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NATURAL VENTILATION IN COURTYARD AND ATRIUM BUILDINGS

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ABSTRACT. This paper reports on an experimental investigation into the ventilative performances of courtyard and atrium buildings for cooling purposes. Several models of these structures were tested in isolation in a wind tunnel. The ventilation was assessed from actual airflow rates measured by the means of orifices plates inserted in the models. The effect of the courtyard geometry and its orientation to the wind were examined as well as the possibilities of inducing higher ventilation rates by roofing the courtyard and exploiting the pressure field over the roof. The study highlighted the prime importance of the orientation of the building to the oncoming wind and the potential and limitations of some ventilation strategies that could be used in the atrium structures.

1. INTRODUCTION

Open and covered courtyards are common architectural features which provide light, ventilation and other functions to buildings. The potential that these structures can offer to reduce the energy loads of buildings, and in particular cooling, have recently been given closer attention /1/. In warm humid climates the main exigence to achieve thermal comfort without resorting to mechanical refrigeration is to provide strong cross ventilation. In this respect is is not well known whether courtyard or atrium structures will meet these requirements and what are the most influential parameters in their ventilative performances. For example, covering the courtyard with a roof might induce higher air movement by either exploiting the large suction over an adequately designed roof or by deflecting the air into the atrium. Again little is known about the efficiency of any of these ventilation strategies. The scope of this study is:

- To assess the ventilative performances of some courtyard and atrium buildings.
- To examine the effect of the courtyard geometry and the orientation to winds.
- To test the efficiency of several possible ventilation strategies that an atrium structure can use.

2. EXPERIMENTAL APPARATUS AND TECHNIQUES

To have the facilities to test systematically the effect of several courtyard geometries and atrium roof types called for the use of models in a boundary layer wind tunnel. Of the ventilation measuring techniques available, it was chosen to measure directly the ventilation rates through the model by the means of small orifice plate devices. The use of pressure distributions to predict airflow rates was considered inadequate when roof vents are used /2/.

2.1 The Wind Tunnel

The tests were carried out in the Sheffield University's 1.2 x 1.2m boundary layer wind tunnel, which was exhaustively described by Lee /3/. A suburban velocity profile was generated with a power-law exponent of 0.24.

2.2 Modelling Criteria

The most significant parameter to ensure similarities in the flow pattern between the model and the prototype are the geometry similarity, the Reynolds number and the blockage ratio of the model in the wind tunnel. To match the full scale Reynolds number with that of the model is practically impossible. Fortunately, once the flow is turbulent, the flow characteristics becomes Reynolds number independent for sharp edged bluff bodies. The Reynolds number independence of the internal flow was assessed from the pressure loss across the model. This parameter remained fairly constant for Reynolds numbers between 3.5×10^3 and 1.3×10^4. Although these values were lower than the value suggested for internal flow Reynolds number independence (2×10^4) /3/, it was believed that dynamic similarity was achieved for almost all the working range. The blockage in the wind tunnel was kept less than 4%.

2.3 Model Buildings

2.3.1 The Courtyard Models

The models that represented four storey courtyard buildings at 1:100 scale were assembled in Lego-like model elements. Eleven pieces were constructed to cover the range of courtyard sizes tested. The models were made of perspex and had perforated facades, with 10mm diameter circular holes totalling a facade porosity of 11.4%. Four of the model elements had one orifice place device mounted, each in a different floor height (see Fig. 1). The device was a square edge plate of 17mm diameter inserted between two short brass pipes of 25mm diameter, and fitted with two corner pressure tappings. The device was calibrated against a precision commercially available flowmeter.

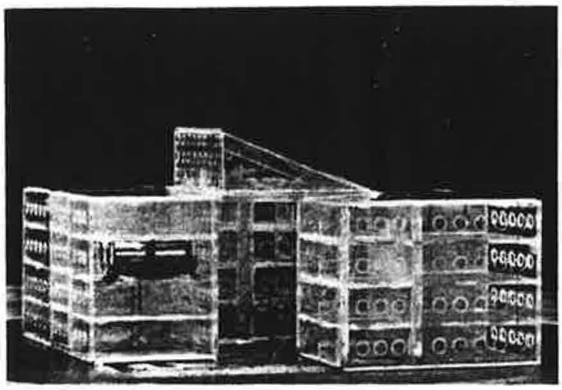

Figure 1: Orifice Plate Model.

2.3.2 The Atrium Models

Aluminium models fitted with pressure tappings were used to gain knowledge of the pressure field around atrium models with several roof shapes. For the airflow measurement, the orifice plate model elements were used. Five types of roofs were tested (flat, pyramidal, pitched and monopitched roof). Only the monopitched roof was selected for the flow tests since it had a large side under high suction (Cp = -0.95), as well as a side under positive pressure (Cp = +0.26). Orientated differently the same roof had a large area under a slightly negative pressure (Cp = -0.09). Cp is the pressure coefficient related to the dynamic pressure on roof height.

2.4 Test Procedure

The courtyard depth (D) and width (W) were changed from 0.5 to 1.5 times the model height (H). The measurement of the pressure drop across the orifice plate and the dynamic pressure at the gradient height were taken at wind approach angles from 0° to 360° in 30° and 45° increments, and for the atrium test from 60° to -60°. The roof effects were tested on one building size (H/W = 1,H/D = 1). The porosity of the roof was altered from 0% to 1.9%, 3.8%, 5.7% and 23% when testing the roof under suction, but kept to 5.7% and 23% for respectively the positive and near atmospheric pressure strategies. The results were presented in the form of a non dimensional flow coefficient CQ:

$$CQ = Q/(A\ Vr)$$

where Q is the flow rate measured, A the area of the openings in one storey and in one facade and Vr the velocity at the roof height. CQ is in other words the ratio of the velocity at the opening to that at the roof height.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Courtyard Models

3.1.1 Effect of the wind incidence

The orientation to the wind had the most significant effect on the ventilation. Orientating obliquely the building to the wind not only increased the overall flow but resulted also in a more even distribution within the building than when it was perpendicular to the wind. At normal wind incidence, the air velocity at the openings in the windward sides were between 0.38 and 0.50 time that at the roof height, whilst on the lateral sides CQ was 0.05 to 0.18 and only 0.03 to 0.13 on the leeward side. At a wind angle of 30 degrees the average air velocity passed from 0.18 to 0.27 (a 50% increase) and a more uniform distribution within the building existed. CQ was increased by a factor of 2 in the leeward side and by a factor of 2 to 4 in the lateral sides. At 45 degree wind incidence, the highest averaged values of CQ for the whole building were obtained (0.28), and a more even distribution. Yet, the improvement of the downwind side were accompanied by a decrease in the air velocity in the windward sides (CQ was only 0.24 to 0.36). At a normal wind incidence, a large vertical rotating vortex dominated the flow in the courtyard. The negative pressures encountered in the inner walls were close to that in the downwind external walls. When the wind striked the building at an angle, not only the external walls should have been under a higher suction but the inner walls probably experienced a rise in pressure due to a downwind movement of air caused by vorticies emanating from the upwind roof edge. As a result, the pressure drop rised significantly.

3.1.2 Effect of the Geometry of the Courtyard

In contrast with the dramatic changes in CQ caused by the change in the orientation to winds, the geometry of the courtyard had fewer effects. The changes in the overall flow coefficient CQ was at most 18% (and even lower, 5%, at oblique wind angles). The windward side was particularly insensitive to any alteration of the courtyard configuration. On the leeward side, the changes of the depth or the width affected the CQ magnitude and the flow direction at discrete points rather than the average values. The changes on the vertical distribution of CQ with the alteration of the depth are shown in Fig. 2. At the biggest depth (1.5H), the air was moving outwards (from the courtyard to the outside) in the two extreme floors and inwards in the two mid-height floors. This particular flow distribution resulted probably from changes in flow regime in the courtyard, where first the flow was skimming the roof crests, generating a slow rotating vortex. At bigger depths the flow starts to wash over the courtyard face without a stagnation point. Similar observations were made on the pressure distribution in rows of buildings when the spacing was changed /5/.

3.2 Atrium Buildings

Depending on the ventilation strategy, the atrium building had lower or higher air velocities than the open courtyard. Among the atrium configurations tested, the atria exploiting the low pressure on the roof had generally the lowest average air velocities. The deficit of pressure that existed in the atrium and resulting from the roof suction affected the pressure drop on the downwind sides of the models where the external walls experienced a relatively low pressure. On the other hand, the air velocity on the windward side increased. As a result, the distribution of the flow within the model was very uneven. The more openings there were in the roof the less even was the distribution of the flow and the lower the CQ values on the downwind sides. Locating the roof openings in a positive pressure region resulted in the highest CQ averaged value (0.28) at normal incidence. The pressure drop on the downwind sides benefitted from the built up pressure in the atrium. At an oblique angle, however, the outside upwind walls experienced lower pressure than at normal wind incidence and consequently the pressure drop at this location was affected. The atrium with a closed roof and with the roof having openings located near the atmospheric pressure had at any wind angle one of the fourth highest CQ values. The reason was that the resulting pressure in the atrium building was half way between the pressures on the upwind and the downwind external walls. Orientating obliqely the buildings to the wind had a very beneficial effect on the ventilation except for the atrium using the roof suction strategy.
The atrium models showed all higher average CQ values than the open courtyard, (up to 40% higher) at normal wind incidence. At 30 degrees, the highest increase was 12% and reduced to 5% at 45 degrees. To appreciate the ventilative performances of these buildings the best indice was the ratio of the CQ values averaged over the whole building to its standard deviation. Fig. 3 summarises the results.

4. CONCLUSION

In conclusion, orientating the courtyard with an angle (30° or 45°) to the wind had a very beneficial effect on the ventilation, resulting in higher air velocity on the downwind sides. On the

other hand the geometry of the courtyard had marginal effects. Exploiting the suction effect over a covered courtyard was not rewarding, the pressure forces not being large enough to overcome the suction experienced on the downwind walls. The best results were achieved by closing the roof or locating the openings in a near atmospheric pressure zone. These ventilation strategies resulted in higher air velocities than for the open courtyard.
The experiment was undertaken on isolated models. It is possible that these concluding remarks might not apply for courtyards or atria in an urban settlement, where the flow field could be affected by neighbouring buildings. A study of shielding effects is currently in progress.

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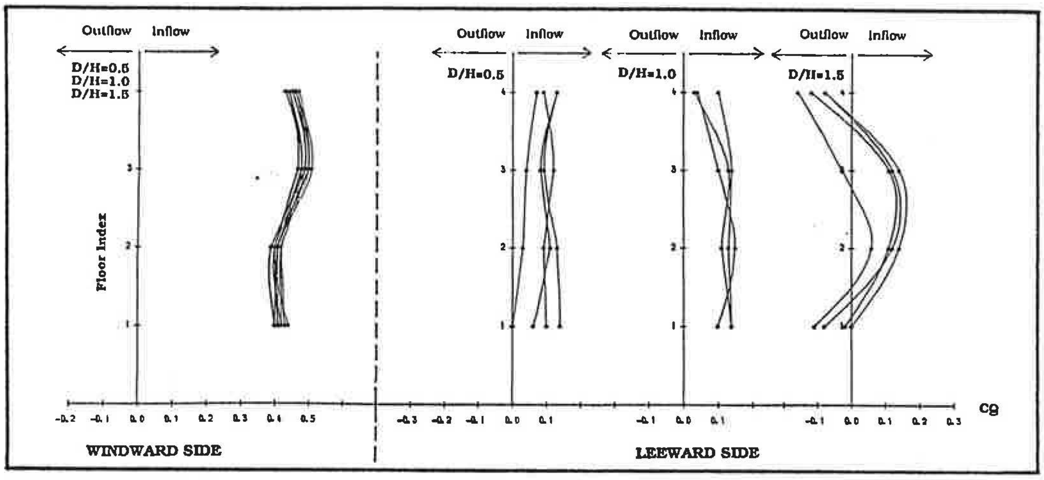

Figure 2: Effect of changing the courtyard depth on the vertical distribution of the flow coefficient on the leeward and windward sides. (The relative depth (D) was changed from 0.5 to 1 and 1.5 the model height (H)).

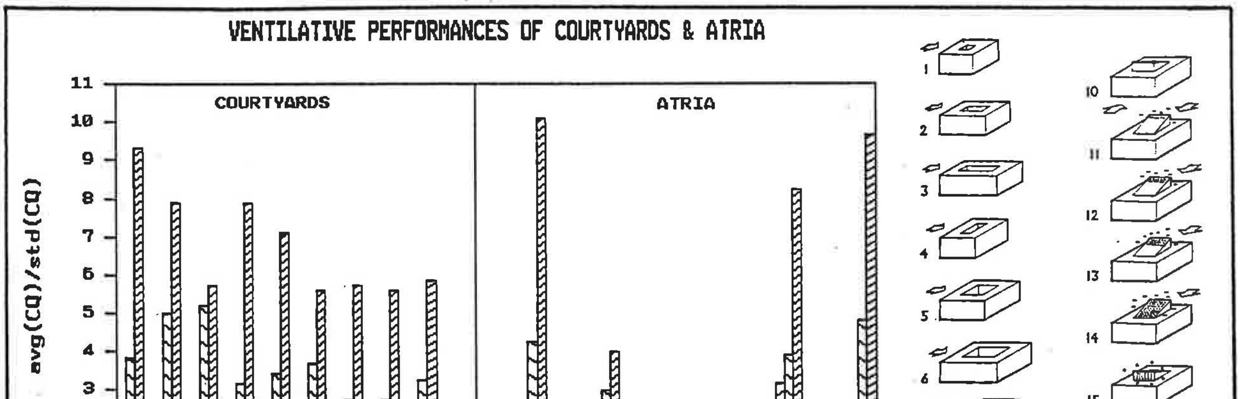

Figure 3: Ventilative performances of courtyard and atrium buildings for 0, 30 and 45 degrees wind incidence. Avg (CQ) and Std (CQ) are respectively the average and standard deviation of the flow coefficient.