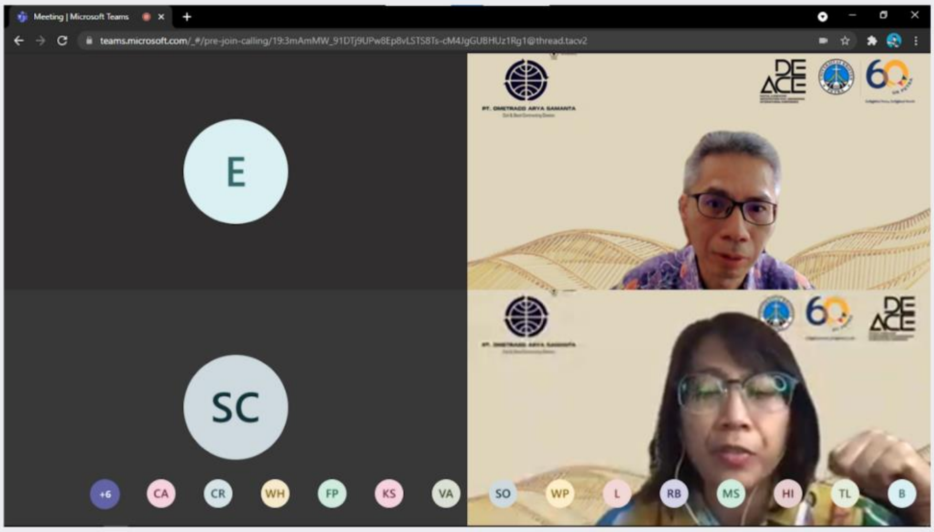

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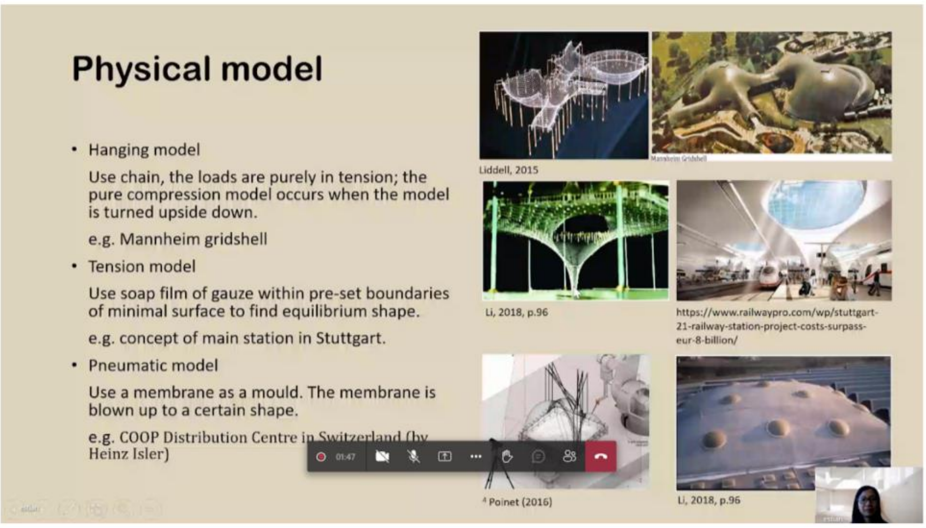


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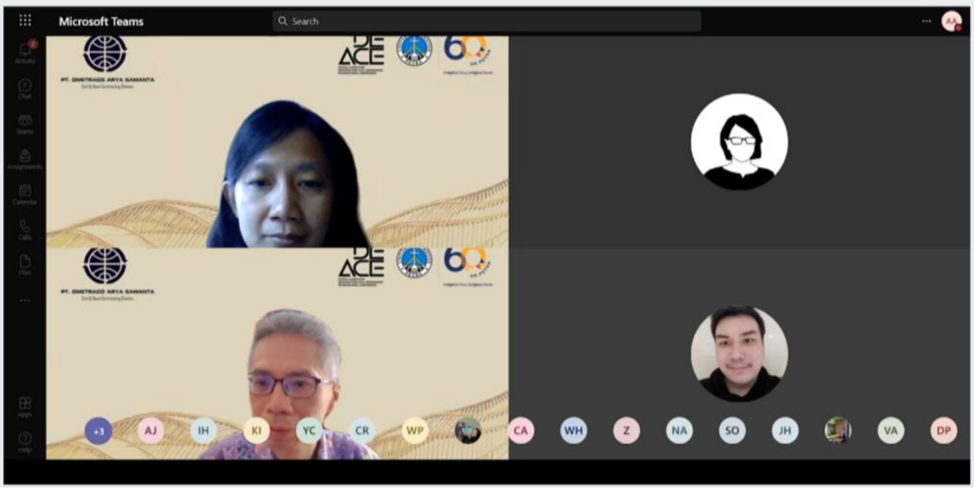

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# The study of shear wall uses in buildings during the architecture design process

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# The study of shear wall uses in buildings during the architecture design process

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**Abstract.** In Indonesia, an earthquake-prone area, building designs must be earthquake resistant, and using shear walls is one of the ways to make buildings more earthquake resistant. However, determining the requirements and optimal position of shear walls is difficult. Miscalculating in their positioning can cause torsion and other unpredictable behavior. Previous studies were done to know shear walls' optimal areas and positioning. The first way was trial and error, but this method was ineffective and took a long time. The second way, MATLAB programming, is actually very effective since the needs and orientation of the walls can be determined precisely. Nevertheless, not all structural engineers and architects master the programming language. This study, therefore, proposes relatively simple formulas and procedures to determine the optimal area and positioning of shear walls for architects preliminary design during architecture design process. The accuracy test for the formulas and procedures was carried out using ETABS simulation experiments on 10 building models with various irregular categories. The result showed the formulas and procedures proposed in this study were quite accurate in calculating the needs and position of shear walls. Optimal conditions, furthermore, were quite easy to achieve in symmetrical geometric compositions (1 or 2 axes) while organic or random geometric compositions were quite difficult to achieve. When the use of shear walls achieves optimal condition, the strength and stiffness of a building are increased, and the distribution of its strength and stiffness is relatively even, hence anticipating deformation behavior and reducing building eccentricity.

## 1. Introduction

In earthquake-prone countries like Indonesia, buildings must be designed to withstand earthquakes. The process of designing earthquake-resistant buildings should be started from the architecture design process by considering the geometric aspects of buildings which eventually affect buildings' structural behavior in carrying lateral earthquake loads [1].

Buildings with regular geometry configurations are relatively more resistant to earthquakes than buildings with irregular geometric configurations when facing earthquakes, particularly the strong ones [2]. The demand for buildings due to population growth and limited locations in big cities eventually causes the occurrence of buildings with irregular configurations [3]. Irregularities in buildings can trigger torsion due to the eccentricity between the center of mass and the center of rigidity. Shear walls are generally used to decrease torsional effects on buildings, and these walls also stiffen and reduce the deformation due to earthquake loads [4]. However, the efficiency of using shear walls heavily depends on their positioning. Getting the optimal shear walls' positions is very difficult, and if these walls are incorrectly placed, it can even trigger greater torsion [5]. To obtain guidance for the optimal position of the shear walls, several researchers [4–6] conducted trial-and-error simulations with ETABS. This first method was conducted by varying the placement of shear walls in several geometric configurations of irregular buildings, and the results were compared to find out the most optimum position. The optimization, nonetheless, could not be applied to other irregular configurations and the required shear wall areas were also unknown. Several other researchers [7–10] used software such as MATLAB to immediately obtain the optimum position and orientation and the required areas. This method is actually practical, yet not all architects understand this kind of complex matrix programming software.

In order to overcome this obstacle, this study proposes relatively simple formulas and shear wall positioning procedures to obtain the preliminary shear walls' areas and optimal positions. 10 building models with various categories of irregularities were used to test the procedure. The first stage of this simulation was 5 irregular building models without shear walls were analyzed using the ETABS to get the outputs, namely fundamental period, mode, participating ratio, and eccentricity. Based on these outputs, a simple calculation of the shear wall areas was conducted using the proposed shear wall positioning formulas and procedure. The next step is the addition of shear walls to each building model to improve its irregularity and to make it relatively regular. The five irregular building models with shear walls were then analyzed again to find fundamental period, modes, participating ratios, and eccentricity as the outputs. The outputs, both before and after applying shear walls, were compared to determine the accuracy, strengths, and weaknesses of the proposed formulas and procedure. Guidance for architect's preliminary design during architecture design process was then made as the reference in designing buildings' geometry with irregular configurations and in using shear walls to improve the buildings' dynamic behavior to be relatively regular so that it is more resistant to earthquakes.

## 2. Research methods and models

### *2.1. Research methods*

This research is an experimental simulation study that aims to test the proposed mathematical models and procedures with ETAB's modal analysis and structure analysis software. Such 'testing theory' process is commonly conducted in the field of engineering [11].

The sampling technique employed in the selection of the simulation model was purposive sampling. According to Nasution [12], in purposive sampling, samples are carefully selected so that they are relevant to the research design. Thus, in this research, those 5 simulation models were considered to have relatively varied geometric configurations, so they were able to describe the real irregular geometric configurations.

### *2.2. Models*

The building modules used were 5×5 m. There were 10 building models simulated in the study, namely 5 irregular building models without shear walls (Figures 1 to 5) and five irregular building models with the shear walls (Figures 1A to 5A). The structural properties of each model can be seen in Table 1.

Models 1 to 5 (Figures 1, 3, 5, 7, and 9) used the moment resisting frame structure, while models 1A to 5A (Figures 2, 4, 6, 8, and 10) used the dual system structure with moment resisting frames and shear walls. The simulated earthquake zone was with Ss = 1.5g and S1 = 0.6g while the building, functioning as an office, had the assumed dead load = 400 $kg/m^2$ and the assumed live load = 250 $kg/m^2$. Geometrical data, structural properties, and building loads were input into ETABS, and structure analysis and modal analysis were carried out to get the outputs that consist of Period (T), Shape Mode Translation (Ux, Uy), Rotation (Rz), and Centers of Mass and Rigidity.

Period (T) is the fundamental period of a building structure that is used to measure the stiffness level [13]. A building is considered to be rigid if T < Tmax while it is considered flexible if T > Tmax. The definition of Tmax is the maximum period allowed in a building based on the values of Ss and S1, the type of structure, and the height of the building.

**Table 1**. Structural properties of Models 1 to 5 and Models 1A to 5A.

| Models | Number of floors (height-m) | Dimension beam (cm) | Dimension column (cm) | The thickness of stories plate (cm) | The thickness of shear wall (cm) | Grade | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Concrete ($kg/cm^2$) | Reinforcement ($kg/cm^2$) | Stirrup ($kg/cm^2$) |
| 1 & 1A | 10 (40 m) | 25×40 | 60×60 | 12 | 25 | 300 | 4000 | 2400 |
| 2 & 2A | 10 (40 m) | 25×40 | 60×60 | 12 | 25 | 300 | 4000 | 2400 |
| 3 & 3A | 7 (28 m) | 25×50, 30×60 | D 65 | 12 | 25 | 300 | 4000 | 2400 |
| 4 & 4A | 10 (40 m) | 25×40 | 60×60 | 12 | 25 | 300 | 4000 | 2400 |
| 5 & 5A | 10 (40 m) | 25×40 | 60×60 | 12 | 25 | 300 | 4000 | 2400 |

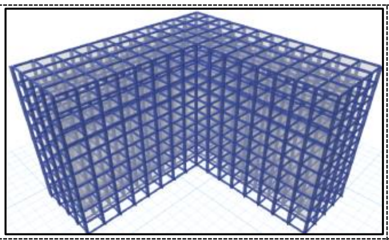

**Figure 1.** Model 1.

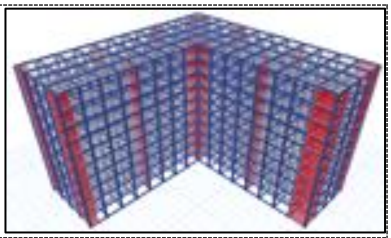

**Figure 2.** Model 1A.

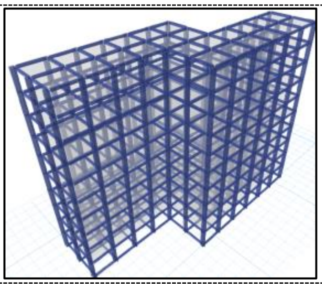

**Figure 3.** Model 2.

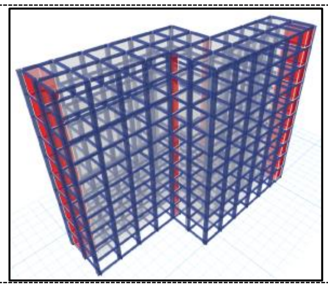

**Figure 4.** Model 2A.

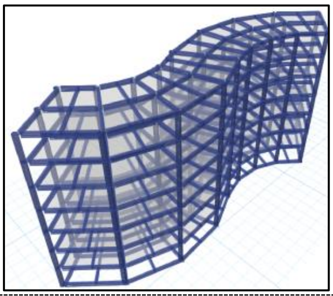

**Figure 5.** Model 3.

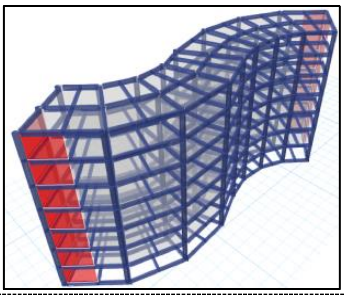

**Figure 6.** Model 3A.

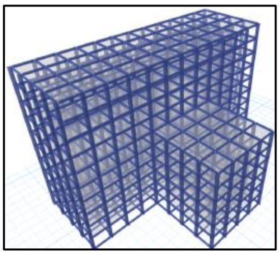

**Figure 7.** Model 4.

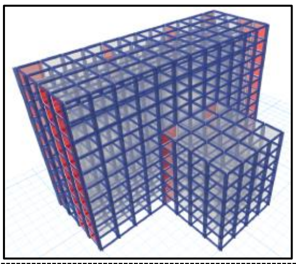

**Figure 8.** Model 4A.

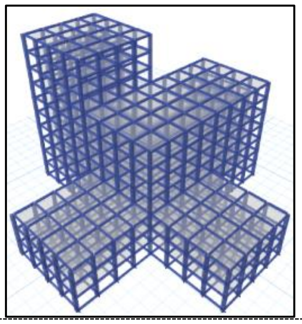

**Figure 9.** Model 5.

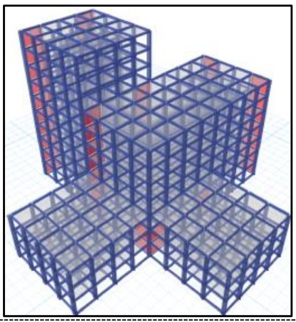

**Figure 10.** Model 5A.

Shape mode (Ux, Uy, and Rz) is the variation of deformations that may occur in a building. Shape mode measures buildings' regularity level. Buildings with mode 1 = translation, mode 2 = translation and mode 3 = rotation can be categorized as regular buildings [14]. When the value of mode 1 to mode 3 is between 0 and 1, which means when it gets closer to 1, translation towards the X-axis and Y-axis and rotation of the Z-axis are dominant.

Centers of mass and rigidity are used to measure the potential level of torsion in a building. Torsion is caused by the eccentricity between the center of mass and the center of rigidity or, in other words, the center of mass does not coincide with the center of rigidity [15]. Eccentricity occurs due to the irregular geometric configuration. Based on the Simplified Vulnerability Analysis (SVA) of Architectural Design [16]; the eccentricity ratio $e_{ri} \leq 0.1$ means potential for small torsion, the eccentricity ratio $0.1 < e_{ri} < 0.3$ means potential for medium torsion, and the eccentricity ratio $e_{ri} \geq 0.3$ means potential for large torsion.

## 3. The proposed formulas and procedure

There are several steps to take in designing shear walls position in the building:
As the first step, determine the required shear wall area using the formulas below [17].

$$A_{SW} \geq 0.0012 \sum A_{pi} \tag{1}$$

where,

$A_{SW}$ = The minimum shear wall area per floor
$\sum A_{pi}$ = The gross cumulative area of floors

For the second step, determine the distribution of shear walls on the building's floors. The positioning and orientation of the shear walls must consider:

- The balance of the plan and position of shear walls in order to avoid the potential for the next greater torsion.

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- The relatively equal stiffness between the X- and Y- axes of the plan. The weak axis gets more wall area orientation than the strong axis, so both axes have the relatively same stiffness (see Figure 11).

$$A_{SW-X} = \frac{Y}{(X+Y)}.A_{SW} \tag{2}$$

$$A_{SW-Y} = \frac{X}{(X+Y)}.A_{SW} \tag{3}$$

where,

$A_{SW}$ = The minimum shear wall area per floor
$A_{SWX-}$ = The shear wall area of the X-axis
$A_{SWY-}$ = The shear wall area of the Y-axis
$Y$ & $X$ = The building dimension towards X- and Y-axes

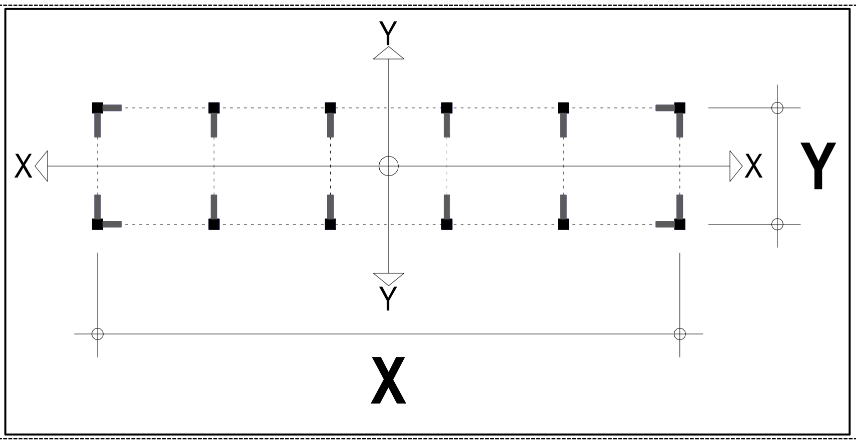


**Figure 11.** Positioning and orientation of the shear walls based on the principle of balance and equivalence of stiffness on X- and Y- Axes.

For the third step, simplify the complex plan (Figure 12) by dividing it into several blocks of rectangular plans so that they can also be analyzed using the previous second step.

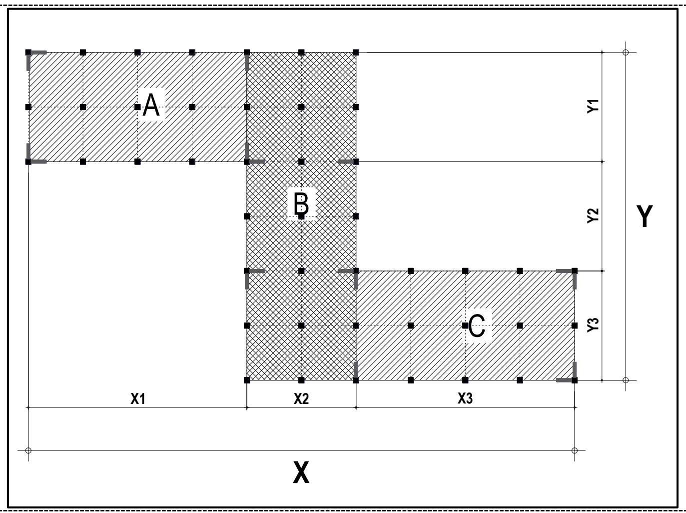


**Figure 12.** The positioning and orientation of the shear walls in buildings with the same height described in the complex plan.

- With the formulas below, calculate the proportional shear wall area of each block. Blocks with larger plans also have larger shear walls and vice versa:

$$A_{SW-A} = \frac{L_A}{(L_A + L_B + L_C)}.A_{SW} \tag{4}$$

$$A_{SW-B} = \frac{L_B}{(L_A + L_B + L_C)}.A_{SW} \tag{5}$$

$$A_{SW-C} = \frac{L_C}{(L_A + L_B + L_C)}.A_{SW} \tag{6}$$

where,

$A_{SW-A}$, $A_{SW-B}$, $A_{SW-C}$ = The shear wall areas in A, B, and C blocks.

$L_A, L_B, L_C$ = The areas of blocks A, B, and C.

- After the shear wall area of each block is found, determine this shear wall area on each X- and Y- axes based on formulas 2 and 3:

$$\text{Blok A} \rightarrow A_{SW-AX} = \frac{Y1}{(Y1 + X1)}.A_{SW-A} \tag{7}$$

$$A_{SW-AY} = \frac{X1}{(Y1 + X1)}.A_{SW-A} \tag{8}$$

$$\text{Blok B} \rightarrow A_{SW-BX} = \frac{Y}{(Y + X2)}.A_{SW-B} \tag{9}$$

$$A_{SW-BY} = \frac{X2}{(Y + X2)}.A_{SW-B} \tag{10}$$

$$\text{Blok C} \rightarrow A_{SW-CX} = \frac{Y3}{(Y3 + X3)}.A_{SW-C} \tag{11}$$

$$A_{SW-CY} = \frac{X3}{(Y3 + X3)}.A_{SW-C} \tag{12}$$

where,

$A_{SW-AX}$, $A_{SW-BX}$, $A_{SW-CX}$ = Shear wall areas on the X-axis of blocks A, B, and C

$A_{SW-AY}$, $A_{SW-BY}$, $A_{SW-CY}$ = Shear wall areas on the Y-axis blocks A, B, and C

In the fourth step, for the complex plan where the buildings have significantly different heights, separately calculate the shear wall areas of each mass block that have different heights according to steps 2 or 3 based on the mass composition and the heights.

In the fifth step, to find out the number and length of shear walls, divide the shear wall areas from formulas 2, 3, and 7 to 12 on each X- and Y- axes by the number of shear walls that will be distributed to each axis. Furthermore, to determine the length, the aforementioned shear wall areas are divided by the shear wall thickness (t min = 25 cm). There are several ideal distributions of shear wall locations [18–21], namely on the corners of the building (Figure 13a), along the sides of the building if> 30 m (Figure 13b), at the intersection of building masses (Figure 13c) and at the core of the building (Figure 13d). All of these locations can increase the structural rigidity and strength and reduce torsion, and they can also be installed either separately or together.

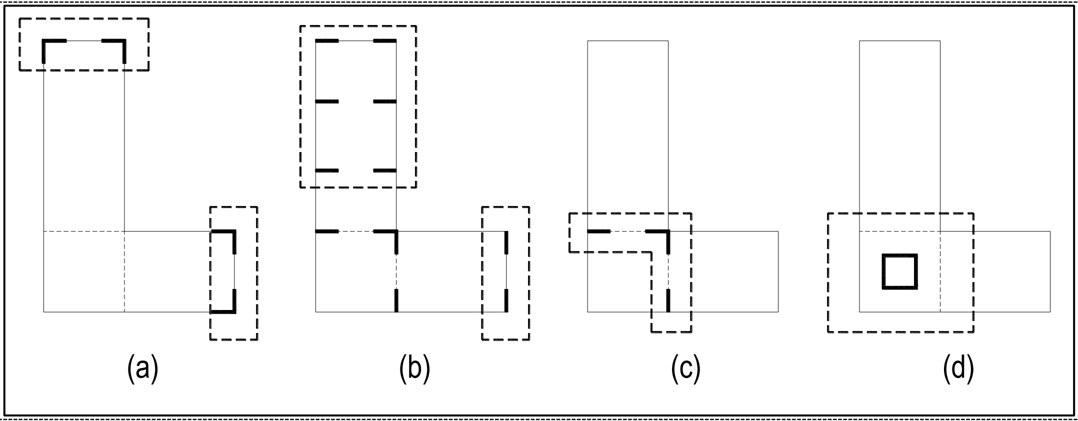


**Figure 13.** The ideal positioning of shear walls: a) on the corners, b) on the sides, c) at the intersection of building masses, and d). at the building's core.

## 4. Results and discussions

*4.1. Models 1 and 1A*

Model 1 (Figure 1) was installed with shear walls and became model 1A (Figure 14). For the calculation of shear walls, the building mass was divided into mass A and mass B. With formulas 1 to 12, it was found that the need of mass A for shear walls was 6 © 5 m on the X-axis and 2 © 2.4 m and 6 © 5 m on the Y-axis. The need of mass B for shear walls, on the other hand, was 6 © 5 m on the X-axis and 2 © 5 m on the Y-axis.

The addition of shear walls also increased the building's stiffness by reducing the fundamental period of model 1. Before using shear walls, its fundamental period was 1.921 seconds (Table 2a), and after using shear walls, its fundamental period was 1.008 seconds (Table 2b). This period is also still below the required Tmax = 1.09 seconds.

Based on the shape mode in model 1, modes 1 and 2 had the same translation value and were not dominant while mode -3 was rotation and dominant (Table 2a). This means that the occurring translation on both Y- and X- axes is not uniform or there is a diagonal translation. Thus, model 1 can be categorized as an irregular building. In order to improve its deformation behavior, shear walls were placed in model 1A on the building's corners, on the building's sides, and at the intersection of mass A and mass B. The deformation behavior, then, significantly improved in which modes 1 and 2 = translation and dominant and mode 3 = rotation and dominant (Table 2b). Model 1A, hence, can be categorized as a regular building.

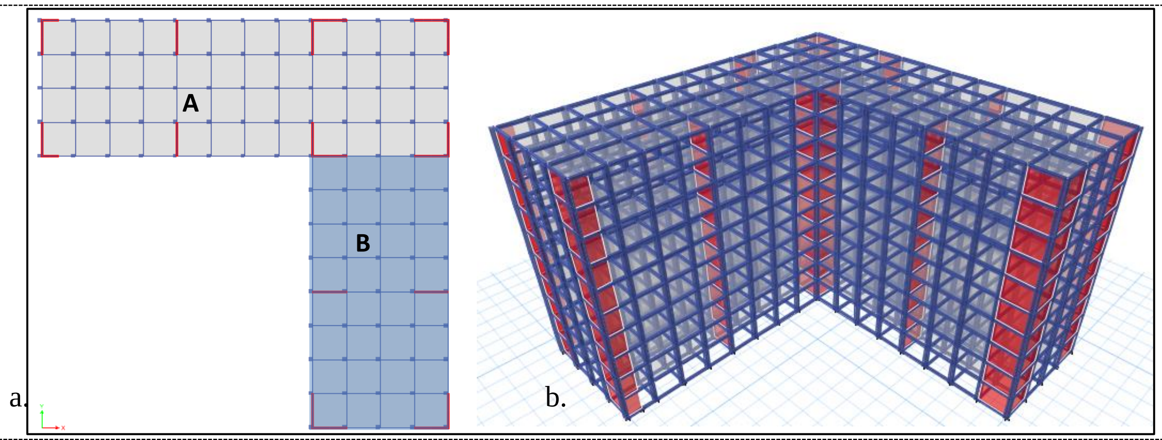


**Figure 14.** Model 1A (after shear walls were installed): a) the plan, b) 3D.

**Table 2.** Modal direction factors of Models 1 and 1A.

| **a). Model 1** | | | | | **b). Model 1A** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Mode** | **Period (s)** | **UX** | **UY** | **RZ** | **Mode** | **Period (s)** | **UX** | **UY** | **RZ** |
| 1 | 1.921 | 0.418 | 0.418 | 0.164 | 1 | 1.008 | 0.941 | 0.006 | 0.053 |
| 2 | 1.908 | 0.500 | 0.500 | 0 | 2 | 0.939 | 0.009 | 0.988 | 0.003 |
| 3 | 1,842 | 0.083 | 0.083 | 0.835 | 3 | 0.752 | 0.005 | 0.006 | 0.944 |

**Table 3.** Eccentricity ratios of Models 1 and 1A.

| **Stories** | **Model 1** | | **Model 1A** | |
|---|---|---|---|---|
| | $\mathbf{e_{rx}}$ | $\mathbf{e_{ry}}$ | $\mathbf{e_{rx}}$ | $\mathbf{e_{ry}}$ |
| Storey10 | 0.013 | 0.013 | 0.016 | 0.062 |
| Storey9 | 0.013 | 0.013 | 0.018 | 0.063 |
| Storey8 | 0.012 | 0.012 | 0.020 | 0.066 |
| Storey7 | 0.011 | 0.011 | 0.022 | 0.071 |
| Storey6 | 0.011 | 0.011 | 0.025 | 0.076 |
| Storey5 | 0.010 | 0.010 | 0.028 | 0.082 |
| Storey4 | 0.009 | 0.009 | 0.034 | 0.088 |
| Storey3 | 0.008 | 0.008 | 0.041 | 0.094 |
| Storey2 | 0.006 | 0.006 | 0.051 | 0.098 |
| Storey1 | 0.002 | 0.002 | 0.059 | 0.093 |

The eccentricity ratio of model 1 was $e_{rx}$ and $e_{ry} < 0.1$ which means that the potential for rotation is small. After the addition of shear walls, the eccentricity ratio of model 1A was $e_{rx}$ and $e_{ry} < 0.1$ or, in other words, the positioning of shear walls was optimal. When the positioning is optimal, it does not cause excessive eccentricity which may cause torsional irregularity configurations [22]. Besides, the main problem of model 1A was the formation of the re-entrant corner irregularity configuration [22]. This condition actually can cause the concentration of forces at the intersection of mass A and mass B, but the presence of shear walls at the intersection can also increase the capacity of the structures to encounter that force concentration.

*4.2. Models 2 and 2A*

Model 2A (Figure 15) was actually model 2 (Figure 3) after the shear walls, and core walls were installed. Model 2 was categorized as a very slender building because the ratio of its height (H) to its width (D) = 40/10 = 4. Meanwhile, the ideal slenderness ratio to reduce building flexibility is H/D < 2 [23]. In order to significantly increase the stiffness of the 2A model, 2 © 2.5 × 5 m of core walls (formulas 1 to 6) were installed at the ends of the building wings in the X- and Y- axes together with 2 © 2 m shear walls towards the X-axis at the intersection of masses A and B. Before the installation of shear walls, the fundamental period (T) of model 2 = 1.942 seconds (Table 4a), and it was then decreased as many as 1.151 seconds after the installation of core walls and shear walls in model 2A (Table 4b). With the fundamental period (T) of the 2A model ≈ 1.09 seconds (T max), it means the stiffness of the model 2A already possesses the required capacity to resist strong earthquakes.

Model 2 had the shape mode, namely mode 1 = translation towards the Y- axis and dominant, mode 2 = rotation towards the Z- axis and dominant, and mode 3 = translation towards the –X axis and dominant; this means that model 2 is categorized as an irregular building, so its deformation behavior needs to be corrected. After shear walls and core walls were installed in model 2A, the deformation behavior improved and it became a regular building where mode 1 = translation towards the X-axis and dominant, mode 2 = translation towards the Y- axis and dominant, and mode 3 = rotation towards the –Z axis and dominant.

The eccentricity ratios of models 2 and 2A = 0 (Table 5), so the potential for torsion is relatively small. The use of shear walls in model 2A prevents the formation of torsional irregularity and re-entrant corner irregularity configurations.

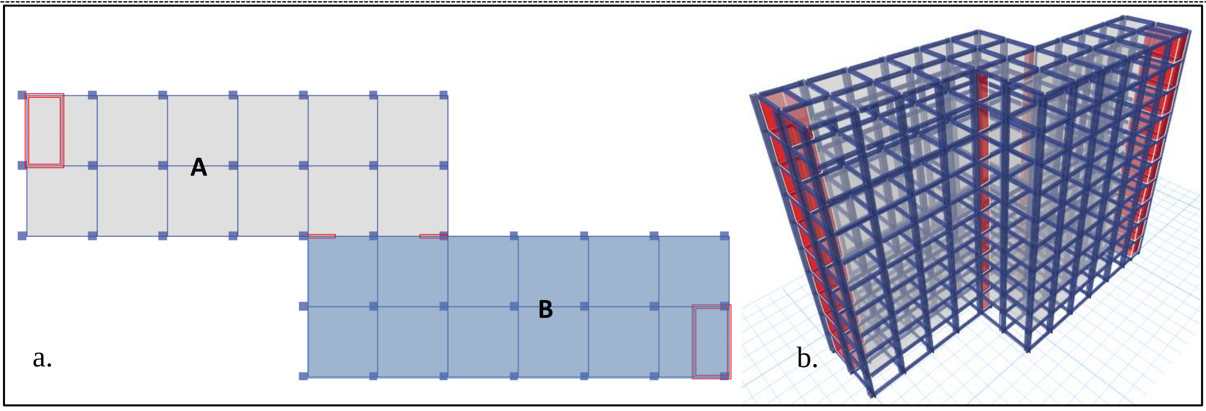


**Figure 15.** Model 2A (after shear walls were installed: a) the plan, b) 3D.

**Table 4.** Modal direction factors of Models 2 and 2A.

| a). Model 2 | | | | | b). Model 2A | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Mode** | **Period (s)** | **UX** | **UY** | **RZ** | **Mode** | **Period (s)** | **UX** | **UY** | **RZ** |
| 1 | 1.942 | 0 | 1 | 0 | 1 | 1.151 | 1 | 0 | 0 |
| 2 | 1.817 | 0 | 0 | 1 | 2 | 0.955 | 0 | 1 | 0 |
| 3 | 1.813 | 1 | 0 | 0 | 3 | 0.655 | 0 | 0 | 1 |

**Table 5.** Eccentricity ratios of the Models 2 and 2A.

| **Stories** | **Model 2** | | **Model 2A** | |
|---|---|---|---|---|
| | $e_{rx}$ | $e_{ry}$ | $e_{rx}$ | $e_{ry}$ |
| Storey10 | 0.000 | 0.000 | 0.000 | 0.000 |
| Storey9 | 0.000 | 0.000 | 0.000 | 0.000 |
| Storey8 | 0.000 | 0.000 | 0.000 | 0.000 |
| Storey7 | 0.000 | 0.000 | 0.000 | 0.000 |
| Storey6 | 0.000 | 0.000 | 0.000 | 0.000 |
| Storey5 | 0.000 | 0.000 | 0.000 | 0.000 |
| Storey4 | 0.000 | 0.000 | 0.000 | 0.000 |
| Storey3 | 0.000 | 0.000 | 0.000 | 0.000 |
| Storey2 | 0.000 | 0.000 | 0.000 | 0.000 |
| Storey1 | 0.000 | 0.000 | 0.000 | 0.000 |

*4.3. Models 3 and 3A*

Model 3 needed shear walls to improve its performance, and model 3A (Figure 16) was the model where shear walls had been installed. From formulas 1 to 3, it was found that model 3 needed 4 © 4.2–5 m of shear walls.

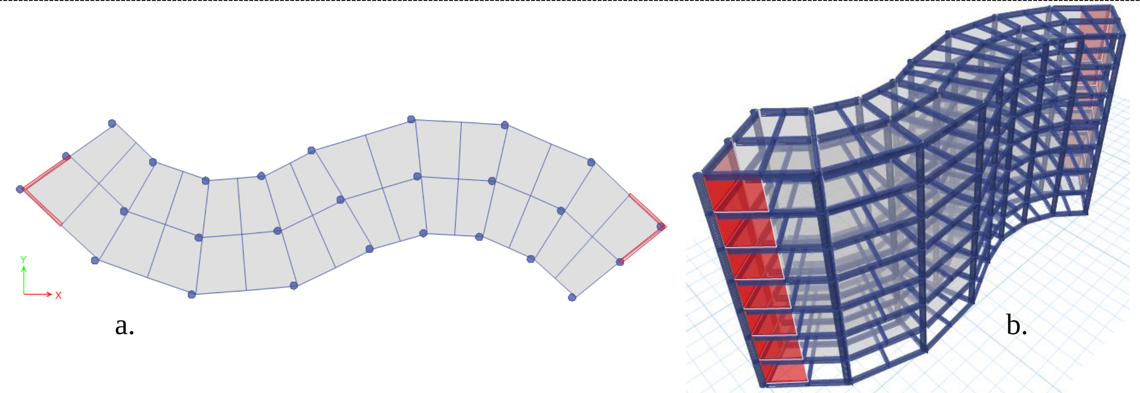


**Figure 16.** Model 3A (after shear walls were installed): a) the plan, b) 3D.

**Table 6.** Modal direction factors of Models 3 and 3A.

| a). Model 3 | | | | | b). Model 3A | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Mode** | **Period (s)** | **UX** | **UY** | **RZ** | **Mode** | **Period (s)** | **UX** | **UY** | **RZ** |
| 1 | 1.099 | 0.021 | 0.940 | 0.04 | 1 | 0.690 | 0.701 | 0.299 | 0 |
| 2 | 1.049 | 0.001 | 0.042 | 0.958 | 2 | 0.569 | 0.299 | 0.701 | 0 |
| 3 | 1.029 | 0.979 | 0.019 | 0.003 | 3 | 0.398 | 0 | 0 | 1 |

**Table 7.** Eccentricity ratios of Models 3 and 3A.

| **Stories** | **Model 3** | | **Model 3A** | |
|---|---|---|---|---|
| | $e_{rx}$ | $e_{ry}$ | $e_{rx}$ | $e_{ry}$ |
| Storey7 | 0.004 | 0.006 | 0.004 | 0.020 |
| Storey6 | 0.003 | 0.006 | 0.004 | 0.023 |
| Storey5 | 0.003 | 0.005 | 0.005 | 0.029 |
| Storey4 | 0.003 | 0.005 | 0.006 | 0.036 |
| Storey3 | 0.003 | 0.005 | 0.006 | 0.043 |
| Storey2 | 0.003 | 0.004 | 0.005 | 0.048 |
| Storey1 | 0.002 | 0.002 | 0.002 | 0.044 |

The fundamental period (T) the model 3 before the installation of shear walls was 1.099 seconds (Table 6a), and after shear walls installation (the model 3A), its fundamental period (T) was 0.69 seconds (Table 6b); it means it is less than T max (0.83 seconds). Installing the shear walls, thus, significantly increased the building's stiffness in overcoming potential strong earthquakes.

The mode shape of model 3 is categorized as an irregular building because mode 1 = translation, mode 2 = rotation, and mode 3 = translation (Table 6a). After shear walls installation at the ends of the building wings, the performance of the 3A model improved where modes 1 and 2 = translation, mode 3 = rotation and all of these modes were quite dominant (Table 6b).

That the entire eccentricity ratio of models 3 and 3A $e_{rx}$ and $e_{ry}$ is less than < 0.1 (Table 7) means that the potential for torsional irregularity configuration in model 3A is not a crucial problem for this organic-shaped building. However, the potential for the formation of non-parallel system irregularity configurations [22] in model 3A must be considered since the installation of shear walls does not simply eliminate the potential for torsion and excessive stress that can cause unexpected local damage [24].

### *4.4. Models 4 and 4A*

Model 4 (Figure 7) had masses with different heights. The deformation behavior of model 4, actually, was still quite good, but there was translation and rotation that were not dominant enough (Table 8a). Therefore, it was necessary to install shear walls as in model 4A (Figure 17) to improve the deformation behavior. For the calculation of its shear wall mass, mass A and mass B were divided in which only mass A became the focus while mass B was not really considered because it was relatively small. Based on formulas 1 to 3 for mass A, the results showed that the shear walls were 4 © 5 m towards the X-axis and 6 © 5 m towards the Y-axis.

The fundamental period (T) of model 4 = 1.832 seconds (Table 8a) and after the shear walls were installed, its fundamental period (model 4A) = 1.151 seconds (Table 8b); hence T of model 4A ≈ 1.09 seconds (Tmax). This means the stiffness of the 4A model meets the prerequisite earthquake resistance.

Model 4 was actually categorized as a fairly regular building since mode 1 was translation, mode 2 was translation, and mode 3 was rotation, but mode 1 and mode 3 were not dominant enough (Table 8a). In this model, mode 1 translation was mixed with rotation, and Mode 3 rotation was mixed with translation. This condition indicates that the performance of the deformation behavior can still be improved. After shear walls were installed at the ends of the building's wings, on the sides of mass A, and at the intersection of mass A and mass B; the performance of the deformation behavior improved in which mode 1 translation towards the X-axis and dominant, mode 2 translation towards the Y-axis and dominant, and mode 3 rotation towards the Z-axis and dominant (Table 8b).

The potential rotation in model 4 towards X-axis was relatively small ($e_{rx}$ <0.1) but the potential rotation towards the Y-axis was categorized as medium (0.1 <$e_{ry}$<0.3) from the stories 6 to 10 (Table 9). After the shear walls were installed in model 4A, the potential rotation towards the X-axis was kept small ($e_{rx}$ <0.1) while the eccentricity towards the Y-axis ($e_{ry}$ <0.1) on the stories 6 to 10 could be reduced so that the potential rotation was relatively small (Table 9). Therefore, the potential torsion in the vertical geometric configuration [22] with a symmetrical composition and the re-entrant corner irregularity configuration in model 4A can be controlled by the shear walls.

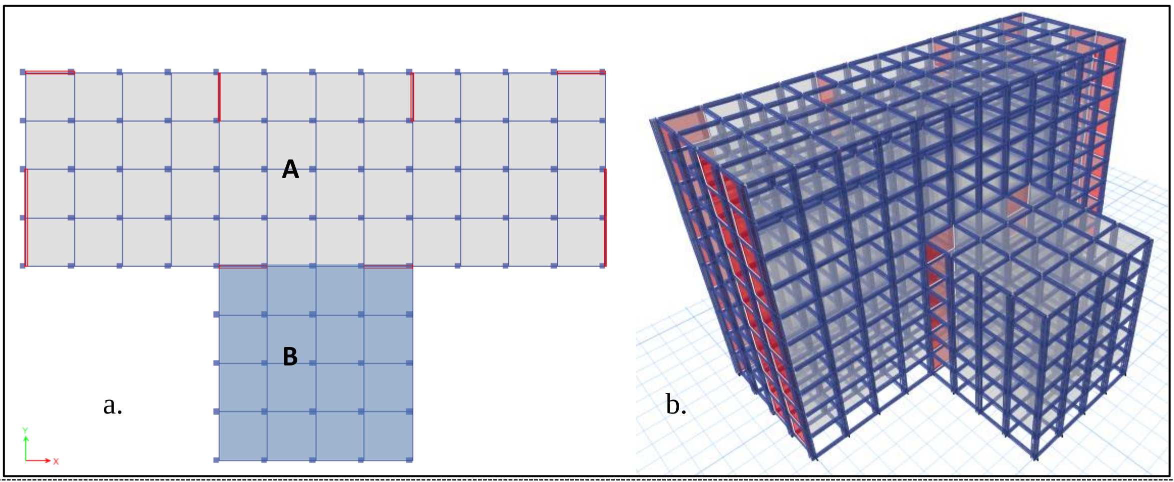


**Figure 17.** Model 4A (after shear walls were installed): a) the plan, b) 3D.

**Table 8.** Modal direction factors of Models 4 and 4A.

| a). Model 4 | | | | | b). Model 4A | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Mode** | **Period (s)** | **UX** | **UY** | **RZ** | **Mode** | **Period (s)** | **UX** | **UY** | **RZ** |
| 1 | 1.832 | 0.657 | 0 | 0.343 | 1 | 1.151 | 1 | 0 | 0 |
| 2 | 1.777 | 0 | 1 | 0 | 2 | 0.841 | 0 | 1 | 0 |
| 3 | 1.593 | 0.355 | 0 | 0.645 | 3 | 0.629 | 0.032 | 0 | 0.989 |

**Table 9.** Eccentricity ratios of Models 4 and 4A.

| **Stories** | **Model 4** | | **Model 4A** | |
|---|---|---|---|---|
| | $e_{rx}$ | $e_{ry}$ | $e_{rx}$ | $e_{ry}$ |
| Storey10 | 0 | 0.136 | 0 | 0.058 |
| Storey9 | 0 | 0.160 | 0 | 0.073 |
| Storey8 | 0 | 0.188 | 0 | 0.085 |
| Storey7 | 0 | 0.218 | 0 | 0.094 |
| Storey6 | 0 | 0.190 | 0 | 0.055 |
| Storey5 | 0 | 0.076 | 0 | 0.005 |
| Storey4 | 0 | 0.062 | 0 | 0.012 |
| Storey3 | 0 | 0.053 | 0 | 0.027 |
| Storey2 | 0 | 0.047 | 0 | 0.040 |
| Storey1 | 0 | 0.044 | 0 | 0.044 |

*4.5. Models 5 and 5A*

The deformation behavior in model 5 (Figure 9) can be categorized as the regular building, but its rotation mode is not dominant enough. In order to fix this, the mass of model 5A (Figure 18a) was divided based on the height difference, but the calculation of its shear walls only focused on masses A and B while mass C was not considered because it was relatively small. With formulas 1 to 3, the obtained results were 2 © 5 m of shear walls towards the X-axis for mass A, 4 © 5 m of shear walls towards the X-axis, and 4 © 5 of shear walls towards the Y-axis for mass B (Figure 18).

The fundamental period (T) of model 5 = 1.562 seconds (Table 10a), and then its stiffness increased after shear walls were installed in which its fundamental period (T) = 1.039 seconds (Table 10b). This period is still below Tmax = 1.09 seconds, so the stiffness of the 5A model is still in accordance with the required standard for strong earthquake resistance.

Model 5 was with mode 1 = translation towards the X- axis and dominant, mode 2 = translation towards the Y-axis and dominant, and mode 3 = rotation towards the Z-axis and less dominant (Table 10a). This model actually can be categorized as a regular building, but the weakness is that mode 3 was not dominant enough, and it was a challenge whether the deformation behavior could be corrected like the previous models. After two shear walls were installed at the ends of mass A, at the intersection of masses A and B, at wingtips of mass B building, and 4 shear walls were installed at the intersection masses B and C; the deformation behavior of the model 5A improved. This deformation behavior became mode 1 = translation towards the Y-axis and dominant, mode 2 = translation towards the X-axis and dominant, and mode 3 = rotation and quite dominant (Table 10b).

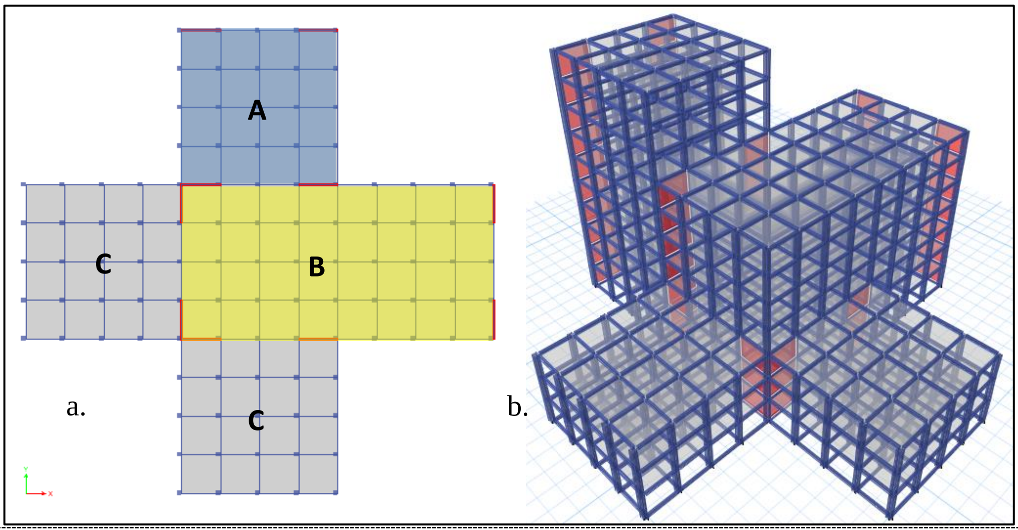


**Figure 18.** Model 5A (after shear walls were installed): a) The Plan, b) 3D.

**Table 10.** Modal direction factors of Models 5 and 5A.

| a). Model 5 | | | | | b). Model 5A | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Mode** | **Period (s)** | **UX** | **UY** | **RZ** | **Mode** | **Period (s)** | **UX** | **UY** | **RZ** |
| 1 | 1.562 | 0.814 | 0.019 | 0.167 | 1 | 1.039 | 0.014 | 0.929 | 0.056 |
| 2 | 1.385 | 0.008 | 0.989 | 0.003 | 2 | 0.817 | 0.979 | 0.004 | 0.018 |
| 3 | 1.019 | 0.359 | 0.053 | 0.588 | 3 | 0.592 | 0.14 | 0.155 | 0.705 |

**Table 11.** Eccentricity ratios of Models 5 and 5A.

| **Stories** | **Model 5** | | **Model 5A** | |
|---|---|---|---|---|
| | $e_{rx}$ | $e_{ry}$ | $e_{rx}$ | $e_{ry}$ |
| Storey10 | 0.021 | 0.061 | 0.043 | 0.035 |
| Storey9 | 0.033 | 0.097 | 0.067 | 0.007 |
| Storey8 | 0.056 | 0.168 | 0.125 | 0.054 |
| Storey7 | 0.034 | 0.166 | 0.164 | 0.059 |
| Storey6 | 0.001 | 0.130 | 0.132 | 0.016 |
| Storey5 | 0.026 | 0.123 | 0.102 | 0.004 |
| Storey4 | 0.058 | 0.135 | 0.045 | 0.016 |
| Storey3 | 0.068 | 0.127 | 0.016 | 0.021 |
| Storey2 | 0.057 | 0.104 | 0.021 | 0.013 |
| Storey1 | 0.048 | 0.087 | 0.058 | 0.035 |

Model 5 had vertical geometric irregularity configurations because it had several masses with different heights. It can be seen in Table 11 that the vertical geometric irregularity configurations with random composition caused eccentricity towards the Y-axis direction from stories 2 to 8 in the medium category ($0.1 < e_{ry} < 0.3$), and such conditions can create significant potential torsion. It turned out that after the shear walls were installed in model 5A, the eccentricity with the medium category

($0.1 < e_{rx} < 0.3$) still occurred towards the X-axis from stories 5 to 8. This condition means that the formation of torsional irregularities in models 5 and 5A is caused by vertical geometric irregularity configurations with random compositions, and such problem is not easy to control. The installation of shear walls in the 5A model only controls the formation of the re-entrant corner irregularity configurations.

## 5. Conclusions

From the calculation of all formulas, guidance about shear wall requirements and the steps for shear wall installation in models 1A to 5A can be made as follows:

- The formulas 1 to 12 and steps 1 to 5 are quite accurate in calculating the areas and locations of shear walls.
- Optimum installation of shear walls in buildings can be achieved when the strength and stiffness are increased, the distribution of strength and stiffness is relatively even, the deformation behavior can be anticipated, and the eccentricity can be reduced.
- Installation of shear walls can optimally fix torsional irregularity and re-entrant corner irregularity configurations.
- Installation of shear walls in vertical geometric irregularities can only optimize building irregularity with symmetrical geometric compositions (1 or 2 axes) while building irregularity with random geometric compositions is quite difficult to control its eccentricity.
- Shear wall installation in the configuration of non-parallel system irregularity is quite difficult to achieve optimal conditions. This action can only solve problems related to strength, stiffness, deformation behavior, and eccentricity, whereas the distribution of strength and stiffness is quite difficult to control when the shape of a building is organic and random.
- If the addition of shear walls only causes an insignificant reduction of the fundamental period, consider using the combination of core walls and shear walls.
- The building's predetermined areas and core positions can be assumed as part of the structural column. After structure and modal analyses with ETABS were carried out and the building was evidently categorized as an irregular building, shear walls can be added to fix its irregularity by applying those 12 formulas and 5 steps.

## Acknowledgments

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