WIND TUNNEL TESTS OF THE TORONTO CITY HALL

by

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SUMMARY

Models of the Toronto City Hall were tested in the UTIA low speed wind tunnel. The following tests were carried out:

Steady pressures on the walls of a City Hall model were measured in the UTIA low speed wind tunnel for six wind directions. The pressures were measured at three height stations along both the inside and outside walls of both towers by means of 240 wall pressure taps.

Unsteady wall pressures were measured at four points on the model by embedded microphones, whenever vortex shedding occurred. These tests were also carried out in the UTIA low speed wind tunnel.

Flow visualization tests were made on a City Hall model in a small smoke tunnel. Movie as well as still pictures were taken of the smoke patterns.

Some design changes on the building made a wind-tunnel re-check necessary. Only steady pressures were measured on a model of the revised design, and at two height stations only.

The results show that the steady pressure distribution on the outside walls resembles that on a circular cylinder, with some suction peaks attaining a value of over twice the wind dynamic pressure. The outside pressure distribution is largely responsible for the torsional wind loads on the building, whereas the pressure distribution on the inside walls is fairly uniform and contributes mainly to bending.

The unsteady pressure measurements show that vortex shedding from the model occurs for two wind directions. In these cases the unsteady pressure component exhibits fairly regular fluctuations. A typical r.m.s. value for the unsteady pressure is 10% of the wind dynamic pressure. Owing to the large difference in model and full scale, no definite conclusions are drawn as to the amplitude and frequency of vortex shedding, if any, on the full-scale building.
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**NOTATION**

- **$C_p$**: dimensionless pressure $= \frac{p - p_\infty}{\frac{1}{2} \rho U_\infty^2}$
- **$p$**: local wall pressure
- **$p_\infty$**: ambient tunnel pressure
- **$U_\infty$**: stream velocity
- **$\rho$**: mass density of air
- **$\frac{1}{2} \rho U_\infty^2$**: dynamic pressure of flow (maximum value that $(p - p_\infty)$ can attain)
- **$\mu$**: viscosity of air
- **$Re$**: Reynolds number $= \frac{U_\infty d \rho}{\mu}$
- **$d$**: characteristic dimension of building
- **$\bar{p}$**: root-mean-square value of unsteady component of wall pressure
- **$P_0$**: reference pressure (0.0002 dynes/cm)
- **$U_s$**: wake velocity (velocity at separation point)
- **$P_s$**: pressure at separation point
- **$C_{PS}$**: $= \frac{P_s - P_\infty}{\frac{1}{2} \rho U_\infty^2}$
- **$St$**: Strouhal number, a dimensionless frequency $= \frac{f d}{U_\infty}$
- **$f$**: frequency of vortex shedding
- **$d^t$**: wake width
ARCHITECT'S PREFACE

The new Toronto City Hall consists basically of two crescent-shaped Towers facing the low, dome-roofed structure of the Council Chamber. The Towers rise to heights of approximately 290 feet and 225 feet above a connecting Podium. The construction of both Towers is similar, being a vertical concrete shell with one interior line of columns. The six-inch-thick concrete floor slabs are supported on beams spanning between the back wall and the columns, and cantilevering 16' 6" beyond the face of the columns.

Due to the unusual shape and height of the Towers it was suspected that the standard wind design pressures specified by the City of Toronto Building Code would not be applicable and thus it was decided to have wind tunnel tests performed on a scale model of the City Hall by the Institute of Aerophysics. The results of these tests were used in the design of the Structure itself and also in the design of supports for both the pre-cast concrete facing panels attached to the back walls and the curtain wall construction of the Interior faces of the Towers.

In order to convert the wind tunnel test results to design pressures, an assumed wind velocity distribution was used which varied from 110 miles per hour at the top of the Towers to 60 miles per hour at the bottom.

The final results of the tests produced wind pressures as high as 31 pounds per square foot and suctions as high as 72 pounds per square foot. These values, together with the unusual pressure distributions found from the tests, produced torsion and bending stresses far exceeding those which would be expected from standard design assumptions.

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I. INTRODUCTION

The shell-like structure of the new Toronto City Hall rises to about 290 feet above ground. Aerodynamically - depending on the direction of the wind - it may exhibit the flow characteristics of a diffuser, a nozzle, a semi-cylinder or a whole cylinder. The pressures exerted on the shell surfaces are expected to vary considerably as a function of the direction of the prevailing wind and may be either steady or - at specific wind directions - unsteady, i.e. oscillating. The sophisticated structure of the shells is inherently weak against torsional loads. The unavoidable uncertainties in any attempt to predict these loads made wind-tunnel tests mandatory, and indeed, as noted in the preface, the loads so determined were higher than would have been derived by the application of the Building Code.

The scale (Reynolds number) of the tests was much smaller than desirable. However, no larger-scale wind tunnel was immediately available, and it was felt that, although there is some uncertainty attached to the scale effect, it was preferable to base the design on these results rather than on the building code. The nature of the pressure distributions subsequently obtained has given confidence in their applicability.

Some changes were made in the design of the shell-like structure after the first tests were completed. This made necessary a re-check of the aerodynamic characteristics on which its structural design was based. Hence a second model, corresponding to the revised design, was made and tested.

II. THE TEST PROGRAM

Both models, the original and the revised, were tested in the 36" x 42" test section of the UTIA subsonic wind tunnel.

2.1 Steady Pressure Distributions

For the calculation of loads on the external and internal shell surfaces, pressure distributions - 40 pressures on each height station - were recorded for 3 height stations on the original and for 2 on the revised model for six different wind directions. The maximum wind tunnel speed of approximately 140 mph was used.

2.2 Unsteady Pressures

In case of periodic vortex shedding (Karman vortex street), the frequency of the resulting oscillating loads had to be determined. Embedded microphones were used for this purpose. Besides, exploratory measurements were aimed at providing the amplitudes of local pressures at some points for two critical wind directions. If a critical condition were detected by these tests, further investigation was anticipated.
2.3 Flow Visualization Tests

UTIA's smoke tunnel was used, wherever required for a better understanding of the phenomena encountered. Sample smoke patterns are shown in Fig. 35. Also, wool tufts were used extensively on the first model for the determination of flow direction and flow steadiness at higher wind tunnel speeds.

III. DESCRIPTION OF CITY HALL MODELS

The original model is shown in Fig. 1. Its maximum height is 14.75" (1 inch = 23 feet), which was reduced to 12.87" (= 296 feet) for the revised model, the smaller tower being 250 and 224 feet respectively. The model was made of solid mahogany and was mounted on a circular plywood base plate, bevelled and graduated at the outer edge. Pressure taps were located in horizontal rows at three levels on both the inside and outside walls of the large and smaller towers. Each row consisted of 20 static pressure taps spaced evenly along the arc of the tower. Figure 2 shows a similar layout of the pressure taps for the revised model.

Each row of pressure taps was built into the model wall in the following way: a plastic strip, 1 inch wide, consisting of 20 pressure tubes, and running the full width of the given tower, was mounted horizontally on and flush with the wall at the desired level. Each of the 20 pressure taps in turn was formed by drilling small holes from outside into one of the 20 pressure tubes at the desired location. The upstream ends of the pressure holes were plugged with pins, and the downstream ends were connected by a similar strip of tubes to a multiple-manometer board. Figure 3 shows the location of the pressure-tap height stations on the revised model. As can be seen in Fig. 1, whereas the original model is equipped with three pressure-tap levels, the revised model has only two, since tests on the original model showed little variation of pressure with height.

IV. TECHNIQUE OF TESTING

4.1 Steady Pressure Measurements

The UTIA subsonic wind tunnel, in which the pressure tests were carried out, is shown in Fig. 4. The tunnel was run at maximum speed, about 175 fps,* to obtain as high a Reynolds number as possible. A typical test run with the revised model consisted of rotating the model

* The normal maximum speed of the tunnel is in excess of 200 fps. The reduced value quoted here is a result of the very large drag of the model.
slowly in the airstream through a predetermined 60-degree sector, while observing the 40 pressure readings of, say, the two height stations of the outside wall of one tower on the manometer board. The same procedure was then repeated for the remaining five 60-degree sectors. The wind directions at which readings were taken were kept the same for all pressure readings on a given tower within each 60-degree sector. The direction chosen within each 60° section was that for which the maximum suction was found on the outside of the tower.

Pressure readings were also taken in the two corners of each tower, 1.5 inches from the base, for a number of wind directions. Figure 2 shows the location of these pressure taps.

4.2 Unsteady Pressure Measurements

Unsteady pressures associated with periodic vortex shedding from the building were measured at four pressure taps on the outside walls located at points A, B, C and D (see Fig. 1), four inches below the top edge of each tower. These pressure taps were formed by drilling a vertical hole, 4 inches deep and 5/8 inches in diameter, into the tower at each of these four positions. Each of these holes served to accommodate a microphone, pressure being communicated from the outside to the microphone head by a small drill hole. To ensure undisturbed flow over the wall, the outside opening of this drill hole was taped shut, and the tape punctured with a pin. The microphone was connected to a pen recorder, a sound level meter and an oscilloscope for visual observation.

Pen recordings were made with the microphone at position A and D, the wind direction being 223 and 103 degrees respectively, and wind speed being varied from 75 to 160 fps for each microphone position. Altogether, seven pen recordings were made. At the same time sound pressure level readings in decibels were taken on the sound level meter. The frequency of vortex shedding was calculated from the pen recording by counting the number of times the trace crossed the reference pressure line, and dividing this number by twice the elapsed time.

4.3 Flow Visualization Tests

Flow visualization tests were carried out on a small smoke tunnel. The dimensions of its test-section (1 inch by 12 inch) precluded testing of a model properly scaled for height. Instead, a two-dimensional model having a scale of 1 to 960 was used.

The tests consisted of taking still photographs of the streamline pattern around the model at 15-degree intervals in wind direction, the wind speed being about 6 fps. Furthermore, moving pictures were taken of the streamline pattern, while the model was rotated through 360 degrees in order to show the unsteady flow associated with vortex shedding at certain wind directions.
V. PRESENTATION AND DISCUSSION OF TEST RESULTS

5.1 Steady Pressure Distributions

The pressure coefficient, \( C_p \) (see notation), was calculated for each pressure and, for clarity of presentation (see Figs. 5 to 30), plotted normal to the centre line of each of the two towers, the correct centre line of each tower being approximated by a circular arc. Both inside- and outside-wall pressures for a given level are shown on the same graph. The shaded area represents the resultant pressure coefficient, and the arrows indicate the direction of loading. Attention is drawn to the fact that resultant forces and moments cannot be accurately determined from these graphs (Figs. 5 to 30), since the actual pressures act normal to the walls rather than normal to the assumed centre line of the tower profiles.

Furthermore, velocities in the narrow gap and on the outside of the building were calculated from the corresponding pressure readings. The corner pressures for the revised model were also plotted against wind direction and are shown in Fig. 31.

5.1.1 Inside Walls

When the wide gap between the two towers faces upstream the pressure distribution on the inside walls is positive and rather uniform, with \( C_p \) approaching unity. See for example Fig. 5. This indicates that the air inside the cavity formed by the two towers is virtually stagnant and that therefore most of the airflow is diverted over the top of the towers. When the narrow gap between the towers faces upstream, the pressure distribution on the inside walls is again fairly uniform, but is now negative, \( C_p \) approaching -1, as shown in Fig. 16. This pressure distribution is typical of that found in the wake of bluff bodies, the uniform pressure distribution implying a relatively stagnant wake. A similar inside pressure distribution exists also when either tower faces the wind broadside on. Altogether, the inside pressure distribution behaves as expected.

5.1.2 Outside Walls

The pressure distribution on the outside walls resembles that on a circular cylinder, i.e. a high pressure peak in the stagnation region followed on both sides by a rather large suction peak and a region of separation. See for example Fig. 8. As in the case of a circular cylinder, the suction peaks occur approximately at those points where the free-stream velocity is tangent to the building. On the original model, the maximum suction peak (\( C_p = -2.58 \)) appears on the outside wall of the large tower for a wind direction of 173 degrees, which is about 15% higher than the suction peak on a circular cylinder at the corresponding Reynolds number as given on p. 3-3 in Ref. 1. On the revised model, the maximum \( C_p (= -2.68) \) was found on the large tower at a wind angle of 330 degrees. Downstream of most suction peaks the flow separates from the building, the
ensuing space being filled by a wake of relatively uniform pressure. This is clearly shown on Fig. 8, for $\alpha = 330$ degrees, which shows a region of uniform pressure on the outer surface of the large tower. On the whole, both inside-and outside-wall pressure distributions look reasonable.

In applying model test results to the full-scale building, one must take into account certain scale effects. For a given wind direction and a given point upstream of the separation point, the pressure coefficient remains the same for both the model and the full-scale building. The pressure coefficient behind the point of separation and the position of the separation point, however, depend on the Reynolds number of the flow, defined as

$$Re = \frac{U_\infty d \rho}{\mu}$$

where $d$ is a characteristic length of the building, say, the chord of one tower. Typical Reynolds numbers are $10^5$ for the model and $2.5 \times 10^7$ for the full-scale building.

Now for most bodies there exists a critical Reynolds number for a given flow incidence, at which the separation point rapidly moves downstream for a small increase in Reynolds number, with an attendant increase in pressure in the separated wake. Thus, if the critical Reynolds number for a given wind direction on the building lies between the test and the full-scale Reynolds number, the region of separation on the full-scale building will be smaller and the pressure coefficient there will be higher than on the model. It is difficult to estimate the critical Reynolds number or the magnitude of the changes for the building. They may or may not be comparable to those for a circular cylinder, for which the critical Reynolds number is about $10^5$, the increase in $C_p$ about 70%, and the downstream shift of the separation point about 40 degrees. The wind direction is undoubtedly a significant parameter in this connection. For further information on the phenomenon of separation, non-aerodynamicists are referred to Ref. 1.

5.1.3 Local Velocities

A study of local velocities on the original model revealed that the maximum velocity, corresponding to the maximum suction peak ($C_p = -2.58$) occurs at the outside wall of the larger tower for a wind direction of 173 degrees, the increase in speed over that of the free stream being 90%. The increase in speed through the narrow gap, when the wide gap is facing upstream, is considerably lower, being only 30%. This value does not change much with velocity or building height.

5.1.4 Corner Pressures

Figure 31 shows the variation of the pressures in each of the four corners of the model with wind direction. It can be seen that the
pressures are negative for most wind directions, and that each graph exhibits a more or less pronounced peak. For the corners at the wide gap the peak is positive, and occurs when the corner in question faces into the wind, i.e. when the corner lies in the impact region of the flow. The peaks for the two corners at the narrow gap occur at about the same wind direction, but are negative because of the high wind velocity through the narrow gap. For the same reason one would expect similar suction peaks to appear when the narrow gap faces upstream; instead, only a small variation in pressure can be observed. This unexpected behavior could be accounted for by noting that the corners in this case lie farther downstream in the gap, and are thus exposed to the large-scale turbulence between the two towers, which has the effect of eliminating any large pressure differences.

5.2 Unsteady Pressure Measurements

5.2.1 Variation of the Magnitude of the Unsteady Component of Pressure With Wind Velocity

Figure 32 shows a plot of the root-mean-square value of the unsteady pressure component acting on points A, B, C, and D against the logarithm of the free-stream velocity. The r.m.s. value of the unsteady pressure, $\bar{p}$, is here expressed in decibels, i.e.,

$$\bar{p} \text{ (in decibels)} = 20 \log_{10} \frac{\bar{p}}{p_0}$$

where $p_0$ is a reference pressure (0.0002 dynes/cm).

If we assume that $\bar{p}$ is proportional to $U_\infty^n$, then

$$\bar{p} \text{ (in decibels)} = 20 n \log_{10} U_\infty - 20 \log_{10} p_0$$

Therefore, if $\bar{p}$ varies as the nth power of $U_\infty$, the plots on Fig. 32 should be straight lines with a slope of $20n$. Measurement of the slopes shows that $n$ ranges from 2.4 to 2.9

For point D on the small tower of the original model, the r.m.s. pressure coefficient corresponding to a representative reading of 138 decibels is 0.103, or about 10% of the dynamic load. At 100 mph this would correspond to a fluctuating pressure with an r.m.s. value of 3.3 psf.

5.2.2 Variation of the Vortex-Shedding Frequency with Wind Velocity

As mentioned above, periodic shedding of vortices from the towers occurred for two ranges of wind direction. Figure 33 shows a copy of a pen recording of a typical microphone output. The record shows a fairly regular fluctuation of pressure, suggesting a dominant fundamental frequency with a smaller second harmonic and some residual random com-
ponents. However, only one representative frequency was calculated from each pen recording by the method of zero-crossings, as mentioned earlier. Figure 34 shows a plot of the Strouhal number \( St \) based on this frequency against Reynolds number for both critical wind directions. For comparison the corresponding graph for a circular cylinder (Ref. 2) is also shown. It is evident that there is little agreement between the two graphs except as to order of magnitude, which does agree. Comparison between a circular cylinder and the model therefore leads only to order-of-magnitude conclusions about the unsteady component of the flow around the full-scale building.

A different method of finding the Strouhal number for a given Reynolds number and a cylinder of more or less arbitrary cross-section can be found in Ref. 3. The Strouhal and Reynolds numbers, as used there, are based on wake width and wake velocity rather than on body width and free-stream velocity. Reference 3 shows that this redefined Strouhal number remains fairly constant \( \approx 0.16 \) over the range of Reynolds numbers investigated and is virtually independent of the shape of the body. The problem has thus been reduced to finding the wake width and velocity for a specified flow. Now the wake velocity \( U_s \) can be derived from Bernoulli's equation, i.e.,

\[
U_s = K U_\infty \tag{1}
\]

where

\[
K = \sqrt{1 - C_{PS}} \tag{2}
\]

and \( C_{PS} \) is the pressure coefficient at the point of separation. The value of \( d'/d \) can be found from a plot of \( d'/d \) versus \( k \) given in Ref. 3, there being a graph for each body shaped investigated. In order to find out what shape would have the same effect as the model, \( k \) and \( d'/d \) were calculated for both the pressure model and the smoke tunnel model. The values of \( k \) and \( d'/d \) were calculated as follows:

By definition,

\[
St' = \frac{f d'}{U_s} \tag{3}
\]

Combining Eqs. (1), (2) and (3), and taking \( St' = 0.16 \) according to Ref. 3, yields

\[
d' = \frac{0.16}{f} U_\infty \sqrt{1 - C_{PS}} \tag{4}
\]

and

\[
K = \frac{f}{0.16 U_\infty} \tag{5}
\]

For the pressure model \( k \) and \( d'/d \) were calculated by using Eq. (2) and (4), the value of \( C_{PS} \) being taken from pressure measurements.
For the smoke tunnel model $d'$ was taken from photographs, and $k$ was calculated using Eq. (5). The frequency $f$ was taken from test data in both cases. Plotting the values of $k$ and $d'/d$ so obtained showed that the model had about the same effect as a two-dimensional circular cylinder.

On this basis the vortex shedding periods for both critical wind directions can be calculated for the full-scale building, which turn out to be 15 sec for the large tower, and 12 sec for the small tower. This result, however, is only valid if the following assumptions hold:

a) the Strouhal number based on the wake properties remains constant up to a Reynolds number of $2.5 \times 10^7$. This has been shown to be the case only for Reynolds numbers up to $10^4$, in Ref. 3. More recent experiments (Ref. 5), however, seem to indicate that the wake Strouhal number does remain constant up to $10^7$.

b) the base pressure coefficient, $C_{p_b}$, is invariant with Reynolds number, an assumption which is only true for certain ranges of Reynolds numbers.

VI. CONCLUSIONS

The preceding discussion shows that the steady pressure distribution on the full-scale building can be predicted with a fair amount of accuracy from that on the wind tunnel model, since viscous effects are negligible except in the regions of separated flow. The pressure coefficient there is likely to be higher on the full-scale building than on the model.

In general the flow around the outside of the building resembles that around the outside of a circular cylinder, as shown by smoke tunnel and pressure tests. The resulting outside pressure distribution is mainly responsible for the torsional loads on the building, whereas the inside pressure distribution contributes chiefly to bending loads.

No definite conclusions can be reached concerning the amplitude and frequency of the unsteady pressures caused by vortex shedding on the full-scale building, except that vortex shedding may occur. The reason for this state of affairs is not so much the complexity of the model shape, but the lack of comparative experimental data at high Reynolds numbers.

The Strouhal number for the full-scale building could conceivably have the same value at some wind speed as that corresponding to the natural torsional frequency of the building. In that case buffeting of the building would occur, possibly with large torsional amplitudes. The design remedy to avoid this possibility is to provide adequate torsional stiffness, so that the building natural frequency remains outside the range of vortex-shedding frequencies.
REFERENCES


FIG. 1. ORIGINAL MODEL OF TORONTO CITY HALL IN UTIA SUBSONIC WIND TUNNEL
压力计位置图

压力计标记从1到20。

A距离被分为19个相等的间隔

比例尺 = 0.4162（模型比例尺）

图2. 压力计位置图在修订模型上
FIG. 3. HEIGHT STATIONS AT WHICH PRESSURE DISTRIBUTIONS WERE FOUND ON THE REVISED MODEL
FIG. 4. THE UTIA SUBSONIC WIND TUNNEL
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,
9.0°
DESIGN 2

RUN 1/16
α 17°
LEVEL TOP

FIG. 5.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,
9.0°
DESIGN 2

RUN 1/10
α 17°
LEVEL BOTTOM

FIG. 6.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,
DESIGN 2

RUN 2/14
α 330°
LEVEL TOP

FIG. 7.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL, 90°
DESIGN 2

RUN 27/14
α 330°
LEVEL BOTTOM

FIG. 8.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL, DESIGN 2

RUN 3/15
α 270°
LEVEL TOP

FIG. 9.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,  
90°  
DESIGN 2  

RUN 3/15  
α 270°  
LEVEL Bottom  

FIG. 10.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL, DESIGN 2

RUN 17/23
α 147°
LEVEL TOP

FIG. 11.
FIG. 12.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL, DESIGN 2

RUN 18/24
α 90°
LEVEL TOP

FIG. 13.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,

DESIGN 2

RUN 18/24

α 90°

LEVEL BOTTOM

FIG. 14.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,

DESIGN 2

RUN 122

α 191°

LEVEL TOP

FIG. 15.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL, DESIGN 2

RUN 2/22
α 10°
LEVEL Bottom

FIG. 16.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,
DESIGN 2

RUN 20/21
α 218°
LEVEL TOP

FIG. 17.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,

RUN 20/21
α 210°
LEVEL BOTTOM

FIG. 18.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,  
DESIGN 2  

RUN 8/12  
α 30°  
LEVEL TOP  

FIG. 19.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL, 90° DESIGN 2

RUN 3/12
α 30
LEVEL BOTTOM

FIG. 20.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,

DESIGN 2

RUN 9/13
α 800
LEVEL TOP

FIG. 21.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,
9.0°
DESIGN 2

RUN 9/13
a 300
LEVEL BOTTOM

FIG. 22.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL, DESIGN 2

FIG. 23.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,
9.0°
DESIGN 2

RUN 10/11
α 90
LEVEL BOTTOM

FIG. 24.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,
DESIGN 2

RUN 25/90
α 147
LEVEL TOP

FIG. 25.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,

DESIGN 2

FIG. 26.
CHORDWISE PRESSURE DISTRIBUTION, CITY HALL,

DESIGN 2

RUN 27/28
α 20°
LEVEL TOP

FIG. 29.
FIG. 31. VARIATION OF CORNER PRESSURES WITH ANGLE OF ATTACK ON REVISED MODEL.
FIG. 32. VARIATION OF THE R.M.S. VALUE OF THE UNSTEADY PRESSURE COMPONENT WITH VELOCITY
FIG. 33.  TYPICAL RECORD OF PRESSURE AT UPPER CORNER OF TOWER. (POSITION D)
FIG. 34. VARIATION OF STROUHAL NUMBER WITH REYNOLDS NUMBER FOR THE ORIGINAL MODEL
FIG. 35. STREAMLINE PATTERN AROUND MODEL.

(a) Steady flow. Wide gap faces upstream

FIG. 35. (cont'd) (b) Steady flow
FIG. 35. (cont'd) (c) Unsteady flow. Vortex shedding occurs.

FIG. 35. (cont'd) (d) Steady flow. Narrow gap faces upstream.
FIG. 35. (cont'd) (e) Unsteady flow. Vortex shedding occurs.

FIG. 35. (cont'd) (f) Unsteady flow. Vortex shedding occurs.
FIG. 35. (cont'd) (g) Steady flow.