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Pressure Distribution due to Shear Layer Re-attachment

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SUMMARY When a prismatic structure is subjected to air flow and especially at a small angle of wind incidence, the separated shear layer may re-attach onto the streamwise surface. This results in very high negative pressures under the re-attaching shear layer. Wind tunnel tests were carried out to determine the pressure distribution around a square cylinder. Small adjustable vanes were fitted to the corners so that a vent between the vane and the corner could be introduced. Comparisons of pressures measured around the cylinder with and without the vanes and vents were made. It is shown that the use of such devices can substantially reduce the magnitude of the negative mean and peak pressure coefficients under the shear layer.

1 INTRODUCTION

The pressure distributions around prismatic structures, such as tall buildings and structures and various types of roof structures, have been the subject of numerous studies in recent years. Much of these pressure characteristics appear to be associated with the behaviour of the shear layers separating from the leading edge of the structure and in particular the tendency of the separated shear layers to re-attach intermittently onto the surface of the structure at small angle of wind incidence. Both full scale and model measurements have indicated the existence of very high negative pressures in the region near the leading edge under the re-attaching shear layer.

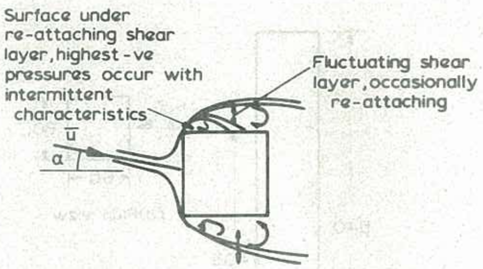


Figure 1 Region of high negative pressures caused by a separating and re-attaching shear layer

An hypothesis relating the high negative pressures and the behaviour of the separated shear layer was proposed by Melbourne (1979). The development of this hypothesis was influenced by the work of Gartshore (1973) who studied the effects of turbulence on the drag and base pressure of prisms. Melbourne's hypothesis, as shown diagrammatically in Figure 1, suggested that the separated shear layer and the pressure underneath fluctuate, and for certain conditions of freestream turbulence, angle of wind incidence, (and radius of leading edge curvature) the shear layer commences to occasionally re-attach onto the surface. As this occurs, the cavity region under the shear layer, which is often referred to as a separation bubble, is no longer vented to the freestream. As freestream flow over the front of the shear layer accelerates, the increased velocity is accompanied by a decrease in pressure. This decrease in pressure causes the initial radius of curvature of the shear layer to decrease which in turn increases the local freestream velocity outside the shear layer and further decreases the pressure. The freestream turbulence of the flow also produces increased turbulent mixing in the shear layer and entrainment of fluid from inside the bubble into the shear layer. The combined effect of entrainment and a decrease of pressure at the boundary causes the re-attached shear layer to move forward towards the leading edge and a reduction in bubble volume and internal pressure. This is an unstable process which proceeds until the shear layer breaks up into a complete separation again and the cavity becomes vented.

One of the effects of the behaviour of a re-attaching shear layer is to cause galloping, which results in a large amplitude cross-wind oscillation, for a number of bluff bodies. Galloping has been shown (Parkinson and Brooks, 1961; Novak, 1969; and others) to occur readily for bluff cross-sections which have fixed separation points, such as square and rectangular bodies, D-shaped and cruciform sections. It was shown that in the presence of a wind normal to a face, any cross-wind motion of the section (which effectively creates an angle of wind incidence), will create a pressure distribution around the section which results in a force in the direction of the motion so that the cross-wind displacement is further increased. The turbulence intensity and the scale of turbulence of the wind flow have very significant effects on the pressure distribution and hence the galloping behaviour of bluff bodies (Laneville and Parkinson, 1971; Barriga et al, 1975; Kwok and Melbourne, 1977; and others). To produce these effects, it was suggested (Gartshore, 1973; and Kwok and Melbourne, 1977) that an increase in freestream turbulence, and in particular fine scale turbulence, increases the turbulent mixing in the separated shear layer and the rate of entrainment of fluid from the wake, and decreases the radius of curvature of the shear layer; thus promoting re-attachment.

The failure of flat roofs on low rise structures and window panels on tall buildings are known to have been caused by the occurrence of very high negative pressures on streamwise surfaces near a leading edge. Some evidence has been presented by Melbourne (1979) and Sharp (1979) to indicate the forward travel of the re-attaching shear layer and the occurrence of very high negative pressure peaks near the leading edge. It was also shown that these negative pressure peaks could be substantially reduced (in magnitude) by venting the bubble under the re-attaching shear layer.

This paper describes a wind tunnel study of the pressure distribution around a square cylinder. Comparisons of results were made to assess the effectiveness of the fitting of small vanes to the corners of the cylinder and venting in reducing the negative surface pressures, and to relate these negative pressures to the behaviour of the separated shear layer.

2 EXPERIMENTAL ARRANGEMENTS

The experiments were carried out in the 2.4m x 2.0m Boundary Layer Wind Tunnel at the School of Civil Engineering, The University of Sydney. A "perspex" model 0.54m high (h) and 0.06m (b) square, as shown in Figure 2, was mounted on a turntable in the working section. In some tests, small vanes made of

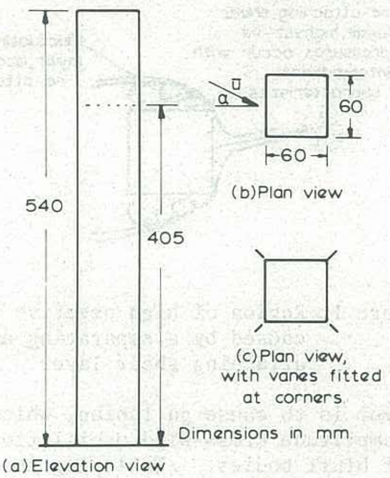


Figure 2 Sketches of the square cylinders tested

5mm wide strips of steel were fitted to the corners of the square cylinder. These vanes were adjustable, so that a small gap could be introduced between the vane and the corner.

The surface pressures at a height of 0.405m (3/4 cylinder height) were measured at a number of pressure taps around the square cylinder. These pressure taps consisted of a small length of 1.5mm O.D. stainless steel tubing fitted flush with the surface of the model. These were connected to a Celesco Pressure Transducer via 600mm long, 1.5mm I.D. PVC tubings. The frequency response of this pressure measuring arrangement was approximately 60 Hz.

A turbulent boundary layer flow was generated in the wind tunnel for the tests. The flow characteristics were similar to wind flow over a suburban area. The power law exponent of the mean longitudinal velocity profile was 0.18. At a height of 0.405m (the height of the cylinder around which surface pressures were measured), the turbulence intensity was 11%, and the integral length scale of turbulence was 0.38m.

Three cylinder configurations, namely plain square cylinder, square cylinder with 5mm wide vanes at the corners, and square cylinder with 5mm wide vanes and a 2.5mm vent between vane and corner, were tested at a mean wind velocity at the top of the cylinder $\bar{u}(h)$ of about 7m/s. The pressures around the cylinder were measured at angles of wind incidence α from 0^o up to 25^o. The mean pressures $\bar{p}$ and standard deviation pressures σ_p were measured using a computing digital voltmeter. The peak negative pressures $\check{p}$ over a period of about 20 seconds were measured using a peak detector. The mean wind velocity at the top of the cylinder and the corresponding dynamic wind pressure $\frac{1}{2}\rho\bar{u}^2(h)$, and the static pressure p_o in the wind tunnel were also measured and used as references.

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

The pressure distributions on the two side walls of the square cylinder are presented in Figures 3, 4 and 5. The results are expressed in terms of pressure coefficients defined as follows:

$$C_{\bar{p}} = \text{mean pressure coefficient} = \frac{\bar{p} - p_o}{\frac{1}{2}\rho\bar{u}^2(h)} \quad \text{—(1)}$$

$$C_{\sigma_p} = \text{standard deviation pressure coefficient} = \frac{\sigma_p}{\frac{1}{2}\rho\bar{u}^2(h)} \quad \text{—(2)}$$

$$C_{\check{p}} = \text{peak pressure coefficient} = \frac{\check{p} - p_o}{\frac{1}{2}\rho\bar{u}^2(h)} \quad \text{—(3)}$$

The effects of angle of wind incidence on the mean pressure distribution around the plain square cyl-

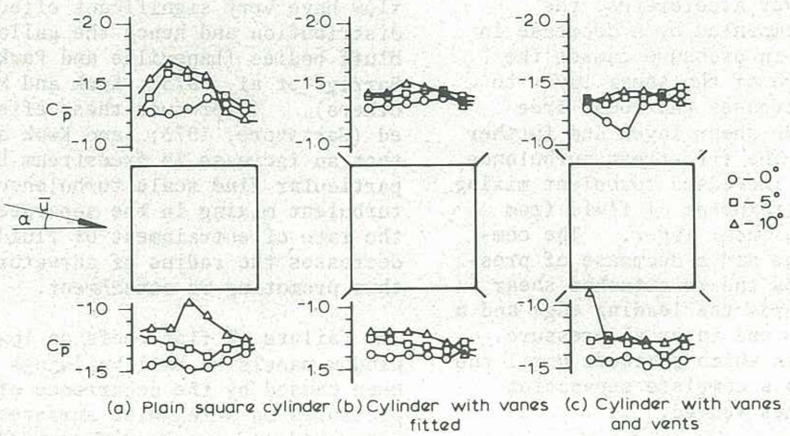


Figure 3 Variations of mean pressure coefficients

inder are shown in Figure 3a. As the angle of incidence is increased to 5°, the separated shear layer begins re-attaching onto the windward side wall. The combined effect of a decrease in pressure associated with an accelerating freestream flow over the front of the shear layer, and the entrainment of fluid from inside the separation bubble into the shear layer causes the re-attaching shear layer to move forward towards the leading edge and a reduction in bubble volume and internal pressure. It can be seen in Figure 3a that there is a substantial increase in the negative pressure coefficients (that is, the pressures become more negative) on the windward side wall, particularly near the leading edge. As the angle of incidence is increased to 10°, the mean pressure coefficients on the leading edge become more negative, while the mean pressure coefficients become less negative towards the rear. This suggests a forward movement of the re-attachment line towards the leading edge. On the other hand, the negative pressure coefficients on the leeward side wall are reduced as the angle of incidence is increased. This combined with the increase in negative pressures on the windward side wall will create a cross-wind force. Furthermore, if any cross-wind motion of the cylinder is established, and thereby creating an effective angle of wind incidence, this cross-wind force will be acting in the direction of motion, so that the cross-wind displacement is further increased. Therefore, the square cylinder is susceptible to galloping excitation as expected.

By fitting a small vane at the corner , the negative pressure coefficients on the windward side wall, especially near the leading edge, are significantly reduced (by up to 10%), as shown in Figure 3b. Up to an angle of wind incidence of 10°, there is little evidence to indicate the extreme forward travel of the re-attachment line towards the leading edge and the corresponding increase in negative pressure. Although the shear layer separating from the vane will occasionally re-attach, it seems that a larger angle of incidence would be required to encourage re-attachment and to establish the instability process. It is also thought that the increase in bubble volume underneath the shear layer might help to sustain the fluid entrainment process and to maintain a less negative pressure even if the instability process does become established.

By maintaining a small gap between the vane and the corner, the bubble underneath the re-attaching shear layer is vented. This apparently causes the instability process associated with a re-attaching shear layer to break down, and prevents the occurrence of the extreme forward travel of the re-attachment line and attendant of high negative pressures near the leading edge. It can be seen in Figure 3c that the negative pressure coefficients on the windward side wall, especially near the leading edge, are significantly reduced (by up to 15%), compared with those on the plain cylinder.

The fitting of small vanes and vents at the corners has a less significant effect on the pressure distribution on the leeward side wall. The negative pressure coefficients over the entire side wall are reduced when the angle of wind incidence is increased, as shown in Figures 3b and 3c. It is interesting to note that there is a significant reduction of the pressure difference between the windward and leeward side walls. Therefore, the magnitude of cross-wind force causing galloping is also significantly reduced.

The pressure fluctuations on the side walls for the three cylinder configurations are presented in Figures 4 and 5. When small vanes and vents are fitted at the corners, there is a significant reduction in the standard deviation pressure coefficients on both side walls, as shown in Figure 4. It can be seen in Figure 5 that the reduction in peak negative pressure coefficients are much more substantial, particularly on the windward side wall and near the leading edge. The percentage reduction in peak negative pressure coefficients on the windward side wall is presented in Table 1 which shows a reduction of up to 40% near the leading edge. These reductions support the earlier suggestions that the fitting of vanes and vents at the corners cause the instability process associated with a re-attaching shear layer to breakdown.

The peak pressures are related to the mean and standard deviation pressures as follows:

$$\overset{v}{p} = \bar{p} + g\sigma_p \qquad (4)$$

or in coefficient form,

$$C_{\overset{v}{p}} = C_{\bar{p}} + gC_{\sigma_p} \qquad (5)$$

where g is the peak factor. The peak factor associated with a normally distributed process is about 4.0. The peak factors of most pressure measurements taken in the tests are significantly greater than 4.5, with a maximum value of about 8.0. This indicates that the pressure fluctuations caused by a re-attaching shear layer contain very intermittent and sharp pressure peaks.

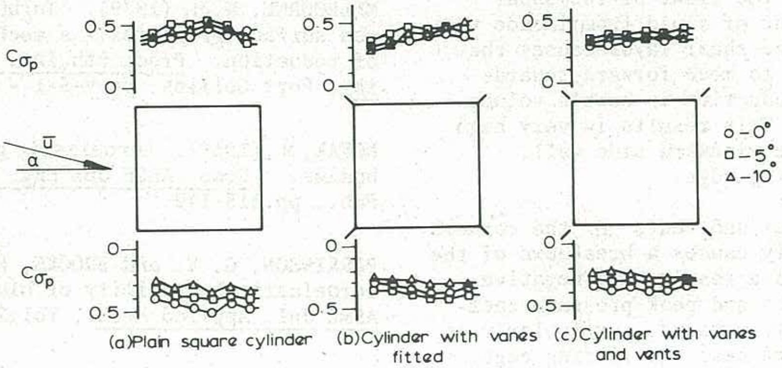


Figure 4 Variations of standard deviation pressure coefficients

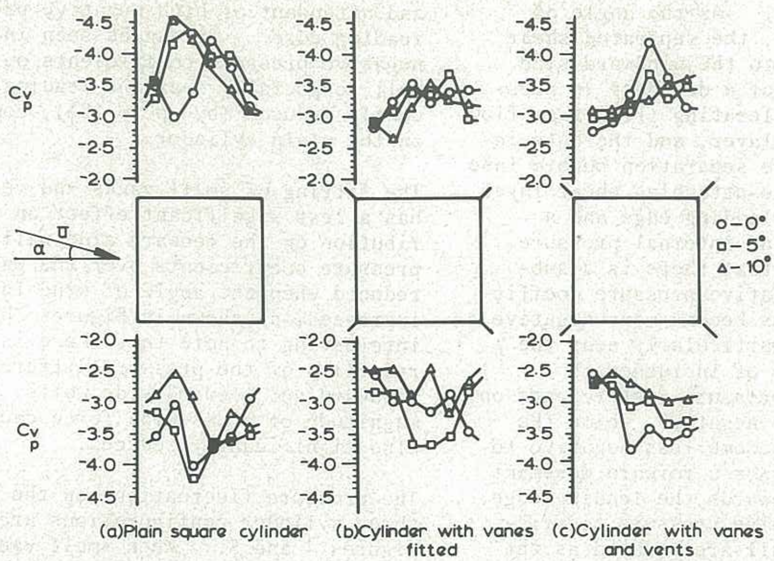
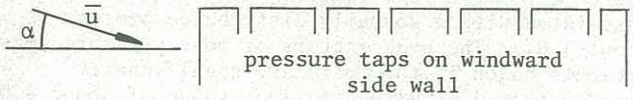


Figure 5 Variations of peak pressure coefficients

TABLE I

PERCENTAGE REDUCTION IN PEAK NEGATIVE PRESSURE COEFFICIENTS ON THE WINDWARD SIDE WALL WHEN SMALL VANES AND VENTS ARE FITTED AT CORNERS

Corners fitted with small vanes	α = 0°	-20	9	5	-23	-7	10
	5°	-12	-25	-22	-17	-6	-13
	10°	-19	-41	-27	-9	0	0
Corners fitted with small vanes and vents	α = 0°	-22	-5	-2	-2	-3	-2
	5°	-9	-29	-29	-7	-19	0
	10°	-13	-34	-27	-17	3	10



4 CONCLUSIONS

When a square cylinder is subjected to air flow and especially at a small angle of wind incidence, the separated shear layer occasionally re-attaches onto the windward side wall. The combined effect of a decrease in pressure associated with an accelerating freestream flow over the front of the shear layer, and the entrainment of fluid from inside the separation bubble into the shear layer causes the re-attaching shear layer to move forward towards the leading edge and a reduction in bubble volume and internal pressure. This results in very high negative pressures on the windward side wall, especially near the leading edge.

The fitting of small vanes and vents at the corners of the cylinder apparently causes a breakdown of the instability process. As a result, the negative mean pressure coefficients and peak pressure coefficients are substantially reduced, particularly on the windward side wall and near the leading edge. In practice the use of such devices can reduce the loads on window panels in tall buildings and the cross-wind excitation of tall buildings and structures. There are also possible practical applications in reducing loads on flat roofs on low rise structures and other types of roof structures.

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