Full Length Research Paper

Modeling roof blown-off

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Experimental survey of roof blown-off was undertaken to determine the main causes of roof blown-off. Data obtained from the survey and experimentation was evaluated and interpreted using statistical correlation and graphical presentation. These data were then incorporated to the model formulation, then a FOTRAN program was developed to make predictions of roof blown-off possible. From the model, it was found out that topographical location, orientation of building to wind direction, roof geometry, pitch angle all have their contributive effects on roof blown-off. The developed model was validated using data obtained from another location. Out of the 55 sets of building predicted by the model, 51 of the predictions were correct. The model is good for the purpose of planning roof design

Key words: Modeling, building orientation, roof geometry, pitch angle, topographical location.

INTRODUCTION

The history of roof structures dates back to the earliest human history. The need for protection from weather elements made the early human beings to live in caves to protect them from the effects of inclement weather. They lived in valleys where shelter from winds was considerable and under trees for protection against the scorching sun (Gniadzik, 1984).

Since the beginning of human existence, many roof styles have been developed and are still being developed to cope with the demands of materials, environmental and technological advancement. The first form of roof was leafy branches bent over the tree to reduce direct effects of rain and keep sun off, this progressed on to cutting down the branches and making a tent out of them; and by trial and error making them stand up and keeping the weather elements out by covering with more waterproof layers. Gniadzik (1984) reported that because of the few needs and simple fulfillment, "primitive man, who, looking for shelter built a hut (using wood as structural member) with a thatched roof". The present forms of roofs are adaptations of the old roofing systems.

A roof has at various times and by various authors been given different definitions. While the World Book Encyclopedia (1995) defines it as the cover of any building including the materials that support it, Paton (2000) describes it as the exterior surface and the supporting structure on the top of a building or generally as the top covering of any object, and yet Ezeji (2004) defined it as a framework on top of a building comprising of steel, timber or concrete on which a covering material is placed.

Arising from these definitions, it can be deduced that a roof is the top covering and sustaining structure for a building. It comprises of structural and non-structural members, fasteners and covering materials. The structural members are the trusses, purlins and wall plates, while the non-structural members are the noggins and slats. The covering materials are the upper coverings and the ceilings. The roof is an integral part of a building that has its outer part directly exposed to the sun and other weather elements while its inner part encloses the attic space (Ezeji, 2004).

The World Health Organization (WHO) recognizes that the roof is one of the important requirements for a house

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to be considered suitable for healthy habitation (WHO, 2005). This is because while a house may be inhabited without some elements of buildings such as partition walls, beams or columns, a house without a roof is not conducive for human and even animal accommodation.

Whenever a roof fails, both the occupants, the properties kept in the affected buildings and external walls of the buildings are frequently threatened by failures in the roofing systems. The cost of repairs or a complete replacement of a failed roof could be enormous. These include cost of repair in terms of material and labour; the cost of alternative accommodation pending the repair of the roof; the cost of treatment for injuries sustained by persons that the roof has fallen on; the cost of treating ailments such as pneumonia to persons directly affected by roof failures; the cost of replacing property loss in the affected building and the trauma and psychological disorientation for those living within any building whose roof has failed.

Roof blown-off is a common occurrence in several parts of Nigeria, and all categories of buildings in the different regions are affected. When it occurs, it does not only result in financial losses but, at times, in injuries and loss of human lives. The roof is an important component of any building and its total failure invariably renders the structure over which it is built uninhabitable. In many building failures, the roof is nearly always affected and may be the only component because of its exposure to the wind and other weather elements. Roof blown-off has social, economic and psychological consequences on the affected people. Owning a house provides social security, as the owner is not subjected to insults or intimidation by a landlord. This security could be lost when the roof of a building fails.

The cost of repairs of damaged roof could be enormous, because of the daily increase in the prices of roofing materials. The situation is even worse in rural areas where early replacement of damaged roofs become almost impossible due to low level of financial resources available to building owners. Numerous Government-owned schools in rural areas have had their roofs blown off and left un-repaired for upwards of three years, reported cases included a block of six classrooms that was blown-off since 2005 and is yet to be repaired in Saint John Primary School, Edunabon, Osun State (Oyebode, 2006).

Delayed actions to replace collapsed roofs during the rainy season may lead to much greater damage to the wall structures which are mainly earth materials thereby exposing the contents of the house to damage. Whenever there is total failure of roofing system, it is often associated with dangers to other buildings and passersby. It also affects facilities such as electric lines. When roof fails especially when it is blown-off and the owner is not able to replace it on time, these will be followed by anxiety, pain and adverse emotional reaction. A great deal of these loss and inconvenience could be

avoided if the conditions that lead to failure of the roofs were understood and precautions taken to guide against them were taken.

In the past, many attempts have been made to solve the problem of roof failures. These included the use of metal straps; construction of block wall on the roof and planting of wind breakers. These methods are not full proof as there are still records of damages even with these in place. The construction of wall on the roof makes roof to be susceptible to leakage because the roof/wall interface may not be adequately taken care of. Wind breakers, if too close to the house can be broken during wind storm and cause damage to the roof. An understanding of the effects of environmental factors and performance potential of materials of construction would be useful in the design and construction of appropriate roof structures.

These problems arising from roof blown-off are crucial in the development of any community and efforts must be made to minimize or where possible eliminate them. An understanding of the causes and patterns of failures of roofs is necessary to be able to achieve this and therefore, there is need for this research.

Study area

The Southwestern Nigerian states, the location o this research is a zone with bi-modal wind run pattern occurring in April and August (Adenekan, 2000). This zone, lying roughly between latitudes 7.41° and 9.08° to the north of the equator and within longitudes 3.29° and 4.27° to the East of the Greenwich meridian has been found to have strong wind gusting up to 75 Km/h associated with line squalls convective rainfall (Adenekan, 2000). Afolayan (2002) reported that the temperature of the zone is generally high throughout the year with temperatures ranging between 21 and 37°C and with high rain intensity. There are many topographical and altitudinal variations in the zone that promote different climates within short distances from one another. These features favour roof failures and it is necessary to take precautions to guide against them (Adenekan, 2000)

DEVELOPMENT OF ROOF BLOWN-OFF MODEL

Data obtained from the survey and experimentations were evaluated and interpreted using statistical correlation and graphical presentation. These data were then incorporated to the model formulation and a FOTRAN program was developed to make predictions of roof blown-off possible.

The model was developed in modules:

(a) Design speed module (Figure 2)
(b) Angle of attack module (Figure 5)
(c) Topographical location module (Figure 3)
(d) Roof Geometry module. (Figure 4)
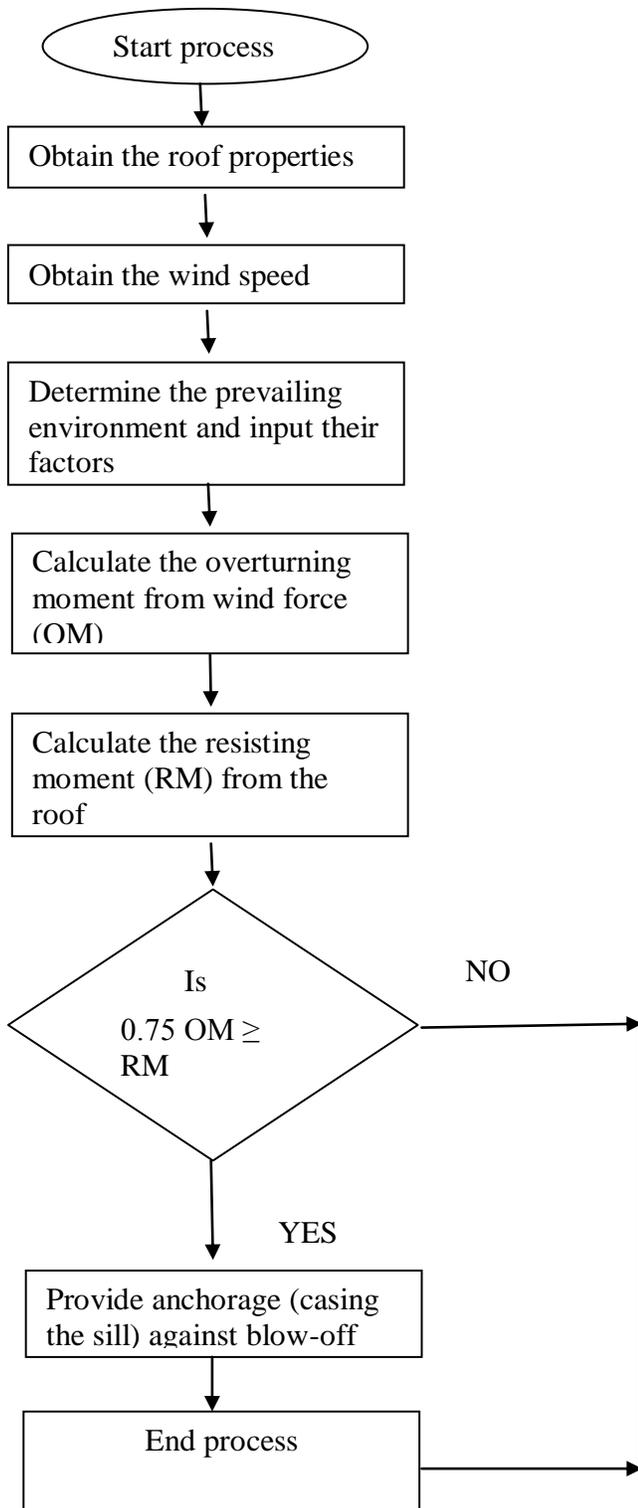
75% of the moment of stability disregarding live loads.
(ii) Roof structure is extremely stiff hence method of analysis is quasi-static.
(iii) Roof is under steady (time-invariant) wind load.
(iv) $F = f(L, H, \alpha, g, \rho, v, \mu, \partial\rho/\partial p, n)$ (1)

Where:
F is the force on the roof (N/ mm^2)
L is the length of the building (identical cross sectional shape) (m)
g is the acceleration due to gravity (m/s^2)
ρ is the density of air (kg/m^3)
v is the mean wind speed (m/s)
µ is the coefficient of viscosity of the wind (m^2/s)
α is the orientation of the building to the wind (degrees)

The process of solving the mathematical problem of blow-off (algorithm) is described in Figure 1.

Design speed

Design wind speed for the zone was modeled using Cook-Mayne (CM) method (Cook and Mayne, 1979) which adopted the Monte Carlo techniques reported by Ulam and Metropolis (1949). These resulted in few working graphs and tables from where the maximum design speed, for life time of different structures and at different margins of risk could be obtained.
The best straight line for western Nigeria is

$$^{V}\text{max} = 90.88 + 11.5Y \tag{2}$$

Building topographical location

On mountain ridges and summits, wind speeds are higher than in the free air at corresponding elevations because of the convergence of the air forced by the orographic barriers (Paulhus et al., 1958). In trying to predict the effect of hill slope on wind speed, the Peronian equation was adopted and considering venturi effects of the hill on fluid flow, the relationship between wind speeds at the summit compared to the plain was obtained.
The volume of fluid flow is related to the pressure in the fluid according to general fluid flow while Peronain also related the flow in gas with height above ground. These two principles were adapted to model wind flow over hills. The wind was idealized as fluid flowing in an imaginary pipe of infinite diameter. Using appropriate mathematical tools the speed along the hill top and the crest was found to be

$$V_s^2 = 0.9984 \frac{h(h+2y)}{(h+y)^2}\left(\frac{(Sin\phi + Cos\phi)^{\frac{9}{7}}}{(Cos\phi + Sin\phi)} - \frac{(Sin\phi)^{\frac{9}{7}}}{Cos\phi}\right) \tag{3}$$

When φ =0 at the plane V$_s$ = V,
V$_s$ is the speed along the slope, in m/s.
Y is the height above the ground, in m.
V is the speed at the bottom of the hill, m/s.
Φ is the slope angle, in degree.

Roof geometry

It is desired to investigate the effect of geometry on total roof failure while other parameters were kept constant and hip roofs and gable roofs were investigated for stability against wind overturning. This roof geometry factor is considered to know how the size and shape of the roof affect roof failure.

Figure 1. Algorithm for the Roof Blow-off Model

Algorithm for determining the blow-off model

Assumptions

(i) The overturning moment due to wind pressure shall not exceed

Design Speed in Western Nigeria
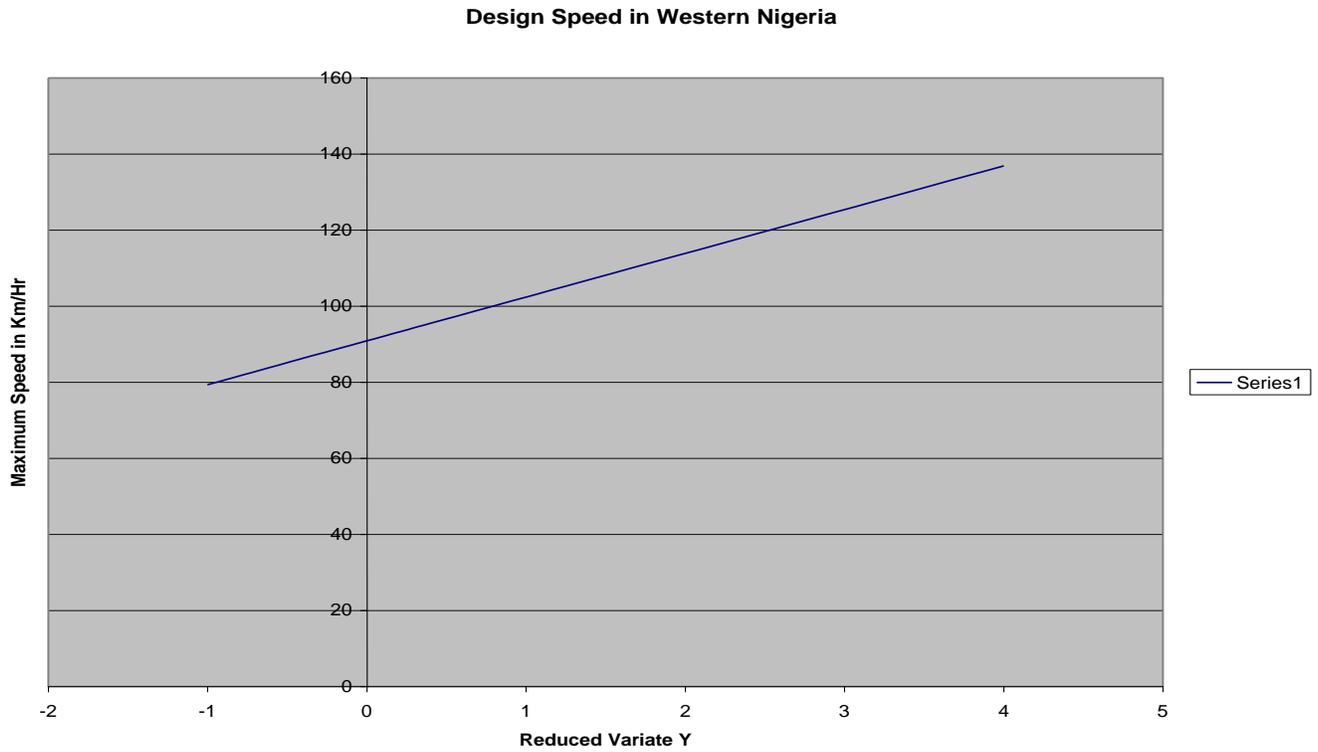
Figure 2. Design speed for Western Nigeria.
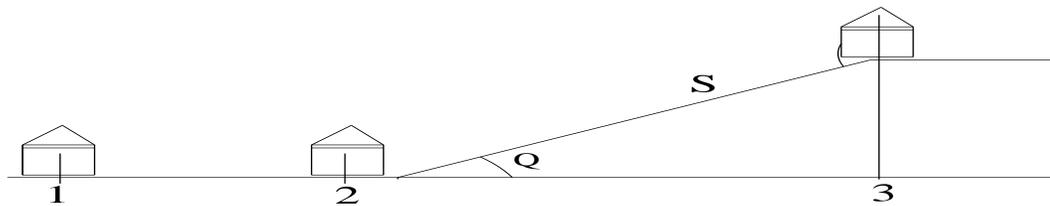
Figure 3. Building topographical location.
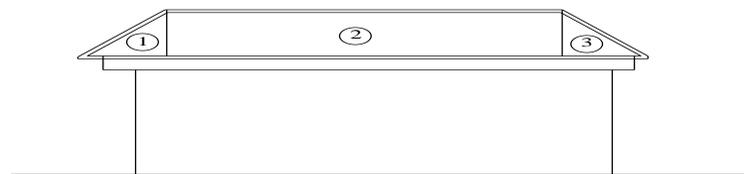
Figure 4. Side elevation view of hip roof.
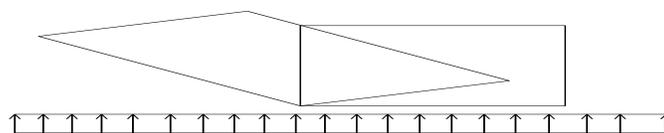
Figure 5. Projected area of wind attack.

Table 1. Calculation of the roof centre of pressure.

Section	Area (A)	X^1	AX^1
1	$\dfrac{(\alpha_1 L)^2 \tan \delta}{2}$	$\dfrac{2\alpha_1 L}{3}$	$\dfrac{(\alpha_1 L)^3 \tan \delta}{6}$
2	$\dfrac{RL^2 \tan \theta (1 - \alpha_1 - \alpha_2)}{2}$	$(1 + \alpha_1 - \alpha_2)L$	$\dfrac{Rl^3}{4} \tan \theta \left(1 - 2\alpha_2 + \alpha_2{}^2 \alpha_1\right)$
3	$\dfrac{\alpha_2 l^2}{2} \tan D$	$\dfrac{(3 - 2\alpha_2)L}{3}$	$\dfrac{\alpha_2{}^2 L^3}{6} \tan D (3 - 2\alpha_2)$

It is believed that the stability of a roof is dependent on the location of the centre of pressure of the roof hence the section below set out to calculate the position of the centre of pressure of the two common shapes in the zone. Table 1 shows how to calculate the center of pressure of roofs of various shapes.

$$\sum A = \alpha_1 l^2 \tan \delta + \alpha_2{}^2 \left(\tan D + \frac{Rl^2}{2} \tan \theta \left(\frac{1 - \alpha_1 - \alpha_2}{2} \right) \right) \quad (4)$$

$$= \left[\alpha_1{}^2 \tan \delta + \alpha_2{}^2 \tan D + R \tan \theta (1 - \alpha_1 - \alpha_2) \right] \frac{l^2}{2} \quad (5)$$

$$= \frac{[l - \alpha_1 - \alpha_2 + 2\alpha_1 l + 2\alpha_2 l] Rl \tan \theta}{2} \quad (6)$$

Since $\dfrac{\alpha_1 \tan \delta}{3} = \dfrac{\alpha_2{}^2 \tan D}{3} = \dfrac{Rl \tan \theta}{6}$ (7)

$$\sum AY^1 = \frac{(\alpha_2 l)(Rl \tan \theta)^2}{6} + \frac{(\alpha_1 l)(Rl \tan \theta)^2}{6} + \frac{(Rl \tan \theta)^2 x (l - \alpha_2 - \alpha_1)}{4} \quad (8)$$

$$= \frac{(3l - 3\alpha_1 - 3\alpha_2 + 2\alpha_1 l + 2\alpha_2 l)(Rl \tan \theta)^2}{12} \quad (9)$$

$$\frac{\sum AY^1}{\sum A} = \frac{l\left[((3 + 2\alpha_1 + 2\alpha_2) - 3\alpha_1 - 3\alpha_2)(Rl \tan \theta)^2 \right] x \, 2}{12 \left(Rl \tan \theta (l - \alpha_1 - \alpha_2 + 2\alpha_1 l + 2\alpha_2 l) \right)} \quad (10)$$

$$Y^1 = \frac{l\left(((3 + 2\alpha_1 + 2\alpha_2) - 3\alpha_1 - 3\alpha_2)(Rl \tan \theta)^2 \right)}{6 Rl \tan \theta (l - \alpha_1 - \alpha_2 + 2\alpha_1 l + 2\alpha_2 l)} \text{ for hip roof} \quad (11)$$

If $\alpha_1 = \alpha_2 = 0$, that is, a gable roof, then

$$Y^1 = \frac{lR \tan \theta}{2} \quad (12)$$

From the above equation, the centre of pressure in hip roof is lower than in gable roof indicating less overturning moment in hip roof than in gable roof.

α_1 = ratio of the length of the point of bevel of the roof in side one.
α_2 = ratio of the length of the point of bevel of the roof in side two.
D = angle of slope at bevel point α_1 (degree).
θ = roof main slope (degree).
δ = angle of slope at bevel point α_2 (degree).
R = B/L.
B = Breadth of the building.
L = Length of the building.

Covering material

The weight and subsequently the resistance of roof to overturning from wind force depend largely on the quantity of the covering materials. Therefore it is necessary to know the area of the covering materials.

The area of the covering materials for hip roof is derived as follows:

$$= (\alpha_1 l \cos \delta)B + (\alpha_2 l \cos D)B + 2(l - \alpha_1 - \alpha_2)\frac{B}{2} \cos \frac{\theta}{2} \quad (13)$$

$$= BL(\alpha_1 \cos \delta + \alpha_2 \cos D + \cos \theta) - \alpha_1 B \cos \theta - \alpha_2 B \cos \theta \quad 14)$$

$$= B(L(\alpha_1 \cos \delta + \alpha_2 \cos D) + \cos \theta (l - \alpha_1 - \alpha_2)) \quad (15)$$

$\alpha_1 = $ ratio of the length of the point of bevel of the roof in side one

$\alpha_2 = $ ratio of the length of the point of bevel of the roof in side two.
D = angle of slope at bevel point α_2 (degree).
δ = angle of slope at bevel point α_1 (degree).
θ = slope of the roof (degree).

If $\alpha_1 = \alpha_2 = 0$ indicating gable, the sheathing area is given by

$$A = BL \cos \theta \quad (16)$$

Hence covering materials in hip roof is greater than that of gable roof with invariably greater resistance.

Roof orientation

Allowance was made for wind forces on the roof assuming the wind from any possible direction to be critical. Thus, in the model the wind was to be considered normal to the plane surface of the roof. The orientation factor is considered crucial as it has been found out that when a building is at angle 45^0 to the incidence wind, the average indoor air velocity is increased (Koenigsberger et al., 1974).

In modeling the angle of attack module, the roof has been positioned in such away that the building is having its breadth across the wind direction as shown in Figure 5. The ratio of the increase in contact area due to certain degree of orientation compared to that at 0^0 orientation is related by the equation.

$$C_a = \frac{Z \sin \theta + B \cos \theta}{B} \tag{17}$$

To obtain the angle at which the orientation to the main wind direction will be critical, Equation 17 is differentiated with respect to θ.

At the critical angle, $\dfrac{dC_a}{d\theta} = 0 \tag{18}$

Hence $\dfrac{Z \cos \theta}{B} = \sin \theta \tag{19}$

Therefore the maximum area of attack is at the critical angle, θ, obtained as

$$\theta = Tan^{-1}\left(\frac{Z}{B}\right) \tag{20}$$

The model description

Air weight (Aw) = ρ_{ai} x attic volume xg (21)

Wind force (WF) = 0.5 ρ_{ao} x Vs^2 x Pa x kg x $(C_L{}^2$ x $C_D{}^2)^{0.5}$ (22)

Pa = $0.25B^2 tan\theta$ x Ca x AR (23)

0.75 (RW+ AW) * Y^1 ≥ WF * Btan θ/2 (24)

It must be noted that Equations 2, 11, 15 and 17 have been incorporated into the model.

Where
ρ_{ai} = Air density in the attic (kg/m^3)
ρ_{ao} = Ambient Air density (kg/m^3)
g = Acceleration due to gravity (m/s^2)
Ca = Angle of orientation factor (degree)
AR = Area ratio factor (m^2)
Y^1 = Centre of pressure (m)
Vs^2 = Design wind speed (m/s)
B = Breadth of the building, (m)
Kg = wind gust factor
CD = coefficient of drag
CL = Coefficient of lift
θ = Roof pitch angle (degree)

Development of a software program to predict roof blown-off

A software program was written in FORTRAN to predict roof blown off. The program development came after the mathematical equation

MW >MR, for blown off to occur.

MODEL VALIDATION

Using FORTRAN program to obtain the overturning and resisting moments, the mathematical model was validated with captured data from survey and existing literatures. During validation another set of locations different from those that were used for modeling were used to validate the model. Out of the 55 sets of building predicted by the model, 51 of the predictions were correct. From Table 2 and Figure 6, four of the fifty simulated results are slightly higher than model overturning moment predictions. This showed that the model is a good prediction of blown-off

Conclusion

The nature, characteristics and the inter-relationship between the various causal factors of roof blown-of were modeled. These factors are those of topographical location, roof orientation to the wind flow direction, roof geometry and the environmental factor of which include wind speed with its return period, and roof height above the ground.

From the results of the study the following conclusions can be drawn:

1. Wind effect on a roof is most severe when the main span of the roof is oriented at 450 to the main wind direction.
2. Wind speed uphill is far higher than the speed at the valley, hence propensity of roof blown-off is highest at mountain top.
3. Hip roof has better resistant to wind uplift than gable roof because the cetre of pressure of hip roof is lower than in gable roof indicating less overturning moment in hip roof than in gable roof.
4. There were no statistical differences between the roof blow-off model predictions and post model survey data.

RECOMMENDATION

The model has shown that hip roof is more stable and more resistant to roof blown –off than gable roof. It is also concluded that the critical angle of attack on building roofs is increased with increase in length to breadth ratio of the roof. The model has also revealed that the wind speed uphill is greater than the speed at the valley or at the plain gound increaseing with the slope of the hill. The

Table 2. Model versus Simulation results.

Model	Simulation
59.23	58.34
57.02	58.44
53.45	51.86
06.03	04.61
02.9	02.39
00.92	00.85
00.92	00.85
02.8	02.56
15.88	14.49
08.04	06.82
04.98	03.58
01.99	01.19
08.56	07.51
19.67	18.08
28.06	26.95
17.02	15.18
16.67	14.67
70.98	73.45
130.02	125.55
150.05	147.72
38.45	36.16
46.24	44.52
48.45	47.08
110.05	117.12
25.37	23.37
47.23	45.89
60.02	57.66
41.45	40.26
45.23	44.69
35.45	33.09
40.05	38.23
37.24	35.8
30.68	28.92
12.68	11.12
10.8	8.69
21.87	20.02
12.02	10.52
45.08	42.68
32.05	30.14
57.3	55.22
66.89	65.54
33.65	31.96
06.04	04.65
50.03	48.55
60.98	59.27
46.08	44.29
62.12	65.07
66.32	64.93
75.06	73.02
71.02	69.58
44.37	42.27
76.14	74.23
28.38	26.09
24.02	22.05
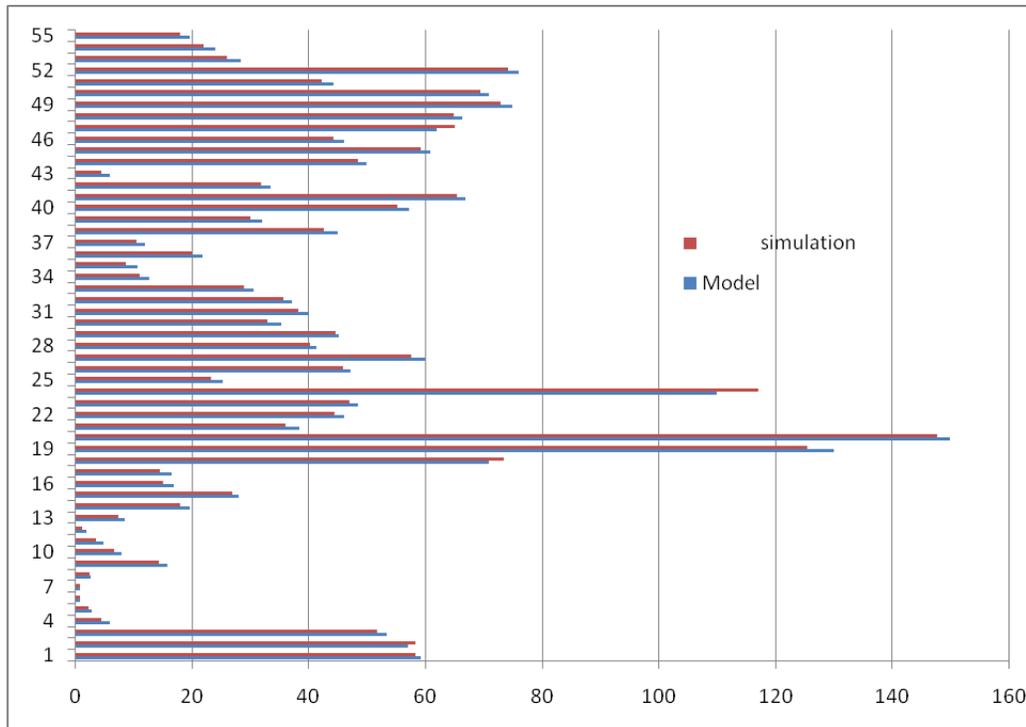
Figure 6. Model versus Simulation Results.

model is a good companion of consulting engineers in their roof design planning and is therefore reccommended for use.

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