Review Paper:

Wind loads on roof of low-rise buildings

Singh Jagbir*and Roy Amrit Kumar
Civil Engineering Department, National Institute of Technology Hamirpur, H.P., 177005, INDIA
*jagbir@nith.ac.in

Abstract

The statistics from previous cyclone reports and other relevant studies have shown a huge property loss and the loss of lives in both cyclone-prone areas and non-cyclonic areas. It is impossible to stop cyclones, but it is possible to minimize losses and to save lives from cyclone disasters. The wind load on a low-rise building is pertinent to a seemingly well-researched area. In present study, the effects of roof shape, roof slope, aspect ratio, interference effect etc. and the role of wind tunnels, wall of wind, CFD and wind standards in wind force investigation have been discussed. Several research attempts have involved the effects of wind force on roofs of low-rise structures for so many past years. The theme remains a live region of inquiry, though there are so many motives for this investigation. In addition to the wide range of variables required, a reasonably large number of components disturb wind force on the roofs of low-rise structures.

Furthermore, a huge number of structures indeed come under the "low-rise" investigation class forming new significant information pertinent to the protection of engineering structures, and even more relevant to the loads of partially planned ones. Generally, wind codes are preferred for building design against wind loads in various countries, but in some studies, even the code values seem inaccurate.

Keyword: Wind tunnel test, CFD studies, Turbulence Models, Low-rise building, Wind code, Roof angle.

Introduction

Every year, many natural disasters happen on earth, and the cyclone is the most dangerous[58,87,94] and table 1 shows the statistics from past reports. Cyclones are dominating not only in the number of deaths, but they are causing about 50 percent of total losses by all-natural disasters.

Bhola 1970 in Bangladesh and West Bengal (India), Bangladesh cyclone 1991, Hurricane Issac 2000 in U.S. State, 2006 in Bermuda, 2012 in U.S. State, Katrina 2005 in Louisana (U.S. State), Nargis 2008 in Myanmar, Arthur 2014 in U.S. State and Hudhud 2014 in India and Nepal caused a massive number of deaths and property loss in hundreds of millions of U.S. dollars.[13,48,104,105]

Reports of these hurricanes have shown that cyclones with peak wind speed more than 180 km per hour caused more destruction as compared to those of less peak wind speed while the duration of hurricanes has a rare impact on losses.

As per the reports, it becomes necessary to carry out the studies on hurricanes and their preventive measures. To prevent cyclones is not possible or not in reach of a human being because tornadoes occur naturally but precautions or preventive measures may be taken. A large number of building roofs have been destroyed by cyclones[104] showing a massive requirement of the study of buildings in cyclone-prone areas.

Table 1
Billion-dollar events to affect the U.S. from 2000 to 2017* (CPI-Adjusted)[94]

S. N.	Disaster Type	No. of Events	Percent Frequency	CPI-Adjusted Losses (Billions Dollars)	Percent of Total Losses	Average Event Cost (Billions Dollars)	Deaths
1	Draught	14	10.5%	118.7	14.9%	8.5	461
2	Flooding	16	12.0%	48.7	6.1%	3.0	224
3	Freeze	3	2.3%	5.0	0.6%	1.7	1
4	Severe Storm	67	50.4%	152.1	19.1%	2.3	1070
5	Tropical Cyclone	19	14.3%	437.4	55.1%	23.0	2721
6	Wildfire	11	8.3%	25.3	3.2%	2.3	155
7	Winter Storm	3	2.3%	7.2	0.9%	2.4	82
8	**All Disasters**	**133**	**100%**	**794.4**	**100.0%**	**43.2**	**4714**

Research or studies has already been carried out for safety from hurricanes like post-disaster studies, disaster management, cyclone proof houses etc. but also then after every cyclone, a vast number of people become homeless. That may be due to the high cost of cyclone proof construction, or may be technology is away from the reach of cyclone-prone area residents. That is why cyclone proof construction and wind load resistance require more research work in this area.

Low-rise structures used for commercial, industrialized, inhabited, and other functions and high-rise buildings can be categorized as the larger number of structures are built around the world. Post-tornado research has shown that building rooftops are critical elements that often suffer severe damage. Also the roofs are highly vulnerable to robust wind uplift forces.[109-123] These structures are built in various forms of territory and countryside with different types of roofs. Flat roof, mono slope roof, canopy roofs, gable roof, hip roof, pyramidal roof, saw-tooth roof, multi-span gable roof, mansard roofs, troughed roofs, domed roof, curved roof, arched roof, and stepped roofs are main types of roofs used for low rise building.

The stability of roofs in regions besides the high seismic regions is determined primarily by wind forces. And this feature is more apparent in areas of heavy storms like coastwise regions, open territories, and peak of hills. Also, for the roof wind design, it is required to investigate the wind uplift resistance of the roof.[17] The roof buildings with long-span are commonly used as public structures like arenas for high visibility[97], exhibition centers, and transport interchanges due to their beautiful shapes and capability to provide large space without inside pillars.

Such roofed structures frequently become attuned to wind loading movements due to their light-weight and low structural stiffness. While the short-span structures provide resistance to the wind where space and structure stand for one to one, they can be basic post and beam spatial bays explained by lineal components, or form active where the flexibility of material responds to form. While particular and close in scale, short-spans can become crowded with redundancy and self-similitude. The study of the effect of wind on a structure comprises of two components specifically (i) summing up of wind forces and (ii) approximation of their reaction to these forces.

Experimentally as well as numerically, a lot of work has been done on the effect of storms on low rise structures. In experimental studies, wind velocities around the model can be measured by 2D Laser Doppler Anemometry, and for pressure measurement, pressure taps are used on the surface.[45] Also, the laser doppler velocimetry (LDV) and particle imaging velocimetry (PIV) are two strategies to observe the velocity fields in experimental studies.[2] Similar to other wind tunnels, a tornado-like simulator had been used in Tokyo Polytechnic University to get more real pressure results[33] and identical to the tornado-like simulator, the fragility modeling approach is utilized to analyze the effect of future-wind structures to tackle the constraints of traditional fragility modeling.[68]

Along with wind tunnel tests, there are other strategies to determine the wind load i.e. numerical analysis, analytical study, and theoretical modeling. In a numerical study using finite element analysis, the method was found sufficient to understand the structural behavior and uplift the wall's roof attachment capability.[83]

The earth surface behaves like a boundary layer, so it necessary generates boundary layer in wind tunnel to obtain better results.[4] A boundary layer in an ABL wind tunnel may be thin or thick and the model may be investigated for both the parameters i.e. apex angle and the angle of attack.[3] The inflow boundary layer profile depends upon the topography of the region.[103]

In a numerical study of the surface-mounted pyramid, the apex angle and the attack angle have existed for the maximum turbulent intensity and the maximum reattachment length.[19] The suction on building model with setback has significant effect of wind angle.[49,53] Aspect ratio is another parameter that affects wind load. In an experimental study of long-span, low-rise building models with a large roof slope, the authors found that with a rise in aspect ratio, the suction on the leeward roof and on wall increases.[34]

In a study of three aspect ratio (rise to diameter) 1/2, 1/3, and 1/6 in case of cylindrical roof, the aspect ratio 1/6 was found independent on Reynolds number (6.90×10^4 to 8.28×10^5).[71] In another study of the gabled canopy roof, the canopy length had an extensive influence on pressure or suction coefficients on the roof surface.[73] Also, in the case of hip-roof, the roof pitch had an impact on the magnitude of pressure coefficients, but the pattern of pressure coefficients remained the same.[47]

Along with the parameters (apex angle, attack angle, aspect ratio, etc.), there is interference effect of nearby buildings in case of both low-rise and high rise buildings. In an interference wind tunnel study, the comparative height of the upwind side building caused an increase in wind load on a low-rise structure.[69] Surrounding buildings were many times found beneficial as they generally reduce the suctions on the roof.[96]

The wind loads cause positive pressure and negative pressure (suction) in the case of almost all buildings and along with positive and negative pressure, there are shear force and torsional load due to the wind, and in a study of flat and gable roof, both the shear force and the torsional moment were found significantly higher for gable roof than the flat roof.[32]

Different parameters affect wind load on low-rise buildings and on the basis of all these parameters, the further study is divided into four major parts. At first, different methods were used to investigate the wind load. Various methods i.e. wind tunnel analysis, numerical simulation, wall of wind or open country method and analytical investigation have been discussed.

Methodologies

Different researchers have been used different methods for the investigation of wind forces on roofs of low rise structures. Wind tunnel testing, CFD modeling and simulation, mathematical modeling, and theoretical modeling have been used significantly in previous studies. In some cases, full-scale testing in open country and Wall of Wind (WOW) methods also have been used for field experiments. Collecting real-time wind velocity and pressure data in live tornadoes are difficult.

That has mostly restricted the study of wind vortices to laboratory simulators and numerical models. Attempts were made to measure characteristics of wind load based on studies of wind load such as vortices simulated in laboratories and with CFD programs. Still, there have been few attempts to measure the loading caused by the swirling tornado winds in the form of force and pressure coefficients on low-rise buildings.

Wind Tunnel or Scaled Studies: Wind tunnel test is the most appropriate method for testing building models for wind loading and pressure coefficients, force coefficients, i.e. drag and lifts coefficients are achieved on the surface of building models. There are various types of wind tunnels, but mostly atmospheric boundary layer wind tunnel[39] has been used for wind load studies on buildings because the earth's surface is rough, and there are obstructions.

So for getting more accurate results ABL wind tunnel is the right choice and the correct simulation of the boundary layer is required.[56] It is necessary to check the efficiency of the wind tunnel at a sufficient interval of time. In a similar study, ABL wind tunnel apparatus for environmental flow investigations at Assiut University was found capable of maintaining long-run steady flow features and reproducible flow configurations.[39] And in a similar study, wind tunnel for high turbulent flows at COPPE/UFR was found well working in comparison with already available wind tunnel data of other authors.[16] The horizontal wind load on a greenhouse was analyzed using an atmospheric boundary layer wind tunnel.[23]

For an atmospheric boundary layer wind tunnel, it is required to create an atmospheric boundary layer. Different types of roughness devices like roughening blocks, rods, roughening elements etc. have been used for boundary layer generation.[16,29,41,51] The type, size and positions of roughness devices depend upon the requirement of the kind of boundary layer and the atmospheric boundary layer characteristics depend upon the topographic area, for which the study was carried out.

In wind tunnel testing, the pressure at different points on the building model's surface is obtained by locating the pressure taps on the surface of the model. The location of pressure taps is an essential parameter in wind pressure analysis through wind tunnel experiments. For a wind tunnel study, the model geometry, model located in the wind tunnel, and positions of pressure taps are shown in fig. 1.[107] The design of the pressure tap configuration depends upon the type of study if the investigation is of extreme events or some other kind of study.[25]

In a research investigation of wind pressure on roof tiles, 256 taps were used with six different configurations, and the standardized tap configuration gives the higher values of lift coefficients than in the case of all six arrangements.[88] So the previous studies show that the locations of pressure taps can affect the results significantly.

Wind tunnel experiments are highly trustworthy and the outcomes of wind tunnel testing match with the results of full-scale tests too. The results (mean and fluctuating wind pressure) of a study from both the scales that is full scale (field laboratory) and 1:50 scale (Wind tunnel experiment) were found almost similar.[43] For a large scale (1:40), an open circuit wind tunnel also has been used to investigate the wind pressure or to know the effect of wind direction and blockage on wind pressure distribution on flat canopy roof.[70] In another ABL wind tunnel study, wind pressure on the rooftop is analyzed, and a 1:50 scale had been used for the model.[15]

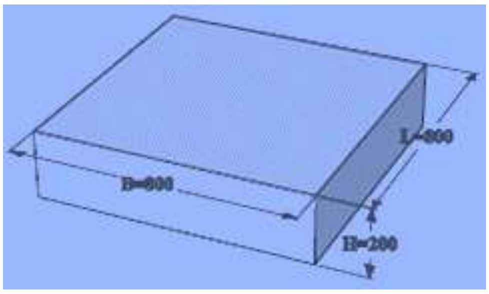

Fig. 1(a): Experimental model Geometric variables of flat roof model(unit: mm)[107]

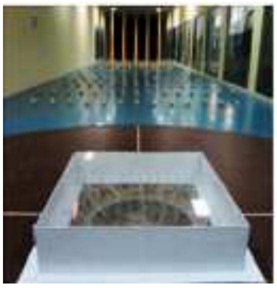

Fig. 1(b): Model in the wind tunnel[107]

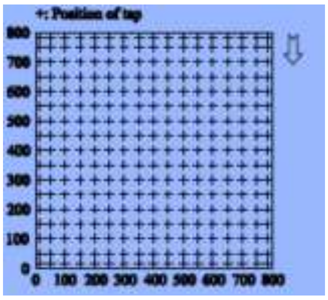

Fig. 1(c): Location of pressure taps[107]

The wind tunnel requires time to time maintenance to minimize the errors and to obtain accurate results. For a similar objective, the ABL wind tunnel at the Technische Universität München (TUM) had been tested, and it had been found that the ABL characteristics need to regenerate for better test results and to increase the efficiency of wind tunnel.[51]

Several wind tunnel studies were done in the past which are continued in the present. Wind tunnel test method seems most appropriate among all available techniques of wind load study and it is a good source for checking the accuracy of other methods. For getting good results from wind tunnel testing, it is necessary to check the boundary layer characteristics of wind tunnel time to time, and locations of pressure taps should also be as per standard guidelines. In wind tunnel testing, any shape of building model may be tested, or different types of boundary layers may be created while in CFD or other methods, it is not so easy.

Full-Scale Studies: For full-scale wind load studies, wall of wind is a good option and provides efficient results. This type of testing may be carried out on any kind of structure. In another full-sized experimental investigation, more accurate wind loading as per American Society for Testing and Materials (ASTM) E1592 test slot has been used and it was found that corner suctions for the trapezoidal roof have been underestimated by ASCE 7-10.[38]

A wall of wind (WOW) is an experimental method to analyze the wind load on full-scale building models. By the use of the wall of wind method, different types of studies on different kinds of structures have been carried out. A full-sized wind testing apparatus is generically called as Wall of Wind (WOW), as shown in fig. 2 and it has been utilized to evaluate wind-induced internal and external pressure coefficients on eaves of hip roof found considerably lower than gable roof.[99] A wall of wind always provides more realistic wind loading conditions as compared to other experimental methods.[61]

In a wall of wind, the number of fans also vary and different types of roughness devices are used. The number of fans of each study depends upon the kind of hurricane that needs to simulate. In an analysis of wind loading on concrete roof pavers, 12 fans were used to produce up to a category 5 Saffir–Simpson Scale typhoon wind speed.[10] In another Wall of Wind (WoW) study, effects of wind over the roof corner and edge sections had been investigated by using a 6-fan testing facility proficient of producing an extreme continuous wind velocity of around 56.1 m/s (125.5 mph).[22]

Many full scale (using a wall of wind) studies of roof pavers or roof tiles at Florida International University (FIU) were performed, it was found that negative pressures cause significant uplifting force on roof pavers.[6,38] The same wall of wind arrangement has also been used to investigate the internal wind pressure in case of a low-rise structure with single or multiple openings.[38]

The wall of wind at FIU has also been tested for judging wind-driven rain intrusion, and it was found proficient of testing full-sized single-story building models subjected up to 56 m/s (125 mph) wind velocities and 762 mm/h (30 in./h) of rainfall.[21] The wall of wind full-scale studies is also used to validate the wind pressure results from other methods.[11]
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Full-scale testing in an open country is another method for wind load investigation of full-scale building models. Similar to wind tunnel experiments, pressure taps are fixed on the model's surfaces to detect the wind pressure. As shown in fig. 3, a full-scale analysis may be carried out in the open country by fixing pressure taps on model surfaces, a graph showing the distribution of mean pressure coefficients has also been shown in fig.[79]

In an investigation of the wind pressure on cable suspended roof by three methods i.e. full scale, wind tunnel, and numerical study, results from numerical analysis agree with wind tunnel testing and field testing. While in the same study, the wind pressure values from the CFD study were lower than those from the other two methods.[26]

Fig. 2: Low-rise building with a gable and a hip roof in front of WOW in a testing position[99]

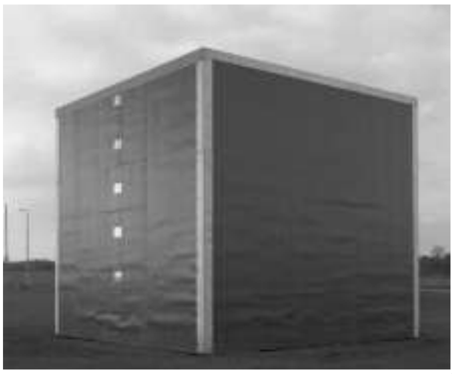


Fig. 3(a): The 6m cube in open country[79]

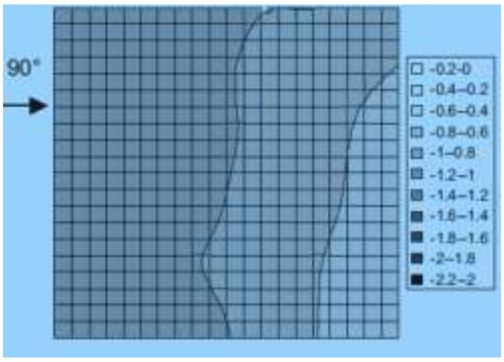


Fig. 3(b): Mean pressure coefficient distributions on the instrumented quarter of the roof[79]

Full-scale studies on wind loads on low rise buildings are a good option for measuring the capability of small structures to withstand against high winds or cyclones. In the past, many full-scale studies were carried out using the wind wall method or by installing pressure taps on full-scale models in open country. The results of full-scale measurements also have been used to check the accuracy of CFD simulations and other investigation methods. Full-scale testing is assumed to be more precise and accurate, as carried out in a real situation and geometrical errors will be negligible. The only disadvantage of this method is that it seems costlier as compared to other methods because of its expensive apparatus and big size models.

CFD Studies: Computational Fluid Dynamics (CFD) may be used for different studies like airflow around a building complex, natural cross ventilation in a building, single-sided natural ventilation design etc. And among all available methods of wind load analysis, CFD can provide comprehensive and useful information and has become a common and attractive design tool.[28] CFD simulation is a multi-functional and exceptionally beneficial apparatus, and is thus ultimate tool for assessing the unsteady aerodynamic forces on the pulsating roofs in a widespread reduced occurrence range.[30] CFD decreases both time and cost in design and investigation, and offers thorough and visualized information.[24,81]

Lot of studies have previously been carried out on CFD simulation of structures. To determine the pressure coefficient values, flow streamline, velocity vector and number of correlated variables etc. through the model surface, the CFD study is a very helpful tool.[102]

Also the CFD simulation is useful to understand the underlying physics of boundary layer separation and wake formation.[102]

As an alternate to wind tunnel apparatus, the CFD simulation has gained huge popularity during recent decades specially to determine wind induced actions and effects on buildings. A reasonable numeral of investigations has been conducted by the use of CFD simulation as a substitute of wind tunnel experiments and the outcomes attained from CFD simulations are sufficiently reliable with experimental outcomes.[20]

In CFD modeling and simulation, there are different models to simulate the wind flow. The precision in CFD is also affected by numerical settings including model.[76] Different types of models are used to simulate different types of flow. A brief outline of frequently used turbulence models in present engineering applications is given as follows:

a) Spalart–Allmaras (S–A) Turbulence Model: The Spalart – Allmaras model is a single equation model that resolves a modeled transportation equation for turbulent viscosity in the kinematic eddy.[89] The Spalart – Allmaras model was explicitly considered for wall-surrounded flow applications in atmosphere. And it has been proved to provide decent outcomes for boundary layers subject to adverse pressure gradients. The model is also becoming more common in applications of turbo machinery.

b) k-ε Turbulence Model: The K-epsilon (k-ε) turbulence model is by far the most basic model utilized in CFD for the simulation of mean flow features for turbulent flow surroundings.[40] It is a double-equation framework which provides a common explanation of turbulence through two equations of transport (PDEs). The novel impulse for the K-epsilon model was to enhance the mixing-length model, and to look for a substitute to recommending algebraically turbulence length scales in modest to high complicated flows.

The k-ε turbulence model is used for different CFD studies. The domain size has been investigated in a numerical study using a k-ε model, and the results were satisfactory.[75] The numerical results using k-ε turbulence model were found with good agreement when compared with wind tunnel results of a hip-roof low-rise building and the mesh generation and pressure distribution have been shown in fig. 4.[47] Also k-epsilon turbulence model was found better than SST turbulence model in study of Y-plan shaped building.[82]

Different numerical studies i.e. wind load on the domed roof and isolated gable roof, uplift force analysis, aerodynamic mitigation and shape optimization study, airflow around the low-rise building, and wind flow distribution in an urban area are carried out using a k-ε model. And in all these studies, obtained results have a good match with wind tunnel results.[7,12,55,64,65,100]

c) k–ω (k–omega) Turbulence Model: The k – omega (k – ω) turbulence model[106] is a popular double-equation turbulence model utilized as a closing for the Reynolds-averaged Navier-Stokes equations (RANS equations), in computational fluid dynamics. The model tries to calculate the turbulence by the use of two partial differential equations for two variables k and ω with the turbulence kinetic energy (k) being the first variable and the specific dissipation rate (ω) being the second.

The k-ω models are derived for wall-bounded flows, and when used in boundary layer flows, no additional wall damping terms are required.[63] Simulation results between the models k-ε and k-ω/SST were compared and have shown a noble ability of a k-omega model to calculate the start-time of dynamic stall due to its boundary layer adjustments.[18]

d) SST (Menter's Shear Stress Transport) Turbulence Model: The turbulence model SST is a broadly used and is a vigorous double-equation eddy-viscosity turbulence model in CFD.[60] The models merge the K-epsilon turbulence model with k-omega turbulence model where the k-omega is considered for the inner section of the boundary layer and the k-epsilon is utilized in unrestricted shear flow. The SST models boundary conditions are the same as the k- ω model. The SST model is fairly indifferent to the unrestricted stream value of ω.[63]

e) Large Eddy Simulations Turbulence Model: Large-eddy simulation (LES) is a turbulence model used in CFD, and at first it was proposed for simulation of atmospheric air currents by Joseph Smagorinsky in 1963.[63] LES is widely used in a extensive variety of engineering applications containing atmospheric boundary layer simulations, acoustics, and ignition.[95] In a study of natural ventilation, when the LES model is used, it is found better to simulate the indoor airflow and outdoor airflow separately.[108] For the supercritical Reynolds number flows, for the fundamental issues of a bluff cylinder with a simple section, LES can give a result with sufficient accuracy.[98]

In another study of wind flow around a cylinder with aspect ratio 5:1, when results from LES numerical investigation were compared with experimental outcomes, LES results were found of good concurrence with wind tunnel results.[77]

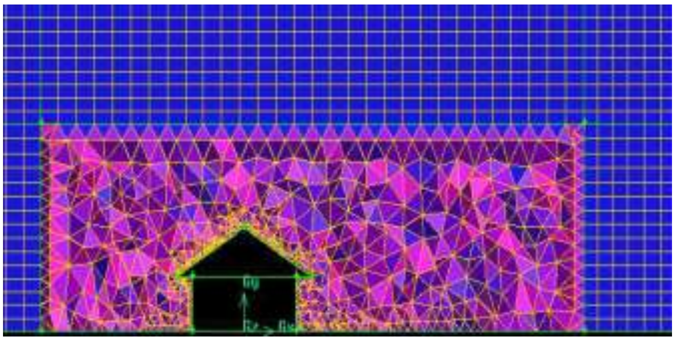


Fig. 4(a): Mesh arrangement near the building[47]

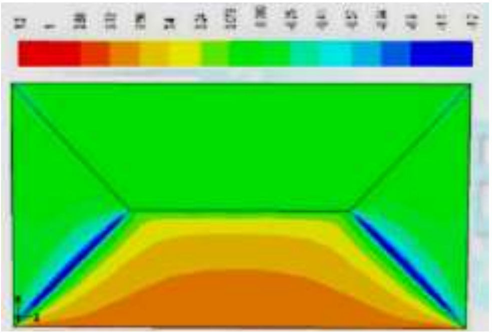
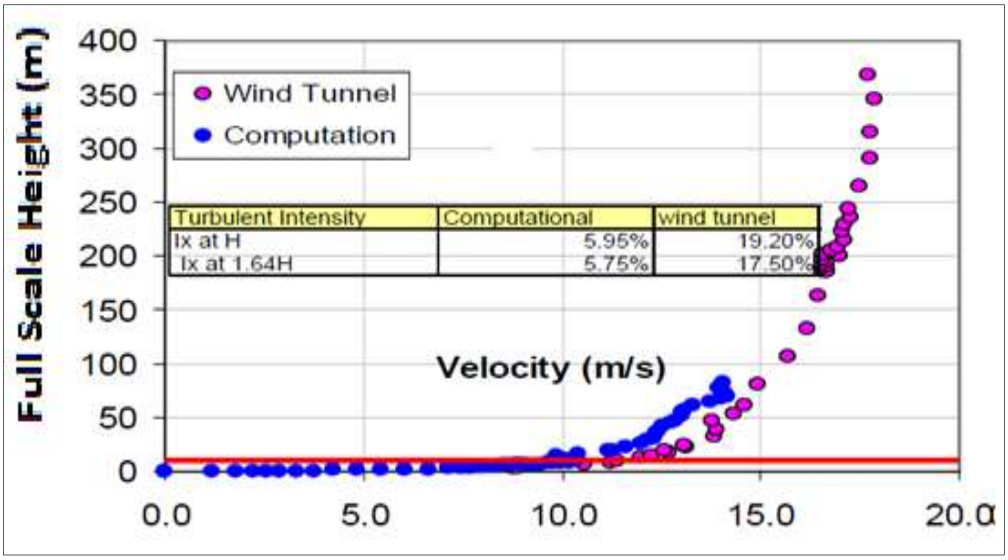


Fig. 4(b): Pressure Coefficients on the roof by Std k-ε turbulence model[47]



Turbulent Intensity	Computational	wind tunnel
Ix at H	5.95%	19.20%
Ix at 1.64H	5.75%	17.50%

Fig. 5: Numerical-wind tunnel comparison for velocity profile and turbulence intensity[50]

In urban studies, the Reynolds Averaged Navier Stokes Equations (RANS) models were found with better accuracy than the LES model.[57] Also, in the case of a low-rise building, internal wind forces calculated from LES are found to be in decent agreement compared to those achieved from wind tunnel data[77] and in another study it predicted mean static pressure accurately.[124]

The suitability and usefulness of a simulation model also depend upon the time taken by the numerical model to simulate the building model. Along with the sufficient accuracy in results, the time taken by the model to carry out the simulation should also be less. The pressure coefficients for the low rise structure were acquired from LES and compared to those acquired from the wind tunnel measurements at Ontario, and it is noticed that the calculation times needed to find the records of a length equivalent to wind tunnel records are currently excessively significant as shown in fig. 5.[50]

As everyone knows, the CFD simulation method is more attractive and feasible as compared to other methods of wind load analysis, and may be because of this, CFD use is increasing day by day. For wind load studies, mainly RANS k-ε modeling and large eddy simulations have been used. A comparison of CFD results with wind tunnel tests or full-scale test results has been taken in many studies, and a strong agreement was reached in the case of k-ε modeling, while LES has a lack of it. Studies show that large eddy simulation works better for indoor airflow studies as compared to around building airflow or over roof airflow studies.

Roof Geometries

In India, the mainstream of structures falls under the group of low-rise buildings, and the available information on the subject of wind flow around such structures seems very low, and also the wind flow is affected by architectural features.[5] Even after the devastating effects of wind loads, there were few attempts to quantify wind-induced loading. Low rise building models had been used to research the impact of variations in the construction of roof geometry on wind loads.

The building orientation for the wind direction and the translation speed of the simulated wind was also varied accordingly to study their effects. Different roof geometries i.e. plane roof, canopy roof, gable roof, hip roof, troughed roof, mansard roof, curved roof, domed roof, and conical roof, have been studied with the help of wind tunnel testing and CFD modeling. Different roof geometries have shown different wind behavior for wind pressure distribution and pattern of velocity streamlines.

A gable roof is a common type of sloppy roof used in hilly areas. A gable roof model as displayed in fig. 6(a) has been analyzed by CFD simulations and wind tunnel testing, and the pressure force on the upstream-side of the roof becomes positive as the roof pitch increases.[100]

In another experimental study of the gable roof, the recirculation regions were found near the leeward side of the roof.[65] A gable roof low-rise building had been investigated through the concept of GEF, and the GEF is a dimensionless coefficient for quantifying the influence of turbulence on the distribution of wind force.[84] For geometry like a hyperbolic paraboloid roof, the wind load study requires ad hoc wind tunnel or CFD simulation. The hyperbolic paraboloid roof is shown in fig. 6(b).[80] (Rizzo and Sepe 2015).

When it comes to the complicated roof shapes, the domed roof may be considered in this category. In many studies, geometries have also been modified to improve wind resistance. A domed roof has been used to cover large buildings in Iran like mosques, churches, schools etc. and a typical domed roof with openings is shown in fig. 7.[1]

In an analytical, theoretical, and numerical study of different roof types (shape-based), the flow of wind around the domed and pitched roofs is found to be more complicated than in other roof shapes.[59] In another experimental study of the domed roof, complicated recirculation flows were found around the roof.[74]

Vaulted canopy roof (VCR) is another type of roof, and in a study of planar canopy roof (PCR) and vaulted canopy roof (VCR), the local minimum loads close to the ridge were found considerably lower on VCR than on PCR.[62] Arc shape roofs are used for industrial buildings and sometimes are sensitive to wind load. In a study of an arc-shaped roof, the change in wind pressure due to the attached canopies was found noticeable but not intense.[66] An experimental and CFD study of the long-span curved roof has shown that complex geometries with several parameters can be investigated through CFD simulation.[30]

Two cantilevered long-span roof models long have been analyzed by wind tunnel testing, full-scale testing and numerical analysis. And it is proposed that the finite element method based numerical analysis can satisfactorily predict the dynamic characteristics of the complex long-span structure.[27]

The studies which include more than two roof shapes are minimal in number where different types of roof have been investigated in a single study. In a similar study of three different roof shapes i.e. gable, hip, and pyramidal roof, the uplift behavior during a cyclone was such that a gable roof has the highest chances of uplifting. A pyramidal roof gets the lowermost uplift among these three roof shapes, as shown in fig. 8.[86] Individual studies are carried out for the roof shapes that are not included in the Wind Codes or Standards; a similar study was carried out on the pyramidal roof building model, and the results are used to design a pyramidal roof to resist wind loads.[31]

In another study of pyramids, the findings show that the difference in the base angle for pyramidal buildings has a more important impact on the moment than the height.[44] In reliability analysis of the industrial building as shown in fig. 9, damage risk was found double if a door or window fails at the time of storm.[93]

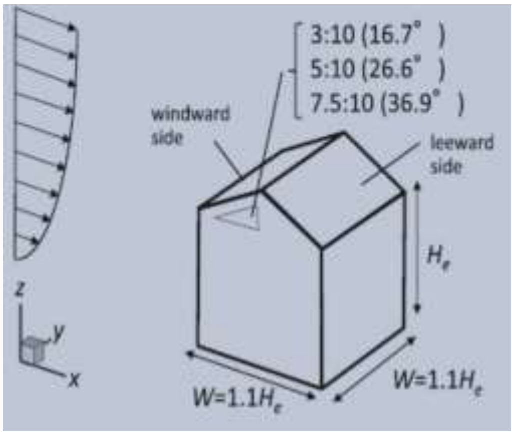


Fig. 6(a): Schematic view of gable-roof building model[100]

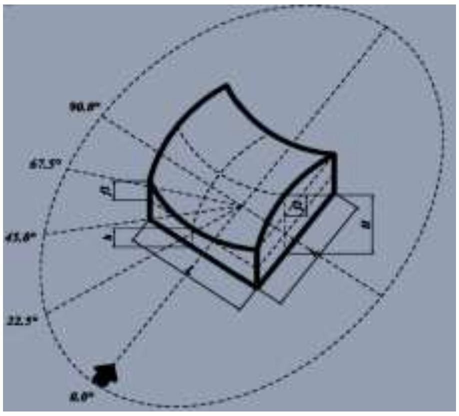


Fig. 6(b): Geometrical parameters of the hyperbolic paraboloid roof model[80]

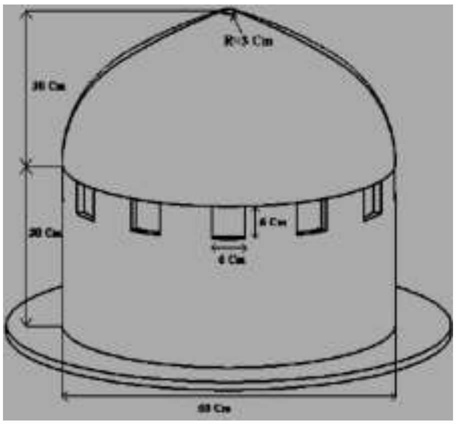


Fig. 7(a): L Domed roof model and its dimensions[1]

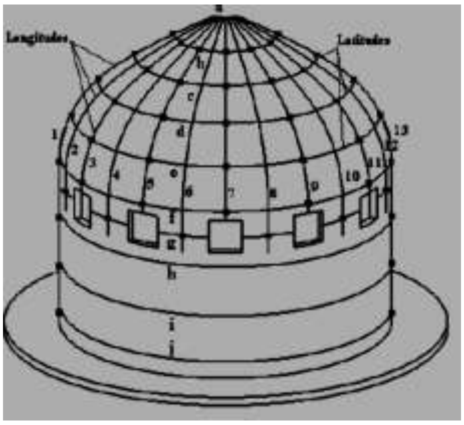


Fig. 7(b): The model of the dome with the longitudes and latitudes and locations of pressure tabs[1]

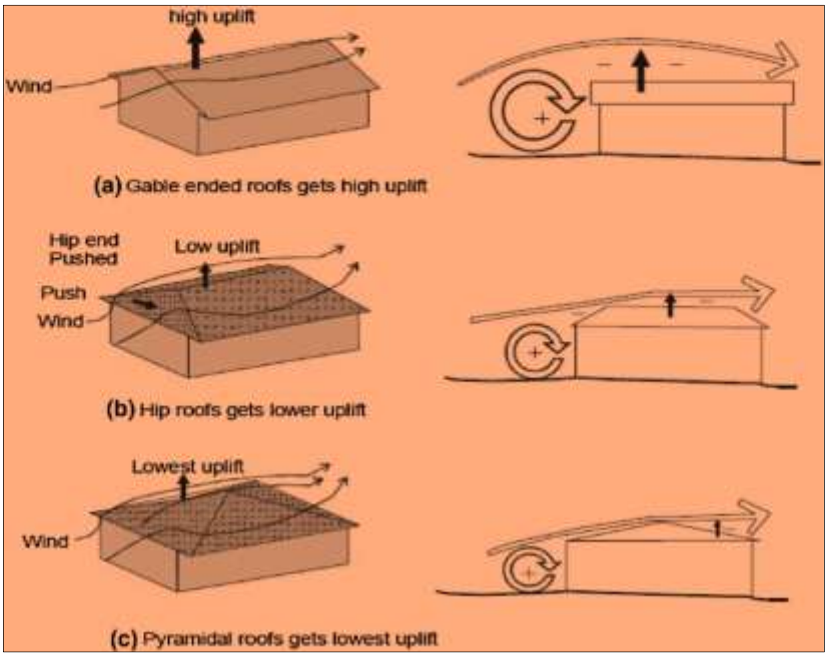


Fig. 8: Wind capacities of different types of roofs[86]

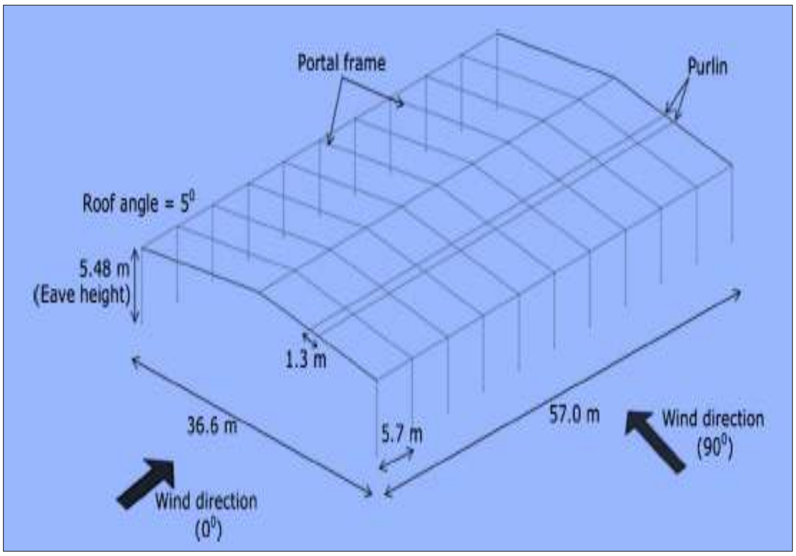


Fig. 9: The layout of an industrial building[93]

The pyramidal building exhibits exciting features from an aerodynamic engineering perspective. The pyramidal geometry displays different mechanical fluid properties compared to other configurations e.g. rectangular, sharp-edged, mostly due to the vertical wall taper.

A large number of studies of various types of roofs have been carried out in the past. The flat roof and gable roofs have been investigated in more studies as compared to other types of roofs. That may be because of their simple geometry, as studies show that gable and flat roofs are found subjected to higher uplift and suction forces. Very few studies have been carried out on pyramidal-shaped roof buildings and they found highly capable of resisting extreme wind loads, that is why more studies have to be carried out on pyramidal roofs. Furthermore, a lot of studies may be carried out on building roof geometries that may be roof shape or may be the size of different parts.

Wind Code Information

A lot of information about the calculation of wind forces on roofs of low rise structures has been given in different standards or codes i.e. ASCE/SEI 7-10 (American Society of Civil Engineers), IS:875 (Part 3)-2015 (Indian Standard PART 3 WIND LOADS), BS 6399-2:1997 (Loading for buildings-Part 2: Code of practice for wind loads), EN 1991-1-4:2005+A1:2010 (E) (Euro code 1: Actions on structures - Part 1-4: General actions -Wind actions), and AS / NZS 1170.2:2011 (Structural Design Actions Part 2 - Wind actions). Basic wind speeds for different regions have been given in maps or tabular forms.

External and internal pressure coefficients have been provided for several types of roofs i.e. plane roof, gable roof, curved roof, hip roof, troughed roof, mansard roof, saw-tooth roof, mono-slope roof, grandstand roof, domed roof, arched roof, and canopy roof for different wind directions and various slopes or roof angles.[8,9,46,90-92] A noticeable difference among values of mean pressure coefficients for gable roof with roof pitch 30° may be seen in codes of practice of twelve different countries, as shown in table 2.[52]

In a study of wind loads, estimation on buildings factor approach from National Building Code of Canada (NBCC) is used and it was found that across-wind and torsional moments on open exposure buildings have a significant effect of interference[72] and in some other study by using wind pressure data from NBCC. r-largest order statistics (r-LOS) method found a good alternate to the approximation of great design wind speed.[67]

Many studies show that the code values are not much accurate. And difference in values from codes and individual findings has been noticed. Similarly, an underestimation of the total uplift force in Canadian and American Wind Standard was found when results from full-scale testing of the low-rise wood building were compared with the code values. Also in a dynamic analysis of drift, the Nigerian wind code of practice is found more conventional than the Russian.[14]

In three other full-scale low-rise building studies, resulting values were found different from those of Australian/New Zealand Standard, AS/NZS1170.2:2002, and the American Standard ASCE 7-02.[35,42,125]

In wind standards of different countries, it has been tried to cover most of the roof shapes for providing wind pressure coefficients as shown in table 3. Also then there are few complicated roof shapes, which have not been included in the wind standards. It can be seen from table that the domed and arched roof are given only in American wind standard while a pyramidal roof and conical roof have not been given in any of the following wind standards.

Different formulas are given in wind standards to calculate the wind load and different wind codes or standards suggest different formulas or equations to calculate wind velocity and design wind pressure. The formulas from six different wind standards are enlisted in table 4.

In a wind tunnel study of mono-sloped canopy roof, gable roof, and troughed roof, the authors found that the results had a good match with the provisions of the Australian/New Zealand (AS/NZ) Standard[91] in case of mono-sloped canopy roof while the results of the other two roof types are found different up to some extent.[101] In some other laboratory-simulated tornado study, the force coefficients on the gabled roof were found 50% greater than the standard values (ASCE 7-02).[35]

In another study, extreme peak pressures force on the top edge of low-rise buildings have been found to be greater in value than those governed by ASCE 7-10. A study of internal forces on low-rise, full-scale structures with openings also found values in the Australian / New Zealand Wind Actions Standard, AS / NZS1170.2:2002, and American Standard ASCE 7-02 were found unconservative, but the proofs for the same were not enough.[85]

Many countries of the world have their wind codes, and those codes have values of pressure coefficients and other guidelines for buildings to be constructed in different parts of that specific country. A considerable variation among pressure coefficients in wind codes of different countries may be seen. That may be because of the change in topography and environmental aspects.

Not precisely, but approximately most of the building designers use wind code guidelines, so values in code must be correct in all details. But it is also seen in a few studies that a considerable difference was found between wind tunnel test values and wind code values, so wind codes too need a rechecking of all the values and guidelines.

Table 2

Comparison of mean pressure coefficients on gable roof building from various codes of practice ($h/w \le 1/2$, $3/2 < l/w < 4$, roof slope $\theta = 30°$, wind normal to ridge)[52]

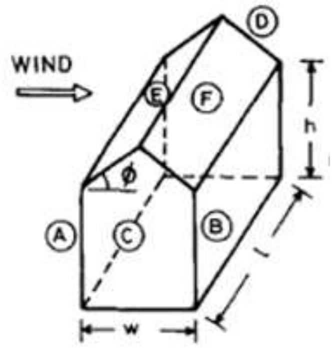
No.	Country	A	B	C	D	E	F	
1	India	0.70	-0.25	-0.60	-0.60	0.00	-0.40	
2	Australia	0.80	-0.25	-0.60	-0.60	-0.20	-0.70	
3	Canada	0.70	-0.50	-0.70	-0.70	-0.56	-0.50	
4	Czechoslovakia	0.80	-0.60	-0.60	-0.60	0.00	-0.40	
5	Japan	0.80	-0.40	-	-	0.15	-0.50	
6	New Zealand	0.90	-0.50	-0.70	-0.70	-0.50	-0.70	
7	Portugal	0.80	-0.50	-0.70	-0.70	-0.10	-0.50	
8	Rumania	0.80	-0.40	-0.40	-0.40	0.20	-0.40	
9	Sweden	0.80	-0.40	-0.40	-0.40	0.20	-0.40	
10	UK	0.70	-0.25	-0.60	-0.60	0.20	-0.40	
11	Uruguay	0.80	-0.40	-0.40	0.40	-0.20	-0.40	
12	USSR	0.80	-0.60	-0.60	-0.60	0.00	-0.40	

Table 3

Different roof shapes covered in five different codes for pressure coefficients[9,46,90-92]

S.N.	Wind Code	Types of Roofs (Pressure Coefficients Available)
1	India [I.S.:875 (Part3) 2015]	Mono-slope roof, curved, pitched, grandstand, saw-tooth, free-standing double slope, troughed and combined roof
2	Australia/New Zealand [AS / NZS 1170.2:2011]	Gable, hip, saw-tooth roofs, pitched roofs of multi-span buildings, curved, mansard, and troughed roofs
3	England [BS 6399-2:1997]	Flat roof with and without parapet, gable, hip roof saw-tooth, pitched roofs of multi-span buildings, curved, mansard, and troughed roofs
4	European Code [EN 1991-1-4:2005+A1, Euro code 1 Part 1-4, Wind actions]	Flat, mono-pitch roof, canopy, gable, hip, curved, mansard, and troughed roofs
5	America [ASCE Standard ASCE/SEI 7-10]	Flat, mono-slope, canopy, gable, hip, saw-tooth, multi-span gable, mansard, troughed, domed, arched and stepped roof

Table 4
Formulas for wind velocity and design wind pressure from various wind standards[8,9,46,90-92]

Wind Code	Design Wind Speed and Design Pressure Formula	Factors used (for wind velocity calculation)	Factors used (for wind pressure calculation)
India [I.S.:875 (Part 3) 2015]	$V_z = \overline{V_b}.k_1.\overline{k_{2,i}}.k_3.k_4$ $p_d = p_z.K_d.K_a.K_c$	k_1 - Prob. Factor (Risk coefficient) k_{2i} - Terrain roughness/ht factor k_3 - Topography factor k_4 - Imp. Factor for cyclonic region	K_d Wind directionality factor K_a Area averaging factor K_c Combination factor
Australia/New Zealand [AS / NZS 1170.2:2011]	$V_{site\ \beta} = V_R.M_d.M_z.M_s.M_t$ $p = (0.5\rho_{air}).[V_{des}]^2 C_{fig} C_{dyn}$	$V_{.R.}$ – Regional 3s gust wind speed M_d - Wind Directional multiplier M_z - Terrain/ht multiplier M_s – Shielding multiplier M_t – Topographic multiplier	*[Design wind speeds ($V_{des,\Theta}$) shall be taken as the maximum cardinal direction site wind speed (V_{site})]* ρ_{air} - Air density C_{fig} - Aerodynamic shape factor C_{dyn} - Dynamic response factor
England [BS 6399-2:1997]	$V_e = V_b.S_a.S_d.S_s.S_p.S_b$ $q_s = 0.613{V_e}^2$	V_b - Basic wind speed S_a - Altitude factor S_d -Direction factor S_s - Seasonal factor	V_e - Effective wind speed S_p - Probability factor S_b - Terrain and building factor
European Code [EN 1991-1-4:2005+A1, Euro code 1 Part 1-4, Wind actions]	$V_b = C_{dir}.C_{season}.V_{b,0}$ $q_p(z) = c_e(z).\frac{1}{2}\rho.{V_b}^2$	V_b - Basic wind velocity $V_{b,0}$ – Fundamental value of basic wind speed C_{dir} - Directionality factor C_{season} - Season factor	c_e - Exposure factor ρ - Air density
America [ASCE Standard ASCE/SEI 7-10]	$q_z = 0.613.K_z.K_{zt}.K_d.K_e.V^2$		K_z - Velocity pr. exposure coff. K_{zt} - Topographic factor K_d - Directionality factor K_e -Ground elevation factor q_z - Velocity pressure at z ht. V - Basic wind speed
Japan [AIJ Recommendations for Loads on Buildings]	$U_H = U_0 K_D E_H k_{rw}$ $q_H = \frac{1}{2}\rho {U_H}^2$	$U_{.H.}$ – Design wind speed U_0 - Basic wind speed $K_{.D.}$ - Directionality factor $E_{.H.}$ - Wind speed profile factor k_{rw} – Return period conversion factor	q_H - Design velocity pressure ρ - Air density

Conclusion

Significant research has been carried out on loads on low rise structures. Results from different investigations show the influence of roof geometry, percentage opening provided, and the atmospheric boundary layer etc. The following points are concluded:

- In available studies of wind loads on pyramidal-shaped roofs, limited studies are done on pyramidal shape roofs. Hence a lot of work on this should be carried out in the future.

- No code information is available for wind load on pyramidal roofs i.e. values of pressure coefficients and other guidelines.
- CFD modeling and simulation is the cheapest method for the determination of wind pressure coefficients and wind flow phenomena around buildings, but it needs a good knowledge of the software.

- Wind tunnel test values match with values from CFD simulations, so CFD simulation and modeling can replace wind tunnel testing in most cases but not in all.

- Wall of Wind (WOW) method for full-scale testing is a good option, but it seems costlier as compared to other methods because of the large size of models and its expensive apparatus.

- In few studies, code or standard values for pressure coefficients were found different from recent wind tunnel test results with a noticeable difference. Hence, codes, too, need a thorough rechecking of values and should be revised.

Acknowledgement

We would like to convey our exceptional thanks and appreciation to National Institute of Technology Hamirpur, H.P., for providing resources and to the Ministry of Human Resource Development, India for providing research assistantship. We also thank friends Kanika Sharma and Shakshi Goyal for helping in the present study.

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(Received 16th September 2020, accepted 09th December 2020)