Analysis of wind loads in the building with a variation of roof shapes

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Abstract. The Indonesian’s geographical position, which makes Indonesia frequent disasters due to wind, objects unable to withstand the wind can lift or shift these objects. This condition causes damage, such as a roof that is raised or floating. Buildings in Indonesia generally use gable roofs, hip roofs, and one-sided sloping (shed) roofs, while several types of roofs can be used in buildings, such as mansard roofs and curved roofs. This study uses a quantitative approach, which records and analyzes research data and performs data calculations with statistical calculations. This research compares wind loads based on SNI 1727-2013 Minimum Load for Planning of Buildings and Other Structures with different roof shapes in Bandung to determine the effect of each roof shape on wind loads on buildings and obtain roof shapes. With the smallest and largest wind load influence. Based on the research results, the displacement value in the roof structure due to wind loads is 0.025118 m (Hip and Gable), 0.018352 m (One-sided Sloping z1), 0.036073 m (One-sided Sloping z2), 0.027238 m (Mansard), 0.017629 m (Curved). Buildings with curved roofs produce minor wind load effects, and buildings with one-sided sloping roofs have the most significant wind load effects.

1. Introduction
The multi-story building is proof of the progress and development of a country [1]. Structural systems in buildings have also progressed to increase the strength and resilience of building structures to withstand loads, one of which is wind loads by looking at the geographical position of Indonesia with tropical climatic conditions, which have humidity above 75%. This condition causes instability of the air masses due to the west monsoon and east monsoons and triggers storms on the mainland [2]. These extreme weather conditions occur during the transition between the rainy season to the dry season or vice versa, making Indonesia frequent disasters due to winds prone to damage to building parts.

Tornadoes contributed 21% of all disasters in Indonesia, and based on data analysis, wind disasters in Java are the most affected area [3]. There have been many storms since 2011-2014, as well as in 2013. In March and October, the incidence of typhoons was relatively high.

Suppose an object is unable to withstand the flow of the wind, it can cause the object to be lifted or shifted, this condition causes damage, such as the roof will be lifted or floated, the body of the building will oblique [4], and a building with a strong wall and roof connection structure will make the building lift/slam. So the need for planning for loading wind loads on building roofs.

The condition or location of the building also affects the wind speed, which will impact the magnitude of the wind load on the building [5]. Wind speed in a place is influenced by the height of the place from the ground. So the higher the building from the ground level, the faster the wind speed received by the building. This condition occurs because of the influence of obstructions on the building, which causes the airflow velocity to be slow.

Buildings in Indonesia generally use gable roofs, hip roofs, and one-sided sloping (shed) roofs, while several types of roofs can be used on buildings, such as mansard roofs and arched roofs.
Regarding the shape of the sloping roof with several other angle variations, it is concluded that the same building height is also directly related to the wind. This means that roofs with large angles can be categorized as high-risk buildings in the event of wind damage.

Bingbing San [6], who conducted research on curved roofs, revealed that cylindrical roofs with a rise to span ratio (R/S) of 1/6.25 limiting were most effective in attenuating high suction on the roof surface. The previous research on the wind in buildings with variations in roof angles and ratios, such as curved roofs, has been carried out. Based on previous research and conditions in Indonesia, especially Java Island, this research was conducted to form a roof with the smallest wind load effect. A study was conducted on wind loads on buildings with different roof shapes according to SNI 1727:2013 Minimum Loads for Planning Buildings Other Structures [7].

2. Methods
2.1. The Effect of Wind on Buildings
A building that is limited by walls and a roof is built to protect its occupants. The pattern of airflow when the wind reaches the surface of the building will condense and cause positive (+) windward pressure. Then the air will be deflected to the side of the building, thus creating negative pressure (-) downwind [8].

Several parameters can affect the amount of wind pressure and suction in the building, which is wind speed. In figure 1 generally, the wind speed continues to increase along with the increase in the height of the building. Several factors affect the pattern of airflow and wind speed by the building itself, namely the height of the building, the shape of the roof, and other architectural forms [9].

2.2. Wind Load SNI 1727-2013
SNI 1727-2013 is the adoption of "SEI/ASCE 7-10, Minimum Design Loads for Buildings and Other Structures, which has been adapted to the loading conditions needed on buildings and structures in Indonesia such as dead loads, live loads, flood loads, rain loads, and wind loads as well as for ice and snow loads are not discussed because conditions or climate in Indonesia do not occur in winter[10] [11] [12]. Wind pressure on buildings is influenced by several factors such as wind speed, wind direction, topography, wind blowing effects, roof shape, and building closures.

2.2.1 Basic Wind Speed (V)
As in table 1, The amount of wind load acting on buildings depends on the wind speed. According to the risk category of buildings and other structures, the basic wind speed (V) used in the calculations to determine the design wind load shall be determined by the competent authority.
Table 1 Max Wind Speed of 10 years

| Year | Max Wind Speed (m/s) |
|------|----------------------|
| 2010 | 9                    |
| 2011 | 6                    |
| 2012 | 6                    |
| 2013 | 26                   |
| 2014 | 36                   |
| 2015 | 23                   |
| 2016 | 10                   |
| 2017 | 15                   |
| 2018 | 15                   |
| 2019 | 9                    |

2.2.2. Wind Direction Factor (Kd)
The wind direction factor is determined based on the type of structure. Table 2 shows that different building shapes produce different wind direction factor values.

Table 2 Wind Direction Factor

| Structure Type                                | wind direction factor, Kd |
|-----------------------------------------------|--------------------------|
| Building                                      |                          |
| main wind load-bearing system building components and cladding | 0.85                     |
| arch roof                                     | 0.85                     |
| chimney, tank, and similar structure          |                          |
| rectangular                                  | 0.9                      |
| hexagon                                       | 0.95                     |
| round                                         | 0.95                     |
| freestanding solid walls and solid freestanding billboards and bonded billboards | 0.85                     |
| open billboards and grid frames              | 0.85                     |
| tower truss                                   |                          |
| triangles, rectangles, and squares           | 0.85                     |
| other cross-section                          | 0.95                     |
2.2.3. Exposure Categories
Determining the value of the factors that affect the wind load is categorized into several categories of exposure based on environmental and building conditions.

2.2.4. Topographic Factor (Kzt)
The topographic factor is the effect of increasing wind speed due to the condition of the building's location. It must be included in the calculation to determine the design wind load, as in figure 2.

![Figure 2 Topographic Factors (Kzt) [13]](image)

If the condition and location of buildings and other structures do not meet all of the above requirements, the topographic factor is taken as Kzt = 1.

2.2.5. Wind Blow Factor (G)
The wind gust effect factor is determined based on the stiffness of the building. For a rigid building, the wind blowing factor value can be taken as 0.85. For flexible buildings, it must be calculated by the formula

\[ G_f = 0.925 \left( \frac{1 + 1.712 \gamma + \frac{g_Q^2 + g_V^2 R^2}{1 + 1.712 \gamma}}{1} \right) \]  

\[ (1) \]

\( G_f \) = wind factor for flexible buildings.

\( g_Q \) = peak factor for background response.

\( g_V \) = wind response peak factor.

\( G_R \) = peak factor for the resonant response.

The value of \( g_Q \) and \( g_V \) in equation one must be taken as 3.4, and for the value of \( G_R \), it is sought using the formula

\[ G_R = \sqrt{2\ln(3600n_1)} + \frac{0.577}{\sqrt{2\ln(3600n_1)}} \]  

\[ (2) \]

2.2.6. Internal Compression Coefficient (GCpi)
The value of this coefficient is determined according to the classification of building closures [7]. In Table 3 the plus and minus signs signify the pressure acting towards and away from the internal surface, respectively.
Table 3 Coefficient of Internal Pressure (Gcpi)

| closure classification       | (Gcpi) |
|------------------------------|--------|
| open building                | 0      |
| partially enclosed building  | +0.55  |
| +0.55                        | -0.55  |
| enclosed building            | +0.18  |
| -0.18                        |        |

2.2.7. Velocity Pressure Exposure Coefficient
The value of the velocity pressure exposure coefficient is determined based on the exposure category and the height of the building from the ground, as shown in table 4. B is urban and suburban areas, forested areas, or another area with a lot of melee barriers have the size of a single-family residence or more big. C is an open plain with scattered barriers that have height is generally less than 9.1 m, including open areas flat and meadow. D is flat areas, unobstructed areas, and water levels. This category filled with fine mud, salt fields, and unbroken ice.

Table 4 Velocity Pressure Exposure Coefficient

| high above ground level, Z | Exposure |
|----------------------------|----------|
| ft                      | m        | B   | C   | D   |
| 0 - 15                  | 0 - 4.6  | 0.57 | 0.85 | 1.03 |
| 20                      | 6.1      | 0.62 | 0.90 | 1.08 |
| 25                      | 7.6      | 0.66 | 0.94 | 1.12 |
| 30                      | 9.1      | 0.70 | 0.98 | 1.16 |
| 40                      | 12.2     | 0.76 | 1.04 | 1.22 |
| 50                      | 15.2     | 0.81 | 1.09 | 1.27 |
| 60                      | 18       | 0.85 | 1.13 | 1.31 |
| 70                      | 21.3     | 0.89 | 1.17 | 1.34 |
| 80                      | 24.4     | 0.93 | 1.21 | 1.38 |
| 90                      | 27.4     | 0.96 | 1.24 | 1.40 |
| 100                     | 30.5     | 0.99 | 1.43 | 1.43 |

2.2.8. Velocity Pressure ($q_z$)
Velocity pressure ($q_z$) is reduced as high as $Z$ with the following formula (3):

$$q_z = 0.613 K_d K_z K_{zt} \frac{V^2}{N/m^2}$$

- $K_d$ = wind direction factor
- $K_z$ = Velocity pressure exposure coefficient
- $K_{zt}$ = certain topographical factors
- $V$ = basic wind speed
- $q_z$ = Velocity pressure is calculated using equation three at height $z$
- $q_h$ = Velocity pressure is calculated using equation three at the average roof height.

2.2.9. External Pressure Coefficient ($C_p$)
The direction because will determine the direction of the wind coming and the current going where the coefficient of external pressure for the wall is influenced by the ratio of the dimensions of the building
(L/B). In Table 5 explains the magnitude of the velocity pressure based on the pressure on the wall. In Table 6 and 7 determined based on the classification of the type of roof used on the building.

**Table 5 Coefficient of Wall Pressure (Cp)**

| Surface                        | L/B   | Cp  | used with |
|--------------------------------|-------|-----|-----------|
| the wall on the side of the wind is coming | whole value | 0.8 | qz        |
|                                | 0 - 1 | -0.5|           |
| the wall on the side of the wind away | 2     | -0.3| qh        |
|                                | >= 4  | -0.2|           |
| edge wall                      |       | -0.7| qh        |

**Table 6 Roof External Pressure Coefficient**

| wind direction | on the side of the wind coming | on the side of the wind go |
|----------------|--------------------------------|---------------------------|
|                | angle. B (degree)              | angle. B (degree)         |
| h/L            | 10    | 15  | 20  | 25  | 30  | 35  | 45  | >60 | 10 | 15 | >20 |
| perpendicular | <0.25 | -0.7| -0.5| -0.3| 0.2 | 0.2 | 0.0 | 0.01B | -0.3| -0.5| -0.6 |
|                |       | 0.18| 0.0 | 0.2 | 0.3 | 0.3 | 0.4 | 0.4 |    |    |     |
| ridge for B > 10 degrees | 0.5  | -0.9| -0.7| -0.4| 0.3 | 0.2 | 0.2 | 0.0 | 0.01B | -0.5| -0.5| -0.6 |
|                |       | 0.18| 0.18| 0.0 | 0.2 | 0.2 | 0.3 | 0.4 |    |    |     |
|                | >1.0  | -1.3| -1.0| -0.7| 0.5 | 0.3 | 0.2 | 0.0 | 0.01B | -0.7| -0.6| -0.6 |
|                |       | 0.18| 0.18| 0.18| 0.0 | 0.2 | 0.2 | 0.4 |    |    |     |

**Table 7 Coefficient of Curved Roof External Pressure**

| Condition | height-to-span ratio | in the quarter of the wind coming | half center | in a quarter of the wind gone |
|-----------|----------------------|----------------------------------|-------------|------------------------------|
| roof on elevated structure | 0 < r < 0.2 | 0.9 | -0.7 - r | -0.5 |
|          | 0.2 < r < 3*        | 1.5r - 0.3                      | -0.7 - r    | -0.5 |
|          | 0.3 < r < 0.6       | 2.75r - 0.7                     | -0.7 - r    | -0.5 |
| roof that is at ground level | 0 < r < 0.6 | -0.7 - r | -0.5 |

2.2.10. Wind pressure

In the end to calculate the wind pressure in flexible buildings must be determined by the following equation:

\[ p = qGCP - q_i(GC_{pi})(lh/f_{t2})(N/m^2) \]  \( (4) \)

\[ p \] = design wind pressure (N/m²)

\[ q \] = wind wall velocity pressure coming \( (q_z) \) (N/m²)
3. Results and Discussion

3.1. Analysis Stage

The initial modeling of the analyzed building was a building with a gable roof and hip, unilateral sloping (Shed), mansard roof, and curved roof with the same building dimensions.

Figure 3 Floor Plan

Analysis of the wind load and determine the wind load parameters of SNI 1727-2013 to calculate the wind load. Modeling and analysis of buildings against wind loads using Structural Analysis Program to determine the effect of wind loads on each shape of the roof of the building. Comparing and concluding the results of the analysis based on the data and discussion of wind loads following the research objectives

3.2. Research Object

The object of research is a building with the same dimensions. The building is made with different roof variations, where in general, the use of roofs in Indonesia uses a gable, hip, and one-sided sloping roof as shown in Figure 4. The following are the specifications of the building that will be made:

1. One-sided sloping roof with a slope of 25°.
2. Gable and hip roof with a slope of 30°.
3. Mansard roof with a slope of 70°.
4. Curved roof.
5. With a building plan of 12x12 m², with a building height of 16 m.
6. Plan drawings.
Wind load analysis based on SNI 1727-2013 with the same building dimensions but different roof shapes. This is done to see the effect of the roof on the air pressure in the building. It has been stated previously, explaining that if an object is not able to withstand the flow of wind, it can cause an object to be lifted or shifted, and in Figure 5 it can be seen the influence that occurs in the building, where the building undergoes changes or changes deflection.
Table 8 Recapitulation of Displacements

| Height (m) | Displacement (mm) | Height (m) | Displacement (mm) | Height (m) | Displacement (mm) | Height (m) | Displacement (mm) | Height (m) | Displacement (mm) |
|------------|-------------------|------------|-------------------|------------|-------------------|------------|-------------------|------------|-------------------|
| 0          | 0                 | 0          | 0                 | 0          | 0                 | 0          | 0                 | 0          | 0                 |
| 4          | 7.329             | 4          | 6.216             | 4          | 9.213             | 4          | 7.503             | 4          | 5.974             |
| 8          | 15.645            | 8          | 12.902            | 8          | 20.233            | 8          | 16.074            | 8          | 12.351            |
| 12         | 21.593            | 12         | 17.114            | 12         | 29.011            | 12         | 22.279            | 12         | 16.295            |
| 16         | 24.985            | 16         | 18.159            | 16         | 35.482            | 16         | 25.9              | 16         | 17.727            |
| 19.46      | 25.118            | 21.6       | 18.352            | 21.6       | 36.073            | 18.86      | 27.238            | 17.93      | 17.629            |

To compare and find out the shape of the roof that causes the greatest and least effect on the building, Table 8 is made in graphical form as follows.

![Comparison Graph of Height Against Displacement](image)

Figure 6 Comparison Graph of Height Against Displacement

In the graph above, all lines show an increase in displacement as the height of the building increases, which means that the taller a building is, the greater the wind load on the building. The height of a building that uses a unilateral sloping roof with an angle of 25° is the tallest building compared to a roof with, and a building with a unilaterally sloping roof with the wind direction coming from the high wall side (z2) shows a larger displacement than the others. In contrast, in the building with a unilaterally sloping roof, the wind direction from the low wall side (z1) shows a smaller displacement to approach a building with a curved roof. This is in line with previous research where the greater the angle of the roof, the greater the area of the roof that is in contact with the incoming wind flow.

The graph also explains that the wind direction greatly affects the condition of the building and the wind load, and the taller the building, the wider the surface area of the building exposed to the wind, resulting in a greater wind load on the building. It shows the lowest building height and the smallest displacement value in buildings with a curved roof compared to other roof forms.
For buildings that use Hip and Gable roofs, they show stability, where the height and displacement in the building are not too high and not too low. In contrast, the displacement value is more significant than buildings with a mansard roof shape, although their height is lower than buildings with hip and gable roofs.

Then the roof shape that has the most significant influence on wind loads is a building with a unilateral sloping roof shape with a maximum displacement value of 0.036073 meters. The building with the least influence on wind loads and is more efficient at holding wind loads is a building with a curved roof shape with a maximum displacement value of 0.017629 meters.

4. Conclusion
The roof shape with the greatest wind load effect is a building with a unilateral sloping roof with a maximum displacement value of 0.036073 meters. The building with the smallest wind load effect is a curved roof shape with a maximum displacement value of 0.017629 meters. Buildings more efficient against wind loads are buildings with the smallest wind load effects, namely buildings with curved roofs.

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