THE DRAG ON TWO-DIMENSIONAL RECTANGULAR CYLINDERS IN SMOOTH FLOW AND TURBULENCE

E.D. Jancauskas[1]

Introduction

Basic information on the lift and drag forces on two-dimensional bluff sections is of fundamental importance to the wind engineer in predicting loads on civil engineering structures. While some work of varying quality has been performed in smooth flow, little has been done to produce a comprehensive catalogue of these forces under turbulent flow conditions (which, indeed, are the very conditions with which the wind engineer is primarily concerned).

As part of a broader research project dealing with the cross-wind excitation of bluff structures (Jancauskas [1983]), the author measured the lift and drag forces on a wide range of two-dimensional sections in both smooth flow and turbulent flow. This paper, after describing the experimental installation in which these measurements were made, focusses on the drag measurements. An accompanying paper, "The Lift on Two-Dimensional Rectangular Cylinders in Smooth Flow and Turbulence", deals separately with the lift measurements.

Nomenclature

The drag forces exerted on a structure, F_D, is defined as the component of the total aerodynamic force in the direction parallel to the mean flow. Drag force can be expressed as a drag coefficient, C_D, using the following equation:

$$C_D = \frac{F_D}{\frac{1}{2}\,\rho\,\bar{u}^2\,b\,a} \qquad \ldots 1$$

where ρ and $\bar{u}$ are the density and velocity of the incident flow
b and a are the span and thickness of the structure under test.

Configurations Tested

Drag measurements were performed on a total of 9 different sections, all of which were either square or rectangular in cross-section. The chord-to-thickness ratios for the sections varied between 0.25 and 16.67. All edges were sharp.

The models had a maximum chord of 300 mm and all models had a span of 800 mm (determined by the width of the wind tunnel working section). Apart from two models which were designed specifically for testing the effects of blockage, the thickness of the models did not exceed 75 mm; this thickness represented a maximum blockage ratio of 3.75%. The angle of attack of the models was varied between 0° and ±15°.

The models were tested in 3 different turbulence configurations; these had turbulence intensities of 0.6% ("smooth flow"), 5% and 12½%. The longitudinal integral scales of turbulence for the 3 configurations were 39 mm, 33mm and 84 mm, respectively. All testing was conducted at Reynold's numbers of between 10^4 and 2×10^5 (based on model chord).

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[1] James Cook University of North Queensland

Experimental Installation

All measurements were performed in a specially developed two-dimensional working section, as shown in Figure 1. This working section was 2 metres high by 1 metre wide by 2 metres long and was inserted, with the use of a suitable contraction and diffuser, into the 2 metre x 2 metre working section of the Monash University 450 kW wind tunnel. The model under test was installed horizontally across the centre of the working section and was supported on either side in a force measuring balance. This balance enabled the lift, drag and moment (about the spanwise axis) exerted on the model by the flow to be measured.

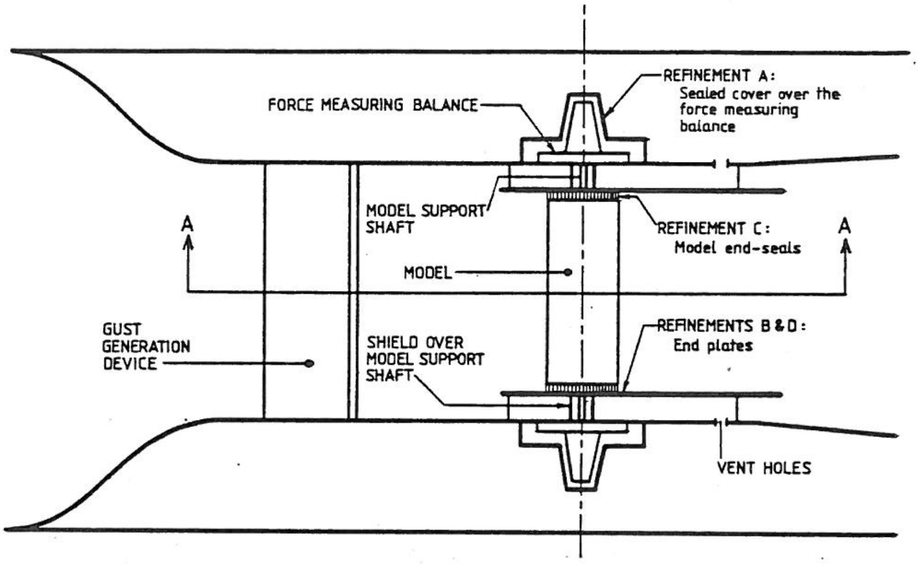

FIGURE 1 - PLAN VIEW OF THE TWO-DIMENSIONAL WORKING SECTION

Considerable care and effort were directed towards developing true two-dimensional conditions in the working section. In this quest, a number of refinements were introduced. The most significant of these were a pair of floor-to-ceiling end plates mounted 100 mm out from the insertable working section walls. These served to skim off the boundary layers growing on the working section walls and to prevent secondary flows from developing around the ends of the model. Details of this and the other refinements can be found in Jancauskas [1983]. The final result was an installation which demonstrated a high degree of two-dimensionality in the characteristics of both the flow and the models that were tested in it.

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 26 different section / turbulence configurations tested. Drag coefficients are presented for angles of attack (α) of 0°, 5°, 10° and 15°; in all cases the drag coefficients were symmetrical about 0° angle of attack.

It should be noted that the drag data presented in Table 1 has not been corrected for the effects of blockage. However, as will be seen in the following section, the effect of blockage (in all cases) leads to a conservative measurement.

TABLE 1 - SUMMARY OF DRAG COEFFICIENT RESULTS

CHORD-TO THICKNESS RATIO	DIMENSIONS: CHORD X THICKNESS (mm x mm)	BLOCKAGE RATIO	TURBULENCE LEVEL (Iu)	C_D at			
				$\alpha=0°$	$\alpha=5°$	$\alpha=10°$	$\alpha=15°$
16.67	300 x 18	0.9 %	Smooth	1.05	1.65	2.94	4.08
16.67	300 x 18	0.9 %	5 %	0.58	2.20	5.25	6.67
16.67	300 x 18	0.9 %	12½ %	0.22	1.04	2.33	3.76
10	300 x 30	1.5 %	Smooth	1.40	2.24	3.61	4.42
10	300 x 30	1.5 %	5 %	1.40	2.08	2.98	3.50
10	300 x 30	1.5 %	12½ %	1.39	1.92	2.96	4.18
6	300 x 50	2.5 %	Smooth	1.19	1.53	2.35	3.22
6	300 x 50	2.5 %	5 %	1.39	1.80	2.86	3.45
6	300 x 50	2.5 %	12½ %	1.60	1.78	2.38	3.18
4	300 x 75	3.75 %	Smooth	1.31	1.71	2.33	2.49
4	300 x 75	3.75 %	5 %	1.66	2.12	2.96	3.53
4	300 x 75	3.75 %	12½ %	1.24	1.41	1.88	2.43
3	150 x 50	2.5 %	Smooth	1.44	1.59	2.08	-
3	150 x 50	2.5 %	5 %	1.20	1.65	2.17	2.53
3	150 x 50	2.5 %	12½ %	0.99	1.18	1.73	2.17
2	150 x 75	3.75 %	Smooth	1.74	1.70	1.88	-
2	150 x 75	3.75 %	5 %	1.49	1.67	2.17	-
2	150 x 75	3.75 %	12½ %	1.20	1.29	1.78	2.30
1	75 x 75	3.75 %	Smooth	2.29	2.12	1.77	1.80
1	75 x 75	3.75 %	5 %.	2.25	2.00	1.94	-
1	75 x 75	3.75 %	12½ %	1.85	1.61	1.68	1.86
0.625	47 x 75	3.75 %	Smooth	3.35	3.14	2.69	2.30
0.625	47 x 75	3.75 %	5 %	3.10	3.02	2.64	1.96
0.625	47 x 75	3.75 %	12½ %	2.71	2.67	2.63	2.31
0.25	18 x 75	3.75 %	Smooth	2.97	2.88	2.73	2.55
0.25	18 x 75	3.75 %	12½ %	2.93	2.90	2.89	2.86

The Effect of Blockage on Drag

Blockage effects result from the confinement of the flow around the model by the wind tunnel walls. In the particular case of bluff bodies, with their large associated wakes, the effect may be considerable in preventing the streamlines and wakes from expanding in the way that they would in unconstrained freestream flows. As a consequence, the local velocities in the vicinity are increased and the pressure distribution on the model changes, thereby affecting the lift and drag forces.

Filling an obvious deficiency in the literature, Courchesne & Laneville [1979] performed a comprehensive experimental evaluation of the effects of blockage on the drag of two-dimensional rectangular cylinders in smooth flow. They presented their drag correction data empirically in the following form:

$$\frac{C_{D_c}}{C_D} = 1 - \xi \left[\frac{AM}{AS} \right] \qquad . . 2$$

where C_{D_c} is the corrected drag coefficient

C_D is the measured drag coefficient

AM is the frontal area of the model

AS is the cross-sectional area of the wind tunnel test section, and

ξ is an empirical correction coefficient.

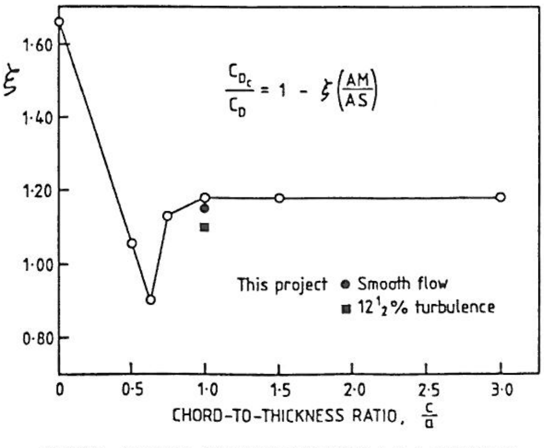

FIGURE 2 - EMPIRICAL CORRECTION COEFFICIENT ξ AS A FUNCTION OF CHORD-TO-THICKNESS RATIO FOR RECTANGULAR CYLINDERS IN SMOOTH FLOW (AFTER COURCHESNE & LANEVILLE, 1979)

Figure 2 shows the value of ξ (in smooth flow) as a function of the chord-to-thickness ratio $\left(\frac{c}{a}\right)$ of the model. As can be seen, the maximum value of ξ occurs for a flat plate perpendicular to the flow $\left(\frac{c}{a} = 0\right)$, the mimimum occurs for $\frac{c}{a} = 0.625$, and for $\frac{c}{a} \geqslant 1$ the value of ξ remains constant up to $\frac{c}{a} = 3$ (the maximum chord-to-thickness ratio tested).

Therefore, based on Courchesne & Laneville's data, the maximum blockage correction that would apply to the drag data presented in this paper can be easily calculated. The maximum blockage effect would have occurred for the 47 x 75 mm rectangular section $\left(\frac{c}{a} = 0.24\right)$, which had the largest value of both the correction coefficient ($\xi \approx 1.4$) and blockage ratio $\left(\frac{AM}{AS} = 0.0375\right)$. Therefore, substituting into Equation 2, it is found that the maximum correction would be 5%; for the majority of cases, however, the correction would be significantly less than this. In smooth flow, the value of either ξ or blockage ratio (or both) is less for all other models; for example, the correction on the 300 x 30 mm rectangular section would be less than 2%. In turbulence, because of its tendency to decrease the wake size, the drag blockage corrections could be expected to be lower than the corresponding smooth flow correction.

As part of the investigation, a series of measurements were performed to spot-check the value of Courchesne & Laneville's empirical drag correction coefficient ξ. These measurements consisted of measuring the drag (at $\alpha = 0^\circ$) on three different sizes (hence, three different blockages) of square section cylinder in both smooth flow and the 12½% turbulence configuration. The two resulting values of ξ are shown on Figure 2. It can be seen that the measured data confirms Courchesne & Laneville's value of ξ in smooth flow to within 3%:

Courchesne & Laneville	$\xi = 1.18$
This study	$\xi = 1.15$

Furthermore, as suggested above, the correction in turbulence was less than the corresponding smooth flow correction, although only slightly:

This study, smooth flow	$\xi = 1.15$
This study, 12½% turbulence	$\xi = 1.10$

Comparison with Drag Data from other Experimental Sources

The drag data was found to compare reasonably well with that given in the literature. In smooth flow, the drag data was compared with the compilation of data presented by Courchesne & Laneville [1979]. To facilitate the comparison, the measured smooth flow drag coefficients at $\alpha = 0^\circ$ (corrected for blockage using Courchesne & Laneville's correction) have been plotted as a function of chord-to-thickness ratio, together with the best fit curve from Courchesne & Laneville (Figure 3). It can be seen that, with the exception of the 18 x 75 mm rectangular section ($\frac{c}{a} = 0.25$, where the discrepency was approximately 30%), the measured data agreed with that of Courchesne & Laneville to within 10%. In all cases the measured drag was greater.

Comparisons with drag data measured in turbulent flow were more difficult to draw due both to the scarcity of data and the variations that existed in the turbulence intensity, turbulence scale and blockage ratio (all of which affect the values of the drag coefficients). Nevertheless, where comparisons were possible, the agreement with the literature again appeared to be reasonable, being perhaps a little better than ±10%. For example, as shown in Table 2, data measured by Miyata & Miyazaki [1979] under similar conditions compared well:-

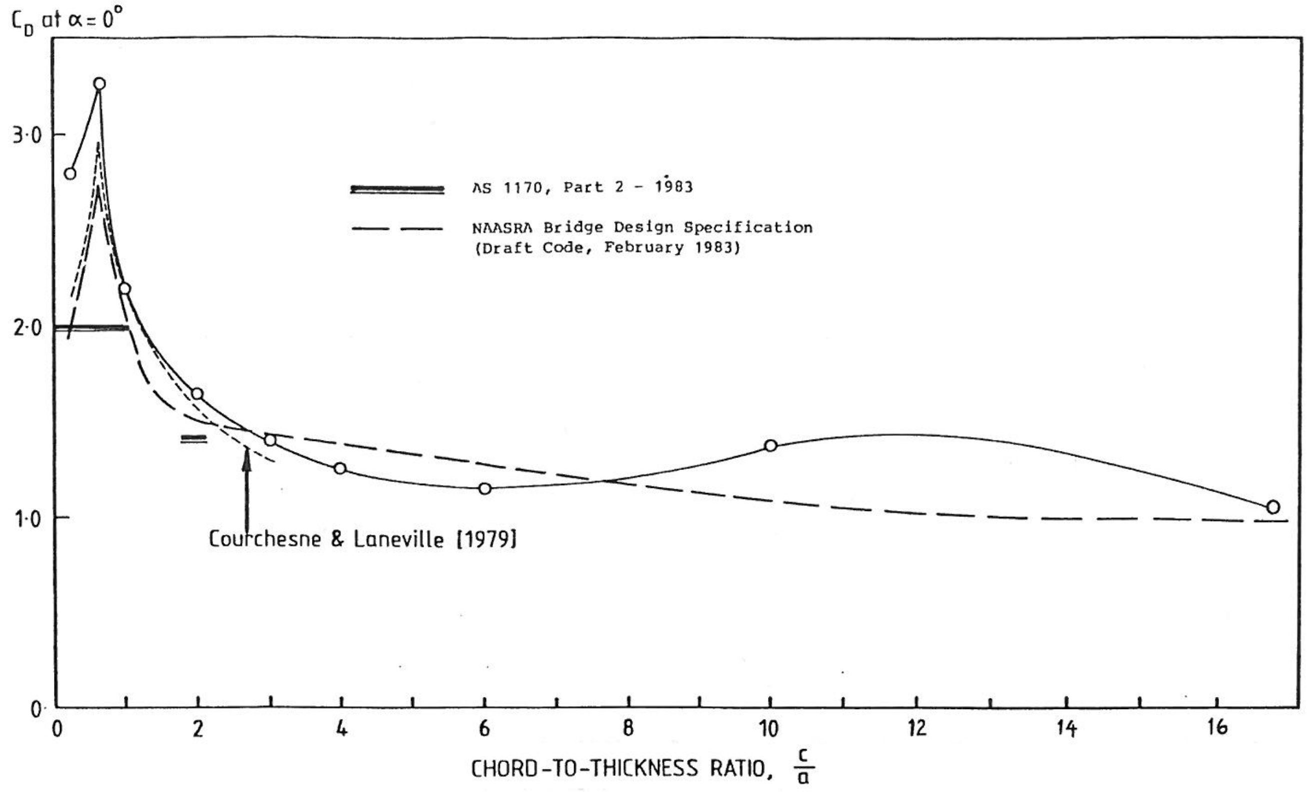

FIGURE 3 - SMOOTH FLOW DRAG COEFFICIENT AT $\alpha = 0^o$ (CORRECTED FOR BLOCKAGE) AS A FUNCTION OF CHORD-TO-THICKNESS RATIO.

TABLE 2 - DRAG COEFFICIENTS FOR THE 1:1 AND 2:1 SECTIONS IN 12½% TURBULENCE COMPARED WITH DATA FROM MIYATA & MIYAZAKI [1979].

	1 : 1 square section				2 : 1 ($^c/_a$) rectangular section			
	I_u (%)	L_{ux} (mm)	Blockage Ratio (%)	$C_{D_\alpha} = 0°$	I_u (%)	L_{ux} (mm)	Blockage Ratio (%)	$C_{D_\alpha} = 0°$
MEASURED DATA	12.6	84	3.75	1.85	12.6	84	3.75	1.20
MIYATA & MIYAZAKI	11	73	4.2	1.92	11	73	4.2	1.32

(comparable Reynold's numbers)

Comparison with Code Drag Data

Both AS 1170, Part 2 - 1983 and the NAASRA Bridge Design Specification (Draft Code, February 1983) give information on the drag on two-dimensional rectangular cylinders, although neither code takes account of the turbulence intensity of the flow. As the code data is based on measurements made in smooth flow (which is generally accepted as producing maximum drag), the code data has been compared with the measured smooth flow drag coefficients, once again using Figure 3.

In the case of AS 1170, it can be seen that data is available for only a very limited range of chord-to-thickness ratios. Furthermore, the given drag coefficients underestimate the measured values by up to 50%. This section of the code is obviously outdated and in need of revision - no further discussion is warranted.

On the other hand, the NAASRA Code (which is based on data from BS 5400, Part 2 - 1978) covers a full range of chord-to-thickness ratios and exhibits basically good agreement with the measured smooth flow drags. There are, however, a number of areas where the code could be used to give loads which are not conservative.

Firstly, for chord-to-thickness ratios of 2 or less, the NAASRA drags are consistently lower than those measured both in this study and by Courchesne & Laneville. Indeed, reference to Table 1 will show that only when the turbulence intensity is 12½% do the measured coefficients fall below the NAASRA values for these geometries.

Secondly, as stated above, the code makes no distinction for the turbulence level of the flow. While for the majority of the sections the effect of increasing the turbulence is to decrease the drag, the measured data suggests that for sections with chord-to-thickness ratios above 4 it is possible to have the opposite effect. Further measurements, aimed at veryifying these observations, are warranted.

Thirdly, NAASRA Note 5 to Figure 2.8.1 (which is identical to BS 5400 Note 5 to Figure 5) states that "where a superstructure is subjected to inclined wind not exceeding 5° inclination, C_D shall be increased by 15%". Reference to the $\alpha = 0^\circ$ and $\alpha = 5^\circ$ columns of Table 1 will show that for sections with chord-to-thickness ratios of 4 or greater, the increase in drag due to 5° inclination significantly exceeds 15%.

Finally, it can be seen that the measured drag coefficients for the 10 : 1 cylinder are significantly above the NAASRA value. However, it should be noted that for this particular study measurements of drag force were of lesser importance than those of lift force and were therefore accorded a lower priority in the design of the force measuring balance. As a result, the drag sensitivity of the force measuring balance was by no means optimal and for the very slender sections, where the magnitude of the drag force was small and the magnitude of the lift force was large, it became difficult to maintain the standards of accuracy and repeatability that the author would have liked. Experimental verification of the drags for these slender sections is therefore required.

Conclusions

- Comparisons with other experimentally measured drag coefficients reported in the literature show good agreement.
- The two-dimensional drag coefficient data given in AS 1170, Part 2 - 1983 is far from satisfactory and in need of review.
- The two-dimensional drag coefficient data given in the NAASRA Draft Code is basically sound. There are, however, a number of areas where the code appears to be unconservative.

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