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Strain measurements at the GPO Tower, London

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This paper describes a research project undertaken at the Building Research Station to measure wind pressures on the GPO Tower, London, and dynamic strains in the tower shaft. The development of a suitable pressure transducer, which uses strain gauges as sensors, is described together with the installation at the tower. Some of the problems of strain gauging large civil engineering structures are outlined.

The problem of calculating wind loads on large structures is not altogether new, but has become increasingly important. The past decade has seen the emergence of new design and construction techniques, which have enabled a great variety of structures to be built that are very much taller than their predecessors. These same techniques have also tended towards a reduction of the safety margins of strength inherent in traditional brick and masonry construction. Many high rise blocks are much lighter and less stiff than older buildings, and external walls are often not load-bearing but merely a light-weight cladding. Consequently, the problem of calculating the wind loads imposed on whole buildings, and on various parts of buildings, has assumed a new importance. The accurate calculation of these loads is often extremely difficult, and one does not have to look far to see evidence of costly damage caused by the under-estimation of wind effects.

In 1960 the Building Research Station started a programme of full-scale wind pressure measurements on tall buildings in central London, among them the GPO Tower. The success of this programme depended upon the development of a suitable pressure transducer, and this is described in the first part of this paper. The second part of the paper describes the equipment and installation which recorded strains in the shaft of the GPO Tower, as well as pressures at a large number of points widely dispersed on the surface of the building.

The pressure transducer

Among the requirements for the performance of the pressure transducer, two were of particular importance. First, it was required to measure pressures of very short duration, down to about 0·1 second. This determined the frequency response of the device. Secondly, so that the loadings experienced by cladding components could be assessed, it was desirable that the pressures recorded should be representative of the average pressures occurring over the area of cladding components. For this purpose the active area of the transducer was made as large as possible, compatible with easy installation in typical curtain walling and with the requirement of a suitable frequency response.

It was also desirable to obtain an electrical output suitable for continuous remote recording. These considerations ruled out any design based on liquid manometers. Further specifications were:

i. The transducer should record both positive and negative pressures and discriminate between them.

ii. The expected pressure range was $\pm$ 1200 N/m^2, corresponding to 45m/s wind speed.

iii. The required accuracy was $\pm$ 10 N/m^2.

iv. The transducer should be capable of withstanding overload without damage.

No transducer was available which satisfied these requirements. The design developed at the Building Research Station is shown in Fig. 1 and it has met all the above requirements in practice. It is essentially a shallow cylindrical box 5·5 in (140 mm) in overall diameter and approximately 1·2 in (30 mm) deep, one face of which comprises a pressure-plate. The instrument was designed to be fitted into curtain walling components so that the pressure-plate was flush with the surface of the building (Ref. 1).

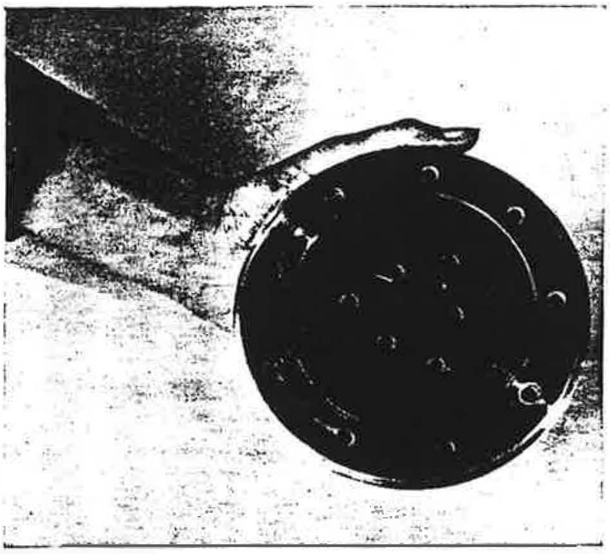

Fig. 1. Front view of pressure transducer

Description of the transducer

Figure 2 is an exploded view of the transducer. The rigid circular pressure-plate *D* is mounted from the body *B* on three cantilever bars *C* spaced symmetrically in a plane. The narrow annular gap between the pressure-plate and the body is sealed by a thin flexible membrane *M* which, while accommodating the movement of the pressure-plate, isolates the interior of the transducer from the external pressure and thus allows the interior to be vented to a reference pressure via the nozzle *N* provided on the back of the body. The difference between the external and reference pressures exerts on the pressure-plate a load which is transferred to the three cantilevers. The strain thus produced is measured by foil resistance strain gauges fixed to the cantilevers.

The pressure-plate comprises two discs, each about 4 in (100 mm) in diameter, which are screwed together trapping the sealing membrane between them, while the outer edge of the membrane is clamped to the body by a ring *A*. The sensitivity of the transducer to acceleration is minimised by making the pressure-plate as light as possible compatible with strength and rigidity. This is achieved by making the pressure-plate hollow and by using light–alloy. The plate is screwed to a boss *E*, also of light–alloy, which serves as a central anchorage for the three cantilevers. The boss is dimensioned so that the back of the transducer body acts as a stop which limits the deflection of the pressure-plate. This prevents over-straining of the cantilevers. The composite unit comprising the two parts of the pressure-plate and the boss has a total mass of 0·25 lb (100 g).

Melinex sheet 0·012 mm thick is used for the sealing membrane. It produces negligible restraint on the movement of the pressure-plate in the normal working range of the instrument, which is up to 0·10 mm deflection. In this respect it is superior to all the other materials tried.

The cantilever bars are made of cast iron which has a lower Young's modulus than steel, giving the instrument increased sensitivity. The bars are 2·4 in (62 mm) overall length and 0·25 × 0·20 in (6 × 5 mm) in section. A central length of 1·3 in (34 mm) is thinned down by surface grinding to 0·25 × 0·03 in (6 × 0·75 mm) in section.

Each end is secured by two screws which constrain the cantilevers to bend in reflex curvature, and four resistance strain gauges are attached to each bar as near as possible to the positions of maximum bending moment. These are 6 mm linear foil gauges, bonded with strain gauge cement which is allowed to cure at room temperature for about 24 hours while the gauges are squeezed flat under weights. After assembly the gauges are wired to form a Wheatstone bridge, each arm consisting of three gauges in series from the corresponding position on each cantilever. By this means the deflection of the cantilevers is averaged, and since every strain gauge is active the maximum possible sensitivity is obtained. Connection is made to the bridge circuit through a four-way plug *P* mounted on the back of the transducer. The bridge may be energised with ac or dc up to a maximum of 5 V.

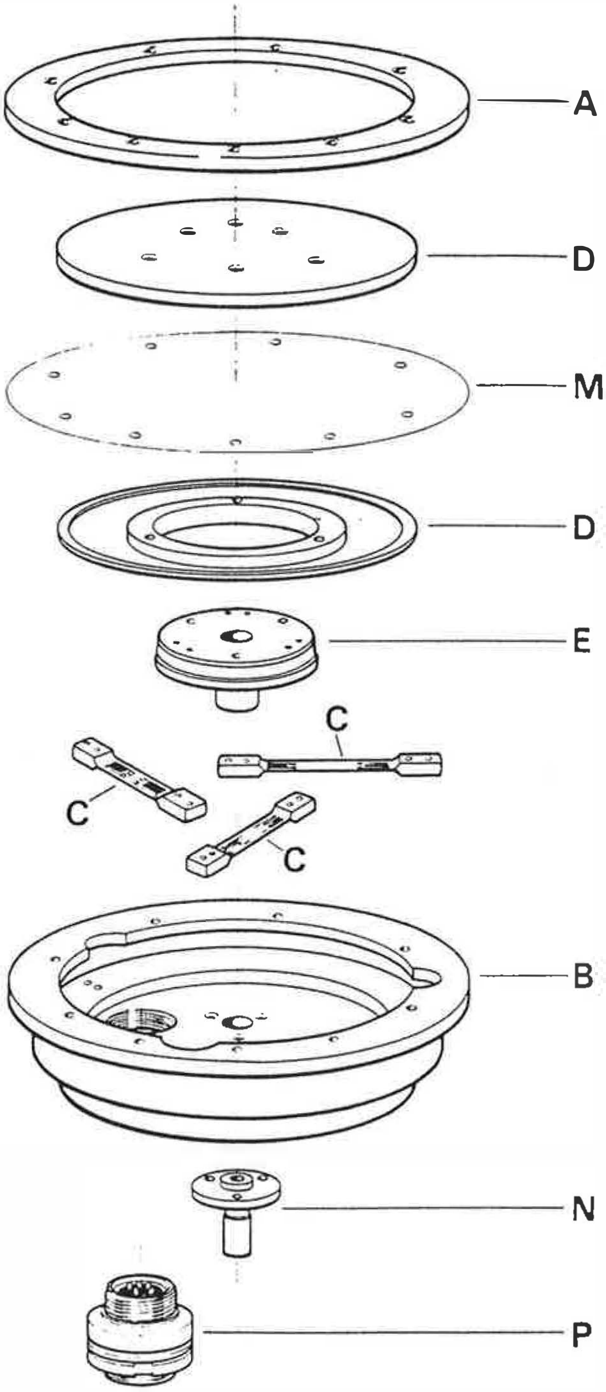

Fig. 2. Exploded view of pressure transducer (Ref. 1)

A	Membrane clamping ring	E	Boss
B	Transducer body	M	Sealing membrane
CCC	Cantilevers	N	Venting nozzle
DD	Parts of pressure-plate	P	Plug

Design and manufacture

Since transducers which have been installed in a building are generally inaccessible for frequent checks, the only practical way of measuring the zero position is by recording during calm periods which may be quite infrequent. The long-term zero-stability is therefore crucial to the satisfactory performance of the transducer. The need to respond to short duration pressure changes, combined with the requirement of a relatively large active area, led to a design where the movement of the pressure-plate was very small, thereby minimising the momentum of the moving parts and of the air movement in the venting system. However, this small movement increased the problem of obtaining satisfactory zero-stability.

The two most important factors controlling stability are temperature compensation and freedom from residual stress in the components. The arrangement of the strain gauges ensures complete temperature compensation, because each cantilever has one strain gauge mounted on it from each arm of the Wheatstone bridge.

The actual performance was checked in the range $-10°C$ to $+40°C$ and with the transducers in situ in other office blocks. No significant variation of zero was detected. The strain induced in the cantilevers by a load of 10 N/m^2, which is the level of accuracy aimed at, is only about 4×10^{-6}. This clearly shows the need to maintain a very low level of residual stress in the component parts, which was achieved by selecting materials with a low residual stress content, by annealing, and by careful machining. The grade of aluminium alloy selected for the pressure-plate and body was *NE4*, specified as having a low stress content. The cast iron used for the cantilevers was *Meehanite* GD.

An improvement of zero-stability was obtained by ageing the completed transducers on a special rig. The interior of each unit was connected to a common system in which the pressure was pulsed every few seconds by a piston, by means of which the transducers were subjected to a large number of working cycles before installation. With these precautions, long-term zero-stabilities equivalent to about $\pm 0{\cdot}2$ lbf/ft^2 (10 N/m^2) were achieved.

Calibration

The transducer output is a linear function of pressure, the deviation from linearity being about 1 per cent of full scale. Nominal sensitivity is $0{\cdot}6 \mu V/V$ per N/m^2. That is, if the transducer is energised with 1 volt and the pressure-plate loaded with 1 N/m^2, the output from the bridge will be $0{\cdot}6$ μV. Individual transducers differ from each other in sensitivity owing to slight variations of cantilever thickness, so that each unit requires calibration. Initially calibration was carried out by varying the internal pressure, measuring this with a water manometer and recording the response of the transducer. For comparison, a second calibration was made by loading the pressure-plate with dead-weight, the body cavity in this case being open to the atmosphere. Subsequently dead-weight calibration only was used because it was more convenient.

Frequency response

The frequency response of the transducer was checked up to about 200 Hz. The lowest resonance was found to be about 70Hz. The return period of the pressure-plate to the zero position from full load was also measured and is about 4 ms which corresponds to the 70 Hz resonance. The transducer is quite adequate for measuring frequencies up to 10 Hz or even higher.

Performance in service

The transducers have functioned extremely well in service. Most units have been in situ for three or four years continuously and, apart from one or two units which have developed faults, the calibrations have remained virtually unchanged during this period.

The Installation at the GPO Tower

The GPO Tower is shown in Fig. 3. It is basically a cylinder 580 ft (177 m) high and 52 ft (16 m) diameter. There are interruptions of this simple shape below 130 ft (40 m) and between 355 and 475 ft (108 m and 145 m) above ground level where the circular concrete shaft, from which the floors are cantilevered, is exposed. Above 145 m are the public floors where the glazing is 48-sided, and between 40 m and 108 m are apparatus floors which have 18-sided glazing. At 95 ft (29 m) the sideways movement of the tower is restrained by a collar one floor thick which links the shaft to the top floor of the adjoining telephone exchange building. The floor of the room which housed the recording equipment was level with the top of this link.

Strain gauges

The dynamic response of the tower under the action of wind loads was recorded by strain gauges installed on the reinforcement in the tower shaft just above the link (Fig. 3) at the position of maximum bending moment. At this level, the shaft is a 36 ft (11 m) diameter reinforced concrete tube with 24 in ($0{\cdot}6$ m) thick walls. The reinforcing bars are approximately $1{\cdot}2$ in (30mm) diameter and are placed in two concentric rings near the inner and outer surfaces of the shaft (Fig. 4), the concrete cover being about $1{\cdot}6$ in (40mm). They were made in 16 ft (5 m) long sections and subsequently welded together to form continuous vertical reinforcement. The resistance strain gauges were attached to the centre points of 24 selected bars at the Building Research Station, prior to delivery to the

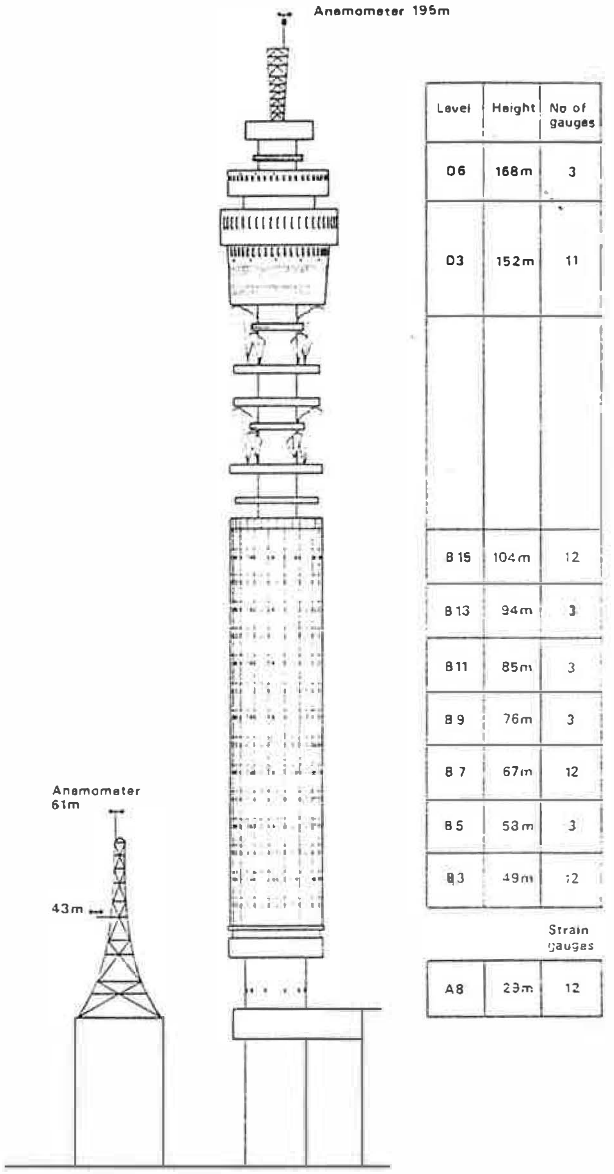

Fig. 3. General arrangement of GPO Tower

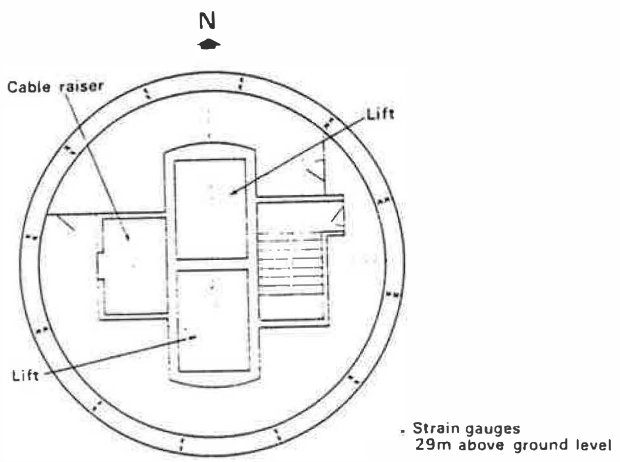

Fig. 4. Plan of equipment floor showing the strain gauge positions

site. Each bar was cleaned in the centre and two 1 in (25 mm) linear foil gauges were bonded to opposite sides of the bar with strain gauge cement, both being positioned so as to record longitudinal strain. After curing of the cement at ambient temperature, 'flying leads' of a suitable length were attached and the gauges were then protected by layers of vacuum wax. The gauged central region of each bar was finally enclosed in a loose fitting rigid metal cylinder and further wax was poured into the gap between this cylinder and the bar, thereby providing a substantial protection. On site, the gauged bars were placed in pairs, one member in the outer and one in the inner ring of reinforcement, at 12 positions spaced at 30 degree intervals round the tower shaft corresponding with the positions of the pressure transducers which were to be mounted in the curtain walling higher up the tower. At each position, the inner and outer bars were connected by a length of electrical conduit which was strapped to the bars and joined to the back of a conduit box, the lid of which was bolted to the shuttering on the inner face of the shaft. This arrangement is shown in Fig. 5. The leads from the strain gauges, entered this conduit by watertight glands and were coiled up inside the conduit box. After the shuttering had been removed the conduit boxes were accessible on the inside wall of the shaft at the level of the recording room and it was an easy matter at a later stage to extend the leads to conveniently placed sockets near the recording equipment.

Pressure transducers

Sixty-two pressure transducers were installed in the curtain walling at nine different levels. At four of these, 160, 220, 330 and 500 ft (49, 67, 101 and 152 m), there were complete rings of 12 transducers spaced at 30 degree intervals around the circumference, while at five other intermediate levels transducers were mounted in the SW quadrant facing the prevailing wind.

Because the transducer was sensitive to acceleration forces, rigid mountings were used in the form of small panes of ½ in (13 mm) thick plate glass. The mountings were designed so that the transducer could be inserted from inside the building, so as to maintain the external surface as nearly smooth and free from projections as possible and thus avoid interference with the external air flow.

Very long cable runs were necessary to connect each transducer with the recording apparatus housed just above the link. Some of these runs were 500 ft (150 m) in length. Four-core screened cable was used, each core being 14 × 0·0076 in. The four conductors, viewed in section, lie at the corners of a square, the capacity between each adjacent pair being approximately the same but different from that between opposite pairs. With cable lengths of this order, care was needed to balance the cable capacity by connecting

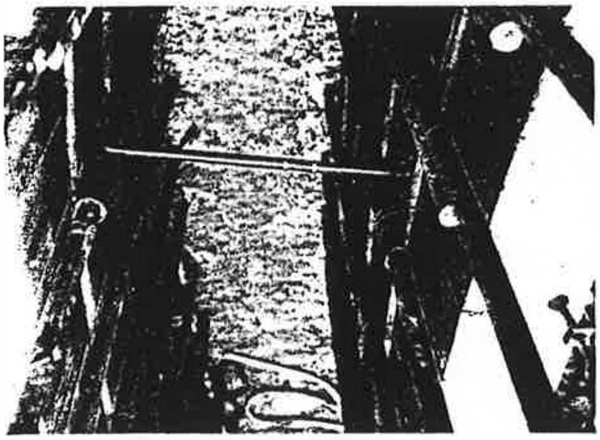

Fig. 5. Installation of the strain gauges

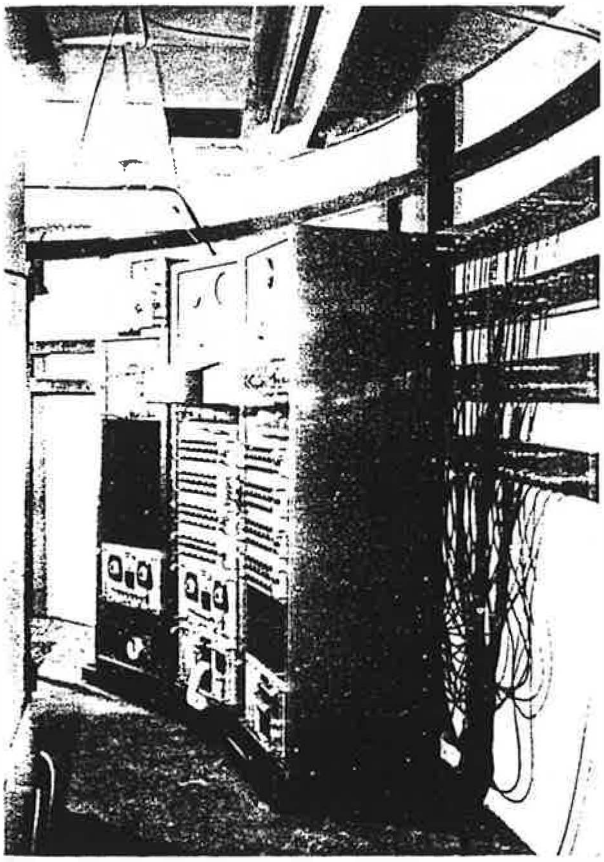

Fig. 6. View of recording room

the corners of the strain gauge bridge in the transducer cyclically round the square, thus ensuring equal capacities across each bridge arm. The remaining, relatively small, residual unbalance was easily accommodated by the trimmer provided on each carrier amplifier. In the recording room the cables were terminated by sockets mounted in trunking on the wall, and the transducers used for recording were selected by plugging into the appropriate sockets (Fig. 6).

Since the transducers measured the difference between the external pressure and a reference pressure, the calculation of overall loads by the summation of simultaneous pressures on different parts of the structure relied upon venting all the transducers to a common reference pressure. This was achieved by connecting each transducer to an external pipe running vertically for almost the entire height of the building. The pipe terminated inside the recording room in the shaft of the tower, a location well isolated from transient external effects by the total absence of windows, ventilators and lift openings. In this way, the reference pressure was as near as possible to the external static pressure. Access to the end of the venting tube in the recording room proved very useful because, by pressurising the system, it was easy to check that all the transducers were functioning.

Recording equipment

Standard, commercially available equipment was used for recording the pressures and strains, and a.c. energisation of the strain gauges and pressure transducers was employed. Recording equipment for 48 channels, shown in Fig. 7, comprises two multi-channel ultra-violet galvanometer recorders, one at the top of each cabinet, and 48 amplifier modules mounted immediately below the recorders. The modules were arranged in groups of 12 attached to an oscillator unit which provided a 5 V, 3 kHz carrier signal for energising the transducers. The amplifier module received the transducer output for detection and amplification. Each amplifier output was connected to a separate galvanometer in the recorders. The number of channels which could conveniently be accommodated on the recording paper was governed by the need to avoid overlapping of the traces while obtaining large enough deflections for accuracy of reading. A maximum of 24 channels, spaced at 10 mm intervals on 300 mm wide paper, resulted in charts of the type shown in Fig. 8.

It was expected that records were likely to be required at times when it was impossible to operate the equipment manually. A controller was therefore designed and built by the Building Research Station, which allowed the recording apparatus to be switched on automatically, either at hourly intervals or when the wind exceeded any pre-set value, or at combinations of both. This unit is shown in Fig. 7 below the amplifier modules. A standard Meteorological Office cup-generator anemometer was used as a wind speed sensor. Two timers were provided which enabled sampling and wind actuated recording periods to be pre-set independently. The duration of these periods could be from a few minutes to several hours. The whole apparatus was switched off automatically when the photographic recording paper was expended.

Records

The photographic paper from the records was collected and subsequently processed in a Bell and Howell ments from the transducers. The results are not included in this paper, but will be published shortly by the Building Research Station (Ref. 2).

Acknowledgment

The authors gratefully acknowledge the assistance and advice given by their colleagues Mr. C. W. Newberry and Mr. R. S. Jerrett. The work described has been carried out as part of the research programme of the Building Research Station of the Department of the Environment, and this paper is published by permission of the Director.

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