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A Note on the Use of End Plates to Prevent Three-dimensional Flow at the Ends of Bluff Cylinders

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A Note on the Use of End Plates to prevent Three-dimensional Flow at the Ends of Bluff Cylinders

- By -

C. F. Cowdrey

June, 1962

SUMMARY

The results are given of some observations of the effects of end plates on the three-dimensional separated flow at the ends of cylindrical models. While these are by no means exhaustive, it is felt that they are of sufficient interest to merit putting on record.

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1. Introduction

At times the need arises to measure the wind forces on cylindrical models of various sections representing long girders, chimney stacks and other elements in modern building. The structural element is considered to be of 'infinite' aspect ratio and means are employed to eliminate the three-dimensional effects that exist at the ends of the model. For this purpose models that completely span the working section of the tunnel are frequently used, the maximum Reynolds number obtainable being limited by the drag capacity of the balance or the maximum acceptable blockage in the tunnel.

By using models of smaller span with small end plates in place of the tunnel walls, the breadth of the model, and therefore the maximum Reynolds number, can be increased without overloading the balance or introducing too much blockage.

For tests carried out in an 'open jet' type tunnel, for instance the Compressed Air Tunnel, finite-span models with end plates are obviously essential.

When high Reynolds number tests were requested on square and dodecagonal cylinders in the Compressed Air Tunnel (Ref.1), information was sought concerning the dimensions of end plates that were necessary to approximate to 'infinite aspect ratio' conditions. A considerable amount of literature is available on the use of end plates in conjunction with unstalled streamlined sections but no reference could be found to their use with models experiencing separated flow.

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In consequence, a pair of end plates were at first used which were considered large enough. However, on measuring the forces on the cylinders, approximately two-dimensional conditions were found to exist only over a limited incidence range. At other incidences the end plates seemed to have substantially no effect. It was necessary to increase their size.

Some visual observations of the flow around the models were carried out in conjunction with the force measurements. In view of the interesting facts that came to light, further visual tests were made in one of the 9 ft × 7 ft elliptical atmospheric Open Jet Tunnels of the N.P.L. using a square cylinder of much larger aspect raio. By reducing the span of this model in stages, the effect of aspect ratio was studied.

Although no great accuracy was sought, or was considered necessary, the information gained would seem to be of sufficient interest to merit putting on record.

Only rectangular end plates were considered, no attempt being made to establish the optimum shape.

2. The Models

The preliminary observations in the Compressed Air Tunnel were carried out on the two models referred to in Ref.1. They were both 4 ft in length, the cross-section of one being a 4 in. square and of the other a regular dodecagon, the distance between parallel faces of which was 6 in. They were supported in turn with the axis horizontal and at right angles to the wind direction, on the normal end supports of the tunnel balance.

The end plates were of $\frac{1}{2}$ in. plywood with the edges chamfered off. Two sizes were considered, namely,

(a) 18 in. square with the model axis 7 in. from the leading edge,

(b) 36 in. long by 24 in. wide with the model axis 9 in. from the leading edge.

These were bolted to flanges at the ends of short lengths of 2 in. diameter brass tubing, which were then rigidly fixed to the balance guard, so that the end plates were normal to the axis of the model; the brass tubing also served to shield the end fittings from the wind.

To prevent any flow of air between the end plates and the model, the small gaps were sealed by the pile of pieces of fur fabric stuck both to the end plates and the ends of the model, care being taken not to introduce too much restraint to the free swinging of the balance.

The model used for the visual tests in the Open Jet Tunnel was a cylinder 1-13/16 in. square in section and 68-3/4 in. long. This was supported in the tunnel on wires to eliminate support interference. In this case, stiff cardboard end plates were used and were attached to the ends of the model by drawing pins.

3. Experimental Procedure

In the Compressed Air Tunnel, visual tests were carried out at atmospheric pressure using a wool tuft at the end of a rod to explore the flow round the model, in addition to a programme of force measurements.

For easier photography, a filament of paraffin smoke was used in place of the streamer for the observations in the Open Jet Tunnel.

The flow around the model was studied in both tunnels for different sizes of end plates. In the Open Jet Tunnel the effect of aspect ratio was also investigated by progressively reducing the span of the model; no force measurements were possible.

4. The Experimental Results

4.1 Force measurements in the Compressed Air Tunnel

In Fig.5, the results are plotted of the measurements of the drag coefficient of the square-section model, using the two sizes of end plates, for a Reynolds number of 0.27×10^6 (the drag coefficient is a non-dimensional coefficient obtained by dividing the drag per unit length of the model by $\frac{1}{2}\rho V^2 a$, where ρ is the air density, V the wind speed and a the length of the side of the square section). These are taken as representative of a whole series at different Reynolds numbers, the variation with Reynolds number being small.

For comparison, some smoothed results from Ref.2, at a Reynolds number of 0.18×10^6, are included. In this case, the model completely spanned the tunnel so that the walls acted as end plates.

As will be seen, there is fairly good agreement between the three sets of results for incidences up to approximately 28° (zero incidence is defined as that at which the faces of the model were either along or normal to the wind direction). It is true that there are systematic differences which cannot be explained with the limited information available and extra work on this would be useful. However, these are small and will not greatly affect the general conclusions to be drawn.

At this incidence there is a sudden decrease in the coefficient for the smaller-end-plate case to substantially the value obtained in the absence of end plates.

4.2 Flow visualisation in the Compressed Air Tunnel

The flow round the model was studied with the aid of a wool tuft for both sets of end plates. As was expected, separation occurred at edge B for all incidences (see Fig.1). On the other surface, however, separation took place at edge A for low incidences and from edge D at incidences in the region of 45°. In between, the exact location of this separation line was uncertain.

The/

The flow in the wake of the model was, as would be expected from such a bluff body, very turbulent with no preferred direction at low angles of incidence. However, at about 28° with the smaller end plates there was a sudden change. Two large spanwise eddies appeared (Figs.2 and 7) which affected the whole span, causing strong outflow along the rear two faces. This change was easily connected with the critical change in the drag.

No such eddies were seen with the larger end plates over the whole of the incidence range.

Thus it would appear that, at around 28° incidence, the smaller end plates completely lost their effectiveness and that the presence of strong spanwise flow over the rear surfaces could be taken as an indication that the end plates were too small.

Using this fact as an indication, the minimum dimensions of the end plates for which there were no end eddies on the square-cylinder model in the Compressed Air Tunnel were found with the model at 45° incidence (it was reasonable to assume that the largest end plates would be needed at this incidence since the blockage would then be greatest). This, subject to the limitations expressed in Section 4.1 was used as the criterion that two-dimensional flow existed over the whole span of the model.

It was found that at least 14 in. of end plate was needed downstream of the model axis (this was taken as a reference point for convenience) and the total width, W, was 8 in. A certain amount was required upstream of the model, but this was not large, about 2 in. seemed to suffice.

These dimensions were not interdependent.

A quick study of the flow over the dodecagonal model showed that the same general conditions applied but were not so well defined. A full investigation into the size of end plates needed for this model was not undertaken through lack of available tunnel time, but the end plates that sufficed for the square cylinder worked equally well with the dodecagonal cylinder.

The tests were then extended in the Open Jet Tunnel.

4.3 More detailed study in the Open Jet Tunnel

With the aid of a smoke filament the flow round the 1-13/16 in. square-section model was studied, again at an incidence of 45°.

It soon became apparent that the spanwise eddies that were present when the end plates were too small were caused by the entrainment of the flow around the end of the model into the dead-air region behind the model (Fig.6 and 7). Thus, the function of the end plates is, in essence, to close the ends of this 'cavity'.

From/

From the observations it was seen that the amount of end plate needed downstream of the model axis decreased somewhat as the aspect ratio was reduced. The values arrived at are shown as multiples of the length of the side of the square in Table 1.

The minimum width, however, was less critical and, in consequence, it was not possible to detect any variation with aspect ratio. The total width could be taken as 2.2 times the side of the square.

When these dimensions were scaled up they were found to be relatively smaller than those obtained for the 4 in. square cylinder in the Compressed Air Tunnel. Consequently this model was examined under the same conditions as the small model. The minimum downstream dimension was, in this case, found to be 9 in. instead of the original 14 in. and agreed reasonably well with the smaller model at the same aspect ratio. When the 2 in. diameter cylindrical supports used in the Compressed Air Tunnel were set up in a similar position, this dimension increased to 12 in. Thus it would appear that an obstruction to the flow around the end plates could have a large influence on their effectiveness.

It did seem possible that small gaps could be left between the ends of the model and the plates while still retaining two-dimensional flow. However, an acceptable limit for each of these gaps was no more than about 1/32 in. Such a small gap would require very accurate alignment of the end plates to ensure free swinging of the balance. It would be far better to allow a reasonable clearance and to use the pile of pieces of fur fabric, stuck both to the model and the end plates, to seal the gaps. This is possible without any serious loss in accuracy of the balance readings.

There was no time available to consider any other factors, or any other shape of model, and dimensions arrived at must be considered as absolutely minimum under ideal conditions. They are, however, not too large for most purposes and it is most likely that large factors of safety can conveniently be applied. Furthermore, a streamer attached to the downstream face of the model near the end will give a quick indication of the effectiveness of the end plates.

Finally, the effect of incidence on the length of the end plate was investigated using the 4 in. cylinder (Fig.4).

5. Discussion of the Results

As indicated above, the purpose of the end plates is to prevent the entrainment of air into the 'cavity' at the rear of the model (see Fig.6). Thus the minimum size of the end plate should be related to the size of this 'cavity'.

An interesting relationship between the amount of end plate downstream of the model and the incidence can be arrived at by making two reasonable assumptions (many factors are ignored which were thought to be of only secondary importance and the final results would suggest that this was justifiable)

First/

First, the size of the 'cavity' is taken as proportional to Δ (see Fig.1). This ignores the influence of the upstream shape of the model and the model to the rear of the edges of separation, both of which are likely to influence the flow.

It was a little difficult to decide on a suitable origin from which to measure the downstream dimension of the end plate. As stated previously, separation occurred from edge B at all incidences and it can be assumed that this would dominate the second separation, which was less well defined.

Therefore, it would seem reasonable to measure the downstream dimensions from the plane through B at right angles to the wind.

In Table 2 the values of $(L+\ell)/\Delta$ (which can be taken as proportional to the ratio of the downstream extent of the end plate to the 'cavity' size) are given for various angles of incidence.

It must be pointed out that the variation shown is less than could be expected in view of the accuracy of the original observations but it seems that the assumptions made cannot be far from the truth.

6. Conclusions

In Section 4.1 it has been pointed out that complete agreement was not obtained between the forces measured with the two sizes of end plates. The differences, however, were small and it is felt that they would not seriously affect the following conclusions.

From the force measurements made with small end plates (Fig.5) it would seem that end plates are either wholly effective or ineffective according to whether their dimensions are larger or smaller than fairly well-defined minimum values. No intermediate stage of reduced effectiveness exists.

Furthermore, these minimum dimensions can be seriously affected by the presence of obstructions to the flow of air round the end plates.

Thus, it is not possible to state the minimum size of end plates that would be required under all given conditions.

However, it is probable that the conditions that existed in the Compressed Air Tunnel during the force measurements, referred to in Ref.1, could be taken as typical. On this basis it is suggested that, for most practical purposes, the minimum values of L and W (see Fig.1 for definition of symbols) could be taken as

$$L = 2\tfrac{1}{2}\,\Delta_{max.}$$

$$W = 2\,\Delta_{max.},$$

where $\Delta_{max.}$ is the maximum value of Δ that is likely to arise during the experiments. (A small amount of the plates should extend upstream of the most forward part of the model, $\frac{1}{2}\Delta_{max.}$ should suffice.)

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In this, the downstream extent of the end plates is measured from the model axis for convenience - it was shown, in the last Section, that $(L+\ell)/\Delta$ is substantially a constant, suggesting that the measurement should more accurately be made from the more upstream of the two separation edges.

It is unlikely that such dimensions would prove to be excessive in all but a few cases and it would be advisable to increase them considerably for safety. However, if it should be essential to keep them to an absolute minimum it is possible, where there is unobstructed flow around the model and end plates, to reduce the value of L to $1\text{-}3/4\ \Delta_{max}$. This should be considered as the absolute minimum.

An easy check can be made of the effectiveness of the end plates by attaching a few wool streamers to the rear of the model - any strong spanwise flow towards the ends of the model would show that larger end plates are needed.

Finally, it is sometimes desirable to use end stubs instead of end plates. These would be of the same cross-section as the model and separated from it by a small gap (this gap should be sealed as indicated earlier).

If the outboard ends of the stubs are in the air stream, spanwise eddies will be set up as shown in Figs.2 and 7. These can extend well inboard as shown in Fig.3 and, in order that the moving part of the model shall be free from spanwise variations, the end stubs would have to be at least of sufficient length to completely contain these eddies.

References

No.	Author(s)	Title, etc.
1.	C. F. Cowdrey and J. A. Lawes	Force measurements on square and dodecagonal sectional cylinders at high Reynolds numbers. N.P.L./Aero/351. August, 1959.
2.	C. Wieselberger and A. Betz	Der widerstand verschiedener körper. Ergebnisse der aerodynamischen versuchsanstalt zu Göttingen. Vol.2, p.33. 1923.

TABLE 1/

TABLE 1

Incidence = 45°   a = 1-13/16 in.

ASPECT RATIO	$\frac{L}{a}$	$\frac{L+\ell}{\Delta}$
9.9	2.48	1.76
11.6	2.48	1.76
16.6	2.48	1.76
18.2	2.76	1.95
19.9	2.76	1.95
26.5	3.03	2.15
33.1	3.31	2.34
37.9	3.31	2.34

Minimum length of end plate downstream of model axis

TABLE 2

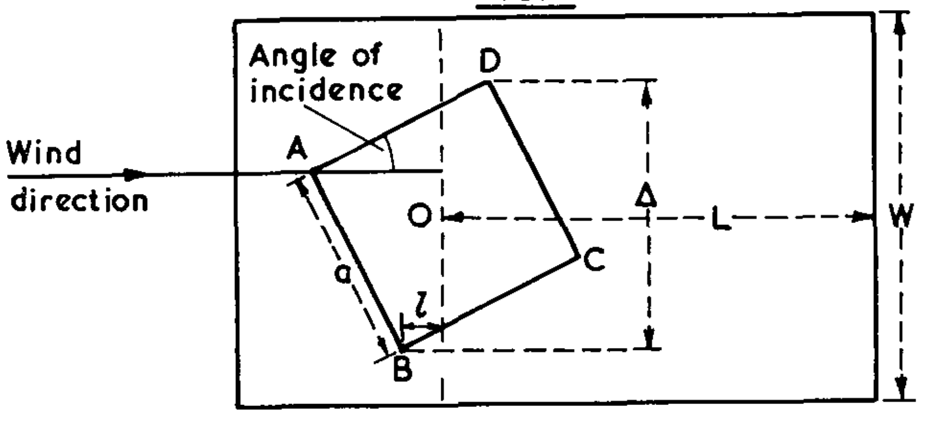
a = 4 in.   Aspect ratio = 12

INCIDENCE (°)	$\frac{L}{a}$	$\frac{L+\ell}{\Delta}$
0	1.13	1.625
11	1.50	1.615
20	1.75	1.60
30	2.00	1.60
45	2.25	1.59

Effect of incidence on the minimum downstream extent of end plate

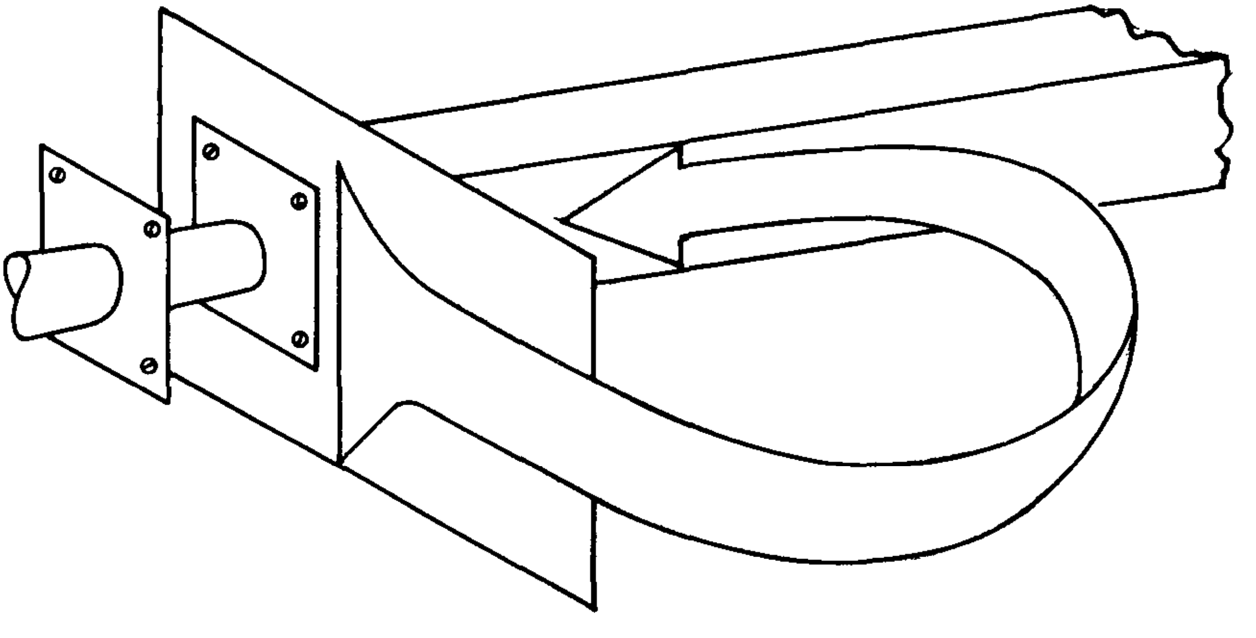
FIGS. 1 & 2

FIG. 1



Dimensions of square cylinder and end plates

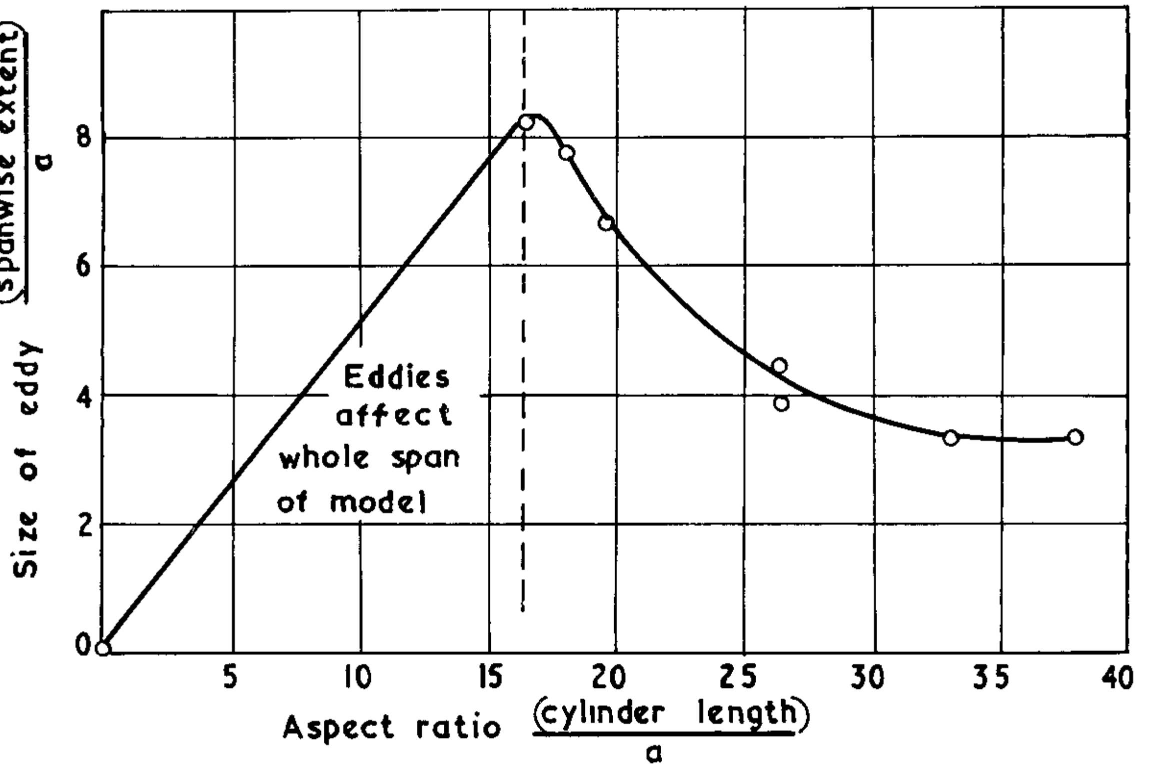
FIG. 2



Sketch of end supports with an indication of an end eddy.

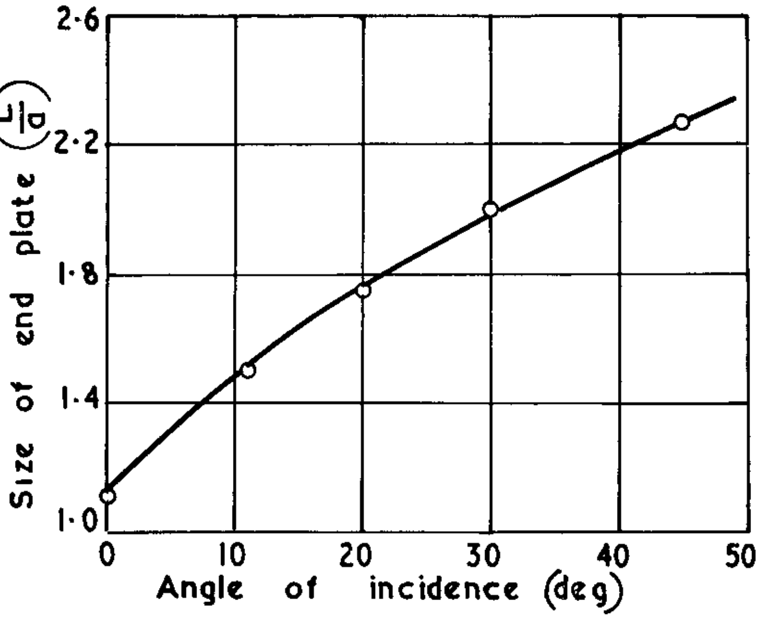
FIGS. 3 & 4.

FIG. 3.



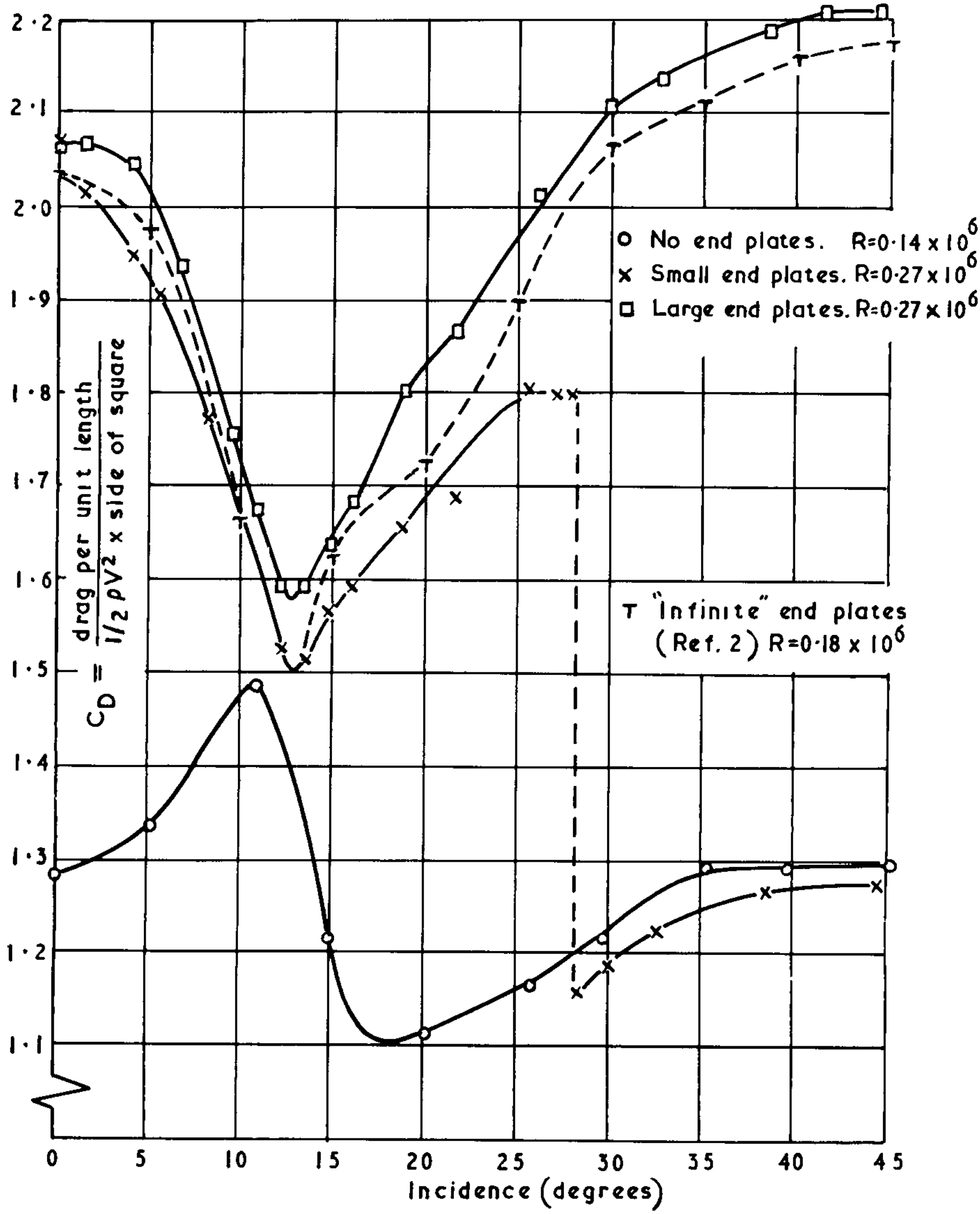
Effect of aspect ratio on spanwise end eddies

FIG 4.



Effect of incidence on end plate size

FIG. 5



Drag of square-section cylinder

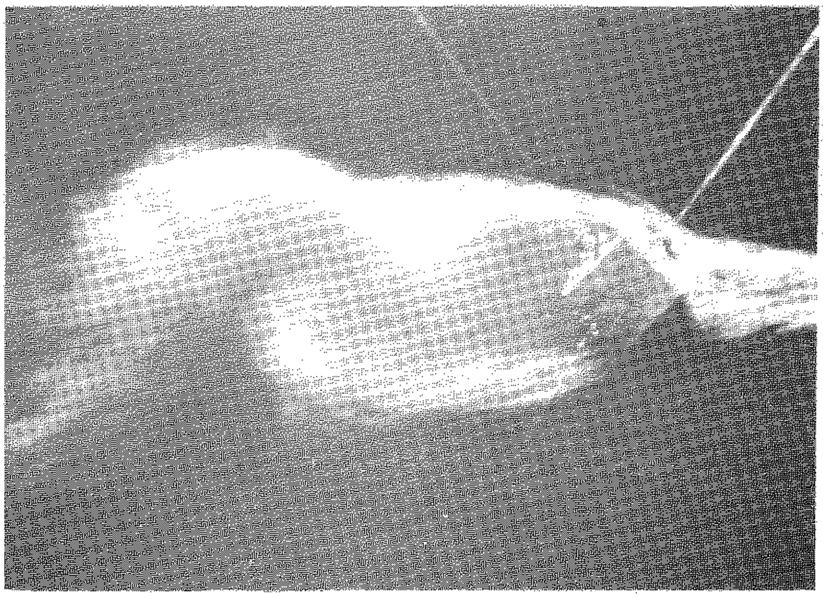


FIG. 6 Photograph of Kármán vortices shed from the edges of a square cylinder

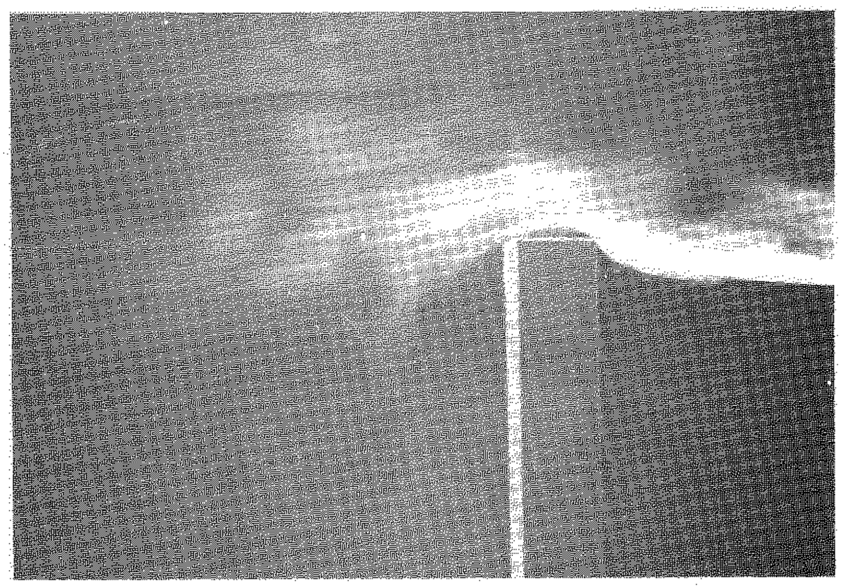


FIG. 7 Photograph of an end eddy from a square cylinder with no end plates

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