Techniques and materials

The monitoring of crack movement with electronic equipment at St. Paul's Cathedral, London

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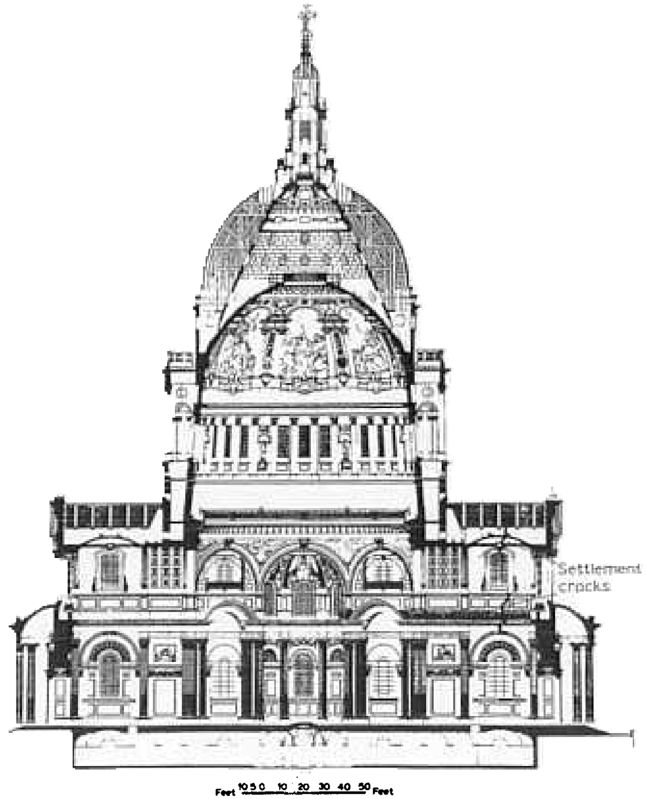

FIG. 1. St. Paul's Cathedral, London: cross section looking east showing the site of settlement cracks bridged by electronic transducers.

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The structural behaviour of buildings has from earliest times exercised the minds of those in whom responsibility has rested for their care and stability.

Masonry structures have an ability to accept and adjust to some deformation before collapse mechanisms develop beyond a critical stage, and this has sometimes led to unjustifiable complacency. 'It has stood for centuries, why should it collapse now?' Yet failures do occur centuries after building. The fall of the Central Tower and Spire at Chichester Cathedral in 1861 is a noteworthy example. Substantial settlements must have been apparent long before the catastrophe occurred, but it was not until they were actually seen to be increasing, following the removal of the Pulpitum, that drastic action was taken to secure the structure and then this proved too late.

For many years mortar pads or thin pieces of glass laid over settlement cracks have served as tell-tales. At best these can indicate that movement may be continuing with no positive information as to its magnitude or direction.

Accurate settlement observations were first introduced at St. Paul's Cathedral by Col. C.E.P. Sankey, R.E, in 1923[1] when fifty-eight levelling targets were installed in the walls just above the Crypt floor level. These were related to a datum mounted on a concrete block resting upon the cast-iron linings of a 21·34 m shaft at Newgate Street. A precise system of recording crack movement was also installed and it comprised the introduction of bronze pins cemented into the masonry on either side of the settlement cracks; the distance between being measured with a micrometer to an accuracy of 0·0254 mm.

In 1965 I introduced a system of three-pin tell-tales at Chichester Cathedral. These were arranged in the pattern of an equilateral triangle with two pins disposed vertically in a single stone on one side of the crack, with the third on the opposite side, thus providing data which could be resolved into horizontal and vertical components. The pins were set from a bronze jig and measurements are taken with a micrometer to an accuracy of 0·0254 mm. More recently the introduction of the Demec gauge has provided a sophisticated micrometer enabling readings to be taken from small discs mounted in a similar triangular fashion upon the surface of the wall. The principal drawback of all of these crack measuring devices is, however, the difficulty of obtaining access to them when in remote locations, often necessitating the use of tall ladders or scaffolding platforms. In consequence the readings may be taken less frequently than is desirable.

The ability of three-pin tell-tales to differentiate between lateral and perpendicular movement led to an experiment at St. Paul's Cathedral with clock micrometers which could be read daily. The site chosen for this experiment was the South Transept where substantial settlements exist dating from the construction of the Cathedral. These settlements,

[1] Report on the foundations of St. Paul's Cathedral for Freeman Fox & Partners by Professor A.W. Skempton, FRS; Dec. 1972/Jan 1973.

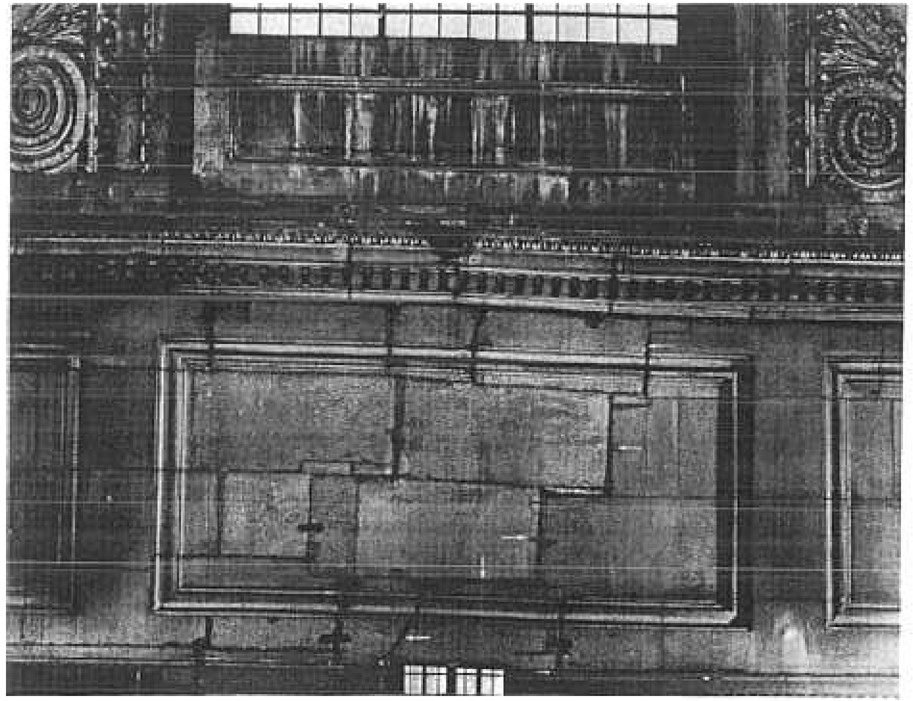


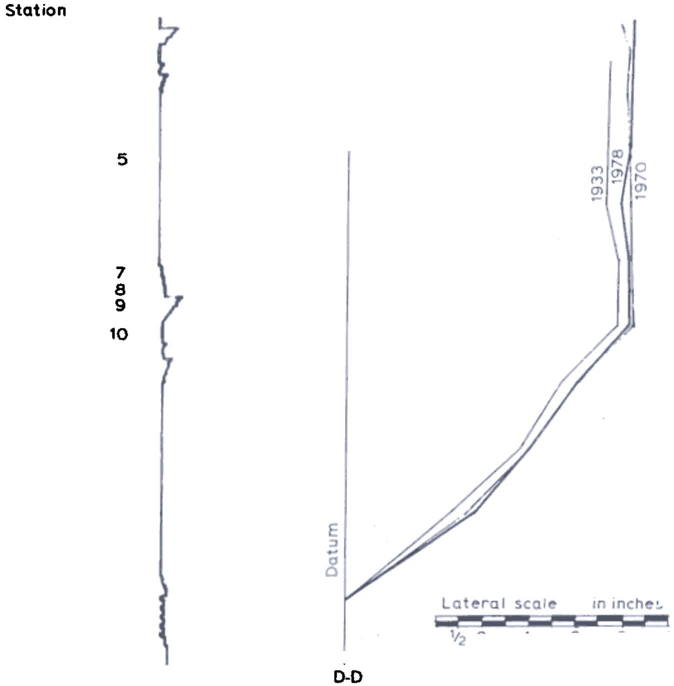
FIG. 2. Settlement cracks (denoted by white arrows) and site of electronic transducers in the South Transept.

resulting from the differential loading of the piers supporting the Dome and the abutting walls of the Transepts, articulate the structure on the line of least resistance. Cracks rise through the arches and windows, gaining in magnitude as they reach the top of the walls above the vaulting (*Figs 1 and 2*). Some of these cracks now measure as much as 50 mm across. They have been repeatedly filled with mortar, breaking again with further movement. Plumbings of the South Wall commenced in 1933 showed an increase of 15·9 mm when re-measured in 1970. Since that date there appears to be little, if any, further extension (*Fig. 3*).

One of the objectives of the present exercise has been to discover the extent to which lateral movement at the upper level of the Transept has resulted from the expansion and contraction of the drum of the Dome due to changes in temperature externally.

The Transept walls above the level of the vaulting are built in two masonry skins separated by a passage (*Fig. 4*). The inner skins connect directly with buttresses supporting the external masonry walls of the drum of the Dome. At this level the Transept walls are fully protected from the direct effects of external temperature whilst the masonry of the

FIG. 3. Sections through the South Transept showing progressive movement from 1933 to 1970.

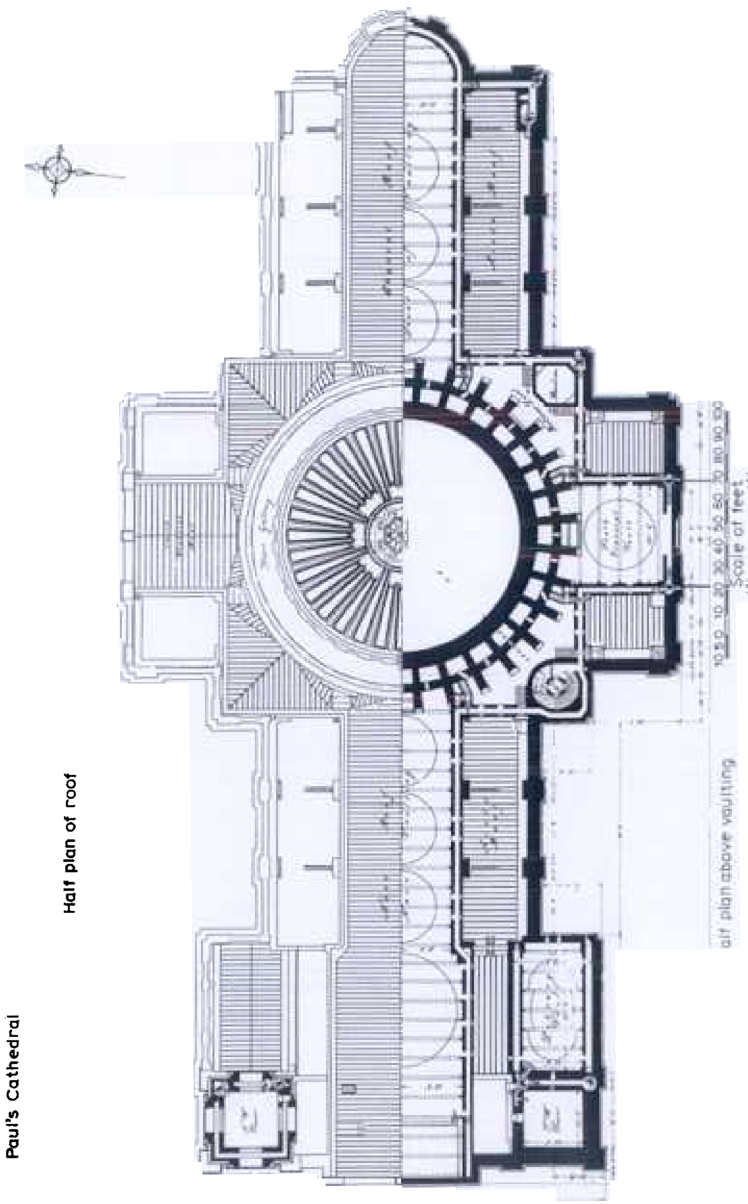


drum is vulnerable to the direct rays of the sun. The expansion of the external masonry of the drum could, therefore, be anticipated to produce some lateral movement in these Transept walls provided this was not entirely absorbed by the elasticity of the masonry.

The placing of a clock micrometer bridging one of these settlements in line with the potential thrust (+/−) proved conclusively that lateral movement did in fact occur with corresponding variation of external temperature.

It was at this juncture that I commissioned Mr. Stuart Gaunt and Mr. Alec Payne of Boorley Electronics to undertake a feasibility study to produce a device which could be incorporated in a system to be read remotely. Their brief consisted of the following:

1. It should measure movements of up to ±5·08 mm with a resolution of 0·0254 mm.
2. It should measure temperature with an accuracy of ±1° C, both in the vicinity of the transducers and externally in the drum of the Dome.



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3. It should have the capability of measuring a number of cracks.
4. It should be capable of providing data which could subsequently be resolved into the horizontal and vertical movements.
5. The read-out station should be easy to operate so that an informed operator could monitor the results on a daily basis.
6. The sensor units should be reasonably weather proof for use in exposed positions.
7. The system must be reliable and have extremely long-term stability as these measurements may need to be carried out over a number of years.
8. The system should be capable of future expansion and have the ability to be interfaced to an automatic data logger and printer.

During the feasibility study several types of transducer were investigated, the first being the strain gauge. This device can measure very small movements with considerable accuracy, but it is unable to cope with large movements directly and so was ruled out for this application. Rotary and linear potentiometric transducers, whilst offering attractive simplicity and cost factors, rely on a sliding contact in their electrical circuit, and the reliability of this was considered doubtful in the long-term unattended environment: ageing of the resistive element was another unknown quantity. Capacitive transducers were another possibility but these did not appear to be in such common supply as other types, or to be readily available in a suitable physical form. Finally, inductive transducers were examined, and here the prospect appeared much more hopeful. There is a large variety of such devices available. There are two principal types of LVDT (Linear Variable Differential Transformer)—AC and DC. The latter are complete with a built-in oscillator and demodulator requiring only a DC power supply and some form of display. AC types have an external oscillator, demodulator and display. At first sight the DC units would appear to be a more attractive proposition, but in practice the AC type can provide a higher order of accuracy, linearity and stability, and therefore this type was chosen for use in St. Paul's Cathedral.

The system installation

Because of the requirement to measure movement in two directions in one place, it was decided to use two transducers at each measurement position. These were mounted on special pins set out in an equilateral triangle as described earlier. In order to set the pins accurately in the masonry, three holes were drilled oversize using a drilling jig, and the three pins then mounted in an accurately machined positioning jig such that the distance between the centres of the pins is as nearly as possible equal to the electrical zero length of the transducers. The holes are then filled with epoxy resin and the three pins inserted, still attached to the jig.

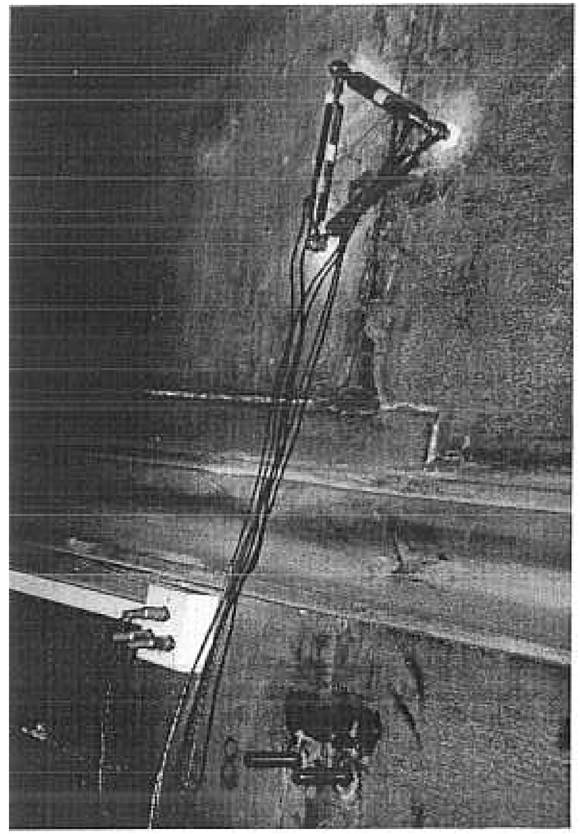


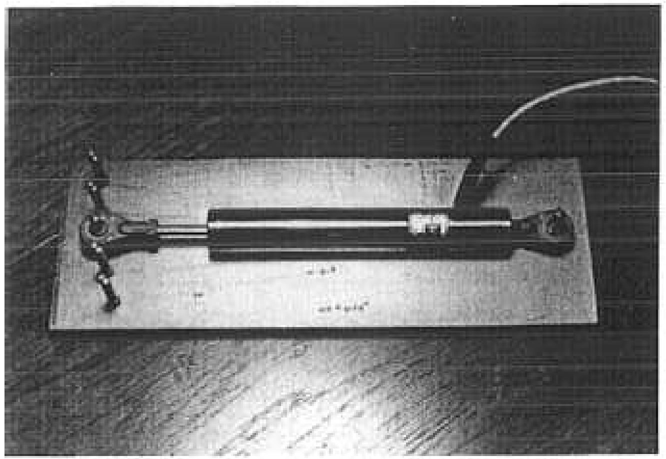
FIG. 5. Electronic transducers bridging the settlement crack in the South Transept with a pair of the original measurement pins below installed by Freeman Fox & Partners.

After the resin has set, the jig is unbolted leaving the pins accurately positioned in the masonry. The transducers are then bolted on to the pins (*Fig. 5*).[2]

The sensitivity of each transducer input has been adjusted so that the digital indicator reads directly in thousandths of a millimetre displacement from the zero position. A sign in the indicator shows the direction of movement. This scale was chosen in order to correlate the data obtained with that of the original micrometer system. The sensitivity is set by mounting the transducer on a special jig (*Fig. 6*) on the end of its cable, setting first the zero length, followed by different extended and retracted lengths, using the zero and span controls on the transducer selector unit.

[2] In order to simplify the fitting, LCDTs with built-in self-aligning spherical bearings at each end were chosen. These bearings could then be bolted directly on to the pins. The particular type selected was the D5/500E grade A1 Transducer, manufactured and supplied in matched pairs by RDP Electronics Ltd of Wolverhampton. These have a total movement of ± 12 mm with a sensitivity of 4 volts/25 mm.

FIG. 6. The transducer calibration gauge.



RDP Electronics Ltd also supplied the necessary modules for their 'Dataspan 2000' instrumentation system. These modules were rack-mounted in a cabinet (*Fig. 7*). The system chosen features a ten-channel selector unit which allows the operator to monitor any one of ten transducers, displaying the output on a digital panel indicator via a single transducer amplifier. This selector can be used either in a manual mode or automatically with the addition of a scanner driver and control unit. The system is at present configured for manual selection of the ten transducers, thus allowing for the monitoring of five crack sites. A sign in

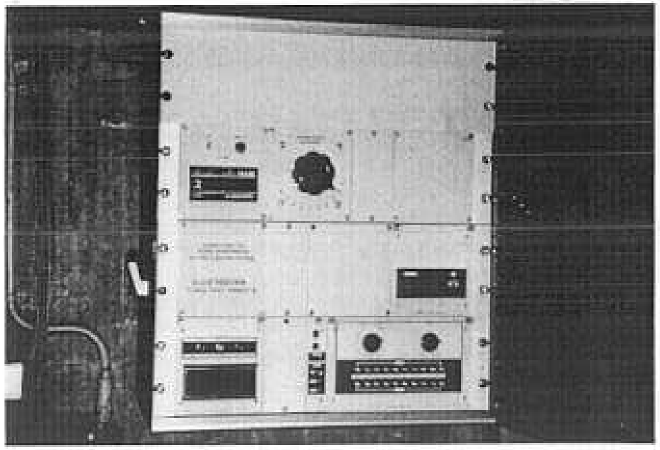


FIG. 7. Control centre scanning ten transducers and temperature sensors.

the indicator shows the direction of the movement. In order to check the long-term stability of the system it was decided to install an additional transducer across the two pins mounted in a single block of stone at one of the measuring sites. The position of these two pins relative to each other should not change but the transducer should be subject to the same temperature variations and length of connecting cable etc as the two measurement transducers at that site. The system has now been installed for three years and the total drift shown on this transducer is only 0·05 mm, most of which occurred during the first two months after installation when the system was settling down. The equipment is kept permanently powered in order to reduce any errors due to warming up.

Temperature monitoring

To correlate crack movements with ambient temperature, a remote temperature monitoring system has been installed with sensors adjacent to the sites of the displacement transducers. Platinum resistance thermometers (PRT), available with a 4-wire connection system, were selected for this purpose in view of the length of cable runs involved.

The PRT sensors are housed in stainless steel probes which are inserted into holes bored into the masonry at points close to the displacement transducers. Good thermal contact is ensured by packing the hole with silicone grease. The PRT chosen was the RT-74 series made by Eurotherm Ltd of Worthing. A digital thermometer unit Analogic Type 2576 is used to provide temperature read-out for the selected sensor in degrees Centrigrade, and a 4-pole rotary switch enables any one of eleven sensors to be monitored. The temperature measuring system is accurate to within 1 °C, although the prime consideration in this case is to measure change in temperature and this can be achieved to within $\pm 0{\cdot}1$ °C.

Recording

Measurements from the transducers are recorded regularly each day at 8.30 a.m. The data thus produced requires conversion from its triangular mode into rectangular form (*Figs 8 and 9*).

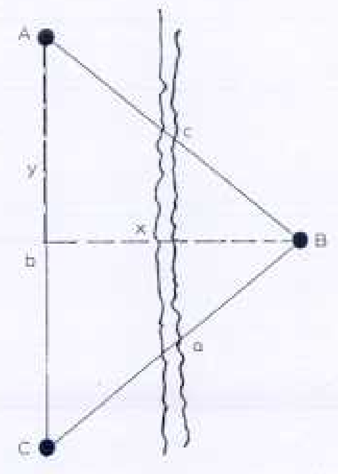
From the precise dimensions measured from the original setting of the bronze pins, the following formula is used.

Solve Angle A for Triangle AB, AC, BC with dimensions taken from templates.

$$\text{Cos } A = \frac{b^2+c^2-a^2}{2\,bc}$$

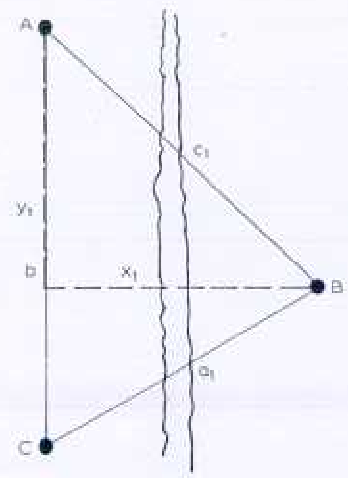
$$= c.\ \text{Cos } A$$

$$= c.\ \text{Sin } A$$



As template

FIG. 8. Template for transducer pins: the precise distance between the pins measured and recorded at installation.



Deformed triangle

FIG. 9. The deformed triangle resulting from crack movement.

Solve Angle A_1 for the deformed triangle

$$\text{Let } AB + \Delta AB = c_1$$
$$BC + \Delta BC = a_1$$
$$AC = b$$

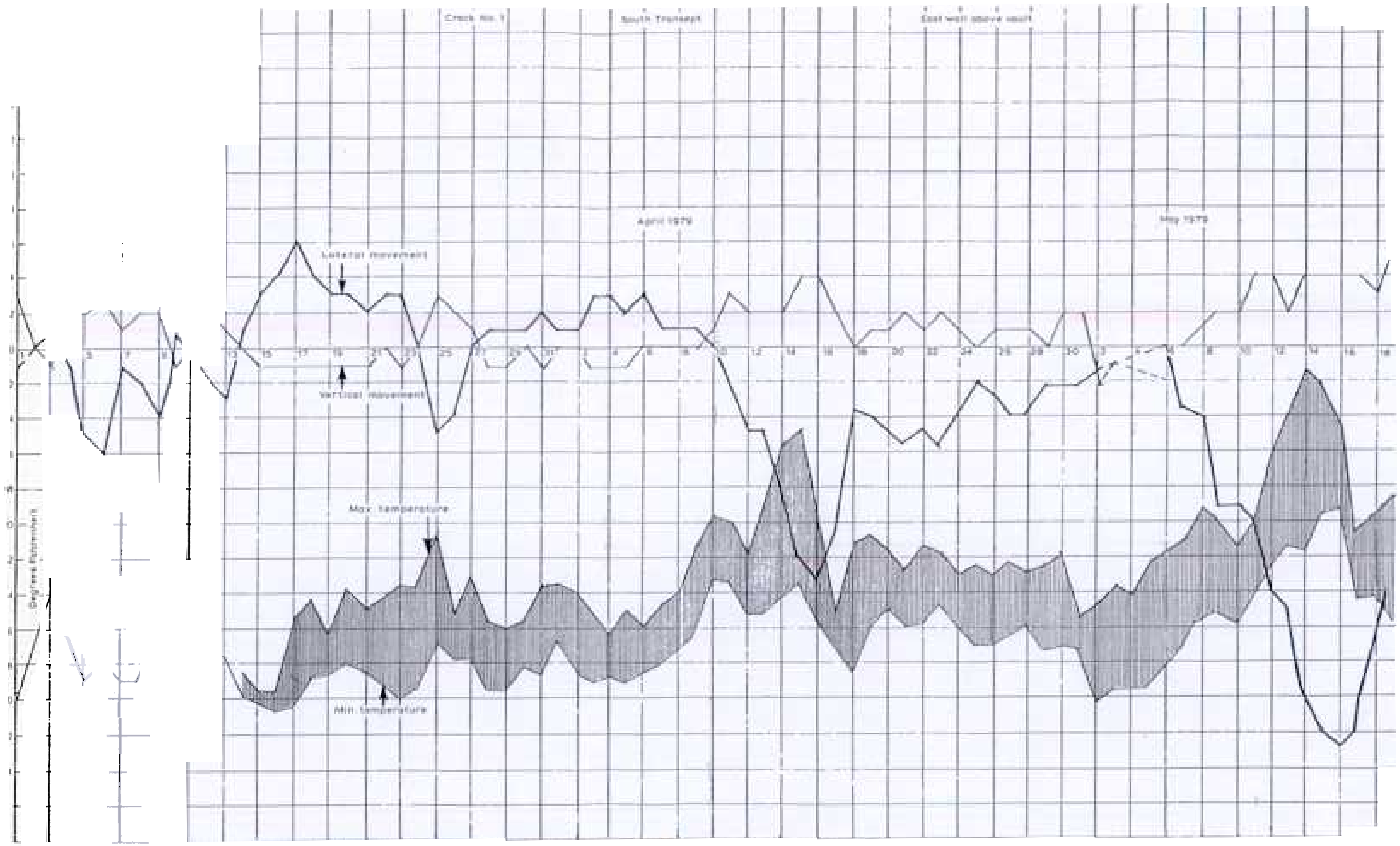
$$\text{Cos } A_1 = \frac{b^2 + c_1^2 - a_1^2}{2.b.c_1^2}$$
$$y_1 = C_1 . \text{ Cos } A_1$$
$$x_1 = C_1 . \text{ Sin } A_1$$

The difference between y and y_1 = perpendicular movement; the difference between x and x_1 = horizontal movement.

In practice the read-outs from the transducers are processed through a Texas-59 calculator with a precomputed programme. It is then plotted with reference to external ambient temperature as recorded by the Meteorological Office.

FIG. 10. (*Fly-out sheet*) Excerpts from recordings of crack movement in the south east wall of the transept above vault. Note the inverse correlation with variations of temperature.

Extracts from the record of Crack No. 1 situated in the east wall of the South Transept above the vault, illustrate the correlation of lateral movement with variations in external temperature (*Fig. 10*). During the past three years lateral movement has ranged over 0·812 mm for a temperature span of 16 °C (*Table 1*).



Crack No. 1
South Transept
East wall above vault
April 1979
May 1979
Lateral movement
Vertical movement
Max. temperature
Min temperature
Degrees Fahrenheit

TABLE 1.

Date	*Average temperature (°C)*	*Lateral (mm)*	*Perpendicular (mm)*
Jan. 1 1980	1·2	+0·132	−0·025
June 9 1980	15·7	−0·587	+0·099
Dec. 28 1980	5·1	0	0
Jan. 13 1981	1·5	+0·145	−0·051
June 14 1981	16·4	−0·587	+0·150

It is evident that the cracks in the east and west walls are performing as expansion joints, and provided that these settlements do not become jammed with debris, the south wall of the Transept should not suffer further disturbance from the lateral thrusts arising from this source. The absence of significant perpendicular movements is not surprising as the most recent pattern of foundation levels recorded by Mr. Thomas of Messrs. Freeman Fox & Partners, indicates a remarkably even settlement which at present exists beneath the eight principal piers supporting the Dome.

A Datalog with remote print-out has now been commissioned to interface with the present system, and it is hoped that this will be installed early in 1982. It is also proposed to extend the surveillance of the system to other structurally sensitive areas in the Cathedral. In the meanwhile further experimental usage of the LVDTs is being undertaken at Chichester Cathedral to discover the effects of thermal movement in the vaulting of the Choir.[3]

[3] The author is indebted to Mr. Stuart Gaunt and Mr. Alec Payne for the technical information included in this article, to Members of the Staff of St. Paul's Cathedral who have assisted in the installation and monitoring of the system, to Jack Edwards, the Consulting Engineer to St. Paul's Cathedral for his collaboration and to the Meteorological Office of the London Weather Centre for temperature data.

Résumé

Depuis plusieurs années on utilise des bandes de plâtre ou de verre fin fixés à travers les fissures de tassement pour servir de témoins aux mouvements de la structure. Mais ces temoins indiquent tout au plus que le mouvement continue; ils ne peuvent ni offrir d'information positive quant à la direction du mouvement, ni permettre de mesurer d'une facon exacte l'élargissement d'une fissure.

Le mesurage exact des mouvements de tassement dans la cathédrale de Saint Paul date de 1923. C'est en cette année que l'on a fait installer 58 points de nivellement dans les murs, juste au-dessus du niveau du plancher de la crypte, qui se rapportaient tous à un niveau zéro. Au même moment on a fait installer un système de mesurage précis pour les mouvements des fissures. Des paires de goujons en bronze ont été fixées dans la maçonnerie de chaque côté des fissures de tassement, et la distance entre eux a été mesurée par micromètre.

C'est dans la cathédrale de Chichester que l'on a introduit pour la première fois des indicatuers à trois goujons, qui ont fourni des données pour les mouvements horizontaux aussi bien que verticaux. L'introduction du calibre Demec a fourni un micromètre sophistiqué que permet de mesurer à partir de petits disques fixés sur la surface du mur dans une pareille disposition triangulaire. La possibilité de distinguer entre les mouvements latéraux et les perpendiculaires qu'offraient les indicateurs à trois goujons a mené à une expérience dans la cathédrale de Saint Paul avec des micromètres-horloges que l'on pouvait consulter chaque jour. Cet article offre un compte-rendu de cette