THE LIFT ON TWO-DIMENSIONAL RECTANGULAR CYLINDERS

IN SMOOTH FLOW AND TURBULENCE

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Introduction

In the preceding paper, "The Drag on Two-Dimensional Rectangular Cylinders in Smooth Flow and Turbulence", the author made the point that there was a need for a more comprehensive catalogue of lift and drag coefficients for two dimensional rectangular cylinders. That paper then proceeded to present the drag coefficients obtained from an experimental investigation of the forces on such a range of structures in both smooth and turbulent flow. In this paper, the corresponding lift coefficients from that investigation are presented and discussed.

Nomenclature

The lift force exerted on a structure, F_L, is defined as the component of the total aerodynamic force in the direction perpendicular to the mean flow. Lift force can be expressed as a lift coefficient, C_L, using the following equation:

$$C_L = \frac{F_L}{\frac{1}{2}\rho\bar{u}^2 b c} \qquad \ldots 1$$

where ρ and $\bar{u}$ are the density and velocity of the incident flow

b and c are the span and chord of the structure under test.

In many applications, it is the component of the total aerodynamic force in the direction perpendicular to the chord of the structure which is of interest. This component is called the transverse force, F_Z, and is related to lift and drag by

$$F_Z = F_L \cos\alpha + F_D \sin\alpha \qquad \ldots 2$$

where α is the angle of attack of the structure.

Transverse force is reduced to coefficient form in exactly the same way as lift force.

Configurations Tested

Lift measurements were performed on a total of 11 different sections. All but two of the models were either square or rectangular in cross-section, the exceptions being a slender symmetrical aerofoil section (designated NACA 0006, and shown in Figure 1) and a sectional model of Melbourne's West Gate Bridge (shown in Figure 2). As with the drag study, the chord-to-thickness ratios varied between 0.25 and 16.67, and the maximum blockage ratio (excluding two models designed specifically for testing the effects of blockage) was 3.75%. For the rectangular models, all edges were sharp.

The models were tested in 3 different turbulence configurations; these had turbulence intensities of 0.6% ("smooth flow"), 5% and 12½%. The longitudinal

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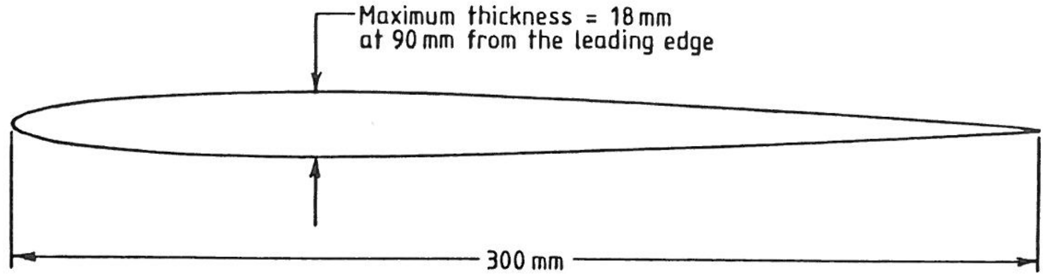

FIGURE 1 - NACA 0006 AEROFOIL SECTION

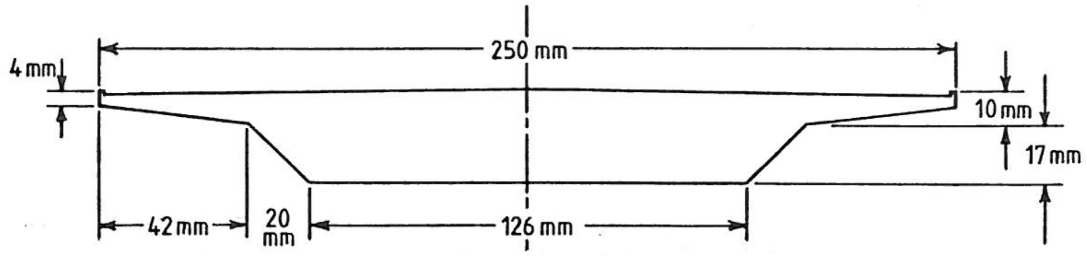

FIGURE 2 - WEST GATE BRIDGE SECTION

integral scales of turbulence for the three configurations were 39 mm, 33 mm and 84 mm, respectively. All testing was conducted at Reynold's numbers of between 10^4 and 2×10^5 (based on model chord).

Experimental Installation

All measurements were performed in a specially developed two-dimensional working section which was installed into the Monash University 450 kW wind tunnel. This working section, which was 2 metres high by 1 metre wide by 2 metres long, is described more fully in the preceding paper and in detail in Jancauskas [1983].

The 5% and 12½% turbulence configurations were generated using uniform bi-planar grids located upstream of the model. The smooth flow (0.6% turbulence intensity) configuration corresponded to the basic unmodified flow in the wind tunnel.

Results

Table 1 summarizes the details and results of the 32 different section / turbulence configurations tested. Lift coefficients are presented for angles of attack (α) of 0°, 5°, 10° and 15°; with the exception of the bridge section (where values have been tabulated for both positive and negative angles of attack) the lift characteristics were symmetrical about 0° angle of attack.

Table 1 also records the maximum lift coefficient that was measured within the range of angles of attack tested. In the majority of cases, this maximum lift corresponded to a clearly defined stall, but in some cases (marked †) the lift was still increasing at the maximum angle of attack tested.

The slope of the lift coefficient curve at $\alpha = 0°$, $\left(\frac{dC_L}{d\alpha}\right)_{\alpha=0}$, and the slope of the transverse force coefficient curve at $\alpha = 0°$, $\left(\frac{dC_{F_Z}}{d\alpha}\right)_{\alpha=0}$, are also given. In the case of the West Gate Bridge model, where there was a change in slope of both of these characteristics at $\alpha = 0°$, both the positive-going and negative-going slopes have been recorded.

TABLE 1 - SUMMARY OF LIFT COEFFICIENT RESULTS

	Section (mm)	Chord-to-Thickness Ratio	Blockage Ratio	Turbulence Level (I_u)	Maximum α Tested	C_L at				Maximum C_L		$\frac{dC_L}{d\alpha}$ $\alpha=0$ (deg^{-1})	$\frac{dC_{F_Z}}{d\alpha}$ $\alpha=0$ (deg^{-1})
						$\alpha=0°$	$\alpha=5°$	$\alpha=10°$	$\alpha=15°$	$C_{L_{max}}$	Measured at α =		
# 3	NACA 0006 Aerofoil	*16.67	0.9%	Smooth	15°	0	+0.49	+0.91	+0.82	+0.97	12.2°	+0.103	+0.103
	NACA 0006 Aerofoil	*16.67	0.9%	5%	18°	0	+0.53	+0.97	+1.07	+1.08	13.8°	+0.104	+0.104
	NACA 0006 Aerofoil	*16.67	0.9%	12½%	22°	0	+0.48	+0.88	+1.15	+1.24	19.8°	+0.097	+0.097
	300x18 Rectangular	16.67	0.9%	Smooth	12°	0	+0.62	+0.65	-	+0.71	7.0°	+0.131	+0.132
	300x18 Rectangular	16.67	0.9%	5%	15°	0	+0.66	+0.91	+0.89	+0.92	9.2°	+0.129	+0.130
	300x18 Rectangular	16.67	0.9%	12½%	20°	0	+0.50	+0.89	+1.02	+1.02	15.0°	+0.106	+0.106
	300x30 Rectangular	10	1.5%	Smooth	15°	0	+0.63	+0.78	+0.75	+0.79	12.3°	+0.163	+0.165
	300x30 Rectangular	10	1.5%	5%	13°	0	+0.71	+0.85	-	+0.87	8.1°	+0.148	+0.150
	300x30 Rectangular	10	1.5%	12½%	20°	0	+0.54	+0.87	+0.96	+0.96	15.0°	+0.111	+0.113
# 4	300x50 Rectangular	6	2.5%	Smooth	17°	0	+0.47	+0.56	+0.63	+0.68†	17.0°	+0.326	+0.329
	300x50 Rectangular	6	2.5%	5%	15°	0	+0.72	+0.68	+0.76	+0.77	7.0°	+0.182	+0.186
	300x50 Rectangular	6	2.5%	12½%	18°	0	+0.59	+0.82	+0.83	+0.84	12.7°	+0.119	+0.124
	300x75 Rectangular	4	3.75%	Smooth	13°	0	+0.57	+0.42	-	+0.58	5.9°	+0.167	+0.173
	300x75 Rectangular	4	3.75%	5%	12.5°	0	+0.59	+0.56	-	+0.61†	12.5°	+0.194	+0.201
	300x75 Rectangular	4	3.75%	12½%	17°	0	+0.60	+0.73	+0.74	+0.75	12.5°	+0.135	+0.140
# 5	150x50 Rectangular	3	2.5%	Smooth	8°	0	+0.34	-	-	+0.43	3.4°	+0.212	+0.220
	150x50 Rectangular	3	2.5%	5%	13°	0	+0.35	+0.33	-	+0.39†	13.0°	+0.149	+0.156
# 6	150x50 Rectangular	3	2.5%	12½%	18°	0	+0.48	+0.59	+0.59	+0.63†	18.0°	+0.121	+0.127
# 7	150x75 Rectangular	2	3.75%	Smooth	10°	0	-0.45	-0.20	-	-0.59	6.8°	-0.078	-0.063
	150x75 Rectangular	2	3.75%	5%	10°	0	-0.39	-0.14	-	-0.40	5.7°	-0.104	-0.091
# 8	150x75 Rectangular	2	3.75%	12½%	15°	0	+0.18	+0.24	+0.32	+0.32†	15.0°	+0.041	+0.051
#10	75x75 Square	1	3.75%	Smooth	15°	0	-0.37	-0.59	-0.55	-0.77	12.6°	-0.088	-0.048
	75x75 Square	1	3.75%	5%	12°	0	-0.44	-0.87	-	-0.88	10.6°	-0.089	-0.050
	75x75 Square	1	3.75%	12½%	15°	0	-0.33	-0.52	-0.30	-0.52	10.0°	-0.068	-0.036
# 9	47x75 Rectangular	0.625	3.75%	Smooth	22°	0	-0.30	-0.62	-0.91	-1.05	19.2°	-0.061	+0.032
	47x75 Rectangular	0.625	3.75%	5%	20°	0	-0.37	-0.72	-1.06	-1.14	16.6°	-0.073	+0.013
	47x75 Rectangular	0.625	3.75%	12½%	20°	0	-0.43	-0.76	-0.89	-0.90	16.0°	-0.083	-0.008
	18x75 Rectangular	0.25	3.75%	Smooth	13°	0	-0.48	-0.92	-	-1.19†	13.0°	-0.094	+0.122
	18x75 Rectangular	0.25	3.75%	12½%	17°	0	-0.32	-0.73	-1.06	-1.20†	17.0°	-0.094	+0.119
	West Gate Bridge	*9.1	1.35%	Smooth	+15°	-0.12	+0.38	+0.61	+0.53	+0.61	+9.7°	+0.096	+0.097
					-18°		-0.56	-0.98	-1.05	-1.11	-12.5°	+0.087	+0.088
	West Gate Bridge	*9.1	1.35%	5%	+15°	-0.13	+0.35	+0.59	+0.42	+0.59	+9.2°	+0.098	+0.099
					-16°		-0.64	-1.15	-1.40	-1.42	-13.7°	+0.101	+0.102
	West Gate Bridge	*9.1	1.35%	12½%	+20°	-0.11	+0.34	+0.65	+0.73	+0.73	+15.0°	+0.086	+0.087
					-20°		-0.52	-0.94	-1.33	-1.44	-19.0°	+0.083	+0.084

Lift characteristic shown in Figure ...

*Based on maximum thickness

† Lift still increasing at maximum α tested

The lift coefficient versus angle of attack characteristics for 8 of the configurations tested are presented in Figures 3 - 10. Table 1 indicates which configurations have been presented.

It should be noted that the lift data presented in both Table 1 and Figures 3 - 10 has not been corrected for the effects of blockage. As with the drag measurements, however, the effect of blockage is to produce a conservative measurement. Blockage effects are considered separately in the following section.

The Effect of Blockage on Lift

Measurements by Modi & El-Sherbiny [1977] indicated that for structures with large chord-to-thickness ratios, the effect of blockage on lift was small. Modi & El-Sherbiny measured the lift versus angle of attack characteristic for flat plates in both smooth and turbulent flow and found that, over the linear region of the characteristics (up to $\alpha = 10°$), blockage had only a very small effect on lift force.

On the other hand, data from the same study showed that for flat plates normal to the flow (equivalent to structures with very low chord-to-thickness ratio), the effect of blockage was very significant.

The results for these two extremes are as one would expect. That is, the blockage effect is large for situations where the flow around the structure is dominated by a large wake, and small for situations where there is an insignificant wake.

However, between these two extremes there is little experimentally obtained information. For this reason, a series of lift measurements were made on two

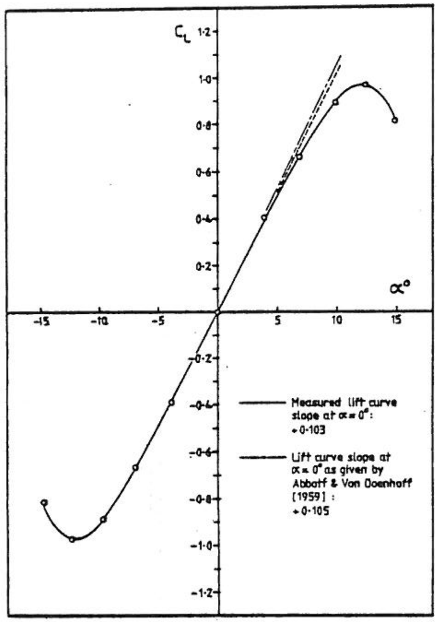

FIGURE 3 - NACA 0006 AEROFOIL SECTION IN SMOOTH FLOW

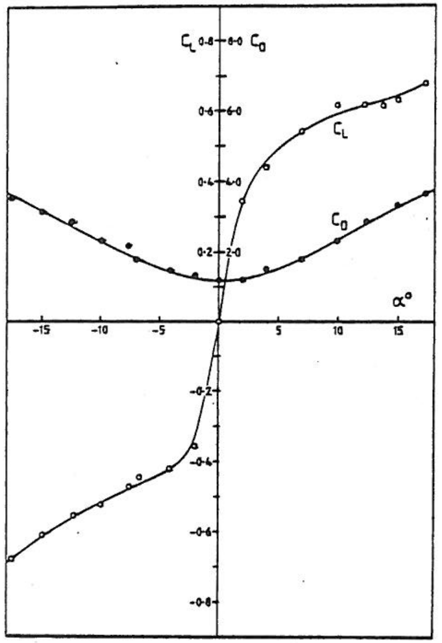

FIGURE 4 - 300 x 50 MM (6:1) RECTANGULAR SECTION IN SMOOTH FLOW

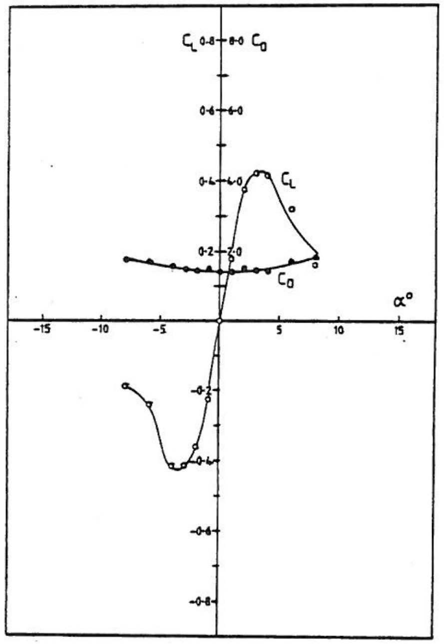

FIGURE 5 - 150 x 50 MM (3:1) RECTANGULAR SECTION IN SMOOTH FLOW

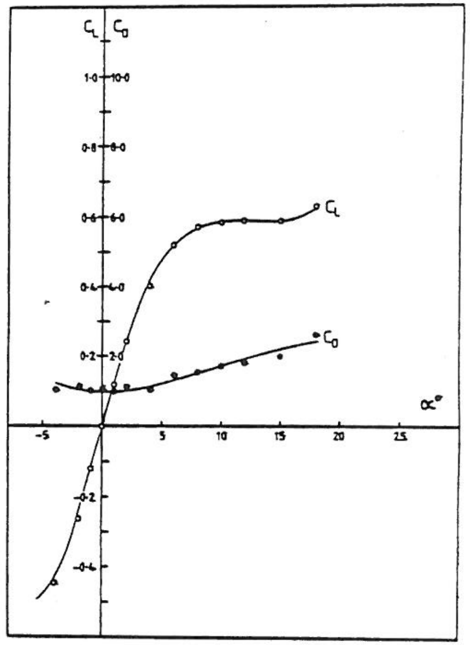

FIGURE 6 - 150 x 50 MM (3:1) RECTANGULAR SECTION IN $12^1/_2$% TURBULENCE

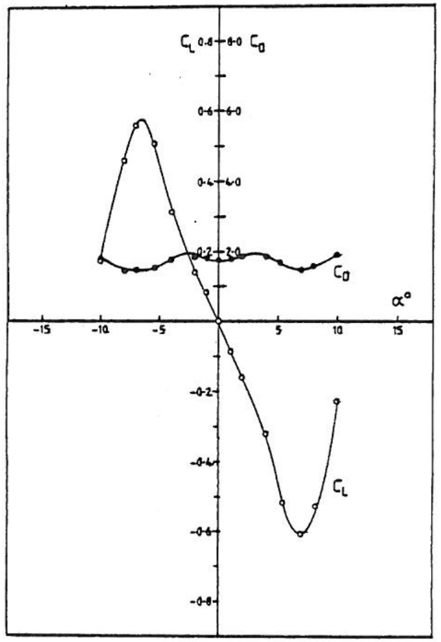

FIGURE 7 - 150 x 75 MM (2:1) RECTANGULAR SECTION IN SMOOTH FLOW

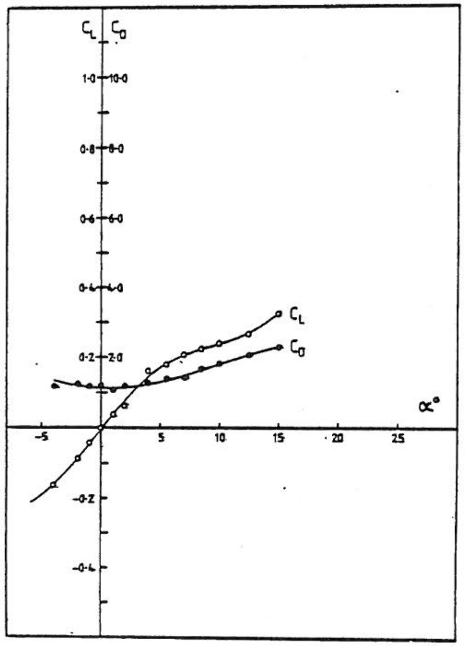

FIGURE 8 - 150 x 75 MM (2:1) RECTANGULAR SECTION IN $12^1/_2$% TURBULENCE

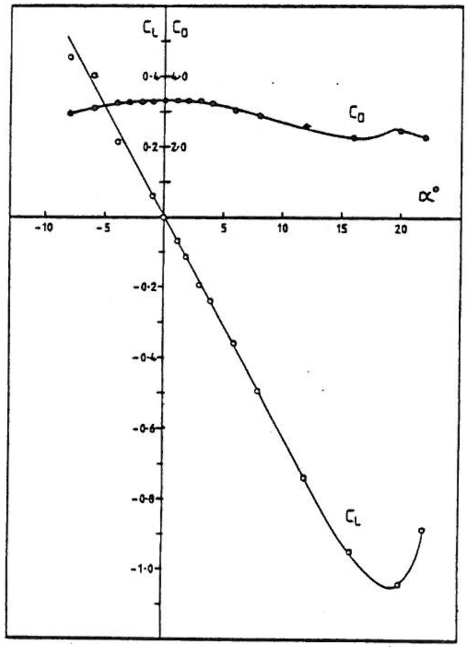

FIGURE 9 - 47 x 75 MM (0.625:1) RECTANGULAR SECTION IN SMOOTH FLOW

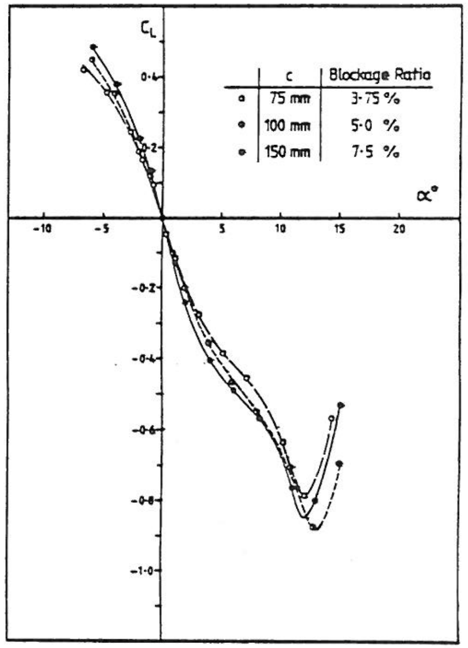

FIGURE 10 - LIFT CHARACTERISTICS FOR THREE SQUARE SECTION MODELS OF DIFFERENT SIZES IN SMOOTH FLOW

increased sizes of square section cylinder in both smooth and turbulent flow. These models, which were also used for the same purpose in the drag investigation, had chords of 100 mm and 150 mm. When combined with the 75 mm square section already tested, this gave three different blockage ratios of 3.75%, 5.0% and 7.5%.

The lift characteristics for the three models in smooth flow are shown in Figure 10. It can be seen that the differences, particularly in the slope at $\alpha = 0°$, are quite significant. The lift curve slope at $\alpha = 0°$ of each model has been plotted against its blockage ratio in Figure 11. Data from a number of other researchers (uncorrected for the effect of blockage) has also been plotted to consolidate the trends. It should be noted that in one case it was necessary to extract the lift curve slope from transverse force and drag force data.

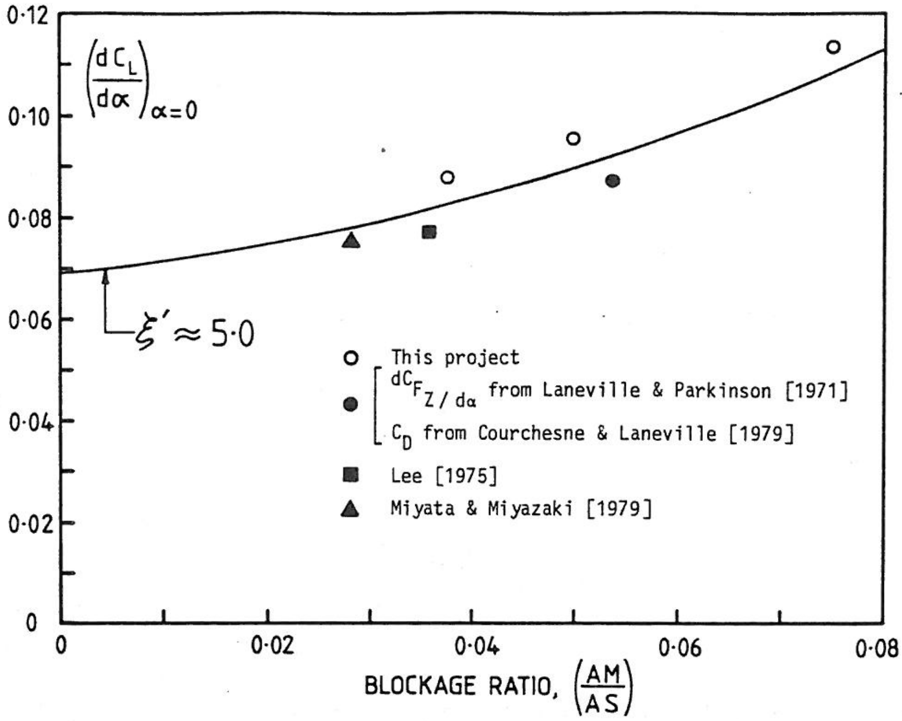

FIGURE 11 - LIFT CURVE SLOPE (AT $\alpha = 0^o$) OF SQUARE SECTION MODEL IN SMOOTH FLOW AS A FUNCTION OF BLOCKAGE RATIO

An empirical correction format equivalent to that used by Courchesne & Laneville [1979] for drag was adopted:

$$\frac{C_{L_c}}{C_L} = 1 - \xi'\left[\frac{AM}{AS}\right] \qquad \ldots 3$$

where ξ' is an empirical correction coefficient for lift.

It was found that an ξ' value of 5.0 provided a good fit to the smooth flow data. A similar set of results for the 12½% turbulence configuration produced an ξ' value of 4.2.

It can therefore be seen, from Figure 11 and the results of ξ', that the effect of blockage on lift for this particular section is large, and considerably greater than the corresponding drag correction given in the previous paper. (This is probably because of the greater dependence of lift on the slope of the shear layer, especially in the region close to the leading edge.) However, as would be expected, the blockage effect decreased with turbulence.

On the basis of the above data, the corrections necessary for the 75 x 75 mm square section model would be approximately 20% in smooth flow and 15% in the 12½% turbulence configuration. These are much greater than has been suggested in the literature. For example, Lee [1975],using the blockage correction method of Allen & Vicenti [1944], computed a correction of only 4% for a square section model with the same blockage ratio.

However, despite the size of the blockage corrections for the square section model, the majority of models could be expected to require a significantly smaller correction. This is not only because the actual blockage ratio is smaller for nearly every other model, but because the value of ξ' could be expected to decrease towards zero as the chord-to-thickness ratio of the model increases.

Comparison with Lift Data from other Experimental Sources

The lift data presented in this paper compares extremely well with that presented in the literature.

The most important comparison was that for the NACA 0006 aerofoil. As can be seen in Figure 3, the lift curve slope for the aerofoil, in smooth flow, was within 2% of the value reported by Abbott & Von Doenhoff [1959]. This was taken as being strong evidence of the two-dimensionality of the measuring system developed in this project.

For the majority of the other configurations, the agreement with the literature was also extremely good (usually well within ±5%). For example, the lift curve slope for the 4 : 1 rectangular section in smooth flow of +0.167 compares well with that quoted by Blevins [1977] of +0.171; similarly, the lift curve slope for the 2 : 1 rectangular section in smooth flow of -0.078 compares well with that quoted by Laneville & Parkinson [1971] of -0.077. It should be noted, however, that for the more bluff sections (with chord-to-thickness ratios less than 3) the agreement was dependent on the relative blockage ratios of the measurements.

Furthermore, the form of the lift curves (that is, their general shape, stall angle, and maximum lift value) all agreed particularly well with those presented in the literature. Where the literature reported measurements made in a number of different levels of turbulence, agreement was again very good; this was so even when the turbulence produced changes in the sign of the lift curve slope.

In some cases, however, there was up to 10% disagreement between the measured and reported lift data. These cases almost invariably occurred in smooth flow with the measured value being the greater. Furthermore, where the literature also reported corresponding measurements in turbulent flow, the differences were greatly reduced, even to the point of being insignificant.

However, where there is a discrepancy, the author favours the data presented in this paper for two reasons. Firstly, the data presented in this paper represents the results of a continuous programme of measurements; it is unlikely that incorrect data would have been produced for only certain configurations. Secondly, the two-dimensionality of the measuring system used in this study was, in a sense, validated by measurements on the NACA 0006 aerofoil section. This was not so, however, for the measuring systems used by the other researchers. The fact that any deficiency in lift was almost always on the part of the value reported in the literature, is indicative of the presence of three-dimensionalities in these systems. Furthermore, when investigating the various three-dimensionalities encountered during the development of the two-dimensional working section, it was observed that turbulence tended to decrease the effect of the three-dimensionalities and made the measuring system more two-dimensional. This is again in keeping with the above observations.

One final comparison that should be commented on is that for the West Gate Bridge section. When compared with the characteristic measured by Vickery & Watkins [1973] on the same sectional model, the smooth flow lift curve was almost identical with regard to both the intercept and slope of the curve at $\alpha = 0°$:-

	Figure 10.34	As measured by Vickery & Watkins
C_L at $\alpha = 0°$	-0.12	-0.10
$\frac{dC_L}{d\alpha}$ at $\alpha = 0°$	+0.096 deg^{-1}	+0.095 deg^{-1}

There were, however, significant differences in stall angle and maximum lift attained for positive angles of attack. The reason for this was that the model, when tested by Vickery & Watkins, had been fitted with 4 mm high strips of wire gauze along each edge (representing the safety rails on the actual bridge). When tested in this study, these strips were removed. The strips apparently had little effect on the lift force for low angles of attack, but for higher angles affected the flow over the leading edge of the model leading to premature stall.

General Discussion

It is worth noting that, with one or two exceptions, each model in each turbulence configuration featured lift and transverse force curve slopes (as measured at $\alpha = 0°$) that were comparable in magnitude with those of the aerofoil section. In fact, of the 32 configurations tested, only 8 had a transverse force curve slope with a magnitude less than 80% of that of the aerofoil. It is therefore obvious that there is a wide range of bluff sections which have the *potential* to receive significant cross-wind forcing from the incident turbulence.

The second feature worth noting is the high values of the lift curve slope developed for the rectangular section models with chord-to-thickness ratios between 3 and 6. Over a limited range of angle of attack, these slopes were up to two and three times greater than that of the aerofoil section. The particularly high value of 0.329 deg^{-1} for the 300 x 50 mm rectangular section in smooth flow should not go unnoticed. The high lifts for these particular sections correspond to the increasing significance of the low pressure region under the reattaching shear layer at the leading edge of the model.

From a design point of view, it should be noted that, in general, the highest lift curve slopes (and hence the highest lifts for small angles of attack) occurred in smooth flow. The maximum lift for a particular section, however, generally occurred in the higher turbulence level due to delayed flow separation; see, for example, Figures 5 and 6.

Finally, it should be noted that, compared to the drag force, the lift becomes a significant force component for sections with chord-to-thickness ratios as small as 0.5 : 1. The lift force becomes the dominant component for ratios greater than about 3 : 1.

Comparison with Code Lift Data

AS 1170, Part 2 - 1983 does not present lift coefficients for two dimensional rectangular cylinders. In the light of the significance of the lift forces relative to the drag forces (discussed above), this is an important omission.

The NAASRA Bridge Design Specification (Draft Code, February 1983) gives an equation for calculating the design lift load on a rectangular section inclined at less than 5° to the flow. This equation is based on a maximum lift coefficient of 0.75 for $\alpha = 5°$. As can be seen from Table 1, this is a good choice, the maximum measured coefficient at $\alpha = 5°$ being 0.72.

Conclusions

- Comparisons with other experimentally measured lift coefficients reported in the literature show very good agreement.
- There is a need for a detailed investigation of the effects of blockage on lift force measurements.
- AS 1170, Part 2 - 1983 gives no lift coefficient data for two-dimensional rectangular cylinders and is in need of review.
- The NAASRA Draft Code provides a satisfactory design value for the lift on a two-dimensional rectangular cylinder inclined at less than 5° to the flow.

Acknowledgements

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