NUMERICAL INVESTIGATION ON THE EFFECT OF WIND PRESSURE ON SKILLION ROOF USING COMPUTATIONAL FLUID DYNAMICS (CFD)

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By

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ABSTRAK

Pada masa ini, kejadian ribut angin sering berlaku disebabkan oleh keadaan cuaca yang tidak menentu yang disebabkan oleh perubahan iklim. Banyak kajian telah dijalankan untuk menentukan kesan tekanan angin terhadap profil bumbung rumah, ini termasuk rumah bertingkat rendah dan luar bandar. Kajian yang dijalankan adalah terutamanya pada jenis bumbung tertentu seperti gabel dan hip sedangkan terdapat banyak bentuk dan saiz bumbung lain yang terdapat di negara ini.seperti bumbung skillion. Selain itu, kod amalan bagi reka bentuk terhadap beban angin hanya mempertimbangkan reka bentuk bumbung gabel, hip dan shed sahaja. Kajian ini menyiasat taburan pekali tekanan bumbung skillion di sepanjang profil rumah bertingkat rendah dan tekanan bersih yang bertindak merentasi sambungan bumbung. Kaedah simulasi pengiraan dinamik bendalir (CFD) menggunakan model pergolakan RNG k-ε digunakan kerana kaedah tersebut mempunyai keupayaan untuk meramal medan aliran dengan tepat. Hasil kajian menunjukkan bahawa kehadiran sambungan bumbung pada model bumbung rata tidak mempengaruhi magnitud tekanan pekali. Walau bagaimanapun, magnitud sedutan terjejas dengan ketara oleh sudut cerun yang lebih rendah kerana sedutan tertinggi yang direkodkan adalah (-1.62) untuk rumah sambungan bumbung 5 pekali. Keputusan juga menunjukkan bahawa pada sudut cerun yang lebih tinggi, sambungan bumbung 15° mencatatkan penurunan ketara dalam nilai sedutan di mana sedutan maksimum terendah (-0.02) berlaku pada Zon B. Oleh yang demikian, pengenalan cerun darjah yang kecil boleh menjadi salah satu faktor yang menyumbang kepada kerosakan rumah bertingkat apabila terkena angin kencang.

ABSTRACT

Presently, windstorm event has been occurring frequently due to unpredictable weather conditions that is caused by climate change. Many studies have been conducted to determine the effect of wind pressure on the roof profile of houses, this includes low-rise and rural houses. The studies conducted were mainly on certain roof types such as gable and hip when there are many other roof shapes and sizes that are available in the country such as skillion roof. Moreover, code of practice for wind loading only considers design for gable, hip and shed roof shapes. This study investigates the pressure coefficient distribution of skillion roof along the profile of low-rise house and the net pressure acting across overhang roof. Computational Fluid Dynamics method using RNG k-ε turbulence model was used as the method has the ability to accurately predict the flow field. The results showed that the presence of overhang roof on the flat roof model did not affect the magnitude of the coefficient pressure. However, the magnitude of suction was significantly affected by the lower slope of angle as the highest maximum recorded suction coefficient is (-1.62) for the 5° overhang roof house. Results also showed that at higher slope angle, the 15° overhang roof house recorded a significant drop in suction values where the lowest maximum suction coefficient (-0.02) happens at Zone B. As such, the introduction of small degrees slopes can be one of the factors that contribute to the damage of the low-rise house when subjected to strong wind.

CHAPTER 1

INTRODUCTION

1.1 Background

In Malaysia, there are many reported cases of roof damages due to thunderstorm. Many people do not concern with the risks that comes when heavy windstorm had towards the house roof. From 2007 to 2012, Chik et al. (2014) assessed the damages caused by windstorms in Malaysia. From the research, they found that roof damages occurred around the northern part of Malaysia and the windstorm damages increase annually.

As a tropical country, Malaysia experiences two monsoon seasons, the Southwest Monsoon and the Northeast Monsoon. In between the two monsoon seasons, there are inter monsoon seasons that also contribute to roof damage cases in the country. Besides, in between there are inter-monsoon seasons and this monsoon brings not only heavy rainstorms in certain parts of the country but also strong winds originating from China and North Pacific. These strong winds or we called windstorms caused great catastrophic towards buildings in rural areas of Malaysia especially damage towards house roof.

Reported cases of roof damages are getting widely covered by news media agency during strong wind events. For instance, one of the cases covered by The Star on Sunday evening, January 30th, 2022, with the title “Tornado-like storm damages many Ipoh homes” occurred in Ipoh. It was reported that roof tiles were blown off during the incident with number of households affected are yet to be confirmed. The damage from the event can be shown in Figure 1.1.

Figure 1.1 Roof damage as reported by The Star, 30th Jan 2022

Localized high suctions and large pressure variations cause the majority of roof damage. These houses' roofs are prone to failure as almost all houses in Malaysia's rural areas have non-engineered roofing systems (Abdullah, 2019).

1.2 Problem Statement

Many houses in Malaysia especially in rural areas are mostly constructed with either gable or hip roof systems. The houses are also constructed as low-rise. Further, the design code used to design for wind loading, the Malaysian Standard (MS 1553:2002) only consider a flat, gable and shed roof system without overhang. The design shape of roof in (MS 1553:2002) can be shown in Figure 1.2. However nowadays, different types of roof system can be found being used such as skillion roof with overhang. The shape of skillion roof can be seen in Figure 1.3. Skillion roof shape is characterized by its two slopes slanting downwards in two directions.

With the difference in shape of the roof, during windstorm events, the outcome of roof damage or collapsed of roof might be less or none as compared to the one normally reported of. Open literature on the study of skillion roof shape is also limited as many studies were done on gable roof shape. Therefore, more studies need to be done to determine the effect of wind pressure towards house with skillion roof with varying roof slopes. The outcome of this study can then be used for future research and design of buildings.

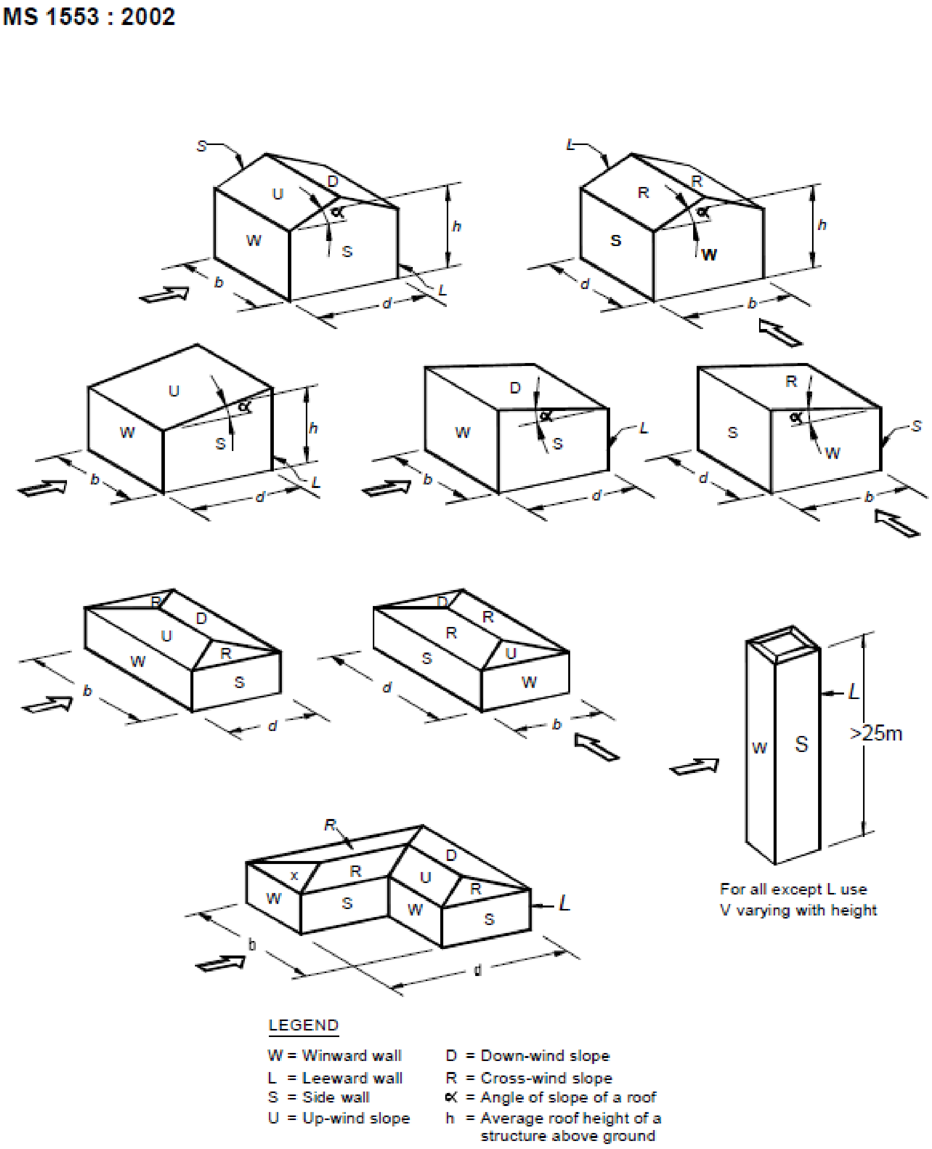


Figure 1.2 The shapes of roof as provided in MS 1553:2002

Figure 1.3 Skillion roof shape house

1.3 Objectives

The objectives of this research are listed below:

1. i. To analyse the pressure coefficient distribution of skillion roof along the profile of low-rise house.
2. ii. To determine the net pressure acting across overhang roof.

1.4 Scope of Work

This study is limited to the following scope of work:

i. Numerical simulation of skillion roof using ANSYS Fluent 14 software.
ii. The roof slope varies from 0°, 5°, 10°, and 15°.
iii. The overhang length of roof is 0.75 m.
iv. Low-rise building of not more than two storey height with 4 m in height
v. The terrain condition considered is flat terrain

1.5 Thesis Outline

This thesis consists of five chapters with four chapters to be further explained. Chapter 2 reviews previous research work that relates to this study and outlines the findings. Chapter 3 describes the procedure to be conducted for the analysis of this study in a summaries sequence on the entire research process. Chapter 4 explains the outcome of the analysis completed in this study. Results of the distribution of pressure coefficients and streamline patterns of wind flow are discusses in detailed manner. Chapter 5 presents the conclusion of the study and reviews the objectives in this study. Recommendations for future studies are also presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Previously, design consideration of roof structures is not emphasised as people are not alert to the catastrophe that may happen from windstorms occurrence. This is particularly true especially in the rural areas. The case is true where rural houses are constructed without considering proper engineering design but from the knowledge of the carpenter themselves acquired through working experiences. Hence, when windstorm events occur, the most common damage found are towards the house roof.

2.2 Wind Damage to Buildings

Wind is a randomly varying dynamic phenomenon composed of a multitude of eddies of varying sizes and rotational characteristics along a general stream of air moving relative to the ground. (Nizamani et al., 2017). Wind flowing in turbulence state and varying in speed can initiate damages to roof house as can be seen from the news reported. However, if it is strong enough to cause damage to buildings it is called windstorm.

Windstorm events have been happening in Malaysia and cause damages to roof buildings especially during inter monsoon season. One event of roof damage cause by thunderstorm in Kuantan, Pahang on the 26th of March 2021 has been reported by news media and shown in Figure 2.1.

Figure 2.1 Roof damage as reported by Bernama, 26th March 2021

2.3 Low Rise Building

According to Malaysian Standard (MS1553:2002), the standard covers structures within buildings less than 200m. However, in the design codes, the term low-rise building is not defined as the subject term varied according to local municipalities and countries worldwide. Low-rise building house can be shown in Figure 2.2.

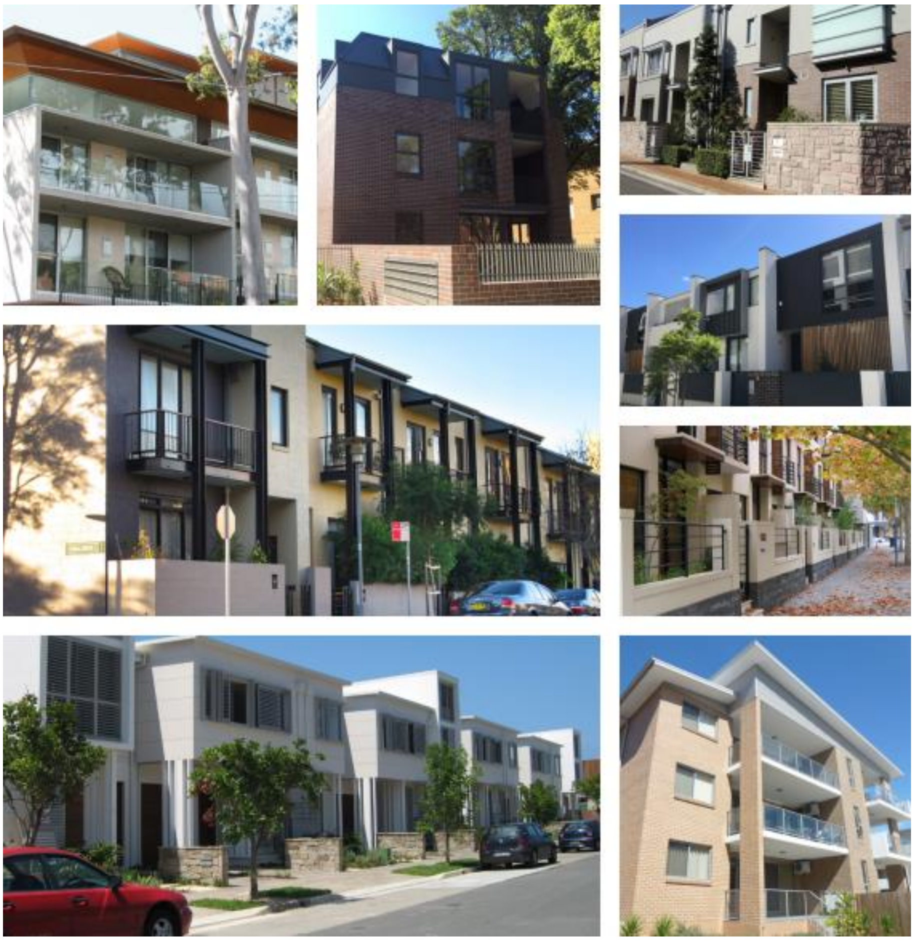


Figure 2.2 Example of Low-rise buildings/houses

2.4 Roof Types

In Malaysia typical roof houses constructed are hip, gable, flat and now with modern ideas and design coming in, roof type such as shed and skillion has also been adapted. Mostly, the roof types in Malaysia are design with overhang as not to allow rainwater from hitting the side wall of the house that can cause decolourisation of the wall paint and leakage as can be seen in Figure 2.3. Skillion roof is characterized by its double slope as can be seen in Figure 2.4.

Figure 2.3 Roof overhang of a house

Figure 2.4 House with skillion roof

2.5 Wind Loading Analysis Test

Analysis of wind loading on buildings can be done using many methods. There have been studies conducted with laboratory experiments, wind tunnel test (WTT) and numerical simulation.

2.5.1 Laboratory Experimental Work

There are only a few experimental studies that have been performed to model the wind uplift effect on roof cladding (Abdullah, 2019). Zaini et al. (2019) investigated on the pull-out force of modified purlin to rafter connections. Type of timber used is Damar Minyak (Araucariaceae) that is common for construction in Malaysia. The experiment was conducted by modifying the purlin to rafter connections. The result was then compared between connections of single nail, double nail, nail and metal strap and nail and rope. It is found that the highest pull-out resistance based on the maximum pull-out force was shown by the nail and metal strap connection and particularly true for timber type Damar Minyak.

Majid et al. (2020) investigated the pull through failure of roof cladding to purlin connection considering overhang roof. Two types of roof cladding were used that are corrugated and trapezoidal types with fastener as the connection. The length of the roof overhang produced significant effect on the roof cladding to purlin connection. Shorter overhang improved the pull through capacity by increasing the stiffness and reducing the tributary area of the wind pressure.

2.5.2 Wind Tunnel Test (WTT)

Wind Tunnel Test (WTT) has been conducted to study the interaction between wind flow and building for many years. The use of WTT has proven to be able accurately simulate wind flow structures around buildings. There are some limitations in WTT such as difficulty in placing pressure taps on overhang part, corner region and on the sharp edge of building models as stated by Walker, (2011). The limitations result in lesser range of problems that can be studied using WTT (Blocken, 2014). Depending on the model to be tested, wind tunnel is also costly and time-consuming (Irtaza et al., 2015). Therefore, Computational Fluid Dynamics (CFD) has been used instead of WTT as the means to analyse the air flow characteristics surrounding buildings. CFD has shown an increasing usage for the past years for many research. Richards et al. (2007) validated the CFD results with WTT data and showed that the CFD was able to predict the pressure coefficient Cp distribution with good accuracy.

2.5.3 Computational Fluid Dynamics (CFD)

Over the last three decades, CFD has been developed rapidly to evaluate the interaction between wind and structures numerically (Yahya, 2016). There are advantages of CFD but there are also limitations. The advantages of using CFD are it is low cost to operate and provide informative results. Jameel et al., (2015) stated that CFD is less time-consuming and easy to handle for evaluating wind effects. However, the limitations of CFD are as reported by Deraman et al. (2018), validating experimental data against CFD models can be extremely complex and time consuming.

While Yahya et al. (2017) discovered that the mesh arrangement of the model in CFD analysis should be fine enough to allow for efficient computation, as smooth meshing and high-quality meshing produce more accurate simulation results.

CFD is a useful tool for simulation of turbulent flow and pollutant dispersion around building. There are many options of CFD such as steady RANS, URANS, LES and hybrid URANS/LES. Considerations on the details of geometry, the computational domain, boundary conditions, the initialization data and iterative convergence should be taken to use the suitable method for analysis as stated by Blocken et al. (2012).

According to Irtaza et al. (2013), the addition term of ε in RNG k-ε has significantly improved the accuracy of the data as it takes low Reynolds number into account that is not available with Standard k-ε. This has made the RNG not only more accurate and reliable but also obtaining better result for a bigger class of flows.

2.6 Summary of Previous Studies

This section summarises the research papers of previous studies as can be seen in Table 2.1. CFD simulations and WTT have been used by researchers in the investigation of wind pressure. Table 2.1, shows that many studies have been conducted focusing on buildings with gable roofs and limited work has been done on skillion roof shape. Skillion roof shapes can be found in many parts of Malaysia thus the need to expand the research work on the effect of wind pressure towards the roof.

Table 2.1 Summary of previous research

	AUTHOR	**METHOD**	**PARAMETERS**
1.	Ozmen et al. (2015)	CFD	Gable roof with different pitch angles
2.	Majid et al. (2016)	CFD	Overhang roofs with different dimensions
3.	Abdullah et al. (2018)	CFD	Flat, depression, ridge, valley topographic
4.	Yahya et al. (2018)	CFD	Isolated single-storey house with extension: Grid sensitivity analysis
5.	Deraman et al. (2018)	CFD	Gable roof of low-rise building
6.	Ruizhou et al. (2019)	CFD & WTT	Gable roof with low roof slope
7.	Singh & Roy, (2019)	CFD	Pyramidal roof of low-rise building

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this study, a few procedures were taken in performing the computer simulation using ANSYS Fluent 14 software. The flowchart of the research study is shown in Figure 3.1. The in-depth study of each section is presented in section 3.2.

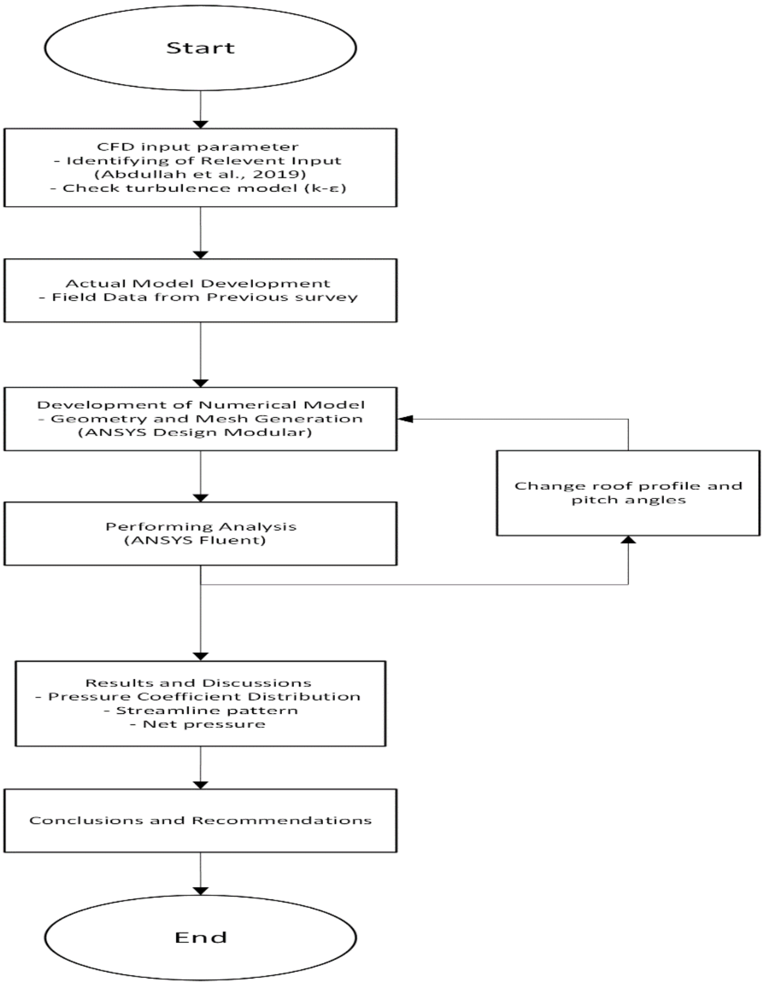


Figure 3.1 Flowchart of conducting the CFD simulation

3.2 Identifying Relevant Input

Before starting the analysis, relevant inputs needed to be established before they are inserted into the ANSYS Fluent 14 software. The input parameters obtained are from Abdullah et al., (2019) who has done the validation exercise by comparing to Tominaga et al., (2015). The inputs can be seen in Table 3.1.

Table 3.1 Input parameter in ANSYS Fluent 14

Item	Data
Computational Domain	128 m × 60 m
Mean wind speed, v	26.4 m/s
Turbulence model	RNG k-ε
Near wall treatment	Standard wall function
Roughness height, Ks	0.035 m
Roughness constant, Cs	0.5
Pressure velocity coupling	Scheme (SIMPLE)
Spatial discretization	Gradient (Least square based) Pressure (Second order) Momentum (Second order)

3.3 Actual Model Development

For the geometry of the house model, it is designed by referring to Zaini et al. (2017) data on previous survey of house in rural areas. The fixed parameters of the length and height of the house is based on field data from previous survey by Zaini et al., (2017). The study stated that using a simple normalisation approach, the best ratio was found to be 3:2:1 representing the length, width, and height of the house, respectively. This ratio can be used as a reference for modelling purposes. The house model consists of only core house without having any extension such as the kitchen house. The height and width considered therefore is 4 m and 8 m, respectively. The schematic drawing of the house model can be seen in Figure 3.2.

The first model started with a flat roof without overhang, a flat roof with overhang and roofs with overhang of varying angles from 5°, 10°, & 15°. The angles for study chosen are as according to design code Malaysian Standard (MS 1553:2002). Overall, this study generated seven models for simulation. For easy referencing, the models were labelled accordingly. The schematic drawing of the house model without overhang is shown in Figure 3.2 and the details dimension of the overall models is shown in Table 3.2.

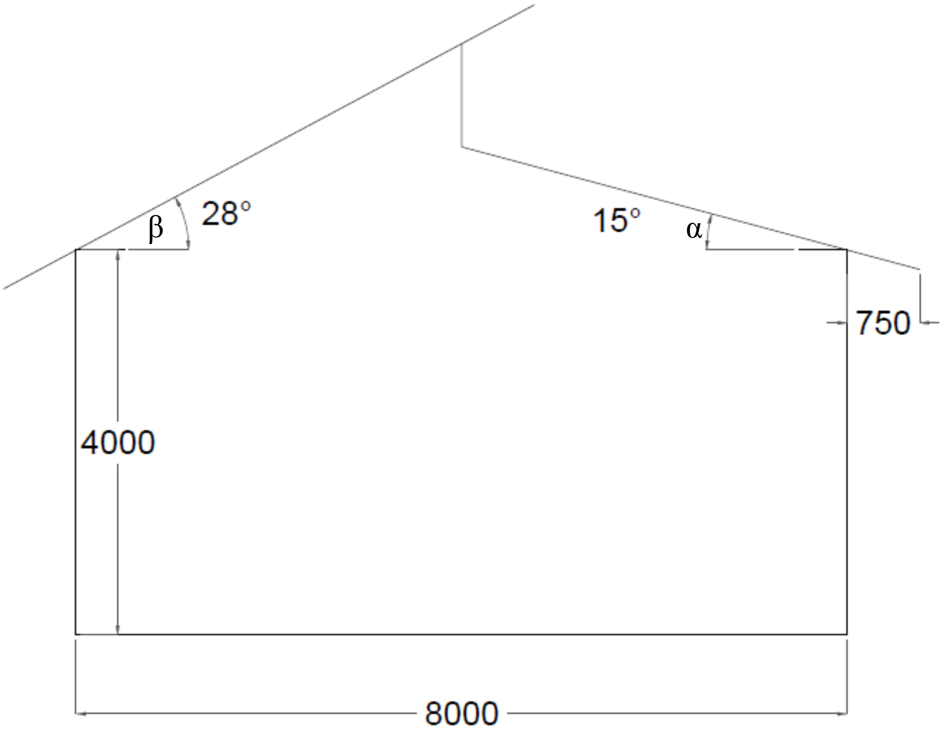


Figure 3.2 Schematic drawing of SR(OH) – 15 house model

Table 3.2 Dimension of the overall models

House Models	**Width (m)**	**Height (m)**	**Slope angles (α)**	**Slope angles (β)**	**Overhang Length (m)**
FR-0	8	4	0	0	0.75
FR(OH) – 0	8	4	0	0	0.75
SR(OH) – 5	8	4	5	10	0.75
SR(OH) – 10	8	4	10	19	0.75
SR(OH) – 15	8	4	15	28	0.75

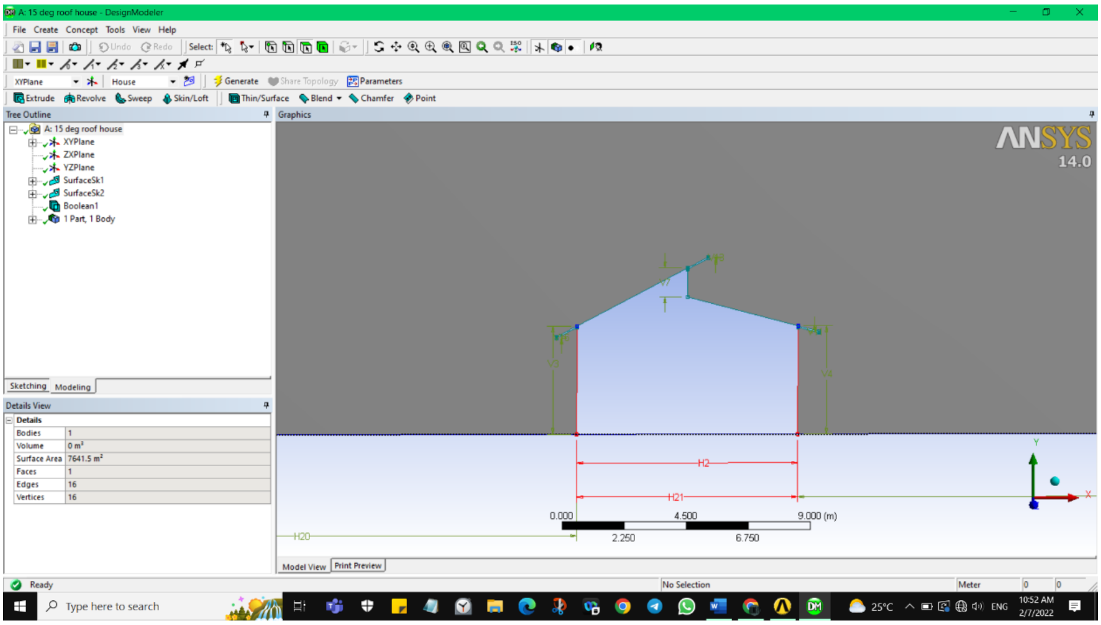
Note*: SR denotes as Skillion Roof, FR denotes as Flat Roof

3.4 Development of Numerical Model

All the process for development was done in ANSYS Fluent 14 software which are explained in detail in the following sections.

3.4.1 Model Geometry

The model of the house is generated in the design modeler of ANSYS Fluent 14 software. The model dimension that has been determined are the width and height of 8 m and 4 m, respectively. The house model as designed in the design modeler can be seen in Figure 3.3.



Details	
Bodies	1
Volume	0 m³
Surface Area	7641.5 m²
Faces	1
Edges	16
Vertices	16

Figure 3.3 House model design using Ansys Modeler

3.4.2 Computational Domain

The boundary surrounding the house model is set at 15H from either side of the model and 15H from the ground to the symmetry (top) where H is the height of the house model. The 15H from either side are the inlet and outlet boundaries. Computational domain and boundary condition is portrayed as in the Figure 3.4. According to Abdullah et al. (2018), the overall dimension must be large to avoid obstruction of the flow development.

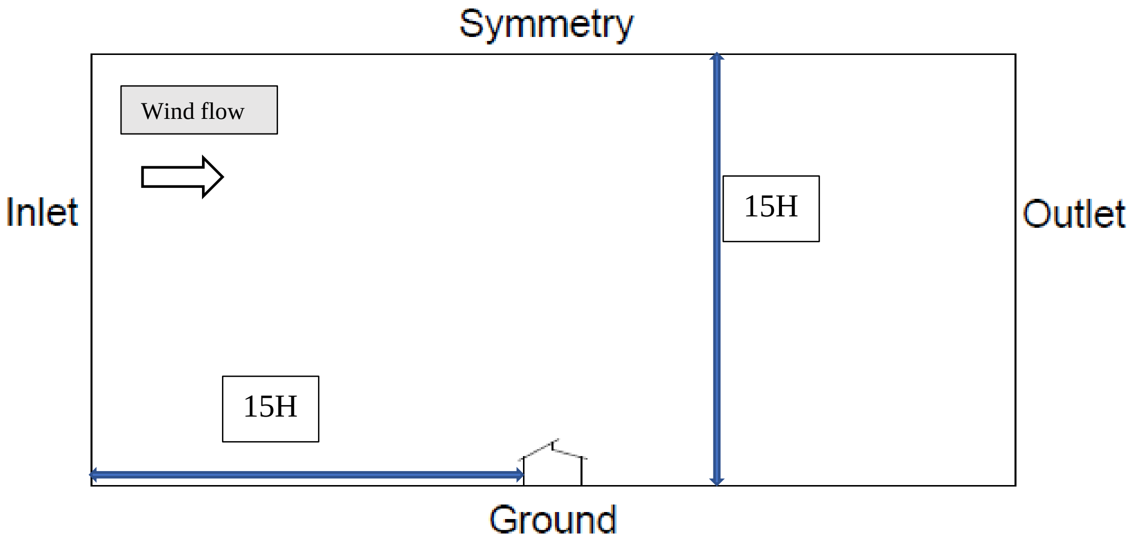


Figure 3.4 Computational Domain and Boundary Conditions

3.4.3 Meshing

Meshing is done once the geometry of the house model has been completed. The importance of meshing is to get the right computational time versus the accuracy of the result. The finer and smoother the meshing, the reliability of the result is stronger but with more computational time taken to complete the analysis of the models. The meshing result of the model can be shown in the Figure 3.5.

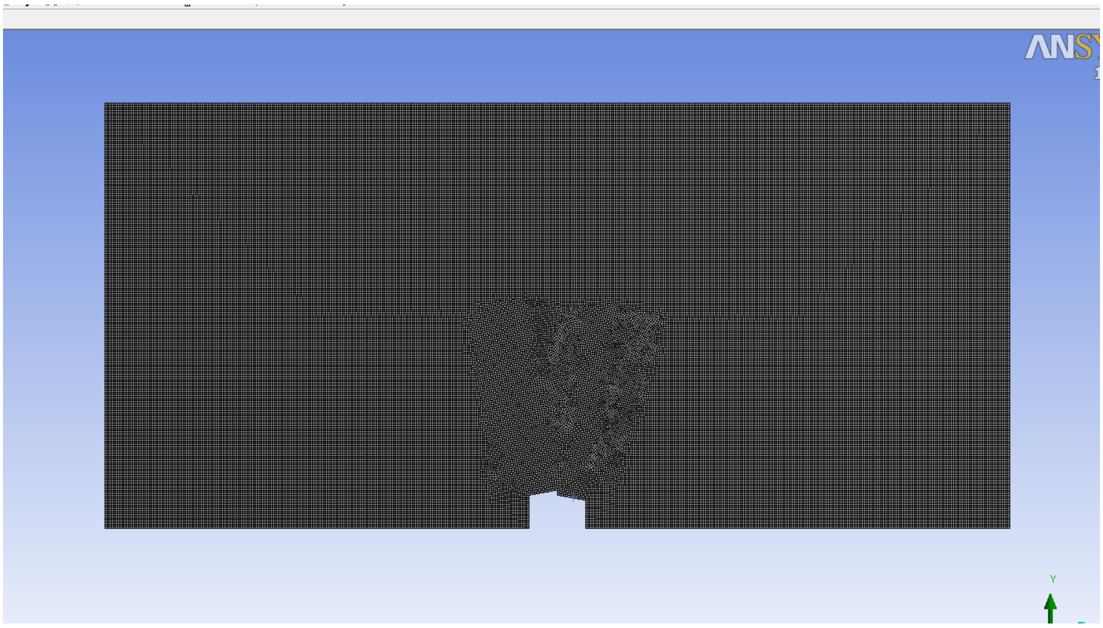


Figure 3.5 Meshing of the house model

3.5 Analysis

The analysis of the effect of wind pressure on the roof models are done in the setup function of ANSYS Fluent 14. The wind velocity was set at 26.4 m/s that represents the approximate speed of a storm at 10 m above the ground surface. This scale can be referred as the Beaufort Scale. The governing equation for a flow through a rectangular domain is given in Equation 3.1.

$$U(z) = U_h \left({}^{z}\!/\!{}_{Z_h}\right)^{\alpha} \tag{3.1}$$

where,

$U(z)$ = Wind speed
U_h = Wind speed at height, z_{ref}
Z = Height
Z_h = Reference height
α = Wind shear exponent

For the pressure, momentum and turbulence equations, second-order differencing was used with a "SIMPLE" pressure-velocity coupling approach (Yahya, 2016). 5000 iterations were used in this study as the requirement to get a stabilise residual.

3.6 Data Analysis

Final results in the form of pressure coefficient distribution profile, streamline pattern and net pressure were to be presented. The pressure coefficient distribution is discussed based on each zone of the house as can be seen in Figure 3.6. Discussion on the magnitude and pattern of the pressure coefficient is discussed in detail in Chapter 4. Furthermore, the streamlines or wind flow pattern for the models were discussed to elaborate on the formation of air flow and to compare the compatibility of the result to the pressure distribution.

The net pressure along the roof overhangs was analysed further and compared with the maximum suction from the pressure distribution of the roof profiles. The formula for obtaining the net pressure is shown in Figure 3.7.

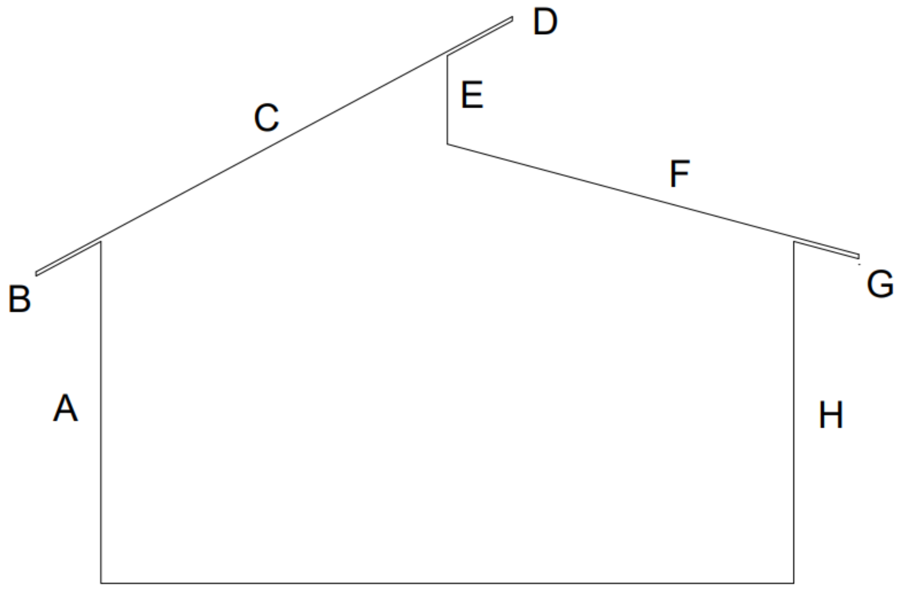


Figure 3.6 Cross section of the house model with the respective zones

<u>Legend</u>

Zone A: Windward wall of the house
Zone B: Windward overhang roof
Zone C: Upward roof of the house
Zone D: Upward overhang roof (middle)
Zone E: Gap height
Zone F: Downward roof of the house
Zone G: Downward overhang roof
Zone H: Leeward wall of the house