WIND TUNNEL STUDY ON CABLE STAYED PAVILION ROOFS
- A CASE STUDY

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ABSTRACT
This paper deals with the experimental study carried out on scaled down models (scale 1:100) of cable stayed pavilion roofs (proposed for a university complex in Trinidad, West Indies), under simulated boundary flow conditions, at the National Wind Tunnel Facility (NWTF), IIT Kanpur. The proposed cable stayed pavilion roofs are flexible structures, hence sensitive to wind loads.

The tests on cable stayed pavilion roof models have been carried out for stand-alone as well as the interfering situations. The pressure coefficients (mean, maximum, and rms) have been obtained at various locations and different wind incidence angles (varying between 0° to 360° @ 10° interval) by testing the model at design wind speed of 45 m/s (162 kmph), as specified by the user. The test results have been presented in the form of Cp- contours, X-Y plots, and tables.

KEYWORDS: WIND TUNNEL, CABLE STAYED PAVILION ROOFS, LOW-RISE BUILDING, RIGID MODEL, STAND-ALONE, INTERFERENCE, PRESSURE COEFFICIENT

Introduction
The cable stayed pavilion roofs are flexible structure; hence wind sensitive and prone to large wind-induced vibrations. Further, wind forces on a structure are usually estimated considering it as an isolated structure; however, the practical situation is far different, since, the structure is invariably surrounded by one or more structure(s) in its vicinity. Thus, the flow fields around the neighboring structures would interfere with each other and create a wind field, which may be much different from that for an isolated structure. Aerodynamic interference between two or more structures has been found to modify the response of each of the structure significantly due to change in flow pattern.

Further, it is not possible to estimate precisely the aerodynamic loads on a structure under interfering conditions using existing analytical models. Thus, wind tunnel studies are generally carried out to estimate the mean and dynamic response of structure under interfering conditions. Also, the standard codes of practice suggest the use of wind tunnel for unusual structural shapes and locations for which sufficient information is not available in the standard codes of practice/literature.

As a part of this project, an experimental study on model (1:100 scale) of cable stayed pavilion roofs (proposed for a university complex in Trinidad, West Indies), has been carried out at the National Wind Tunnel Facility (NWTF), IIT Kanpur; a state-of-the-art facility having test section cross-section of 3.00m x 2.25m and length 8.75m.
The Prototype Structure

The proposed cable stayed pavilion roofs structure is situated between two building blocks, each approximately four storey high (about 15m). As seen in figure 1, two towers are the main supports from which cables in turn support the roof. Uplift is catered by cables, which are anchored to the ground. The plan dimensions of both the roofs are 41.0m x 41.0m, the elevation of top surface of the roofs is 14.5m. The total height of main central pylons is 26.0m.

Need for the Study

The experimental work presented herein deals with a case study. Due to the shape and location of the cable stayed roofs, the designer was interested in determining the most adverse wind loading conditions that the structure might be subjected at design wind speed. Since, the information required for safe and economic design of the structure was not available in the standard codes of practice/literature, wind tunnel study was required.

The main objective of the study was to obtain pressure distribution (Cp - mean, maxima and rms) at various locations on top (upper) and bottom (lower) surfaces of both the roofs, under stand-alone as well as interfering conditions, for varying wind incidence angles.

Test Set-up

Wind Tunnel Facility

The test campaign was carried out at the National Wind Tunnel Facility (NWTF), IIT Kanpur. It is a state-of-the-art, 3.00m x 2.25m closed-circuit wind tunnel, with capabilities of wind speed upto 324 kmph, and interchangeable test sections of 5.75m (upstream) + 3m (downstream) length (total length 8.75m). The NWTF has been provided with various sophisticated measuring and simulation systems. It is equipped with special equipments and instrumentation that include: Sting-type model support system; Turn tables with motor drive and controls; 3-axis automated probe traverse mechanism; Six-component strain gage balance for force measurement; Electronic pressure scanners with 350-point surface pressure measuring capability; Hot wire anemometer; 3D PIV System; 6 watt Argon–ion laser with fog generator for flow visualization; CCTV monitoring and recording and virtual instrumentation (VI) based data acquisition and control system.

Models Used

The rigid models of cable stayed pavilion roof, and surrounding buildings and structures (interfering buildings) lying within close vicinity about 120m radius, have been modeled and fabricated at a geometric length scale of 1:100. The roof models have been fabricated in steel through CNC machining, whereas the surrounding buildings/structures have been fabricated out of timber.

Model Instrumentation

The rigid model of the cable stayed pavilion roofs (both the spans) have been instrumented with ESP scanners (PSI make, steady pressure sensors) as follows;

i. The pressure ports [104 ports on one roof (top and bottom surfaces)] have been provided on both the spans of cable stayed roof to obtain pressure distribution along various cross sections and different test conditions.
a. Pressure ports (at 52 different locations) have been provided to obtain pressure distribution on the top (upper) surface of the cable stayed pavilion roofs (one span).

b. Pressure ports (at 52 different locations) have been provided to obtain pressure distribution on the bottom (lower) surface of cable stayed pavilion roofs (one span).

ii. Thus, total 208 pressure ports [104 ports on one roof span (top and bottom surfaces) x two

Figure 2: Pressure Port Locations on Top and Bottom Surfaces of the Roof Models

Experimental Tests

Wind profile

The proposed cable stayed roofs are to be constructed in Trinidad (West Indies). The targeted mean wind velocity profile in which the prototype cable stayed pavilion roofs are proposed to be situated, corresponds to terrain category II (power law index ‘\( \alpha = 0.14 \)) as per the Indian Standard Codes [IS:875 (Pt-3) 1987, and IS:4998 (Pt-2) 1992].

The target profile parameters at full scale have been taken from the literature and laboratory expertise. As seen from the figures below, there seems to be a good approximation of wind profile in the area. The atmospheric boundary layer (ABL) velocity profile distribution was simulated in the wind tunnel using various roughening devices such as; spires, grid, and blocks, as shown in figure 3. The final configuration of roughening devices, arrived at, after series of preliminary tests, was fixed at the entry of wind tunnel test section.

Figure 3: Arrangement of Roughening Devices in Wind Tunnel for ABL Simulation
The velocity profile and turbulence intensity profile generated in the wind tunnel are shown in figures 4 and 5, given below.

High-Frequency Pressure Integration Study

The objective of this part of the study was to determine wind loads on cable stayed pavilion roofs (both the spans) by measuring fluctuating pressure patterns (time series) on the scaled down rigid models, as per details mentioned below.

The surface pressure measurement was carried out using high-frequency scanners and high speed data acquisition system. Total eight ESP 32-ports electronic pressure scanners have been used, each having a pressure measuring capacity in the range of ± 5000 Pascal. The scanners were calibrated and their performance was checked before they were used in the experiment. The accuracy of pressure measurement system used for the study is within ± 2.5 Pascal. The raw data is acquired through a Windows-based host computer equipped with a high-speed 16-bit Data Acquisition (DAQ) board (commercially known as PCI 6032E board from National Instruments). The application software is developed in LabVIEW, the graphical programming language. Pressure coefficients (mean, maxima and rms) on the roof surface at various cross-sections have been obtained for stand-alone as well as interfering situations.

![Figure 4: Velocity Profile Generated in WT with α = 0.14](image1)

![Figure 5: Turbulence Intensity Profile Generated in WT](image2)

Experimental Study

The cable stayed pavilion roof models were instrumented to obtain pressure coefficients as mentioned above. The wind tunnel tests were performed on the models under stand-alone condition in a simulated boundary layer flow. This provided the reference data for aerodynamic interference study. Gradually the nearby surrounding structures, namely, Central plaza, East building block, and West building block were placed on the turn table at designated (x,y) locations, in separate test runs. This exercise helped in obtaining the interference effect of individual buildings / structures on the cable stayed pavilion roofs under simulated boundary layer flow. Figure 6 shows the photograph of cable stayed pavilion roof being tested under interfering configurations, along with some close-ups of roof model.

The time series of raw data was acquired to obtain the mean, maxima, and rms values of pressure coefficients at various port locations, and different wind incidence angles. The raw data was acquired for 20 seconds at a sampling frequency of 10 kHz. Total eight electronic pressure scanners were used, each having 32 pressure ports.
The pressure coefficients (mean, maximum, and rms) at various locations and for different wind incidence angles (varying between 0° to 360° @ 10° interval) have been obtained by testing the roof models at design wind speed of 45 m/s.

The mean, maximum, and rms values of pressure coefficients have been obtained and plotted (contour and X-Y plots) for various locations on the roof surface. Results are also given in the tabular form.

Results and Discussion

The pressure coefficients (mean, maxima, and rms) have been obtained for different wind incidence angles for various port locations, under stand-alone and interfering situation.

Some typical results of the present study are given in figures 7 and 8. Figure 7 shows contour plots of Cp (mean pressure coefficients) for various ports on both the roof surfaces (top and bottom) at wind incidence angles \(0°\) and \(90°\), under stand-alone condition; whereas figure 8 shows Cp contour plots under interfering condition. However, it is needless to mention that, to make the study comprehensive, tests have been carried out for wind incidence angles varying between \(0°\) & \(360°\) @ \(10°\) interval. Further, in order to make a comparison of test results, the pressure ports on top and bottom surfaces of the roofs have been located symmetrically on top and bottom surfaces (along the same vertical line, Ref. Fig.2).

The test results have been verified through analytical methods (basic calculations), for certain wind incidence angles, to establish authenticity. The tests for repeatability have also been performed by repeating the test under same test conditions at different point of time. It has been observed that there exists a good repeatability of the test data.
Significant changes in the response (for some cases) are observed due to the presence of interfering building blocks. This is mainly due to modifications in the flow field and approach flow characteristics.

For the purpose of explanation, the roof surfaces have been denoted as follows:

- **WT** = West Roof (roof towards west building bock) Top Surface
- **WB** = West Roof (roof towards west building bock) Bottom Surface
- **ET** = East Roof (roof towards east building bock) Top Surface
- **EB** = East Roof (roof towards east building bock) Bottom Surface

![Contour Plots for Cp-mean Distribution on roof surfaces at θ = 0° and 90°](image)

**Figure 7: Contour Plots for Cp-mean Distribution on roof surfaces at θ=0° and 90°**

**Stand-alone Case (without any surrounding structure)**

At **θ=0°**: On major portion of WT roof surface, Cp variation is between -0.14 and -0.05; for WB, the variation is between -0.19 and -0.01. However, at some locations on WT, Cp (suction) is as high as -0.21, and reduces to almost zero (0.02). Further, for WB, Cp goes upto -0.36, and at some places this becomes pressure Cp= +0.22. For ET the Cp variation is between -0.23 and -0.06; for EB the Cp variation is between -0.42 and +0.08.

On bottom side of the roofs (WB and EB), due to tunneling effect (that is, on top side there is clear sky in case of prototype and wind tunnel ceiling in case of model, both are much above; but on bottom/ lower side there is ground/ wind tunnel floor which is much closer) the suction is high on lower side, as expected.

At **θ=90°**: A great similarity is observed between 90° and 270° wind incidence angles. The pattern of Cp variation is similar to that obtained for Theta 0° and 180°, except that, the roofs have been interchanged (WT with ET and WB with EB), as expected. The Cp variation for WT/ WB at θ=90° is between -0.38 and 0.01; for ET, it is between -0.34 and +0.23. However, for EB it ranges between -0.18 and +0.04.

The pattern of Cp variation (including magnitude) as observed at theta 90° is reversed/ interchanged between WT/WB and ET/EB for theta 270° wind incidence angle, as expected.

At **θ=180°**: The pattern of Cp variation WT/ WB and ET/ EB is now interchanged due to the change in wind direction, as expected. The pattern of Cp variation (including magnitude) as seen for WT and WB at θ=0° is now observed for ET and EB respectively. However, there are some locations on WT where suction increases upto Cp= -0.58.

**Interference case (with all surrounding structures in place)**

At **θ=0°**: For WT and WB, Cp variation between -0.32 and -0.11 is observed for major portion of the roof area. At two locations the Cp reduces to almost zero, and at some other places Cp decreases to -0.43. For ET and EB, Cp variation between -0.35 and -0.15 is
observed for major portion. However, on ET near one of the edges, Cp = -0.25, and it varies up to -0.42.

*It may be noted that, due to tunneling effect the suction is high on both the roof surfaces (namely top and bottom), as expected. Further, due to symmetry at 0° similar pattern of Cp distribution is observed for WT/WB and ET/EB.*

![Contour Plots for Cp-mean Distribution on roof surfaces at 0° and 90°](image)

**Figure 8:** Contour Plots for Cp-mean Distribution on roof surfaces at 0° and 90° under Interfering situation

**At 0°=90°:** On WT and WB, Cp varies between -0.26 and -0.22, on maximum roof area. However, at some places on WT the value goes up to -0.45. On ET/EB, Cp variation for maximum area is between -0.30 and -0.23. The pattern of Cp contours for ET and EB is similar to WT and WB respectively. As expected, Cp contours for ET/EB at 0°=90° are quite similar to ET/EB 0°=270°.

**At 0°=180°:** Cp variation similar to that observed for 0°=0° has been observed for 0°=180° with slight variation here and there, as expected.

**At 0°=270°:** This configuration pertains to west building block on upstream side, and east building block on downstream of the roofs. On WT and WB suction varies between -0.35 and -0.24, for maximum area of the roof. However, at some places lowest and highest suction Cp values are -0.40 and -0.21. On ET/EB, Cp varies between -0.29 and -0.19, for maximum roof area. The pattern of contours is slightly different; this is due to different boundary conditions on top and bottom of the roofs.

**Conclusions**

*From the experimental study carried out the following conclusions can be drawn:*

i. The pressure coefficients (*mean, maxima, and rms*) have been obtained for different various wind incidence angles, and for various port locations; under stand-alone and interfering situations.

ii. Suction is observed on the roof surfaces for almost all wind incidence angles; therefore cables need to be designed in such a way that suction is taken care.

iii. Significant changes (shielding and magnification) in Cp distribution on roof surfaces have been observed due to the presence of nearby interfering buildings. The change in pressure distribution is mainly due to modifications in the flow field and approach flow characteristics.

iv. Increase (magnification) in suction due to interfering building is observed for the following cases.
a. Upto 200% increase in Cp (suction) *(i.e. Cp values become upto 3 times)* for major portion of WT/WB; increase of peak suction 100% increase *(i.e. Cp values become upto 2 times)* is observed at theta 0°. This is due to the fact that, because of interfering buildings the flow gets accelerated at some locations.

b. Whereas, for ET/EB, at theta 0°, 50% increase *(i.e. Cp values become upto 1.5 times)* is observed, this is because ET/EB are in the wake of WT/WB at theta 0°.

c. At theta 180°, the pattern observed for WT/WB at 0=0° *(as mentioned above in items iv (a) and iv (b) above)* is now observed for ET/EB.

v. However, due to *shielding* for some locations on WT/WB, Cp reduces by 70% at theta 90°, and no substantial changes are observed for ET and EB. This is because ET/EB are in the wake of WT/WB at theta 90°. As expected, at theta 270°, the above pattern is now reversed.

vi. For stand-alone case the suction changes to pressure at some cases.

vii. Similarity in Cp variation is observed for 0°&180°and 90°&270° wind incidence angles, as expected. Only the roofs are interchanged, i.e. the pattern observed for WT/WB at 0°, is now observed for EB/ET at 180°, and vice versa. Similarly at theta 90°&270°.

viii. Near the edges suction is higher due to separation of flow, as is generally expected.

ix. The data/test results are in line as with what is expected form the basic flow phenomenon, however, some interesting results have been obtained as mentioned in section above.

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