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Experimental Study on the Structural Response of Industrial Shed to Wind Loading

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ABSTRACT: Industrial sheds are quite prevalently used in the construction industry. They are mainly built using steel, as it is generally known fact steel is good in dealing with seismic forces while bad with wind forces. Structural designers and researchers have observed that most of the damage is occurring to claddings and connections rather than on frames. The objective of this paper is to see the development made in addressing the above-mentioned problem. The work of various researchers around the globe is considered and based on that, research work was carried out whose results are a part of this research paper.

KEYWORDS: Industrial shed, Cladding component, Wind tunnel, Wind pressure.

I. INTRODUCTION

The failure of a structure is primarily determined by the wind's action on the structure, which causes pressure differentials inside and outside it. The influence of wind pressures on buildings is controlled majorly by the geometry of the building, angle of wind attack, surrounding topography, and wind flow characteristics. Dynamic loading from wind is essential to both high- and low-rise buildings. They are only of different magnitudes. Among the fundamentals of wind engineering is the relationship between wind speed and structural responses, including failures. These relationships are obtained by integrating data from wind tunnel tests, models for the dynamic structural response, and wind climate data for the structural design of high-rise buildings. Various research has been undertaken to understand and mitigate the vulnerability of low-rise light-frame buildings to damage during wind and the experiments described here are part of that effort.

Structural analysis, wind tunnel tests, wind climate measurements, and wind climate modelling are the most basic and common methods of determining wind load coefficients, wind speed statistics, and structural responses to the wind. The data obtained from this form the basis for our building codes and design standards.

II. RELATED WORK

For analysing wind pressure data on cladding and components of low-rise buildings, Dat Duthinh et al. [1] presented a methodology. The aerodynamic force acting on a specified area was obtained by summing up the pressure time series measured at that area's pressure taps times their respective tributary areas. This operation was carried out for all sums of tributary areas that make up rectangles with aspect ratios not exceeding four. The peak of the resulting area-averaged time series was extrapolated to a realistic storm duration by the translation method. The envelope of peaks and overall wind directions were compared with current specifications. A comparison of the proposed methodology with an alternative method for assignment of tributary areas and area averaging was shown as well. The results obtained for one building and one terrain exposure showed that the negative wind pressure coefficients i.e., suction specified by ASCE 7-10 for gable roofs of low-rise buildings can be too small, by factors ranging from 1.3 to 2.5, whereas the positive coefficients appeared adequate. For walls, both positive and negative pressures were found to be underestimated by current ASCE specifications, by factors ranging from 1.6 to 2.0 and 1.2 to 2.1, respectively.

A light frame industrial building was taken as a topic of study for the comparison of pressure coefficients. Doudak G. et al. [2] undertook this research to understand and mitigate the vulnerability of low-rise light-frame buildings to damage during wind storms. A single-story light-frame wood industrial building was instrumented to measure wind speed,

direction, and external pressures on roof and wall surfaces during natural storms. A small-scale model of 1:200 was used to match full-scaled results with wind tunnel results. Matched boundary wind tunnel observations were undertaken in order to compare measured external pressure coefficients C_p values in the wind tunnel with those extracted from the field data. Mostly wind tunnel mean C_p values compared well with corresponding field values except agreement was relatively poor for taps on the tunnel observations for winds approaching between 90° and 110° . The peak negative pressure coefficient of -2.6 was recorded at 110° and a peak positive pressure coefficient of 0.8 was recorded at 200° both at the western wall of the structure. Overall, it was concluded that estimates of external pressure coefficients were a reliable replacement for field values for the low-rise frame building based on a wind tunnel study. Finally, it was mentioned that the highest peak values measured in the field are well within the provisions of ASCE.

Based on wind tunnel testing and numerical simulation, the wind load and wind speed effect on high-rise buildings with openings were investigated by Fu-Bin Chen et al. [3] in detail. The aim of this study was to effectively utilize wind energy faced by buildings as well as to create a wind-resistant design. FLUENT 15.0 software was used for numerically simulating different models of the building. The wind flow characteristics and the mean wind pressure coefficients were obtained. For the openings of building the wind speed distribution law was presented and amplification at the opening was analysed. Meanwhile, for a 1:300 model of a high-rise building with various opening rates, a series of wind tunnel tests were conducted to assess the fluctuating and mean wind pressure coefficients. Both numerical simulation and wind tunnel results showed good verification with each other. It was concluded that giving an opening in the X direction for 0° to 45° wind angle can obtain a wind speed ratio of more than 1, indicating wind energy can be more effectively used for building.

A wind tunnel was used for testing gable roof models in the study done by Jing X. et al. [4]. For these shed models with different aspect ratios wind pressure distributions were measured simultaneously. Characteristics like mean wind pressure, fluctuating wind pressure, and peak negative wind pressure on the surfaces of the model were analysed. The study was only a preliminary study on gable roof buildings, emphasizing the understanding of wind pressure, through comparisons with existing results and relative wind load codes. This research was conducted to facilitate the wind-resistant design of cladding components and their connections considering wind load path. In the experiment for 0° angle of attack, it was observed that high mean suction occurs in the windward roof leading edge and leeward roof ridge with a peak pressure coefficient of -1.5 in the former position. For 90° angle of attack windward region of walls experienced high suction with a peak suction coefficient of -1.0. It was concluded that the aspect ratio of the building had an effect on the mean wind pressure coefficients, and the effect relates to wind attack angle.

The characteristics of wind pressures acting on the walls and roofs of gable-roofed tropical houses, based on wind-tunnel model experiments, were described by J. D. Holmes [5]. The effects of elevation, roof pitch, and grouping of buildings on the external pressures were discussed, together with some characteristics of internal pressures when there are dominant wall openings. Roof pitches from 10° to 30° were included, and the effect of elevation of the building on columns was also examined. Internal pressures in buildings with dominant wall openings and the sheltering effects on houses within suburban groupings were also investigated. It was found that the effect of elevation is to increase the external wind pressures significantly, the roof pitch has a large effect on the roof pressures when there is a significant wind component normal to the ridge. The shielding effects of upwind buildings are dependent strongly on the ratio of budding spacing to height.

Full-scale testing of low-rise buildings subjected to realistic wind load was taken for research by Kopp GA. et al. [6]. They discussed some of the emerging test methods and challenges being addressed by large-scale and full-scale research facilities being built around the world. The aim of this study was to deal with the rising economic losses associated with natural disasters caused by severe wind storms. Improved testing and theoretical modelling of pressure equalization, and understanding of the nature of gust and storm duration effects on building element response were made as a suggestion for improvement. Along with this numerical modelling of load sharing in flexible statically-indeterminate systems, improved testing for building systems with high leakage flow rates because of system flexibility were some of the things suggested for improvement in conclusion.

The characteristics of near-ground winds during tropical cyclones were reported and discussed by Li J. et al. [7]. Wind velocity spectra, profiles of mean wind speed, turbulence intensity, and turbulence integral length scale were the parameters under consideration for the research. This paper focused on the analysis of the external surface pressures measured on the central cross-section of the gable roof for winds normal to the ridgeline. Pressure coefficients, probability density functions, and power spectra of the measured wind pressures were analysed in detail. It was

observed that for 0° wind attack angle high mean suction occurs in the windward roof leading edge with a pressure coefficient of -1.23. In addition, a wind tunnel experiment of pressure measurements on a 1:50-scaled model of the experimental building was conducted. The field measurements and the model test results were then compared and they showed a good resemblance with a variation of $\pm 10\%$.

The characteristics of mean wind pressure and peak wind pressure on the long low-rise buildings with gable roofs were examined by M. Kanda et al. [8] in this study. The objective of this paper was to clarify the characteristics of mean wind pressure on the end part and the other parts. In this study, the wind pressure measurement and visualization tests were conducted in order to investigate the characteristics of wind pressure on the buildings. The visualization test adopted in this study was the particle tracer method with a laser light sheet. This method makes it possible to visualize accurately the phenomenon by observing the scattered light from the tracer. It was confirmed that the $C_{p_{\text{mean}}}$ tends to have a uniform value when the height of the reference and dynamic pressure was taken midway between the roof apex and the roof eaves. It was also found that the wind direction of maximum and minimum pressure i.e., $C_{p_{\text{max}}}$ and $C_{p_{\text{min}}}$ might not necessarily be $\theta = 0^\circ$ and thus the wind direction is one of the important parameters in deciding the design value.

For the prototype structures with small-scale models built with a different material Murugan Ramu et al. [9] developed a study on the similitude laws. In the study, an attempt was made to develop a scaling law for models to carry out the free vibration analysis of structures, based on the similitude requirement. The established scaling laws were validated analytically using simple test problems. The similitude relationship between the prototype and the model was validated with the aid of a case study using finite element analysis software. The similitude relation between the prototype and the model was validated analytically by considering two cantilever beams with different boundary conditions, loading conditions, and materials. The structure considered for validating the scaling laws using numerical analysis was a roof slab of a nuclear reactor.

The Buckingham pie theorem was used by M. Shehadeh et al. [10] to develop the relations of geometry, loading, and properties between the model and a large structural element. Three independent scale factors which represent three fundamental dimensions, namely mass, length and time were selected for designing the scaled-down model. The results were compared with those obtained from the full-scale structure numerical computations. The effect of scaled-down model size and material on the accuracy of the modelling technique was thoroughly examined. A pad-eye which is a device often found on boats that a line runs through, or provides an attachment point was used as a case study. This study determined a set of dimensionless groups which can be used to correlate data for relating the pad-eye strain due to a static biaxial loading, pad-eye thickness, mating face length, hole diameter, pad-eye outer diameter, pad-eye wedge height, and the modulus of elasticity as the main mechanical property which identify the pad-eye material.

External point pressures at mid-plane and roof corner locations, measured during a wind tunnel study of a 1: 50 geometrical scale model of the Texas Tech University test building, were reported by M. Endo et al. [11]. The midplane laboratory pressures were compared with field and numerical results. The agreement/discrepancy between the compared results was discussed. The roof corner pressures acquired for a wider than previously reported range of the wind azimuth were presented and compared with the available field results. The laboratory data discussed in this paper were limited to those measured on a 1: 50 geometrical scale model. Other geometrical scales, including 1: 25 and 1: 12.5 were also considered, as a part of a broader recent study addressing the effects of Reynolds number and other modelling issues. A better agreement between the laboratory data and field data was seen for the wind azimuth of 270° . The field values were significantly higher than the laboratory data for the wind azimuth of 240° . A comparison of the corresponding peak pressures showed a similar trend. It was seen that for the wind azimuth of 270° the overall field turbulence intensity was lower than that modelled at Colorado state university. For $\theta = 240^\circ$ it was higher than the laboratory turbulence intensity. For $\theta = 270^\circ$ the standard deviation of the laboratory pressure overall was larger than the field pressure.

Based on wind tunnel experiments M. Kasperski [12] made attempts to solve the doubts of researchers regarding the randomness of the extreme wind speeds, appropriate return period of design load, and statistics of the extreme wind speed. An adjusting factor was used by which the mean extreme coefficient was multiplied to account for the dependence of the type of extreme value distribution of the wind speeds. The appropriate length of a single run was obtained based on the design wind speed in full scale.

The prediction of wind-induced internal pressure on a model low-rise building in Nigeria was carried out by Olumide Osokoya [13] using numerical analysis. The test was carried out on a computational model of a building using ANSYS FLUENT software. The renormalization group k- ϵ turbulence model was used to simulate wind impact on the building of size 2.78m x 2.43m x 2.30m with a gable roof slope of 45° at incident angles of 90° and 45°. A comparative analysis was carried out to distinguish the effect of dominant openings and also the direction of the wind on the induced pressure. Results obtained from the tests were the values of pressure coefficients in the interior of the building which were used to characterize the induced internal pressure. Contours, tables, and plots were used as graphical aids for the presentation of results.

At the University of Western Ontario P.C. Case et al. [14] tested low building models with 4: 12 gable roofs of equal height and width, they were modelled at a geometric scale of 1: 100 and tested at the Boundary Layer Wind Tunnel Laboratory. The resulting database provides simultaneously measured instantaneous external pressures for different wind azimuths and two terrain categories. The pressure tap coverage over the exterior of the models allows both structural and local wind loads to be examined. This paper presents comparisons of local pressures and selected structural loads experienced by the low buildings in the suburban and open country exposures. The suburban exposure is shown to produce lower wind loads than those experienced in the open country exposure. Furthermore, a simple building is shown to experience reduced loads as it becomes embedded in an array of similar buildings. It was found on average, an isolated building in a suburban exposure experiences 15% to 25% lower loads than if located with an open country exposure.

Dimensional analysis using the Buckingham theorem along with its applications in physics was the focus of research conducted by Tatjana Misic et al. [15] This paper presented the basics of dimensional analysis in two cases: the resistance force of the fluid that occurs when a body moves through it and the speed of propagation of waves on water. After that, a general approach to dimensional analysis based on the Buckingham theorem was shown.

III. METHODOLOGY

For such kind of study software, wind tunnels, and on-site records can be used. The last 2 methods are generally used. The similarity of wind speed and topography of the area under consideration needs to be matched while carrying out experiments in wind tunnels and software. While if the structure is to be scaled down its dimensional analysis also needs to be required.

In the considered study a 1:35 scaled model of a gabled roof shed was used. This model was tested in a wind tunnel at an orientation angle of 45° to the roof ridge for both internal and external pressure. A total of 10 pressure taps were fixed at the central axis of the model.

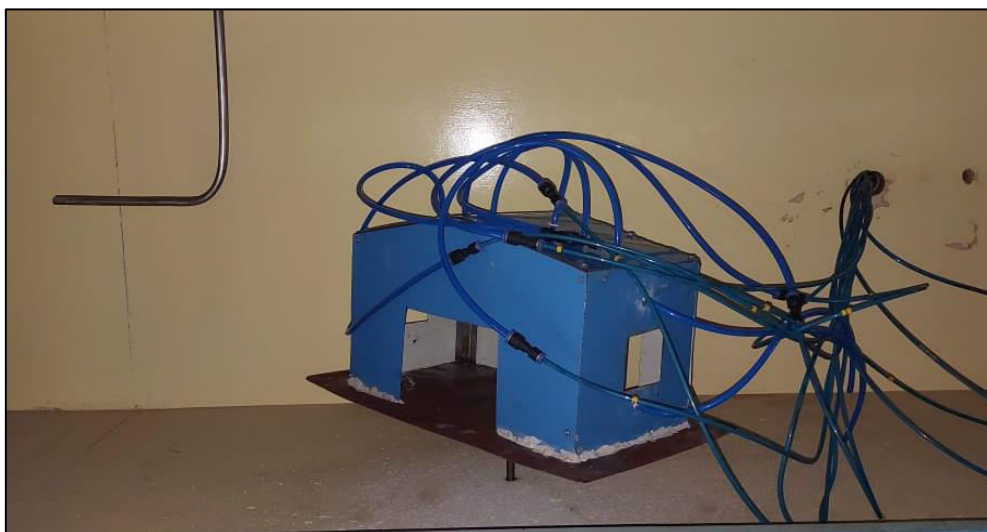


Fig. 1 Shed Model Under Testing for Wind Pressure At 45° to Roof Ridge

IV. EXPERIMENTAL RESULTS

Table 1 External Pressure Distribution of Wind on Industrial Shed Model

Location	Points	Pressure values at 45° for different wind velocity					
		5 m/s	9.12 m/s	10 m/s	15 m/s	20 m/s	25 m/s
Sidewall (windward)	A1	4.7	12.9	14.7	33.6	57.5	91.2
	A2	5.6	13.7	15.5	36.1	67.8	99.7
Roof ceiling (windward)	B1	5.8	16.6	19	42.5	76.2	114
	B2	3.9	10	11.3	24.1	44.1	75.6
	B3	3.7	9.6	10.9	23.4	38.9	65
Roof ceiling (leeward)	C1	4.3	11.4	13	29.4	51.3	82.3
	C2	0.4	1.15	1.3	3.3	6.8	12.6
	C3	0.2	0.7	0.8	1.9	3.7	7
Sidewall (leeward)	D1	4.3	11.2	12.7	28	49.3	78.6
	D2	5.1	13.5	15.4	34.7	62.6	100.9

It was observed that windward sidewall faced comparatively more pressure at upper tap A2, while windward roof ceiling faced peak pressure at tap B1 which is at 42.5 mm from the eave of a column, leeward roof ceiling faced maximum pressure at tap placed near ridge i.e., C1, and leeward sidewall faced peak intensities at bottommost tap D1. From the pressure distribution, it can be said that the critical point is the windward roof at the wall joint B1, as it faced the maximum intensity when the wind attack angle was oblique to the roof ridge.

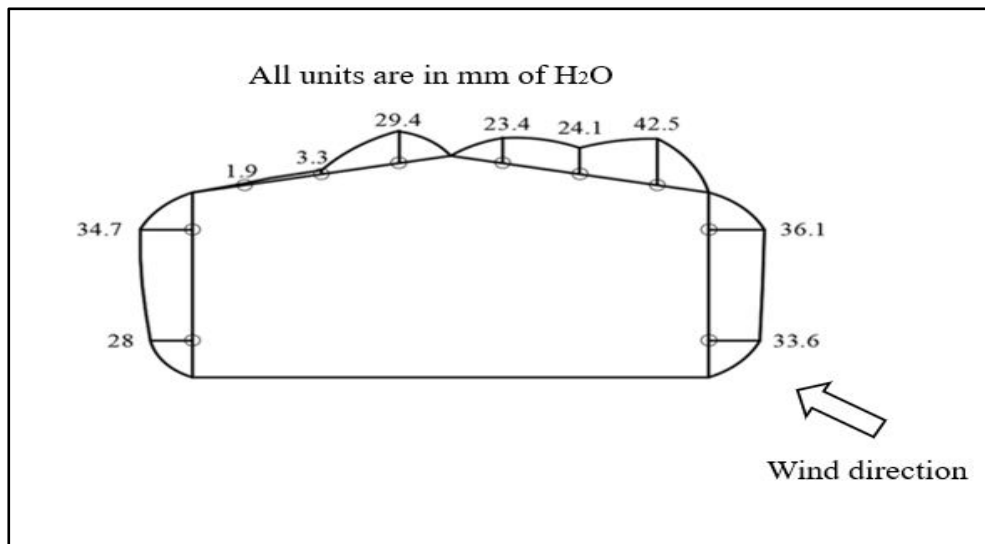


Fig. 2 Wind Pressure Distribution Along the Central Axis of Shed for 15 m/s

Table 2 Internal Pressure Distribution of Wind on Industrial Shed Model

Location	Points	Pressure values at 45° for different wind velocity					
		5 m/s	9.12 m/s	10 m/s	15 m/s	20 m/s	25 m/s
Sidewall (windward)	A1	2.7	8.3	9.6	20.7	37.6	55
	A2	2.7	8.4	9.5	21	38	55.2
Roof ceiling (windward)	B1	1.3	4.2	4.9	11.5	20.9	32.9
	B2	2.8	8.9	10.2	22.1	40	59.5
	B3	2.7	8.7	10	21.7	40.1	58.2
Roof ceiling (leeward)	C1	3.6	11.3	13	27.7	50.9	71
	C2	0.2	0.8	0.9	1.9	3.6	5.8
	C3	0.2	0.7	0.8	2.2	4.4	6.4
Sidewall (leeward)	D1	0.1	0.4	0.5	1.3	3.9	5.7
	D2	0.2	0.8	0.9	2.1	4.2	5.9

It was observed that windward sidewall faced more or less the the the same pressure at both taps A1 and A2, while windward roof ceiling faced comparatively less pressure at tap B1 which is at 42.5 mm from the eave of a column, leeward roof ceiling faced maximum pressure at tap placed near ridge i.e., C1, and leeward sidewall faced peak intensities at upper tap D2. From the pressure distribution, it can be said that the critical point is the leeward roof at the ridge joint C1, as it faced the maximum intensity when the wind attack angle was oblique to the roof ridge.

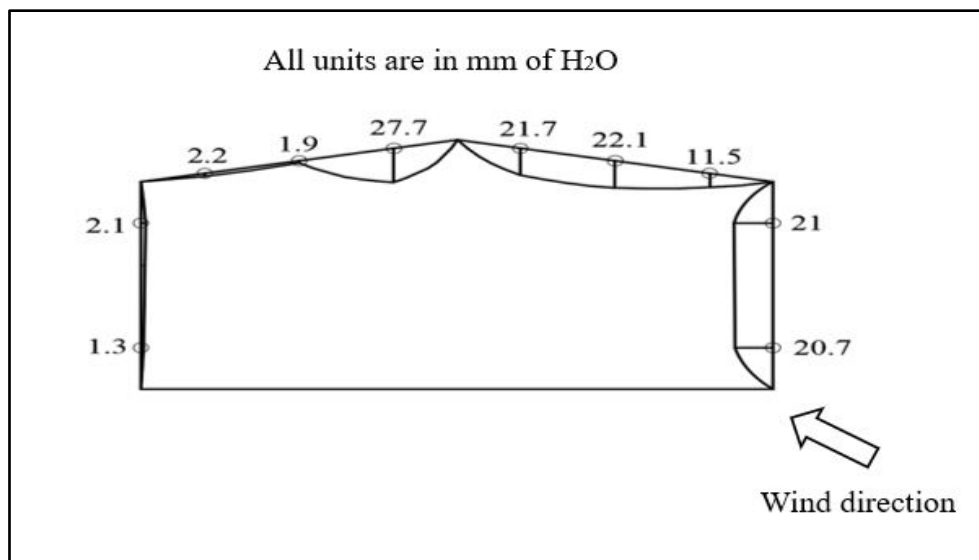


Fig. 3 Wind Pressure Distribution Along the Central Axis of Shed for 15 m/s

IV. CONCLUSION

From the study, it was observed that external pressure generation on cladding is directly proportional to angle of wind attack. The face of shed in the front faced the peak pressure intensities. Maximum internal pressure was observed at the ridge joint and at eaves level. A drastic decrease in internal pressure was observed at leeward side because of provision of fire exit door. This also proves the fact as the opening in structure increases internal pressure decreases.

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