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Wind Pressure Distribution on Low-Rise Buildings with 3-Span North-Light Roofs

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Abstract

Buildings with a low-rise profile typically consist of one to three floors, commonly situated in residential and suburban locales. These structures provide a more close-knit and community-oriented living environment. Often employing traditional materials and construction methods, low-rise buildings seamlessly integrate with the natural surroundings. North Light, characterized by sunlight received through north-facing windows, maintains a consistent angle and color throughout the day as it avoids direct exposure to the sun. This phenomenon results in subdued shadows and a cooler ambiance compared to direct sunlight, owing to the scattering of light by the Earth's atmosphere through Rayleigh scattering. In the realm of construction, low-rise structures, including industrial and factory buildings, are prevalent. Notably, the susceptibility of these constructions to extreme winds has become increasingly apparent. These structures showcase diverse roof forms, such as flat roofs, gable roofs, and hip roofs with various geometric shapes. Wind flow characteristics exhibit significant variations among different roof designs. However, existing codal information often remains limited, typically addressing single-span configurations and specific wind angles. Unfortunately, many codal provisions lack comprehensive data for a broader spectrum of roof forms. To bridge this informational gap, the current research delves into detailed experimental studies focused on 3-span north-light roofs under diverse wind incidence angles. The experiments utilize an open-circuit boundary layer wind tunnel, with models constructed from Perspex sheets. The research yields valuable insights for designers involved in the planning of buildings with diverse roof forms. The results, presented through contour plots of mean pressure coefficients, furnish practical and applicable information for designing and constructing buildings featuring different roof geometries.

Keywords: Wind pressure coefficients, north-light, saw-tooth, wind angle of attack, boundary layer flow, pressure points, Perspex sheet, open circuit wind tunnel

1. Introduction

Since the 1960s, investigations conducted in atmospheric boundary layer wind tunnels on building models have served as the primary means of establishing wind design loads. Given the prohibitive expenses associated with full-scale tests, engineers must depend on the ongoing refinement of wind tunnel experiments for novel building configurations. This approach has remained the principal method for formulating wind design codes, encompassing wind pressure and force coefficients for various generic building shapes. Initial research concentrated on gable-roof structures *(Davenport et al., 1977[a, b])* [8, 9] and monosloped roof designs *(Surry et al., 1985)* [23]. Subsequent to these endeavors, studies were conducted to examine the wind loads *(Meecham, 1992)* [16], particularly vital for evaluating wind loads on low-rise structures. As architectural trends evolve, continuous wind tunnel studies are imperativeto update wind load guidelines and validate existing provisions with the integration of new insights.

The evaluation of wind loads entails gathering data on mean wind pressure coefficients and design wind speeds, typically referenced from various wind codes of practice. The *Australian and New Zealand Code [AS/NZS 1170.2:2011]* provides specific details on external wind pressure coefficients (Cpe) applicable to multi-span buildings with north-light roofs. Similarly, the *British code [BS 6399-2:1997]* offers Cpe values for north-light roofs, which are also applicable to multi-span buildings featuring north-light roofs. The *Euro code [EN 1991-1-4:2005(E)]* and the *American code [ASCE 7-02]* also delineate Cpe values for north-light roofs. It is important to note that the available information specifically pertains to isolated buildings, and there is a lack of data addressing interference conditions in the various wind codes.

Wind forces exhibit spatial and temporal variations across a building's surface. Due to their stochastic nature, estimating peak wind loads is challenging, and analytical determination of wind loads through known mathematical methods remains elusive. Wind tunnel studies enable engineers and scientists to offer a relatively comprehensive evaluation of wind-induced loads on a building, encompassing their spatial and time-varying components. The design wind pressures on buildings are intricate and influenced by various factors.

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A sawtooth roof building is characterized by a series of single-pitch roof monitors, creating a roof shape resembling the sharp teeth of a saw. This architectural design is commonly found in industrial buildings and factories, where the vertical face of the roof monitor incorporates window glazing to allow natural light into the structure. To optimize ambient lighting, sawtooth roofs typically feature roof slope angles ranging between 15° and 25°. Unlike gable roof buildings, the research on sawtooth roof systems is not as extensive. Current wind design parameters are derived from a single building model with a fixed aspect ratio and roof slope, as per *Saathoff and Stathopoulos' work (1992[a, b])* [21, 22]. It remains to be established whether these results can be extrapolated to other building dimensions.

The *ASCE 7-02* provides wind pressure coefficients for various roof shapes, including gable roofs, monosloped roofs, sawtooth roofs, and multi-span gable roofs. In the critical suction zones, wind pressure coefficients for monosloped roofs surpass those for gable roofs by 12%. For sawtooth roofs, critical wind pressure coefficients exceed those for gable roofs by 57% in corners and 88% in edge zones. Interestingly, the design wind pressure coefficients for the corner zone of monosloped roofs are 41% lower than those for sawtooth roofs, despite the apparent geometric similarities between these two building types.

Tieleman (2006) [24] outlined the procedures employed for obtaining pressure coefficients through extreme value analysis of measured data. However, it's important to note that there is no explicit probability distribution specifically applicable to wind pressure time series. Additionally, the largest peak pressure on a model can vary by up to 30% from one measurement to another, attributed to natural variations in the largest peak during a measurement period.

Geurts et al. (2004) [10] demonstrate that the extrapolation method relies on the assumption that the peak value and sampling time adhere to a theoretical relationship. This relationship can be analyzed by handling peaks of subrecords with varying sampling lengths. The peak value for a whole record is obtained by extrapolating the peaks of subrecords using the analyzed relationship function between peak value and sample length. This method is employed to enhance the stability of peak estimation, particularly when the direct peak value for the whole record is deemed unstable.

University of Western Ontario (UWO) wind tunnel experiments were conducted to investigate the effects of roof slope, building height and terrain exposure on the wind pressures occurring on monosloped roof buildings *Surry and Stathopoulos (1985)* [23]. The tests used 1:500 scale monosloped roof models constructed with plan dimensions of 100 mm by 40 mm and low eave heights of 10 mm and 15 mm. The model's roof angle was adjusted in the range of 0° to 18.4° and there were 78 pressure taps installed on the model roof with smallest tributary area being 18 m2 at full scale. The results included the local and area-averaged wind pressures coefficients for seven wind directions (0°, 40°, 60°, 90°, 120°, 140° and 180°). The model's dimensions and wind directions are shown in Fig. 2.2, where 0o represents wind blowing perpendicularly to the higher edge.

Stathopoulos and Mohammadian (1985[a, b]) [19, 20] carried out wind tunnel experiments on 1:200 scale monosloped roof models and the previously examined 1:500 scale UWO model, as described earlier. These tests were conducted at the boundary layer wind tunnel located in the Centre for Building Studies Laboratory (CBS) at Concordia University and also investigated the averaging area effect on wind pressure coefficients for the Concordia models.

Surry and Stathopoulos (1985) [23] conducted a review of research papers focusing on wind loads on low buildings featuring monosloped roofs. In particular, they specifically compared wind pressure coefficients for monosloped roofs with those for gable roofs having similar roof angles.

Holmes (1983, 1987) conducted an investigation on local and area-averaged wind pressures applied to a 5-span sawtooth building with a roof angle of 20°. The building dimensions, reveal that the single span building has plan dimensions of 39 m in length by 12 m in width at full scale, with a low eave height of 9.6 m. The study involved measuring local and area-averaged wind pressures on a 1:200 scaled model, simulated under open country exposure conditions in a boundary layer wind tunnel. The turbulence intensity of wind speed for the simulated open country terrain was maintained at 0.20 at a height of 9.6 m.

Saathoff and Stathopoulos (*1992[a, b]*) [21, 22] carried out wind tunnel tests on building models featuring a monosloped roof as well as 2-and 4-span sawtooth roofs, all with a roof slope of 15 degrees. The models were constructed at a scale of 1:400 and subjected to testing with eleven different wind directions. These wind directions included 0°, 30°, and 150° at 15° increments, and 180°, simulating open country boundary layer flow. The objective of the tests was to investigate wind pressure distributions on these building models.

The earlier investigations have provided insights into the impact of wind on monosloped and sawtooth roof structures. However, existing codes and standards do not offer specific provisions for wind loads on separated sawtooth roofs (as depicted in Figure 1-b). Given this absence of relevant provisions, engineers frequently resort to codified pressure coefficients designed for traditional sawtooth roofs when designing separated sawtooth roofs. The challenge arises from the uncertainty regarding how the presence of flat roof sections may either shield or intensify the wind load effects on the adjacent sloped roofs in such roof geometries.

Building on the work of *Prevatt and Cui (2010)* [18], this current study aims to discern the similarities and differences in wind loads on north-light/saw-tooth roof structure. The objective is to develop codified pressure coefficients specifically tailored for separated sawtooth roofs. Furthermore, the study explores the impact of factors such as separation distance and the number of roof spans on the wind pressures experienced by the roof.

2. Experimental Programme

2.1. Details of Models

Four variations of low-rise buildings with rectangular plans and north-light (monoslope) roofs were developed. One model incorporates Perspex sheets for construction, while the other three are made of plywood.

All models maintain standardized dimensions:

- Length: 400 mm
- Width: 200 mm
- Low-wall eaves height: 150 mm
- High-wall eaves height: 265 mm
- Roof pitch: 30° (refer to Figure 1)

These models are scaled-down representations of a full-scale prototype building with a plan size of 10 m x 20 m at a 1:50 scale. The low-wall height in the model corresponds to 7.5 m, and the high-wall height scales to 13.25 m, as shown in Figure 1 and Figure 2.

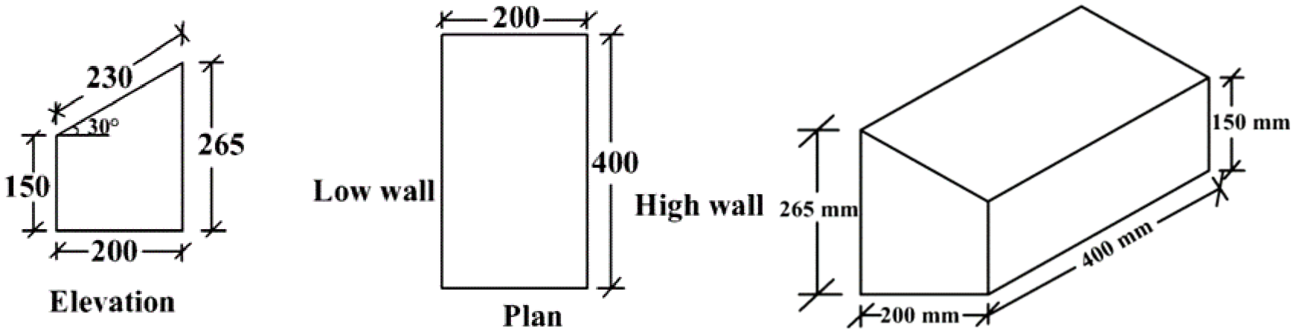

Fig 1: Model of rectangular plan building with north-light roof

Fig 2: North-Light/Saw-Tooth Roof

2.2. Wind Flow Characteristics

The experiments were conducted in an Open Circuit Boundary Layer Wind Tunnel at the Indian Institute of Technology Roorkee, India. The wind tunnel features a 15 m long test section with cross-sectional dimensions of 2 m (width) × 2 m (height).

Flow roughening devices—including vortex generators, a barrier wall, and cubical blocks with side lengths of 150 mm, 100 mm, and 50 mm—were positioned at the upstream end of the test section. These devices were employed to achieve a wind velocity profile corresponding to Terrain Category 2, following the Indian Standard on Wind Loads.

During testing, the model was placed at the center of the turntable within the tunnel. A free-stream wind velocity of 10 m/s was maintained, measured at a 1 m height above the floor of the test section.

This setup ensures the experiments accurately simulate real-world wind conditions, capturing the influence of wind direction and velocity on the models. The flow roughening devices play a key role in generating a representative wind velocity profile for the selected terrain category (refer to Figure 3 and Figure 4)

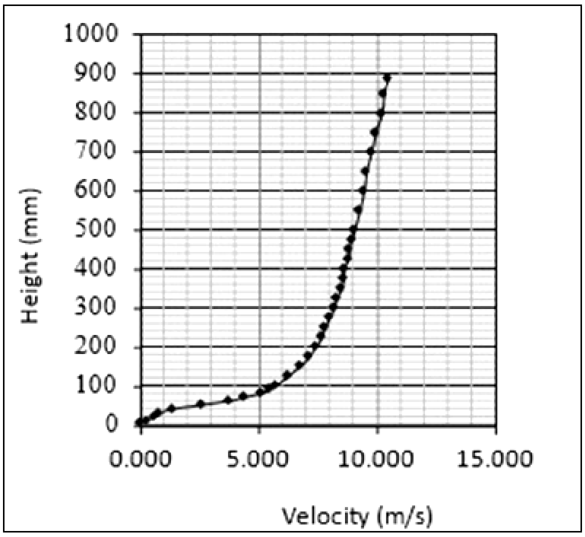

Fig 3: Velocity profile on ordinary scale

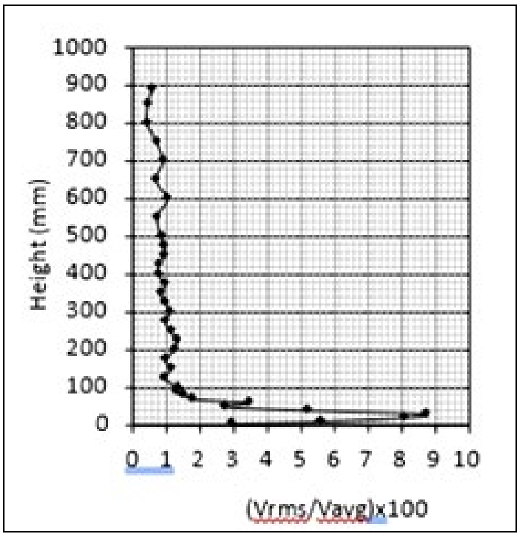

Fig 4: Turbulence intensity profile

2.3. Measurement Technique

The Perspex sheet model is equipped with 35 pressure points distributed across the entire roof surface (Figure 5). This diagram provides detailed information about the distances and locations of these pressure points, as well as the positions of the high-wall and low-wall on the North-Light roof building model.

In the two-span roof building scenario, two models are arranged side by side:

i). Instrumented model – constructed from Perspex sheet

ii). Non-instrumented model – made from plywood

This configuration enables the measurement of wind pressure distribution across the building. Testing Procedure

i). Initial Position (0° Wind Incidence Angle)

- The instrumented Perspex model is placed at the center of the turntable, with the low-wall facing the wind (Figure 6).
- Measurements are conducted, and mean wind pressure coefficients are recorded for all 35 pressure points.

ii). Rotated to 45° Wind Incidence Angle

- The turntable is rotated to a 45° angle (Figure 7), placing the Perspex model on the windward side.
- Wind pressure measurements are repeated at this angle.

iii). Rotated to 180° Wind Incidence Angle

- The turntable is rotated to 180°, interchanging the positions of the Perspex and plywood models relative to the original 0° setup.
- At this angle, the high-wall of the Perspex model faces the wind, while the low-wall is positioned on the leeward side.

This systematic rotation and repositioning allow for a comprehensive understanding of the wind pressure distribution across the roof surfaces under varying wind incidence angles.

After the initial wind pressure measurements, the positions of the Perspex sheet model and plywood models are swapped, and wind pressure values are once again recorded. Photograph 2 documents the setup of the 3-span North-Light roof model within the wind tunnel, particularly under a 45° wind angle of attack. This specific angle of attack facilitates a more in-depth analysis and evaluation of the wind-induced pressures acting on the building model. The photograph serves as a visual record of the experimental configuration during testing, offering a clear depiction of how the model is positioned within the wind tunnel under the prescribed wind conditions

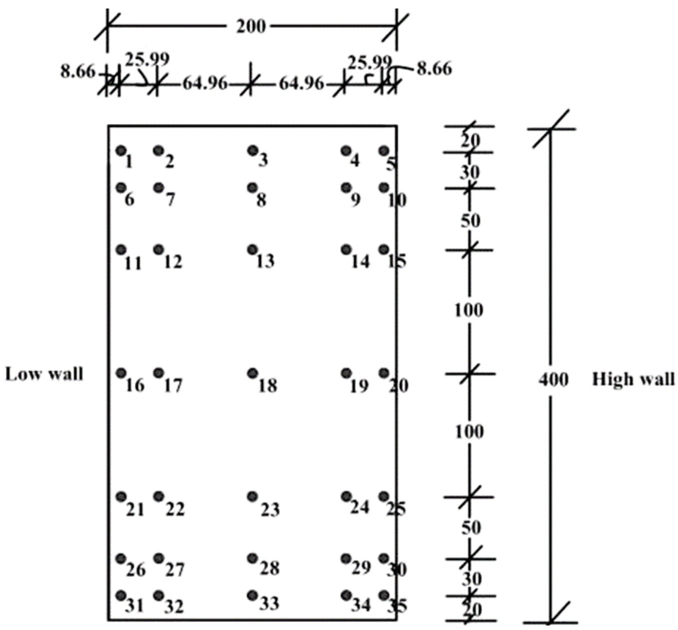

Fig 5: Pressure points positions on north-light roof

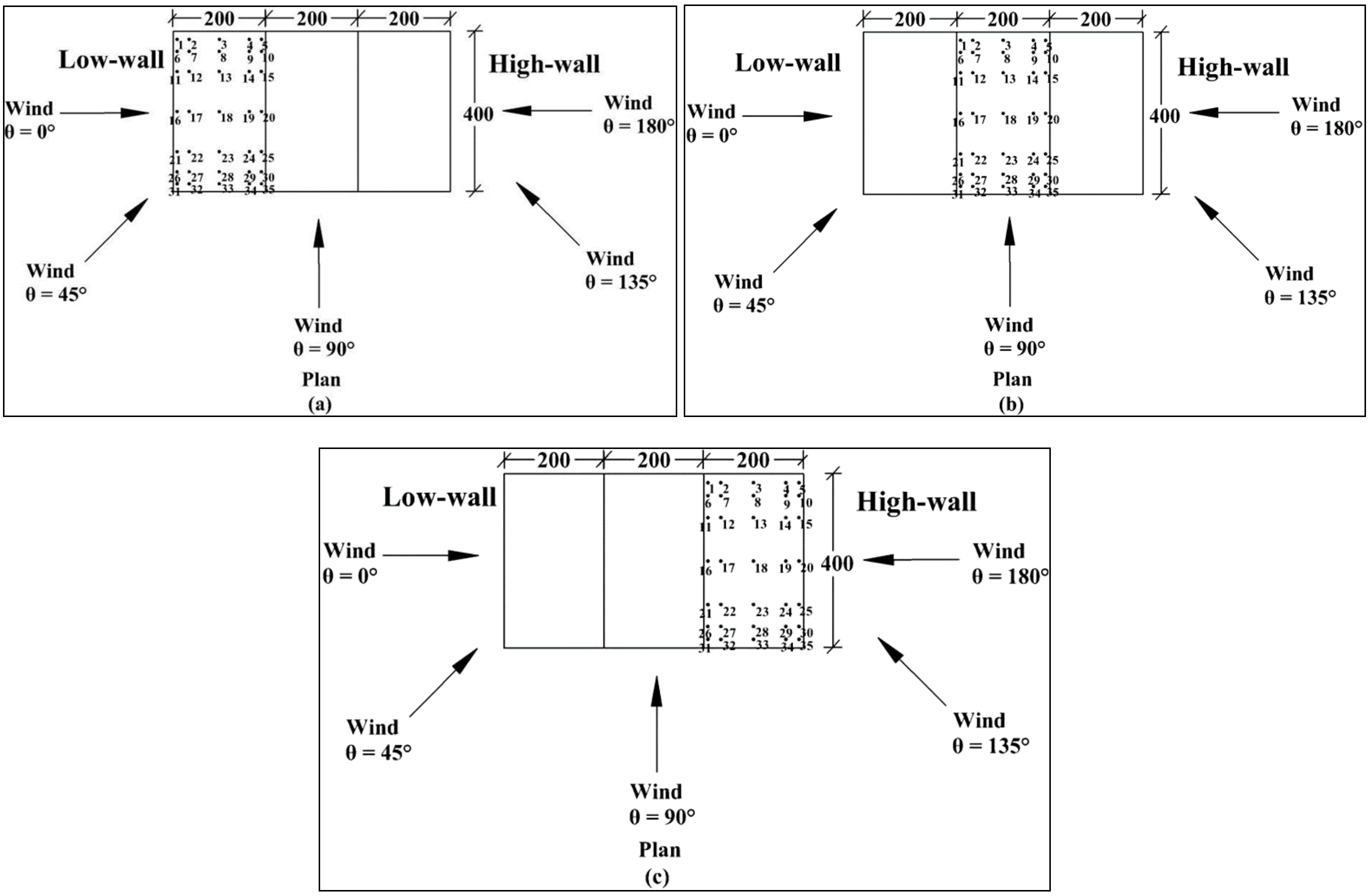

Fig 6: Wind directions on three-span north-light roof building model (All dimensions are in mm)

Fig 7: Three-span north-light roof building model inside the wind tunnel at 135^{o} wind incidence angle

3. Results and Discussion

Contours of mean wind pressure coefficients (Cp) on the roof of building with three-span north-light roof at various wind incidence angles are shown in Figures 8 to 12. Table 1 shows the mean wind pressure coefficients of 3-span north-light roof building under 45° wind incidence angle.

It is noticed that when 3-span north-light roof building is subjected to 0° wind incidence angle (Figure 8) then low-wall is subjected to pressure on windward side of the roof and

therefore pressure is obtained on the windward side of the roof having maximum value of mean pressure coefficient as 0.18 and Figure 8 of contour plot having pressure throughout the low-wall on windward side of the roof.
When the north-light roof is exposed to a 45° wind incidence angle (Figure 9) the pressure is predominantly concentrated on the windward side of the roof, specifically on position 1 of the instrumented buildings. The maximum mean pressure coefficient reaches approximately 0.1, a value lesser than that obtained when the 3-span north-light roof is subjected to a 0° wind incidence angle.
Similarly, values of mean wind pressure coefficients can be obtained from contour plots of other wind incidence angles also.

It's noteworthy to compare these findings with *Saathoff and Stathopoulos' work in 1992[a, b]* [21, 22]. Their research emphasized the need to determine the generalizability of results to a broader spectrum of building configurations. A comparison with *ASCE 7-02* also reveals substantial differences, particularly in extreme wind pressure coefficients between monosloped and sawtooth roofs. The *ASCE 7-02* design wind pressure coefficient (-4.1) contrasts with the extreme wind pressure coefficient determined by *Saathoff and Stathopoulos* (-4.2), which is notably higher than the values obtained in the current research. This underscores the importance of continued research and exploration in understanding wind behavior on various building configurations

Table 1: Mean wind pressure coefficients (Cp) on three-span north-light roof building at 45⁰ wind incidence angle

Pressure point number	Cp		
	Span No. 1	Span No. 2	Span No. 3
1	-0.18	-0.17	-0.14
2	-0.11	-0.20	-0.15
3	-0.12	-0.29	-0.21
4	-0.13	-0.03	0.05
5	-0.15	-0.03	-0.07
6	-0.17	-0.15	-0.10
7	-0.01	-0.12	-0.08
8	-0.06	-0.35	-0.23
9	-0.08	0.29	0.09
10	-0.11	0.03	0.00
11	-0.12	-0.13	-0.06
12	-0.02	-0.18	-0.09
13	-0.01	-0.25	-0.11
14	-0.05	0.11	0.11
15	-0.10	0.03	0.01
16	-0.06	-0.10	-0.13
17	0.06	0.19	-0.21
18	0.04	-0.07	-0.06
19	-0.06	0.05	0.05
20	-0.16	-0.07	-0.05
21	-0.03	-0.58	-0.45
22	0.13	-0.72	-0.50
23	0.10	-0.18	-0.23
24	-0.02	-0.06	-0.04
25	-0.40	-0.31	-0.14
26	0.04	-0.66	-0.57
27	0.10	-0.55	-0.48
28	-0.03	-0.30	-0.25
29	-0.22	-0.21	-0.11
30	-0.39	-0.29	-0.09
31	0.09	-0.70	-0.57
32	0.03	-0.56	-0.53
33	-0.24	-0.49	-0.41
34	-0.29	-0.41	-0.24
35	-0.59	-0.45	-0.22

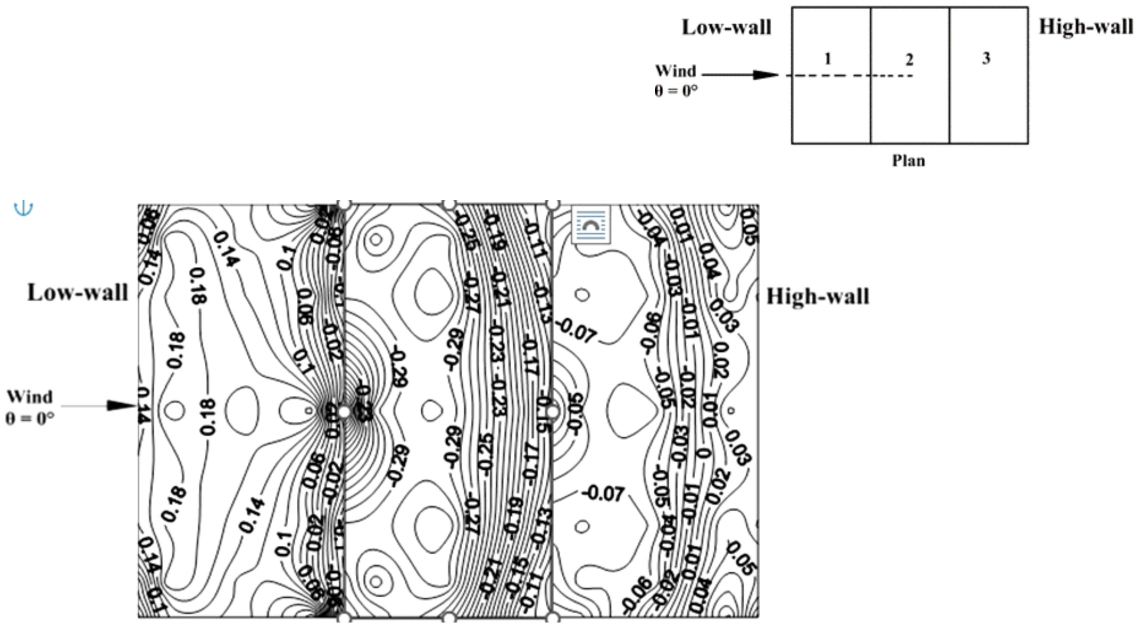

Fig 8: Contours of mean wind pressure coefficients (Cp) on the roof of building with three-span north-light roof at 0⁰ wind incidence angle

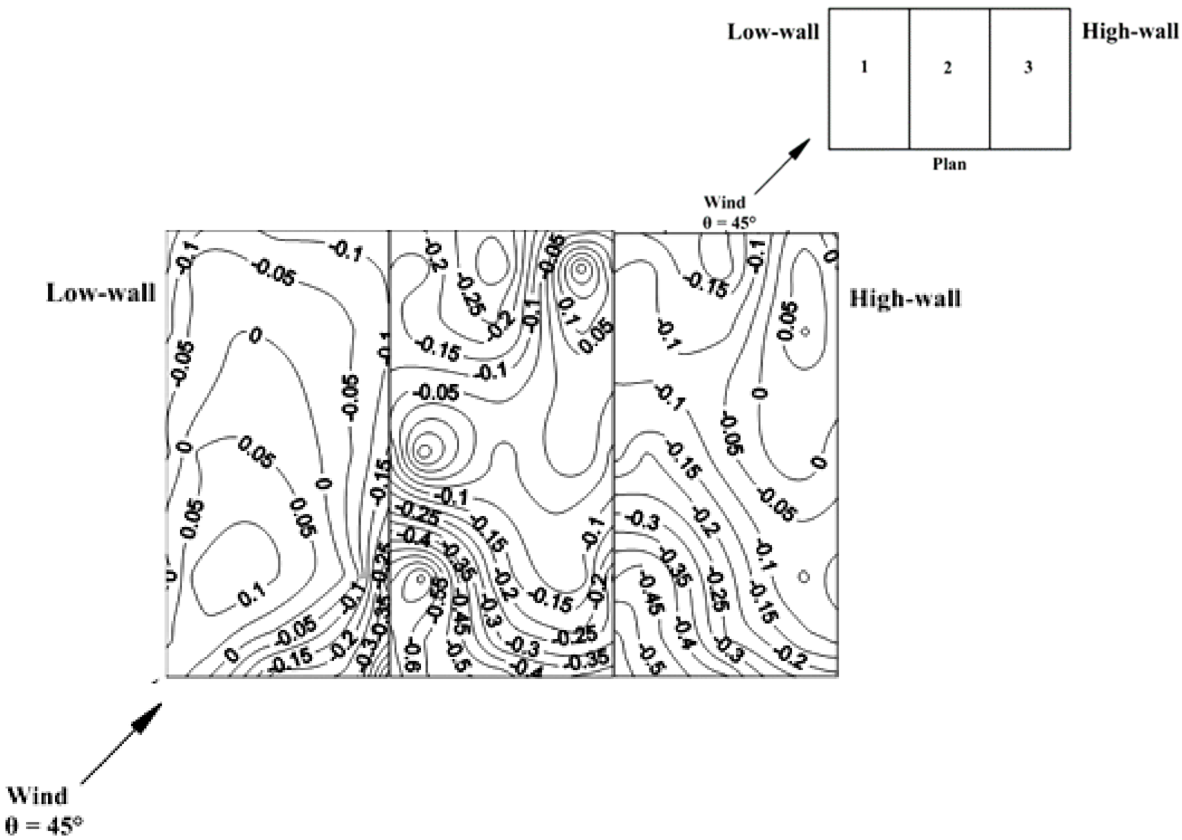

Fig 9: Contours of mean wind pressure coefficients (Cp) on the roof of building with three-span north-light roof at 45⁰ wind incidence ang

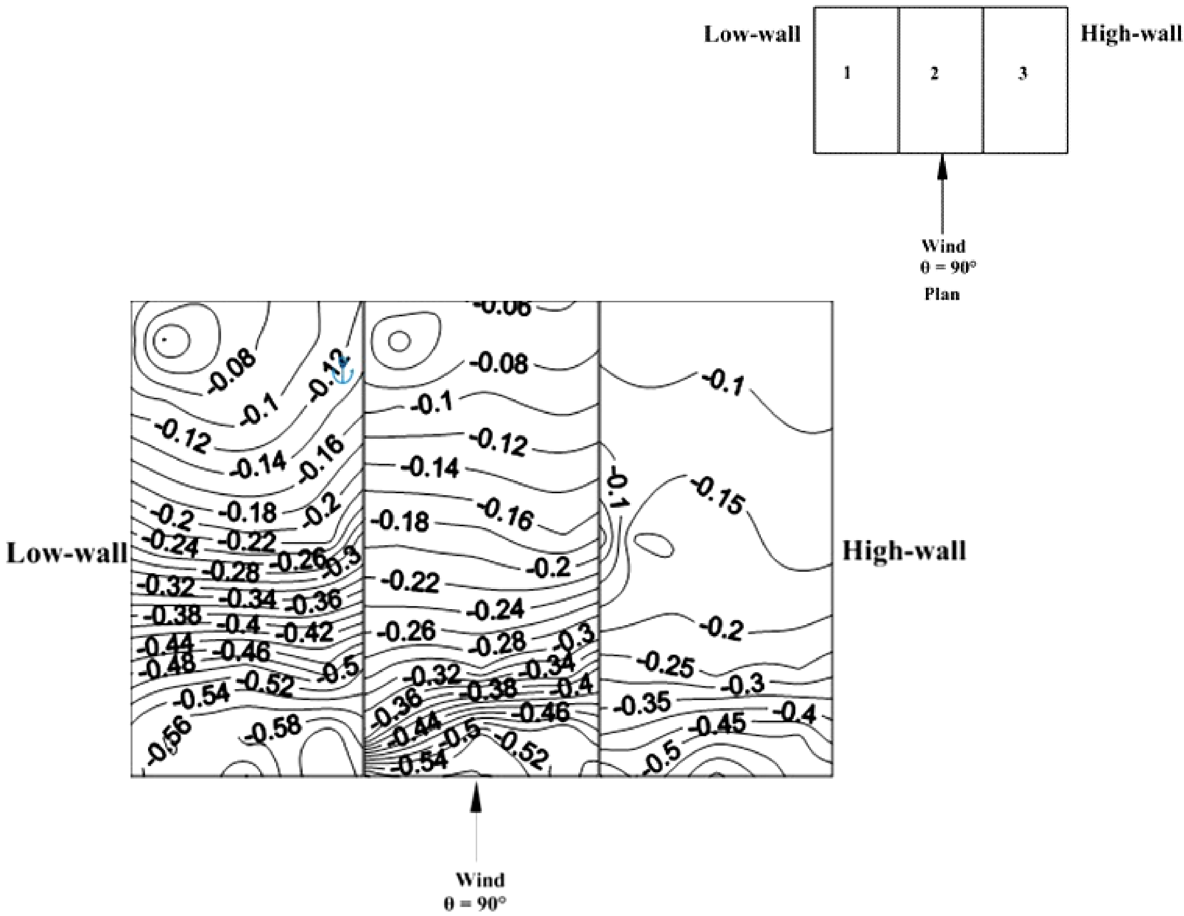

Fig 10: Contours of mean wind pressure coefficients (Cp) on the roof of building with three-span north-light roof at 90° wind incidence angle

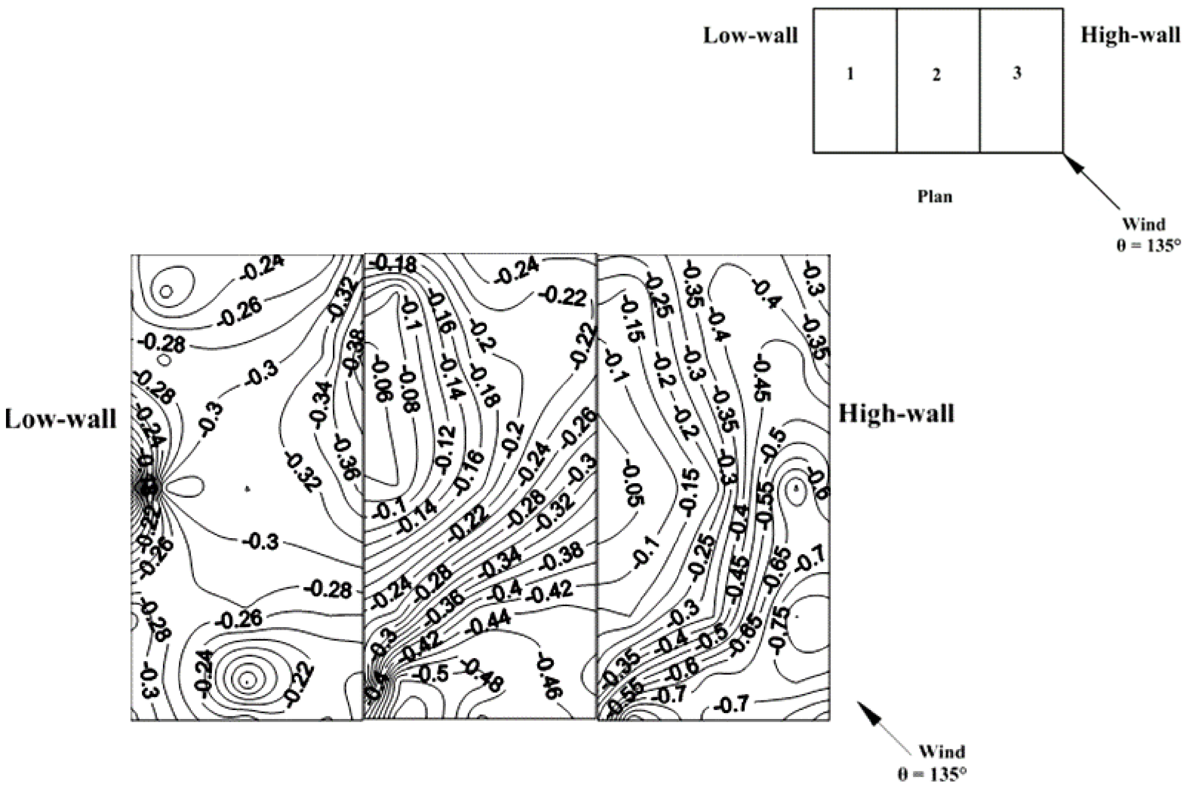

Fig 11: Contours of mean wind pressure coefficients (Cp) on the roof of building with three-span north-light roof at 135° wind incidence angle

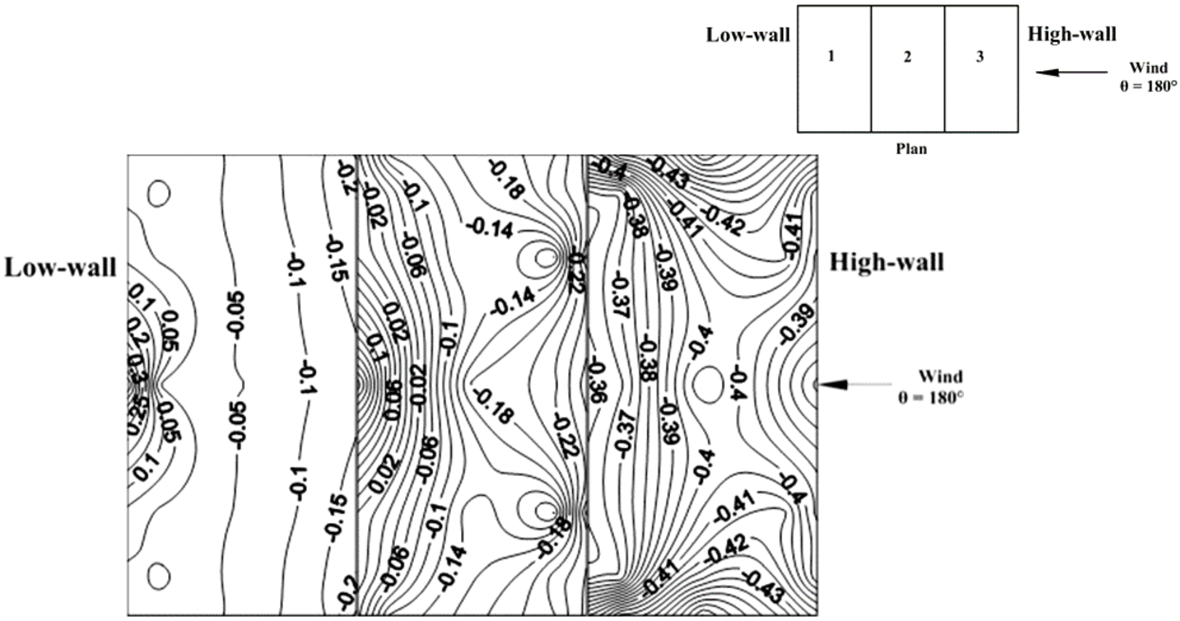

Fig 12: Contours of mean wind pressure coefficients (Cp) on the roof of building with three-span north-light roof at 180º wind incidence angle

4. Conclusions

Wind load standards for low-rise north-light (saw-tooth) roof buildings across various countries typically focus on isolated structures and specific wind incidence angles**.** This narrow scope presents challenges for structural designers in ensuring both the safety and cost-efficiency of similar structures. The experimental results highlight the considerable influence of wind incidence angles on wind pressure coefficient values. These findings emphasize the importance of accounting for the most critical wind direction when designing the structural system of sloping roofs. Failure to do so may lead to inaccurate estimations of wind loads, compromising the structure's performance and safety.

It is crucial to note that, in the experimental setup, only a small section near the windward edge of the hip roof experiences pressure, while the remaining roof surface is subjected to suction. This highlights the necessity for a comprehensive understanding of wind patterns and their effects on different parts of the structure. Structural professionals must consider these factors to ensure accurate and effective design, emphasizing the importance of incorporating detailed wind analysis into the design process for such roofs. This approach is essential for optimizing the structural integrity and overall performance of low-rise north-light/saw-tooth roof buildings in varying wind conditions.

The wind pressure coefficient values exhibit significant sensitivity to wind incidence angles, highlighting the imperative for designers to prioritize the most critical wind direction when developing the structural system for sloping roofs of this nature. Although the wind pressure distribution patterns on buildings with single and two-span north-light/saw-tooth roofs share some similarities, the wind pressure distribution on single-span buildings with north-light roofs in various alphabetical shapes displays distinctive patterns. This observation underscores the necessity for a nuanced design approach, considering not only the roof type but also the arrangement and layout of multiple buildings. Accurately accounting for the complexities of wind interaction in such configurations is essential for ensuring the precision and effectiveness of the design process.

The North-light roof experiences either pressure or suction, contingent upon the direction of the wind. The wind pressure coefficients are significantly influenced by wind incidence angles, prompting designers to prioritize the most critical direction when designing the structural system for monoslope roofs of this type. Notably, existing codal provisions and research publications have predominantly concentrated on two-span north-light/saw-tooth roof structures. Unfortunately, there is a conspicuous lack of information in codal provisions regarding two-span north-light roof buildings, whether rectangular or possessing other geometrical shapes. This informational gap underscores the necessity for further research and the development of codal provisions explicitly addressing design considerations and wind pressure distribution patterns for two-span north-light/saw-tooth roof structures.

This research provides valuable insights, emphasizing the importance of broadening design considerations to include a wider range of roof configurations. A comprehensive approach is essential for achieving accurate and effective structural design. The findings underscore the necessity for codal provisions that reflect the unique characteristics and complexities of two-span north-light roof buildings, ensuring safe, efficient, and reliable designs

References

1. Adriaenssens *et al*. "Evaluation and Optimization of a Traditional North-Light Roof of Industry Plant Energy Consumption", 2013, 1944-1960, https://www.mdpi.com/1996-1073/6/4/1944
2. AIJ (Architectural Institute of Japan). 1993. AIJ recommendations for loads on buildings.
3. Tokyo: AIJ
4. American Society of Civil Engineers (ASCE). (2002). "Minimum Design Loads for Buildings and Structures, ASCE 7-02."
5. AS/NZS. "Australian/New Zealand Standard: Structural design actions. Part 2, Wind actions." AS/NZS 1170.2: 2011, Standards Australia International Ltd., Sydney, Australia, 2011.
6. ASCE 7. "Minimum design loads for buildings and other structures." ASCE 7-10, American Society of Civil Engineers: Structural Engineering Institute, Reston, Va, 2010.
7. Cui. "Wind Effects on Monosloped and Saw-Tooth Roofs", Ph. D. Thesis, Clemson University, 2007.

8. Davenport AG, Surry D and Stathopoulos T. "Wind Loads on Low-Rise Buildings: Final Report of Phases I and II – Parts 1 and 2." BLWTSS8-1977, the University of Western Ontario, BLWT-SS8-1977, Second Edition (November), 1977a.
9. Davenport AG, Surry D and Stathopoulos T. "Wind Loads on Low-Rise Buildings: Final Report of Phases III – Parts 1 and 2." BLWT-SS8-1977, University of Western Ontario, Second Edition (November), 1977b.
10. Geurts CPW, PC Van Staalduinen and MS De Wit. "Towards a Reliable Design of Facade and Roof Elements against Wind Loading." HERON, 2004, 49(2).
11. Holmes JD. "Wind Loading of Saw-Tooth Buildings, Part 1: Point Pressure." International Report Number: 83/17, Division of Building Research, CSIRO, Melbourne, Australia, 1983.
12. Holmes JD. "Wind Loading of Multi-Span Building." First National Structural Engineering Conf., Melbourne, Australia (Aug. 26-28), 1987.
13. Jensen M and Franck N. "Model-Scale Tests in Turbulent Wind, Part II." The Danish Technical Press, Copenhagen, 1965.
14. Kopp GA, Surry D and Mans C. "Wind Effects of Parapets on Low Buildings: Part 1. Basic Aerodynamics and Local Loads." *Journal of Wind Engineering and Industrial Aerodynamics*, 2005, 817-843.
15. Lieblein J. "Efficient Methods of Extreme-Value Methodology." National Bureau of Standards, 1974.
16. Meecham D. "The Improved Performance of Hip Roofs in Extreme Winds-a Case Study." *J. Wind Eng. Ind.* Aerodyn, (41-44), 1717-1726, 1992.
17. Peng and Prevatt. "Wind Load Design Recommendations For Seperated Saw-Tooth Roof Structures", The 13th American Conference on Wind Engineering (13ACWE) Gainesville, Florida, USA, 2017, 21-24.
18. Prevatt *et al*. "Wind Tunnel Studies on Sawtooth and Monosloped Roofs", *Journal of Structural Engineering*, 2010, 1161-1171.
19. Stathopoulos T and Mohammadian AR. "Code Provisions for Wind Pressure on Low Buildings with Mono-Sloped Roofs." Proc. Asia Pacific Symp. On Wind Engineering, Roorkee, India, 1985a.
20. Stathopoulos T and Mohammadian AR. "Wind Loads on Low Buildings with Mono-Sloped Roofs." Proc. 6th Colloquium on Industrial Aerodynamics, Aachen, Germany, 1985b.
21. Saathoff P and Stathopoulos T. "Wind Loads on Buildings with Saw-Tooth Roofs." *Journal of Structural Engineering*. 1992a; 118(2):429-44.
22. Stathopoulos T and Saathoff P. "Codification of Wind Pressure Coefficients for Saw-Tooth Roofs." *Journal of Wind Engineering and Industrial Aerodynamics,* 1992b 41-44.
23. Surry D and Stathopoulos T. "The Wind Loading of Low Buildings with Mono-Sloped Roofs." University of Western Ontario BLWT-SS38-1985, 1985.
24. Tieleman HW, Elsayed MAK and Hajj MR. "Peak Wind Load Comparison: Theoretical Estimates and ASCE 7." Journal of Structural Engineering (July), 2006, 1150-1157