WIND TUNNEL STUDY ON AN INDUSTRIAL STRUCTURE WITH CURVED ROOF

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ABSTRACT

A wind tunnel pressure measurement study was carried out under simulated open terrain condition on a 1:200 scaled rigid model of an industrial structure (coal shed) with multi-segmental curved roof. The model was instrumented with 32 pressure taps (area averaged) at the upper/lower faces of the roof and pressures were measured for both gable end walls being in open and closed conditions. All the pressure coefficients, \( C_p \), were computed based on reference pressure, \( q_{ref} \), corresponding to a reference wind velocity, \( V_{ref} \), of 12 m/s measured at the crown of the model, considered as a reference height, \( h_{ref} \). Pressure data were collected from upper and lower face of the roof for various angles of wind incidence, \( \theta \), ranging from 0° to 360° in 30° intervals. However, in this paper, only the results pertaining to mean (internal, \( \bar{C}_{pi} \) and external, \( \bar{C}_{pe} \)) and standard deviation (internal, \( \bar{C}_{pi}^{+} \) and external, \( \bar{C}_{pe}^{+} \)) of pressure coefficients, for flow (i) parallel \( (\theta = 0^\circ) \), (ii) skewed \( (\theta = 315^\circ) \) and (iii) perpendicular \( (\theta = 270^\circ) \) to ridge of the roof are reported. Further, the measured \( \bar{C}_{pe} \) for both gable end walls in closed condition with flow (i) parallel and (ii) perpendicular to ridge are compared with the values given in some of the national/international codes of practice.

KEYWORDS: CURVED ROOF, WIND TUNNEL, PRESSURE COEFFICIENTS

Introduction

Arch shaped roofs are increasingly used in-built environment where large unobstructed clear spans (Ex: Entertainment/exhibition centres, sports arenas, hangers, etc) are required for functionality purposes. These structures can spring either from ground or at an elevated level. Information of wind loads on curved roofs either from wind tunnel measurements or CFD based numerical techniques is limited. Based on the literature study, it is observed that the rise to span ratio, \( (f/d) \), is strongly affecting the aerodynamic loads on curved roofs rather than the side wall height to span ratio, \( (h/d) \) or building length to span ratio, \( (l/d) \). Since the actual phenomenon of wind flow around/over such structures is too complex, wind tunnel model study is recognised as a reliable design tool to understand the wind induced pressures and its aerodynamic behavior. This paper presents selected results on \( \bar{C}_{pi} \) (or \( \bar{C}_{pe} \)) and \( \bar{C}_{pi}^{+} \) (or \( \bar{C}_{pe}^{+} \)) based on a wind tunnel pressure measurement study conducted on a rigid model with multi-segmental curved roof with gable end walls either being in open or closed conditions.

Published Data/Previous Work on Curved Roof

tunnel tests were carried out by [Holmes (1984)] on a roof of a hanger to determine the peak values of different load effects and comparisons were made of the results with the wind loads derived from Australian Standard [AS/NZS: 1170.2: 2002 (2005)]. Values of wind pressure coefficients for different shapes of curved roofs were reported in a state-of-the-art paper by [Krishna (1989)]. Using wind tunnel and full-scale tests, an area-average pressure measurement study on a house roof in a vortex formation region was reported by [Peterka et al. (1997)]. Wind tunnel tests were carried out by [Blessmann (1998)] to determine the wind load distribution on curved roofs for both isolated and coupled models with equal or different heights. Wind tunnel model studies were carried out by [Ginger (2004)] to determine the wind load distribution on tributary areas near the gable-end of large, low-rise buildings with high-pitch planar and curved roof shapes, for \((f/d) = 0.33\), \((h/d) = 0.5\) and \((l/d) = 4.0\). Wind tunnel pressure measurements study was carried out by [Gupta and Amarendra (2006)] to obtain mean pressure coefficients on rigid models of rectangular shape buildings with cylindrical roofs as well as wall surfaces. The pressure coefficients through a series of parametric wind tunnel studies were reported by [Blackmore and Tsokri (2006)], for flow near perpendicular to ridge, for \((f/d) = 0.05\) to 0.5, \((h/d) = 0.06\) to 1.0 and \((l/d) = 1\) to 10. The evaluated pressure coefficients were compared with international codes of practice of [EN1991-1-4 (2004), ASCE/SEI 7-05 (2006)], and Cook (1990), and proposed an alternative procedure to replace the EN1991-1-4 recommended procedure in the UK National Annex. Based on a wind tunnel study, results on \(\overline{c_p}\) were reported by [Kasperski (2007)], for flow parallel to ridge of the models, for \((f/d) = 0.1\) and 0.2, \((h/d) = 0.2\) and \((l/d) = 1.5\). The results pertaining to net mean \((= \overline{c_{pe}} - \overline{c_{pi}})\) and fluctuating pressure coefficient distributions for present tested model with gable end walls being in open condition was reported by [Lakshmanan et al. (2008)].

**Wind Tunnel Experimental Program**

*Model Fabrication and Instrumentation*

A 1:200 scaled rigid model (Figure 1(a)) of an industrial structure (coal shed) with multi-segmental curved roof was fabricated using acrylic material and tested in Boundary Layer Wind Tunnel (BLWT) under simulated open terrain condition. The model has a length, \((l) = 564\) mm, span, \((d) = 559\) mm, rise of the arch, \((f) = 136.9\) mm, and side wall height, \((h) = 11.80\) mm. The multi-segmental curved roof profile consists of 16 segments (S1 to S16 in the arch direction) to form an arch like shape by means of joining together 1 mm and 3 mm thick acrylic sheets of equal width and length. It may be noted that the different segments have different angles of inclination w.r.t. horizontal and thus the arch is not a smooth curve.

A special method of instrumentation was adopted in the model, in which manifolds with 5 pressure taps, were provided on the upper surface of the roof at a given panel in 1 mm thick acrylic sheet. On the lower surface of the roof i.e., in 3 mm thick sheet, another set of 5 pressure taps manifold were provided with a slightly staggered arrangement (in plan), which is shown in Figure 1(b). Restrictions on the maximum length of tubes connecting the pressure ports to the pressure scanners to achieve the required flat frequency response, available limitation on the number of pressure scanners and the blockage effect are the major issues considered for selecting the present instrumentation system. Accordingly 32 pressure ports (two pressure taps per each segment) using 4 pressure scanners were judiciously distributed to measure the internal/external pressures, covering the entire roof of the model. It may be noted that due to symmetry of the structure, when the arch is rotated from 0° to 360°, the above arrangement of pressure taps permits deduction of pressures at as many as 128 (= 16 x 8) locations on the roof.

*Wind Tunnel Tests, Data Collection and Analysis*

The wind tunnel tests were conducted for three different test cases as given below.
Test case No. | Conditions of gable walls | Status of pressure taps
---|---|---
1. | Both ends open | External closed and Internal open
2. | Both ends open | External open and Internal closed
3. | Both ends closed | External open and Internal closed

For any given test case, simultaneous pressures were measured for the above cases. The model was tested for different angles of wind incidence, ($\theta$) ranging from 0° to 360° in steps of every 30°, including for few other selected skew angles of wind incidence (i.e., $\theta = 45°, 135°, 225°$ and $315°$). Typical views of the model tested in wind tunnel for $\theta = 0°, 315°$ and $270°$ are shown in Figure 2. Average values of three independent runs were considered for every $\theta$ in every test case. The simulated mean velocity of about 12 m/s is considered as reference velocity, ($V_{ref}$), measured at the crown of the model, and all the pressure coefficients were obtained based on reference dynamic pressure, ($q_{ref}$), corresponding to the above reference wind velocity. All the pressure data were acquired for a sampling period of 15 seconds and with a sampling frequency of 1000 Hz.

Figure 2: Typical Views of Model Tested in BLWT

All pressure data were analysed using the software developed in MATLAB format. Results pertaining to $\bar{C}_p$ (or $\bar{C}_{pe}$) and $\tilde{C}_p$ (or $\tilde{C}_{pe}$) distributions for gable end walls being in
open condition, $\overline{C}_{pe}$ and $\tilde{C}_{pe}$ distributions for gable end walls being in closed condition are given below for typical angles of wind incidence ($\theta = 0^\circ$, $315^\circ$ and $270^\circ$).

The mean internal and external pressure coefficients are obtained as given below.

$$\overline{C}_{pi} = \frac{\overline{p}_{int}}{\left(\frac{1}{2} \rho V_{ref}^2\right)} \quad \text{or} \quad \overline{C}_{pe} = \frac{\overline{p}_{ext}}{\left(\frac{1}{2} \rho V_{ref}^2\right)}$$  

(1)

where, $\overline{p}_{int}$, $\overline{p}_{ext}$ = mean internal and external pressures, respectively. $\left(\frac{1}{2} \rho V_{ref}^2\right)$ = reference pressure ($q_c$) due to mean wind speed at the crown of the model.

The standard deviation of internal or external pressure coefficients are obtained as given below.

$$\tilde{C}_{pi} = \frac{\tilde{p}_{int}}{\left(\frac{1}{2} \rho V_{ref}^2\right)} \quad \text{or} \quad \tilde{C}_{pe} = \frac{\tilde{p}_{ext}}{\left(\frac{1}{2} \rho V_{ref}^2\right)}$$  

(2)

where, $\tilde{p}_{int}$, $\tilde{p}_{ext}$ = standard deviation of internal and external pressures, respectively.

Results and Discussions

Test Case No. 1: (a) Distribution of Mean Internal Pressure Coefficients, $\overline{C}_{pi}$

The variation of $\overline{C}_{pi}$ and $\tilde{C}_{pi}$ at the lower surface of the roof are shown in Figure 3.

Figure 3: Variation of $\overline{C}_{pi}$ and $\tilde{C}_{pi}$ for Angles of Wind Incidence ($\theta$). (a) $0^\circ$, (b) $315^\circ$ and (c) $270^\circ$.
For \( \theta = 0^\circ \), the values of \( \bar{C}_{pi} \) are ranging from -0.068 to -0.314 and the variation of \( \bar{C}_{pi} \) is minimum when compared to other angles of wind incidence (\( \theta = 315^\circ \) and \( 270^\circ \)). For \( \theta = 315^\circ \), it is interesting to note that the variation of \( \bar{C}_{pi} \) is found to be suction at the windward region and subsequently, the flow reattaches at the leeward region at the arches 1 and 4. Further, the variation of \( \bar{C}_{pi} \) for skewed angle (\( \theta = 315^\circ \)) have reduction in the magnitudes of suction especially at the arches 1 and 4 (\( \bar{C}_{pi} = -0.415 \) to \( 0.279 \) from \( x/d = 0.39 \) to \( 0.98 \) and -0.462 to -0.042 from \( x/d = 0.46 \) to \( 0.98 \)). For \( \theta = 270^\circ \), the lower surface of roof is subjected to suction (\( \bar{C}_{pi} \) ranging from -0.5 to -0.6, being stabilised even up to \( x/d = 0.68 \) from end ‘O’) and there appears to be a pressure recovery at the leeward region.

(b) Standard Deviation of Internal Pressure Coefficients, \( \tilde{C}_{pi} \)

For \( \theta = 0^\circ \), the variation of \( \tilde{C}_{pi} \) at leeward end (arch 8) and central portion (arch 4) are similar and there appears to be high pressure fluctuations at the windward end (arch 1), may be because of the edge effect. For \( \theta = 315^\circ \) in arch 1, the variation is not only non-symmetric, but also experiences high fluctuations when compared with other arches 4 and 8.

Test Case No. 2: (a) Distribution of Mean External Pressure Coefficients, \( \bar{C}_{pe} \)

The variation of \( \bar{C}_{pe} \) and \( \tilde{C}_{pe} \) at the upper surface of the roof are shown in Figure 4.
For $\theta = 0^\circ$, the upper face of the roof is subjected to suction and the values of $\bar{C}_{pe}$ are relatively low when compared to other angles of wind incidence ($\theta = 315^\circ$ and $270^\circ$). For $\theta = 315^\circ$, the flow is skewed to longitudinal axis of the roof, the $\bar{C}_{pe}$ distribution exhibits a skewed pattern with respect to $\theta = 0^\circ$. For $\theta = 315^\circ$ and $270^\circ$, a small portion at the windward region of arches 1 and 4 is subjected to minimum (positive) pressure, which changes into suction for rest of the roof portions. At arch 4, the values of $\bar{C}_{pe}$ attain maximum suction of about $-0.922$ and $-0.919$ at a distance of $x/d = 0.75$ and $0.25$ from end ‘O’ for $\theta = 315^\circ$ and $270^\circ$, respectively, and thereafter $\bar{C}_{pe}$ reduces to about $-0.338$ and $-0.307$.

(b) Standard Deviation of External Pressure Coefficients, $\tilde{C}_{pe}$

For $\theta = 0^\circ$, the distribution of $\tilde{C}_{pe}$ at leeward end (arch 8) and central portion (arch 4) are similar whereas deviation is found at the windward end (arch 1). For $\theta = 315^\circ$, deviation is found at the arch 1 particularly at the leeward region which experiences high fluctuations when compared with arches 4 and 8.

**Test Case No. 3: (a) Distribution of Mean External Pressure Coefficients, $\bar{C}_{pe}$**

The variation of $\bar{C}_{pe}$ and $\bar{\tilde{C}}_{pe}$ at the upper surface of the roof are shown in Figure 5.

![Graphs showing distribution of mean external pressure coefficients and standard deviation for different angles of wind incidence.](image)

**Figure 5: Variation of $\bar{C}_{pe}$ and $\tilde{C}_{pe}$ for Angles of Wind Incidence ($\theta$). (a) $0^\circ$, (b) $315^\circ$ and (c) $270^\circ$**

For $\theta = 0^\circ$, the variation of $\bar{C}_{pe}$ at leeward end (arch 8) and central portion (arch 4) are similar, whereas at the central portion of the windward end (arch 1) is subjected to high suction (maximum, $\bar{C}_{pe} = -1.221$), relatively, when compared to suction at arches 8 and 4. For
$\theta = 315^\circ$, the variation of $C_{pe}$ at leeward end (arch 8) and central portion (arch 4) are similar, whereas deviation is found at the windward end (arch 1) i.e., maximum $C_{pe} = -1.292$, especially at $x/d = 0.68$. It is interesting to note that the variation of $C_{pe}$ for $\theta = 0^\circ$, $315^\circ$ and $270^\circ$ are similar in both test case Nos. 2 and 3. For $\theta = 315^\circ$ and $270^\circ$, a small portion at the windward region of arches 1 and 4 is subjected to minimum (positive) pressure, which changes into suction for rest of the roof portions. At the arches 1 and 4, the values of $C_{pe}$ attain maximum suction of about $-1.292$ and $-0.903$ at a distance of $x/d = 0.68$ and $0.25$ from end ‘O’ for $\theta = 315^\circ$ and $270^\circ$, respectively, and thereafter $C_{pe}$ reduces to about $-0.678$ and $-0.334$.

(b) Standard Deviation of External Pressure Coefficients, $\tilde{C}_{pe}$

For $\theta = 0^\circ$, the distribution of $\tilde{C}_{pe}$ at leeward end (arch 8) and central portion (arch 4) are similar whereas deviation is found for windward end (arch 1) as observed in test case No. 2. For $\theta = 315^\circ$, the distribution of $\tilde{C}_{pe}$ at leeward end (arch 8) and central portion (arch 4) are similar, whereas deviation is found for windward end (arch 1) particularly near the middle region which experiences high fluctuations ($\tilde{C}_{pe} = 0.272$), at $x/d = 0.54$ from end ‘O’. For $\theta = 270^\circ$, the distribution of $\tilde{C}_{pe}$ at windward end (arch 1) is similar to the variation at the central portion (arch 4) as observed in test case No. 2.

Comparison of Measured $C_{pe}$ with Coidal Values $C_{pe}$

Comparison of the $C_{pe}$ for wind directions (i) parallel and (ii) perpendicular to ridge, which are given in the international codes/published data with the values obtained from the present wind tunnel study is not straightforward, because they depend upon (a) dimensions ($f$, $h$, $d$ and $l$) of the structure, (b) angle of wind incidence, ($\theta$), (c) area, ($A$), over which the pressure coefficients are averaged, (d) reference height, ($h_{ref}$), at which the velocity have to be considered to compute pressure coefficients and (e) flow conditions. For example, the reference height, ($h_{ref}$), is being referred in various literatures, as eaves height or average height of the roof or crown of the roof. Nevertheless, comparison on $C_{pe}$ between the present wind tunnel model ($f/d = 0.245$, $h/d = 0.021$ and $l/d = 1.01$) results with gable end walls being in closed condition and the corresponding values recommended in various national/international codes at different regions for wind flow (i) parallel and (ii) perpendicular to ridge are discussed in the following sections.

(a) For Wind Direction Parallel to Ridge ($\theta = 0^\circ$)

The National code [IS: 875 (Part 3)-1987 (1989)] specifies a value of $C_{pe}$ equal to -0.7 for the full width of the roof over a length of l/2 from the gable ends and -0.5 for the remaining portion. The Canadian code [NBC 1995 (2002)] specifies a value of $C_{pe} = -0.8$ at windward edge and -0.1 at leeward edge, for $h/d = 0.08$. The Australian code [AS/NZS: 1170.2: 2002 (2005)] specifies values of $C_{pe} = -0.9$, -0.4 at windward edge and -0.2, 0.2 at a horizontal distance greater than 3h ($h = \text{average height of the roof}$) from the windward edge, for $h/d \leq 0.5$. The American code [ASCE/SEI 7-05 (2006)] specifies values of $C_{pe} = -0.9$, -0.18 at windward edge and -0.3, -0.18 at a horizontal distance greater than 2h ($h = \text{average height of the roof}$) from the windward edge, for $h/d \leq 0.5$. The Japan code [AIJ (2004)] gives $C_{pe}$ values of -1.126, -0.619 and -0.4 for three different zones in a vaulted roof structure. A value of $C_{pe} = -0.15$ for both the edges and -0.733 at ridge portion, which are applicable to $1/10^{th}$ length at the windward region along the longitudinal direction is recommended by
The Seventh Asia-Pacific Conference on Wind Engineering, November 8-12, 2009, Taipei, Taiwan

[Cook (1990)]. Further, for other regions beyond 1/10th length, value of $C_{pe}$ is ranging from -0.704 to ±0.2, the trend which is similar to [AS/NZS: 1170.2: 2002 (2005)] specifications. From the present wind tunnel model study, it is observed that the entire upper face of the roof is subjected to suction with $C_{pe} = -1.221$ at the windward end (arch 1) and -0.24 at the leeward end (arch 8), which is observed in [IS: 875 (Part 3)-1987 (1989), NBC 1995 (2002), ASCE/SEI 7-05 (2006), and AIJ (2004)].

(b) For Wind Direction Perpendicular to Ridge ($\theta = 270^\circ$)

Comparison of $C_{pe}$ values for three regions recommended in various national/international codes is given in Table 1. The comparison is restricted to the measured mean pressures along the central portion (arch 4) of the model with gable end walls being closed condition.

Table 1: Comparison of $C_{pe}$ at Various Regions as Recommended in Codes of Practice

<table>
<thead>
<tr>
<th>Codes of Practice</th>
<th>Windward</th>
<th>Centre</th>
<th>Leeward</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS: 875 (Part-3): 1989</td>
<td>+0.345</td>
<td>-0.945</td>
<td>-0.4</td>
<td>$C_{pe} = f(h/d)$</td>
</tr>
<tr>
<td>AS/NZS 1170.2: 2005</td>
<td>+0.094 or 0.0</td>
<td>-0.668 or 0.0</td>
<td>-0.346 or 0.0</td>
<td>$C_{pe} = f(h/d)$</td>
</tr>
<tr>
<td>ASCE 7-05: 2006</td>
<td>+0.343</td>
<td>-0.945</td>
<td>-0.5</td>
<td>$C_{pe} = f(h/d)$</td>
</tr>
<tr>
<td>GBJ 9-87: 1994</td>
<td>+0.26</td>
<td>-0.8</td>
<td>-0.5</td>
<td>$C_{pe} = f(h/d)$</td>
</tr>
<tr>
<td>AIJ: 2004</td>
<td>-0.21</td>
<td>-1.118</td>
<td>-0.5</td>
<td>$C_{pe} = f(h/d)$</td>
</tr>
<tr>
<td>Present study (wind tunnel)</td>
<td>-0.25</td>
<td>-0.74</td>
<td>-0.52</td>
<td>$C_{pe} = f(h/d)$</td>
</tr>
</tbody>
</table>

$h_{ave\ roof}$—average roof height; $\mu_s$—shape factor

The following observations are made from Table 1.

- The windward region is subjected to suction as predicted by [AIJ (2004)], high suction at the centre region and relatively low suction at the leeward region, which is observed in many of the codal recommendations.
- Values corresponding to the regions specified in [AIJ (2004)] and in [GBJ 9-87 (1994)] showed reasonable agreement in leeward region.

Summary and Conclusions

In this paper, a wind tunnel pressure measurement study conducted on an industrial structure with multi-segmental curved roof for both gable end walls in open and closed conditions is reported. The measured $\bar{C}_{pi}$ (or $\bar{C}_{pe}$) and $\tilde{C}_{pi}$ (or $\tilde{C}_{pe}$) distributions for typical angles of wind incidence ($\theta = 0^\circ$, 315° and 270°) are presented. For wind direction parallel to ridge ($\theta = 0^\circ$), the variation of $\bar{C}_{pi}$ or $\bar{C}_{pe}$ at the lower or upper face of the roof is subjected to suction, which indicates the insensitiveness of the presence or absence of gable end walls. The values of $\bar{C}_{pi}$ (or $\bar{C}_{pe}$) are relatively higher at windward end (arch 1) when compared to other arches for both the cases i.e., either gable end walls being in open or closed condition. Further, the following observations were made from test case No. 1: (i) For $\theta = 0^\circ$, it is interesting to note that the values of $\bar{C}_{pi}$ are relatively higher at leeward end (arch 8) when compared to other arches 1 and 4; (ii) For skewed angle of wind incidence ($\theta = 315^\circ$), as expected, the suction is stabilised up to $x/d = 0.39$ from end ‘O’ in windward end (arch 1) and there appears to be pressure recovery relatively at faster rate than in middle portion (arch 4); and (iii) For wind direction perpendicular to ridge ($\theta = 270^\circ$), at arches 1 and 4, the suction is stabilised even up to $x/d = 0.68$ from end ‘O’ and there appears to be pressure recovery at the leeward region. The following observations were made from test case No. 2: (i) For a skewed angle of wind incidence ($\theta = 315^\circ$), at all the three arches (1, 4 and 8), the distribution of $\bar{C}_{pe}$ exhibits a skewed pattern with respect to $\theta = 0^\circ$ and (ii) For $\theta = 315^\circ$ and 270°, a small portion at the windward region at the arches 1 and 4 is subjected to minimum (positive) pressure, which changes in to suction for rest of the roof portions. The following observations were made
from test case No. 3: (i) For $\theta = 0^\circ$, it is interesting to note that the values of $C_{pe}$ is relatively higher at windward end (arch 1) when compared to other arches; (ii) For $\theta = 315^\circ$ and $270^\circ$, a small portion in the variation of $C_{pe}$ at the windward region of arch 4 is subjected to minimum suction, which changes into to suction (relatively high) for rest of the roof portions; and (iii) For $\theta = 315^\circ$, at the windward end (arch 1) experiences high fluctuations particularly near the middle portion ($C_{pe} = 0.272$ at $x/d = 0.54$ from end ‘O’).

Further studies are required to derive design recommendations.

Acknowledgements

This paper is being published with kind permission of The Director, SERC, Chennai. The support rendered by the staff of WEL, SERC, for this study is sincerely acknowledged.

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