R. & M. No. 3736

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MINISTRY OF DEFENCE (PROCUREMENT EXECUTIVE)

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

Vibration Amplitudes Produced in St. David's Cathedral by Concorde Sonic Bangs

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LONDON: HER MAJESTY'S STATIONERY OFFICE
1973
PRICE £1.10 NET

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Summary

At St. David's Cathedral, structural vibrations produced by a number of Concorde sonic bangs have been measured and compared with the vibration produced by the structures normal environment. The results show that bang produced amplitudes are not very much greater than the environmental vibration amplitudes. It is unlikely therefore that continued exposure of the Cathedral to sonic bangs would result in appreciably accelerated structural decay.

* Replaces R.A.E. Technical Report 71121—A.R.C. 33 123

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1. Introduction

The general study of the effects of sonic bangs on building structures includes special attention to the effects on buildings which could be more vulnerable to shock or vibration damage because of their particular type, age or condition. Limited experiments pertaining to the study have been carried out before. They have utilised explosive-simulated sonic bangs or real sonic bangs from combat-type aircraft.

The flight testing programme of Concorde 002 was to include a number of flights down the West Coast Route[1] and these flights involved some supersonic flight over land. This, therefore, presented an opportunity of measuring the vibration effects on some buildings of real sonic bangs of the sort which could be expected from a supersonic transport aircraft.

A trial, which was called Exercise Trafalgar, was organised by the then Ministry of Technology to utilise the flight tests to obtain as much information as possible about the effects of the bangs on buildings. A number of experimental teams took part in order to carry out tests on several types of buildings. The teams were stationed along the flight test route at certain locations where there were buildings which had been chosen as being of special interest with regard to their type, condition or historic value. One of the buildings chosen was St. David's Cathedral, Pembrokeshire, and the team which carried out measurements at the Cathedral was staffed by Structures Department of the R.A.E.

This Report describes the experimental procedure which has been used at St. David's and gives an account of the results from the first six flights to cause sonic bangs at St. David's.

2. Description of the Cathedral

St. David's Cathedral (Figs. 1 and 2) is about 5 km west of the aircraft's nominal flight track which runs in a north to south direction. It lies in a hollow about 33 m above sea level, the ground rising sharply to about 70 m on the east side and to about 50 m on the north side.

The building in its present form was started in 1180 AD. There have been alterations and additions since then. There is some evidence to show that the foundations were not adequately suited to the Cathedral's location. The outward and westward lean of the nave pillars (Fig. 3) is remarkable and in the fifteenth century enormous buttresses were built on the north side of the Cathedral (Figs. 2 and 4) to strengthen the nave. The west front was rebuilt in 1789 and again in 1863, and there are now cracks which show that there may again be some structural movement taking place.

3. Object of the Tests

The purpose of the vibration tests at St. David's Cathedral is to attempt to evaluate the possibility of damage to the Cathedral structure by sonic bangs. Earlier experiments have shown that conventionally constructed buildings, in a reasonable state of repair, are unlikely to suffer obvious damage by single bang events and the bangs recorded at the Cathedral confirmed this in that no apparent damage has so far occurred. Nevertheless, there is still the possibility that continued exposure to sonic bangs, over a long period of time, could result in less obvious or cumulative weakening of the structure which could be attributed to materials fatigue.

Such damage can be likened to the gradual deterioration, with time, of the building's fabric which inevitably necessitates occasional repairs. This deterioration must be partly due to the building's normal vibration environment. It is therefore of value, in assessing the possible long term effects of sonic bangs on the building, to measure and compare the vibration produced by the sonic bangs with the vibration produced by the environment. The comparison must, of course, take into account the duration as well as the amplitude of the vibration.

With regard to environmental vibration excitation, the major source of vibration of the Cathedral is wind forces. The effect of the organ playing must also be taken into account however, as this can produce considerable vibration in some parts of the Cathedral. The effect of traffic and of bell ringing have been included in similar tests on other Cathedrals,[2] but at St. David's there is no heavy passing traffic, and the bells are housed in a separate bell tower.

The precise locations at which the thirty or so transducers were placed for vibration measurements are shown in the results tables.

The sonic bang pressure signature was recorded for all bang events.

4. Measurement Systems

4.1. Rotating Cup Anemometer

This was installed to give an average wind-speed indication in the general area of the Cathedral while recording the vibration response of the Cathedral elements to wind forces. The electrical output from the anemometer was recorded on a slow-speed pen recorder.

Rotating cup anemometers have a slow response but are commonly used by meteorological stations for wind-speed measurements. Normally they are mounted at not less than 10 m above level ground and away from trees and buildings. No suitable ground location could conveniently be used however at St. David's and the electrical generator (or rotating cups) part of the instrument was therefore mounted on a 6 m mast which was sited on the bell tower roof. The bell tower is on high ground relative to the main buildings of the Cathedral and is about 50 m away from it. There were no high buildings or trees nearby which might have influenced the readings of the anemometer.

4.2. Gust Anemometers

Gust anemometers were used in this experiment to measure the instantaneous wind-gust velocity and direction during wind-response tests.

The anemometers chosen for this purpose were developed by the Electrical Research Association for research on wind loading on buildings and other structures.[3] The sensing element of the instrument is a perforated sphere, the movement of which is converted by strain gauges to give an electrical output proportional to wind pressure. The full scale response time of the anemometer is approximately 0·1 s, it is therefore able to respond to wind gusts of very short duration. The instrument is bi-directional and its output varies as the cosine of the angle to the sensitive axis, to within 1 per cent throughout 360 degrees of rotation. If two such anemometers are mounted with their sensitive axes mutually at right angles then, from their recorded electrical outputs, the wind pressure and direction at any instant can be calculated. The anemometers were calibrated in a wind tunnel so that wind velocity could be read off a calibration curve.

Two gust anemometers were used at St. David's to measure respectively the north/south and east/west components of wind-gust velocity. They were mounted on a 3 m mast which was sited on the roof of the Cathedral tower, so that the wind environment in the immediate locality of the Cathedral could be studied. During tests on the vibration effects of wind on the Cathedral fabric, the electrical output from the gust anemometers and the signals from the vibration transducers were recorded simultaneously on the magnetic-tape recorder.

4.3. Microphones

These were used to measure the pressure waveform of the sonic bang. Pressure waveforms were recorded for each bang event so that firstly, the vibration response of the building could be normalised to a unified excitation level if required and secondly, any peculiar vibration response could perhaps be related to an unusual wave shape or frequency content in the pressure signature.

The microphones used were Bruel and Kjaer, one inch, Type 4146 capacitance microphones. This type has been developed especially for recording sonic bangs. The pressure equalisation hole in the microphone cartridge is sealed,[4] bringing the lower frequency limit down to below 0·1 Hz. The microphones were used with Bruel and Kjaer FM amplifiers Type 2631, the combination having a frequency bandwidth of 0·1 Hz to 7 kHz. The microphones are easily calibrated in the field using a Pistonphone.

Ideally, microphones used for sonic bang pressure waveform measurements should be used either on the ground in a level open space free from obstruction or raised on a mast to such a heigh (about 100 m) that the pressure signature is not confused by ground reflection effects. Neither of these conditions was practicable at St. David's. The microphone which was used to measure the bang pressure waveform was therefore fixed to an extension to the flagpole on the Cathedral tower. This resulted in the microphone being about 10 m above the tower roof and, since the tower is about 40 m in height, about 50 m above ground level. The recorder pressure signatures show an overlap of the ground reflected wave on to the incident wave and this creates some difficulty in estimating the characteristic overpressure of the sonic bang but this is discussed more fully in Section 5.1.

4.4. Seismometers

Seismometers were used in this experiment to detect vibration in the massive parts of the Cathedral such as the tower. They are ideally suited to this application as they are sensitive, have a very low inherent noise level and response to frequencies as low as 1 Hz. Their disadvantage is that their weight is about 13·5 kg (30 lb), and they can therefore be used only where there is a sufficiently strong horizontal mounting surface. The seismometers have an output which is proportional to vibration velocity and their sensitivity is 0·35 volt per mm/s.

4.5. Accelerometers

Two types of piezo-electric accelerometer were used for measuring vibration in the lighter parts of the structure such as ceilings, roofs and window glazing. One type weighs 230 g (8 oz) and has a sensitivity of about 200 mV/g_n, the other weighs 26 g (1 oz) and has a sensitivity of about 100 mV/g_n.* The lighter type achieves its high sensitivity/weight ratio by the use of a bending effect on its piezo-electric element as distinct from the more common compression effect. Its light weight makes it particularly suitable for window vibration measurements and permits the use of adhesive fixing to most surfaces.

4.6. Strain Gauges

Semi-conductor strain gauges were used to measure strains in the glazing of the leaded windows because the strains were expected to be very small and semi-conductor gauges have a higher gauge factor than some other types. Battery-powered amplifiers were used to amplify the signals from the strain gauges and these amplifiers also supplied the necessary gauge energising current.

4.7. Signal Conditioning

In most cases signals from the vibration transducers needed amplification to raise the level to the 0·5 volt rms minimum input requirement of the tape recorder. Battery-powered amplifiers were used for this purpose to reduce mains frequency interference and battery-powered impedance converters were used with the accelerometers.

Integrating amplifiers were used so that velocity waveforms could be obtained from accelerometer signals. In general, the integrating operation was carried out on the replayed signals from the tape recorder.

4.8. Data Recording

Signals from the various types of transducers were recorded on a 14 channel FM tape recorder. A tape speed of 7·5 in/s was chosen for bang records. Bandwidth limits at this speed were 0 and 2·5 kHz which were considered to be sufficient for adequate resolution of the sonic bang waveform. The tape was not run at a higher speed because of recorder running-time restrictions and some uncertainty about when the bang would be heard. System sensitivities had to be adjusted by experiment.

Environmental tests were recorded at 1·87 in/s tape speed giving a frequency bandwidth of 0-625 Hz which covered all expected building vibration frequencies.

4.9. Data Replay

Bang vibration signals recorded on tape were replayed, either directly or through integrating amplifiers, on to an ultra-violet type recorder. Recorded information could thus be studied immediately after the bang. The UV records were also used for visual analysis in arriving at the results shown in this Report.

In order to measure the rms signal levels of the environmental vibration, recordings were replayed into a high-damped rms voltmeter, the average meter indication then being judged visually. Also, environmental recordings were reproduced on the UV recorder so that the amplitudes of the occasional high peaks of vibration could be estimated.

5. Presentation of Measurements

5.1. Pressure Measurements

The currently favoured measure of the intensity of a sonic bang is its characteristic overpressure near the ground in the open, and this can be estimated from an '*N*-wave' pressure recording by extending the essentially straight sloping line between the bow and stern shocks and measuring its height at a point where it meets a vertical line drawn through the point of onset of the bow shock. The characteristic overpressure can also be obtained from a similar operation on a free-field recorded pressure wave, but in this case the pressure level thus obtained must be doubled to arrive at the generally quoted value.

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* g is the symbol for gramme and g_n the symbol for gravitational acceleration.

As was stated in Section 5.3, it was not possible to make either ground or true free-field pressure measurements at St. David's and this led to some difficulty in estimating the local characteristic overpressures. The recorded sonic bang pressure waveforms are shown in Fig. 5. Waveforms relating to bangs 105, 106 and 108 clearly show the effect of the ground reflected wave superposed on the incident wave. In these three cases the pressures have been estimated from the initial or purely free field part of the waveform, and have been doubled in calculating the characteristic overpressures shown in the results tables. The pressure waveforms from bangs 101 and 110* unaccountably do not have such a clearly defined free-field portion, and doubling or not doubling the pressure estimated in this way are probably equally wrong, the true characteristic overpressures perhaps lying between the two. For the sake of uniformity the pressures have been doubled and it must be remembered, in looking at the results, that the pressures for bangs 101 and 110 given in the tables are probably higher than the true sonic bang pressure inputs to the Cathedral structure.

The estimated characteristic overpressures have also been obtained from theoretical considerations which include the aircraft's altitude and Mach number and the distance of the aircraft's track from the Cathedral. In column 3 of Table 1, two theoretical values for the overpressure are shown. The first is based on an aircraft track given by the ground radar system and the second uses a track given by the aircraft's Decca navigation system. Experimentally obtained characteristic overpressures and signature intervals are also shown in this table.

5.2. Vibration Measurements

It was decided at the commencement of Exercise Trafalgar that all teams should present their vibration data in the same units to enable the measurements made at the various sites to be compared. Velocity was chosen for the common vibration amplitude parameter and tables in this Report show amplitude in velocity terms for all vibration transducer positions. Where acceleration transducers were used, this has necessitated an integration operation on the replayed signals from the tape recorder. Additionally, in these cases, acceleration amplitudes are shown as these could be obtained by direct replay of the recording tapes. Acceleration amplitudes may be of use for comparison with results obtained from other experiments, either in the laboratory or in the field.

It is also possible to obtain displacement amplitudes from the recordings by appropriate integration methods and this has been done for one transducer location only to give an indication of the displacement amplitudes which might be expected. Analysis of the recorded data is not restricted to the information presented in this Report. The magnetic tape recordings have been stored and can be used if more comprehensive or sophisticated analysis is required in the future.

6. Results and Commentary

6.1. Cathedral Tower

The Cathedral tower is fairly high (about 40 m). The ring of eight bells which once hung in the tower was removed many years ago when the tower showed signs of collapse. The tower was strengthened by the addition of metal tie rods and concrete in-filling within the walls. (The bells now hang in a separate bell tower which is about 50 m distant.)

Two seismometers were placed on window ledges in the old belfry which is immediately under the roof, one to measure east-west vibration and one to measure north-south vibration. The results (Table 2) show that the peak vibration response to a sonic bang averages about 1·0 mm/s and that the predominant frequency of oscillation is 2·3 Hz. The recordings show that the tower starts to vibrate in a north-south direction and that, almost immediately, this motion is partly translated into the east-west mode. After the initial movement produced by the shock, the vibration settles down to an almost sinusoidal motion. The peak velocity and the fundamental frequency of oscillation can therefore be used in calculating the approximate displacement. The displacement calculated in this way is shown to have a peak amplitude of about 0·07 mm.

Vibration amplitudes produced by the bang can be compared with those produced by the natural environment. A recording was made of the response of the tower to high winds from a south-westerly direction, which is the prevailing wind direction in that area. From the record, three periods of wind activity were selected in which the wind gusted up to maximum velocities of 19 m/s (37 kn), 28 m/s (54 kn) and 39 m/s (75 kn) respectively with comparatively quiet periods in between. The results show the greatest tower vibration amplitudes during each

* The instrumentation failed to record the pressure signature for bang 109.

of the three periods. For instance, 75 kn gusts produced a tower vibration which was about one third of the amplitude produced, on average, by the sonic bangs. In making such comparisons the duration of the vibration must also be compared. Vibration caused by the sonic bangs dies away in a few seconds, whereas that caused by the wind lasts as long as the wind continues. Furthermore, if these results are plotted (Fig. 6) then the peak tower vibration amplitudes are shown to be proportional to the square of the peak gust velocities. If this is taken to be true, then 100 kn wind gusts (which have been reported in that area) would excite the tower to amplitudes as great as those produced by some of the sonic bangs.

There is a single bell housed in a bell cote on the tower roof. This bell is struck hourly by a hammer, being controlled by the clock mechanism, and it is also rung for a few minutes before Cathedral services. The response of the tower to the ringing of this bell was measured, and the results are shown in Table 2.

6.2. Nave Roof

The nave roof was rebuilt in the late fifteenth or early sixteenth century and is unusually low pitched. The roof is boarded and lead covered and is about 40 m in length by about 15 m span. It has the appearance of being extraordinarily strong (Figs. 7 and 8). The main timbers of the trusses are of about 30 cm (1 ft) square section and the trusses are about 3 m apart. The five vertical posts in each truss are dovetailed into the main members and this probably makes the roof construction unique.

Roof vibration measurements were taken on or near the fourth truss from the west end of the nave. Measurements were made on main rafters, common rafters, purlins and roof boarding as shown in Table 3. Accelerometers were used for this purpose and integrating amplifiers were used to obtain velocity measurements from the recorded accelerometer signals during replay. Table 3 shows the peak velocity of vibration measured on the various roof components. The results show that the environment, in this case a 10 m/s (20 kn) average wind or the organ playing loudly, produces vibration levels which are about 0·2 of those produced by the sonic bang. In the environmental vibration columns, the first figure shown is the amplitude of the greatest peaks which occurred during the environmental recording. The figure in brackets below shows the amplitude averaged over the whole of the recording time which was about 30 s. This value was obtained by reading the signal level on a slow response rms meter and averaging the reading visually over the recording period.

The frequencies shown in the penultimate column are the predominant frequencies obtained from quick visual analyses of the bang records. The 9 Hz frequency which appears commonly is probably the fundamental resonance of the roof. Where two frequencies are shown for one transducer location it indicates that they tended to be excited to the same amplitude. The analyses contained many frequencies as would be expected from shock excitation of such a complex structure having many vibration modes. It was noticed that the waveform of the sonic bang had a considerable effect upon the character of the recorded vibration wave train, the relative amplitudes at the frequencies excited depending on the shape of the pressure waveform. This is considered to be the major reason for the apparent scatter in the peak response measurements.

The peak accelerations obtained directly from the bang recordings are shown in Table 4. They are included in the report for assistance, if required, in comparison with similar experiments.

Although it was decided at the start of the exercise that measurements and comparisons of vibration amplitudes should be made in velocity terms, displacement amplitudes can also be obtained from the recordings. The recorded data from one transducer (at the centre of a main rafter on the north side of the nave roof) was selected for such treatment. In the following table the acceleration and velocity peak amplitudes have been abstracted from the general results, the displacement amplitudes were obtained by further integration. The figures in the third and fourth columns are not necessarily the result of integrating the same section of environmental recording but, to be consistent with the other results in the report, they are the greatest peak amplitudes shown

	Bang 101 125 N/m^2	Bang 105 77 N/m^2	Wind 10 m/s average with 24 m/s gusts	Organ playing loudly
Acceleration mg_n	35	42	1·2	6·8
Velocity μm/s	2500	1700	430	374
Displacement μm	68	41	12	23

after processing the whole of the recording. From this it is obvious that the ratio of bang to environment-produced amplitudes depends on the vibration parameter used for comparison.

A discussion as to which of the three parameters should properly be used for vibration comparisons in damage probability assessment is not within the scope of this Report. This matter is to be included in a laboratory test programme in which the relative damage effects of shock and continuous vibration on building structures and materials is to be studied.

6.3. Nave Ceiling

The nave ceiling (Fig. 9) is flat and is attached to the horizontal tie beams of the roof structure. It is of carved Irish oak and is prized for its artistic qualities. The ceiling appears to be very strongly constructed with regard to its main members, but the panelling is rather fragile. Some of the panels are loose or broken.

Ceiling vibration measurements were made on joists and main beams in the same general area of roof space as the roof vibration measurements. Acceleration transducers were used, their recorded signals being replayed through integrating amplifiers so that velocities could be estimated. The results (Table 5) show that the ceiling vibration levels are of the same order as roof vibration levels (Table 3) when excited by sonic bangs, but that winds caused comparatively little vibration in the ceiling; 24 m/s gusts (47 kn) produced ceiling vibration levels of only about 0·01 of bang-excited vibrations. On the other hand the effects of the organ on the ceiling were in general more pronounced than either the effect of the organ on the roof structure or the effect of the wind on the ceiling. This might be expected because the sound of the organ would act directly upon the ceiling and the ceiling is shielded from direct wind forces. Also, it was noticed during the recording, that the lower pitched organ tones excited resonances in the ceiling. The greatest vibration amplitudes induced in the ceiling structure by the organ playing were about 0·4 of the bang response.

While checking the installation of the instrumentation a 12 stone (76 kg) man walked along the cat-walk in the nave roof space. The cat-walk rests on the roof tie beams and can be seen in Figs. 7 and 8. The resultant vibration was picked up by an adjacent seismometer on a tie beam and detected on the recording apparatus. The greatest vibration peaks were found to be about 0·2 of the peak vibration caused by sonic bangs.

The rms levels of vibration and the predominant frequencies (Table 5) excited by the bangs were obtained by the same methods as were used for the roof. Ceiling acceleration levels were obtained directly from the recordings (Table 6).

6.4. Leaded Windows

In the north transept there is a leaded window array about 4·4 m in width by about 8·5 m in height which occupies a large proportion of the north wall area (Fig. 10). It is composed mainly of ten glazed panels which are rectangular except for the shaped top edge. Eight of these are 0·73 m in width, the central pair are 0·85 m in width. They are all about 3·0 m in height. The glazing is supported by 1·2 cm square section iron saddle bars which are spaced at 0·3 m. The ten panels are all of the same glazing pattern being mainly of diamond-shaped panes and having a narrow border of small rectangular panes.

The glazing is not all of the same age. Three panels were selected for dynamic tests. One of these (the upper left hand side in Fig. 10) is 100 years old and is in poor condition. Another (lower centre in Fig. 10) is 30 years old, while the third (lower left hand in Fig. 10) is 10 years old. The two newer panels were in good condition. There was therefore an opportunity for comparing the dynamic response of three glazed panels which were of different ages but of the same style and approximate dimensions. The attraction of the comparison is enhanced by the fact that the window faces north which is the direction from which the sonic bang wave would arrive. This suggests that the three panels would all be subjected to a sonic bang pressure wave which was undiffracted by the building and therefore of a uniform intensity and waveform.

It is considered that there are three basic ways in which leaded lights can fail due to shock or vibration loading:

(a) Repeated sonic bang loading on one side of the window might produce a permanent distortion of the lead cames, resulting in a 'bowing' of the leaded light.

(b) Continued vibration or repeated exposure to sonic bangs might fatigue the lead or weaken the jointing material between the lead and glass, resulting in a less weatherproof window. This effect must be related to the duration as well as to the severity of the vibration.

(c) The glass could be cracked by a single bang of very high intensity. This would almost certainly be accompanied by serious lead distortion.

Experiments relating to the first effect are currently being conducted at the Cathedral. In these experiments, a micrometer is used to detect any progressive and permanent displacement of the leaded light from its original plane. The results will be published in a separate report.

The second and third effects have been dealt with experimentally at St. David's and they are covered in this Report in the following Sub-Sections, 6.4.1 and 6.4.2.

6.4.1. Velocity measurements. Lightweight accelerometers were attached to the approximate centre of an area between two saddle bars on each of the three panels, and the responses of the panels to sonic bangs and the vibration environment were recorded. The recordings were replayed through integrating amplifiers so that the vibration velocity could be obtained.

The results are shown in Table 7. Note that the results are shown in mm/s rather than μm/s as in the other tables, because the amplitudes of vibration are so much greater than those measured at the other transducer locations. The results show that the window amplitudes excited by the organ playing loudly are, in general, of the same order as, and in some cases greater than, the amplitudes excited by the sonic bang. It was expected that there would be an appreciable response to the organ because leaded windows generally have resonant frequencies within the audio range. It was noticed during the recording that these panels were resonating when some of the low pitched organ notes were played. The 4 Hz frequency which appeared on the recordings is thought to be due to the window vibrating as a whole rather than to the vibration of the glazed panels.

In the wind environment test, the wind was gusting up to 15 m/s (30 kn) and was from the WNW. Wind excited amplitudes of vibration were from 0·1 to 0·5 of the average response to a sonic bang. As the wind had only a small northerly component there is the possibility that a more northerly wind could excite window amplitudes as great as those produced by the sonic bang.

The peak vibration accelerations obtained directly from the recorded accelerometer signals are shown in Table 8.

6.4.2. Strain measurements. Strain gauges were attached to the three leaded light panels in positions and orientation as shown in the results (Table 9). Only a few results were obtained and it was not proposed to continue the measurements because the recorded strains showed that the probability of glass fracture in these windows due to sonic bangs was very low. The results show that the greatest glass strain recorded was 12 μ strain. If the breaking strain of glass is taken to be about 1000 μ strain,[5,6] it would then appear that the intensity of the sonic bangs could be increased by a large factor before glass breakage would be expected.

7. Conclusions

As part of Exercise Trafalgar, structural vibration levels produced in St. David's Cathedral by Concorde sonic bangs have been measured.

The effects of six bangs were recorded within the period 1st September 1970 to 12th December 1970, their intensity varying between 67 and 135 N/m^2 characteristic overpressure. No obvious damage to the Cathedral's fabric was caused by the bangs. During roughly the same period the vibration produced by the Cathedral's normal environment was also measured. The main sources of environmental vibration are wind and organ playing. The bang and the environmental vibration levels are compared in this Report.

Measurements have been made in four areas of the Cathedral. They are the tower, nave roof, nave ceiling and a leaded window array. For any particular measurement area, the environmental vibration depends on the type of environmental input. For instance, the tower and the roof, being exposed to the wind, are excited mainly by wind forces. The lighter components of the ceiling and the window respond more to the organ, possibly because they are directly coupled to the air volume within the building and because they have resonances within the audio range.

The results are arranged in tables so that the vibration amplitudes caused by the bangs and by the environment can be compared. This comparison is generalised in the table overleaf where column 2 is the ratio of the greatest vibration velocity amplitudes produced by the environment to the vibration amplitudes produced by the bangs.

The environmental input shown is that which has produced the greatest amplitude so far measured in that particular area. Each area would, of course, be additionally subjected to lesser environmental forces.

In a comparison of the possible long term structural damage effects of sonic bangs with the gradual deterioration caused by the building's vibration environment, the duration of the vibrations must also be taken into account. For example, the organ can produce greater vibration levels than the sonic bang in the window glazing and it may be in use for as much as a few hours a week while, if commercial supersonic overflights were to become

	$\frac{V_e}{V_b}$	Environmental input
Tower	0·3	39 m/s wind gusts (75 kn)
Nave roof	0·2	24 m/s wind gusts (47 kn)
Nave ceiling	0·4	Organ
Window	1·2	Organ

regular, the total duration of the vibration caused by the bangs would be at most only a few minutes a week. There is little doubt therefore that the organ is likely to cause more window damage than would be caused by sonic bangs.

In instances where the greatest environmental vibration is less than the bang vibration, an estimation of the relative damage effects of bang and environment cannot be made with such confidence. However, it would seem that environmental vibration is probably the more damaging to the structure because, even in these cases, the ratio of vibration times is probably still very much larger than the ratio of vibration amplitudes.

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TABLE 1

Theoretical and Measured Pressure Wave Characteristics
(*see* Section 6.1)

Flight No.	Date	Theoretically estimated characteristic overpressure N/m^2	Measured characteristic overpressure N/m^2	Measured signature interval ms
101	1st Sept. 1970	95, 78	125	240
105	10th Oct. 1970	91, 89	77	207
106	12th Oct. 1970	102, 92	115	225
108	28th Oct. 1970	110, 94	67	224
109	12th Nov. 1970	92	*	
110	12th Dec. 1970	98, 110	135	227

* Instrumentation failure

TABLE 2

Cathedral Tower, Peak Vibration Velocities

	Bang 101 125 N/m²	Bang 105 77 N/m²	Bang 106 115 N/m²	Bang 108 67 N/m²	Bang 109	Wind gusts up to 19 m/s (37 kn)	Wind gusts up to 28 m/s (54 kn)	Wind gusts up to 39 m/s (75 kn)	Bell ringing	Clock striking	Predominant frequencies	Cycles to $\frac{1}{4}$ amplitude (bang only)
Measurement axis	μm/s	μm/s	μm/s	μm/s	μm/s	μm/s	μm/s	μm/s	μm/s	μm/s	Hz	
North-south	690	730	1160	1040	1450	70	180	300	80	100	2·3	16
East-west			800	460	1150	90	160	300	20	50	2·3	16

TABLE 3

Nave Roof, Peak Vibration Velocities

	Bang 101 125 N/m^2	Bang 105 77 N/m^2	Bang 106 115 N/m^2	Bang 108 67 N/m^2	Bang 109	Bang 110 135 N/m^2	Wind 10 m/s average with 24 m/s gusts	Organ playing loudly	Predominant frequencies	Cycles to $\frac{1}{4}$ amplitude (bang only)
	$\mu m/s$	$\mu m/s$	$\mu m/s$	$\mu m/s$	$\mu m/s$	$\mu m/s$	$\mu m/s$	$\mu m/s$	Hz	
4th main rafter from w end, n side	2500	1700					430 (53)	374 (93)	9	6
4th main rafter from w end, s side		1400						860 (101)	9	12
Top purlin		700	2400	1100	1400			171 (49)	9 / 17	10
2nd purlin, n side				2500	600				9 / 11	9
3rd purlin, n side				1100	640				20	15
3rd purlin, s side					1700				9	10
Common rafter, n side				3000					9	10
Common rafter, s side						5900			9	13
Roof boarding, n side						3400			11	7

TABLE 4

Nave Roof, Peak Vibration Accelerations

	Bang 101 125 N/m^2	Bang 105 77 N/m^2	Bang 106 115 N/m^2	Bang 108 67 N/m^2	Bang 109	Bang 110 135 N/m^2
	mg_n	mg_n	mg_n	mg_n	mg_n	mg_n
4th main rafter from w end, n side	35	42				
4th main rafter from w end, s side		19				
Top purlin		23	45	46	18	
2nd purlin, n side				71	48	
3rd purlin, n side				75	50	
3rd purlin, s side					77	
Common rafter, n side				48		
Common rafter, s side						120
Roof boarding, n side						180

TABLE 5

Nave Ceiling, Peak Vibration Velocities

	Bang 101 125 N/m^2	Bang 105 77 N/m^2	Bang 106 115 N/m^2	Bang 108 67 N/m^2	Bang 109	Bang 110 135 N/m^2	Wind 10 m/s average with 24 m/s gusts	Man walking along cat-walk	Organ playing loudly	Predominant frequencies	Cycles to $\frac{1}{4}$ amplitude (bang only)
	μm/s	μm/s	μm/s	μm/s	μm/s	μm/s	μm/s	μm/s	μm/s	Hz	
Centre of central tie beam	2800	1950	3700	2300	2900	8000	40 (8)	500		9	7
4th tie beam from w end, n side		1100								10	16
4th tie beam from w end, s side		700								10	13
Central joist		1200	1400			3700			942 (228)	8 / 20	14
3rd joist, *n* side				2200		8300				11 / 20	15
3rd joist, *s* side						5300				9	6

TABLE 6

Nave Ceiling, Peak Vibration Accelerations

	Bang 105 77 N/m^2	Bang 106 115 N/m^2	Bang 108 67 N/m^2	Bang 110 135 N/m^2
	mg_n	mg_n	mg_n	mg_n
4th tie beam from w end, n side	21			
4th tie beam from w end, s side	34			
Central joist	21	60		75
3rd joist, n side			52	240
3rd joist, s side				80

TABLE 7

Leaded Windows, Peak Vibration Velocities

	Bang 101 125 N/m²	Bang 105 77 N/m²	Bang 106 115 N/m²	Bang 108 67 N/m²	Bang 109	Organ playing softly	Organ playing loudly	Wind wnw 10 m/s average with 15 m/s gusts	Predominant frequencies	Cycles to $\frac{1}{4}$ amplitude (bang only)
	mm/s	mm/s	mm/s	mm/s	mm/s	mm/s	mm/s	mm/s	Hz	
100 year old window	13·4	19·3	10·3	30		1·3 (0·17)	8·7 (1·3)	2·1 (0·5)	4 / 28	3
30 year old window		11·8	6·2	22	10·7	2·3 (0·25)	14·7 (2·0)	5·3 (1·0)	4 / 25	6
10 year old window		12·9	6·9	15	21·3	2·2 (0·25)	16·0 (3·4)	2·7 (0·7)	4 / 40	$5\frac{1}{2}$

TABLE 8

Leaded Windows, Peak Vibration Accelerations

	Bang 101 125 N/m²	Bang 105 77 N/m²	Bang 106 115 N/m²	Bang 108 67 N/m²	Bang 109
	mg_n	mg_n	mg_n	mg_n	mg_n
100 year old window	1200	800	1400	1600	
30 year old window		400	1200	1080	800
10 year old window		720	1400	1800	800

TABLE 9

Leaded Windows, Peak Glass Strains

		Bang 106 115 N/m²	Bang 110 135 N/m²	Bang 111	Predominant frequencies
		μ strain	μ strain	μ strain	Hz
100 year old window	edge horizontal			0·9	44
	edge vertical	3·6			
	centre horizontal	5·0			25
	centre vertical		5·0	12·0	12·5 / 20
30 year old window	centre horizontal	4·4			20
	centre vertical		4·0	6·0	33·0 / 70
10 year old window	edge horizontal			0·8	21
	centre vertical		0·2		33

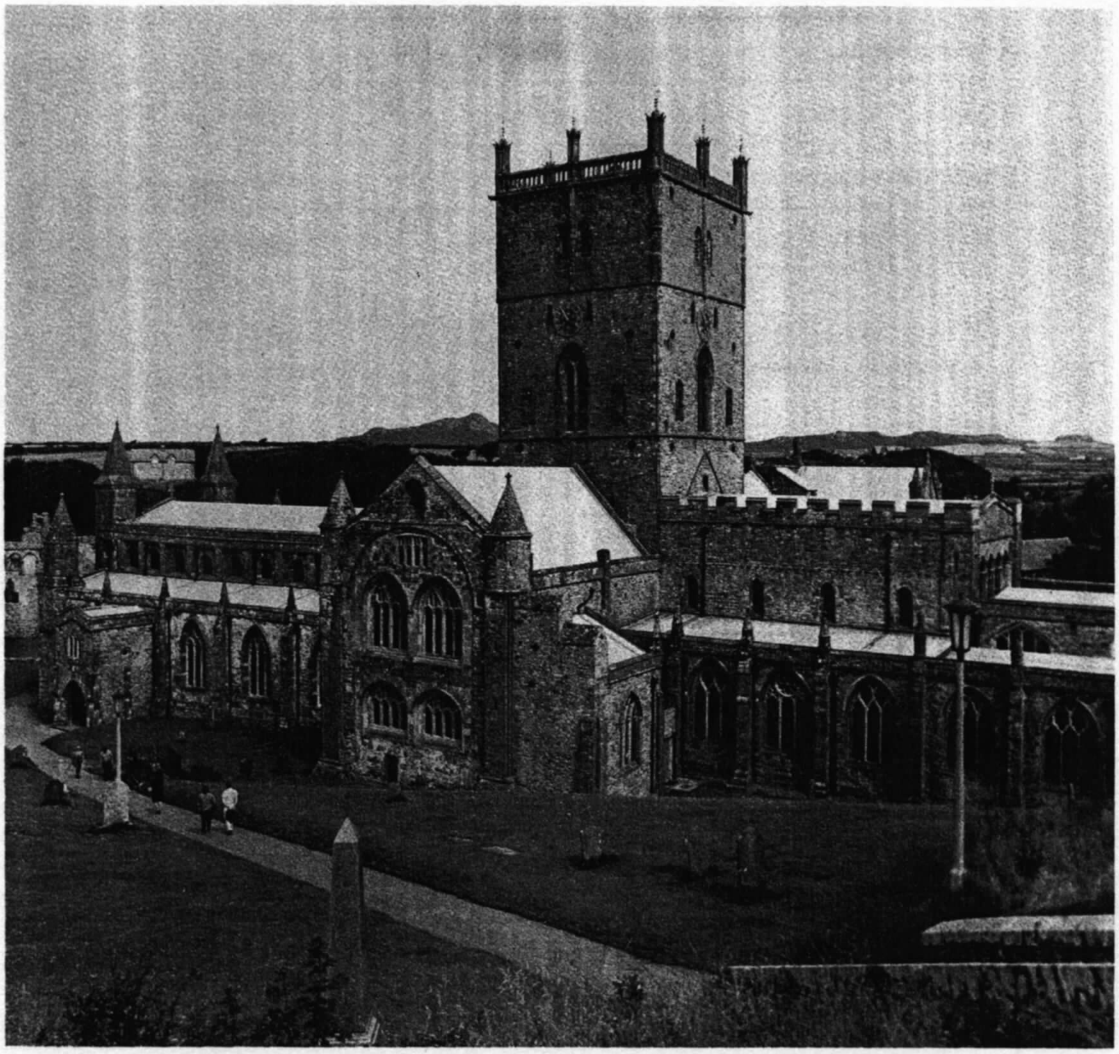

FIG. 1. St. David's Cathedral.

ST. DAVIDS CATHEDRAL

1 Font
2 Dais and Nave Altar
3 Pulpitum or Screen
4 Tomb of Bishop Henry Gower
5 Bishop's Throne
6 Parclose Screen
7 Tomb of Edmund Tudor
8 St. Davids Shrine
9 High Altar
10 Sedilia
11 Vestries
12 Abraham Stone
13 Chapel of the Holy Trinity
14 Relics of St. David
15 Chapel of St. Edward
16 Eastern Ambulatory
17 Chapel of St. Nicholas
18 St. Caradoc's Shrine
19 Thomas Tomkins' Memorial
20 Chapel of St. Andrew
21 Chapel of St. Thomas of Canterbury

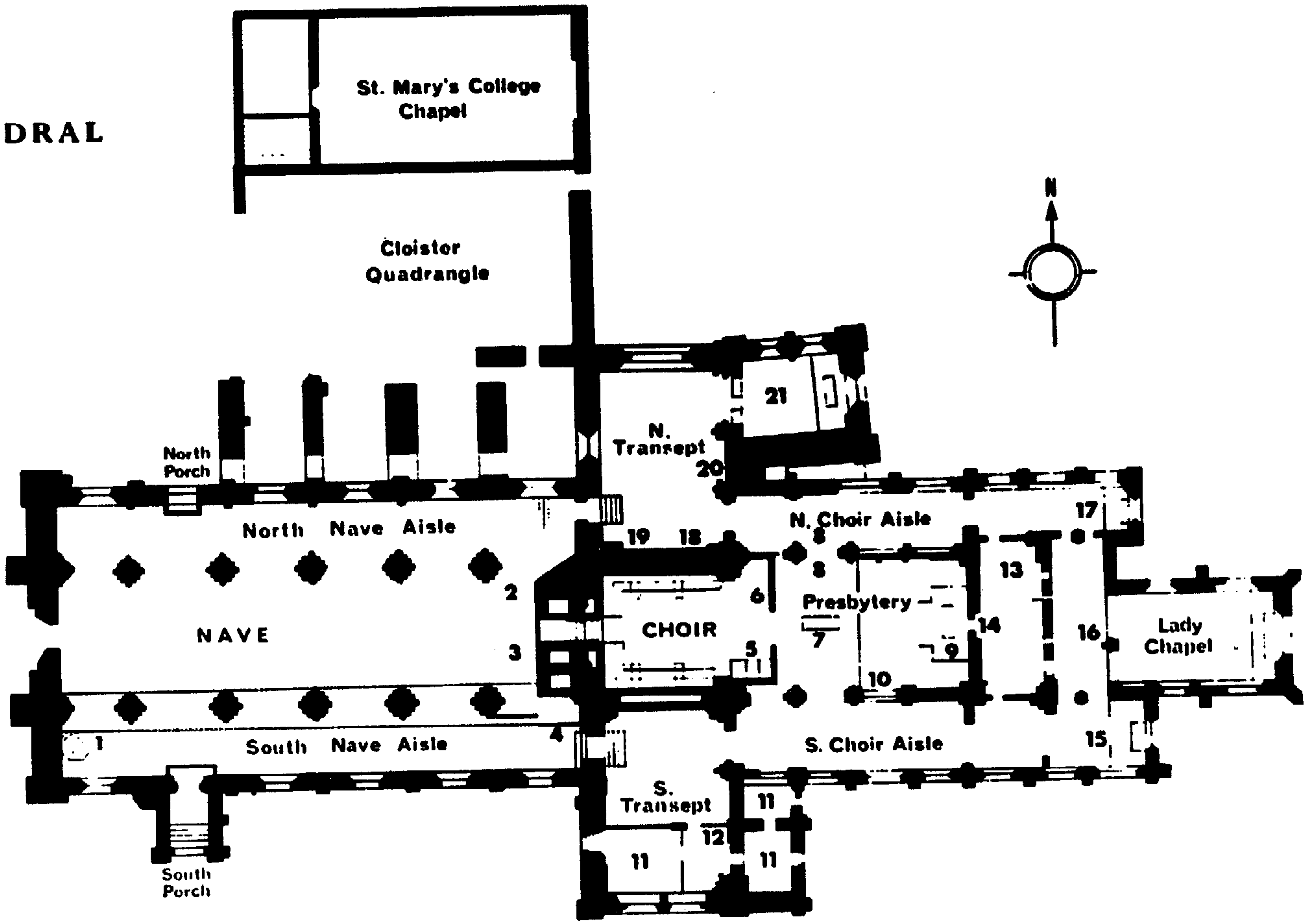

FIG. 2. Cathedral plan.

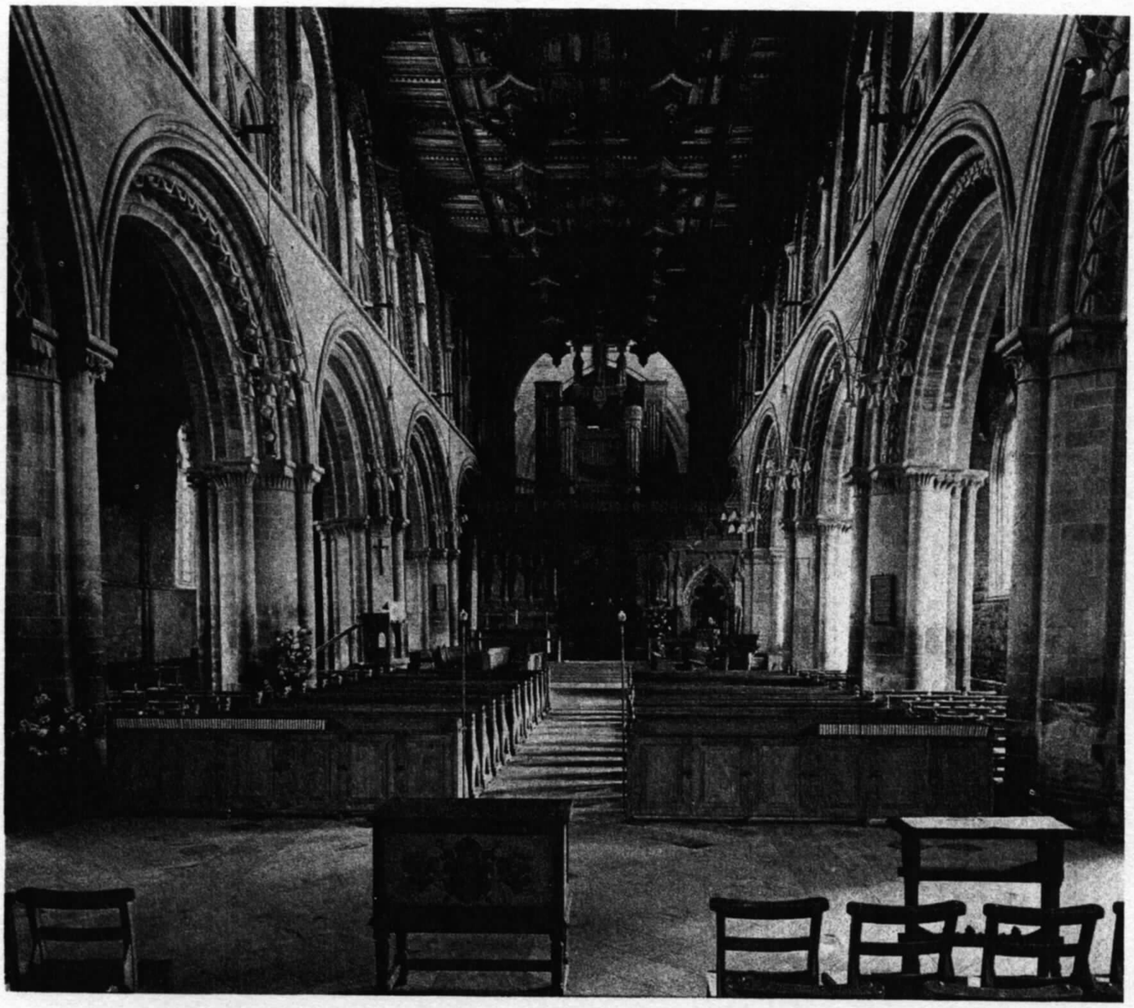

FIG. 3. Nave interior.

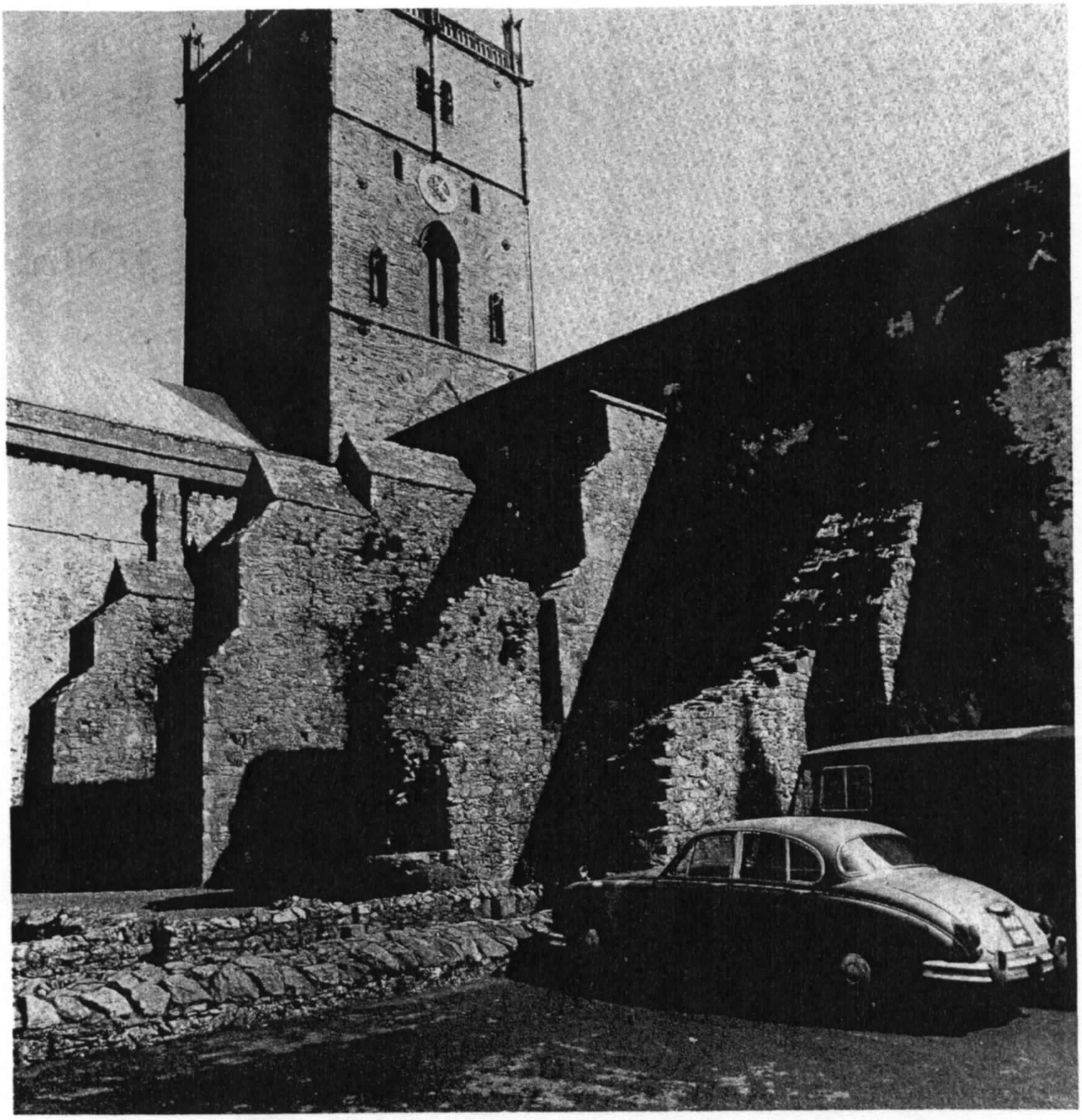

FIG. 4. Buttresses against north wall.

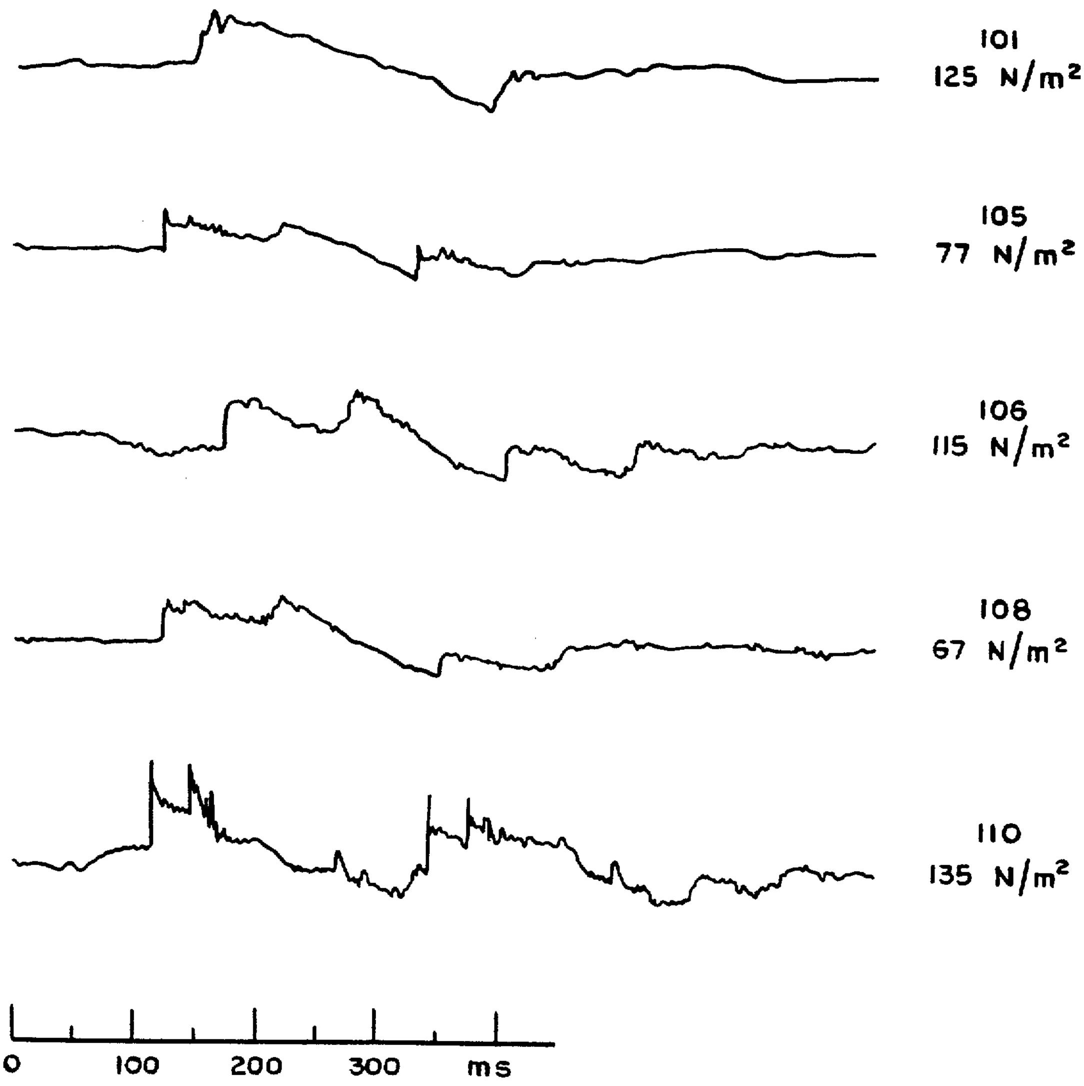

FIG. 5. Sonic bang pressure waveforms.

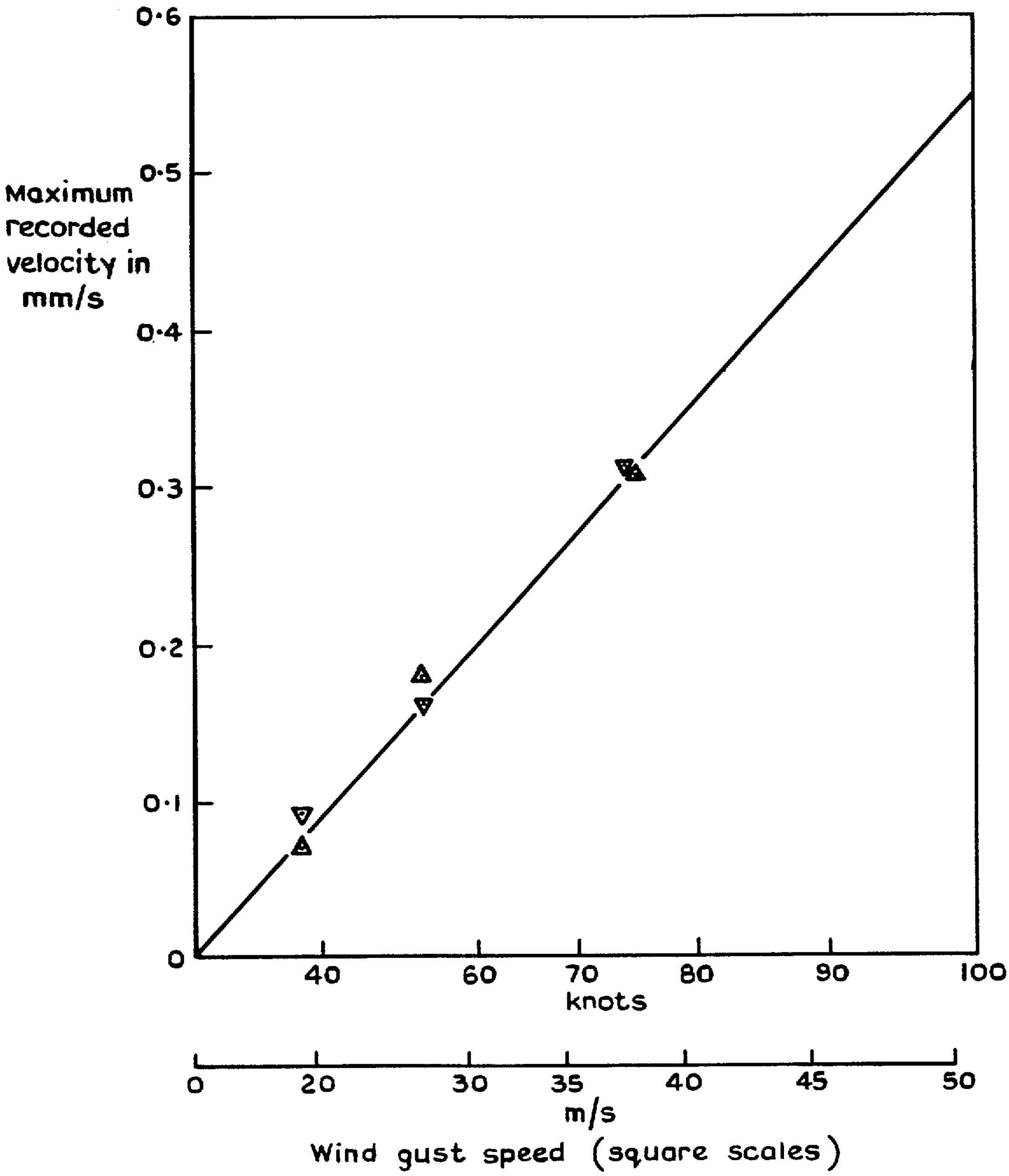

FIG. 6. Tower response.

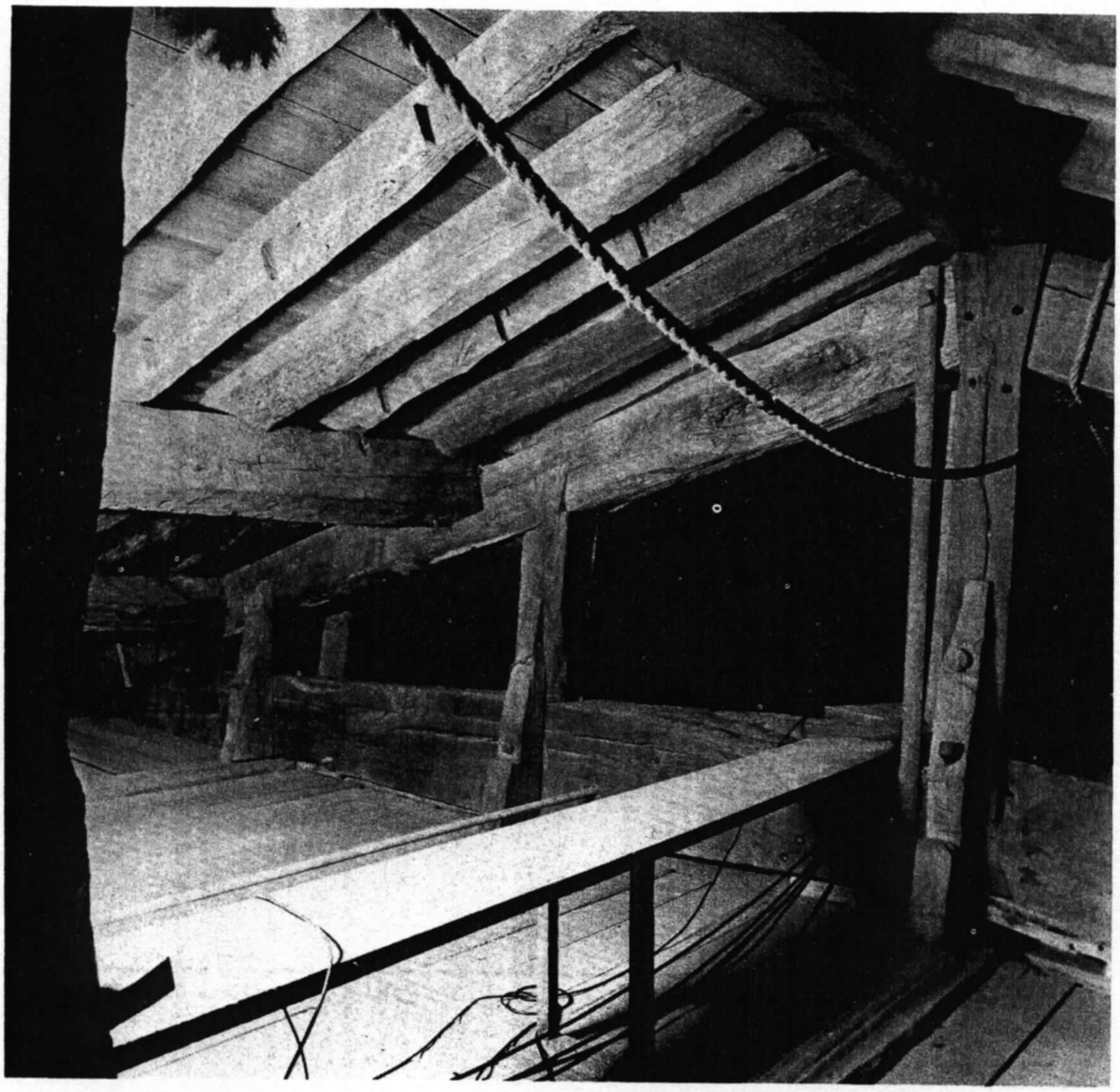

FIG. 7. Nave roof.

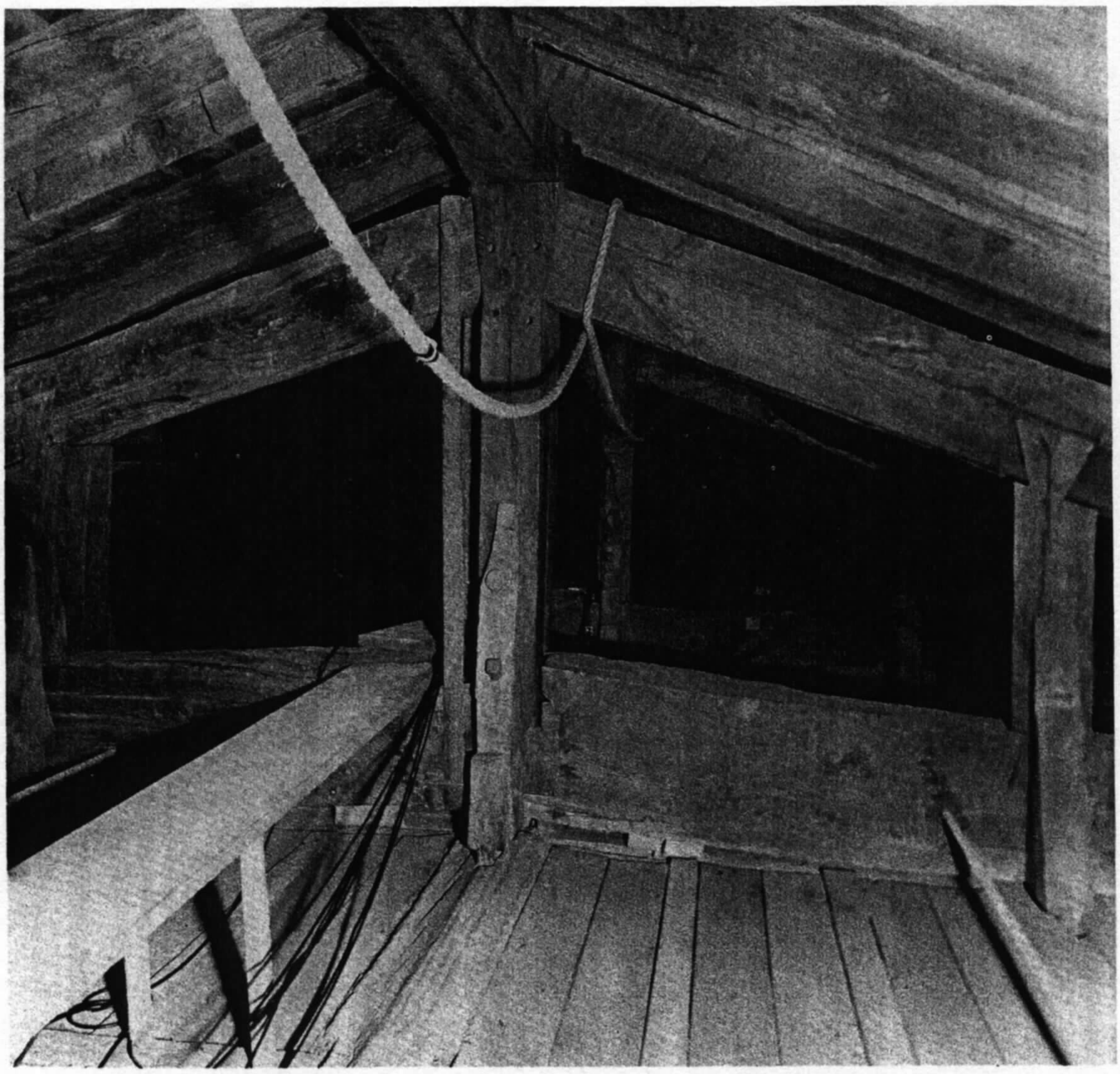

FIG. 8. Nave roof.

FIG. 9. Nave ceiling.

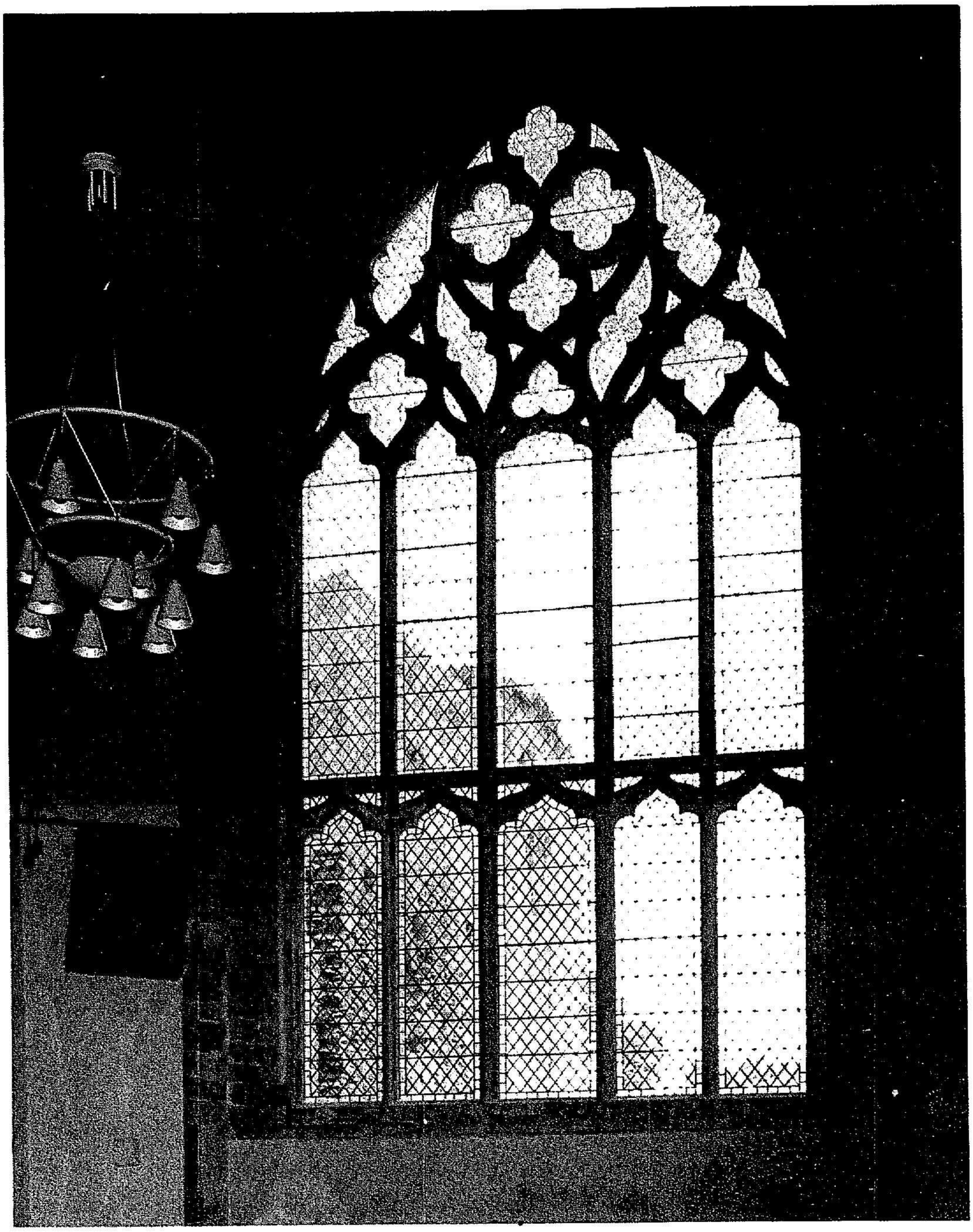

FIG. 10. Window in north transept.

Printed in England for Her Majesty's Stationery Office by J. W. Arrowsmith Ltd., Bristol BS3 2NT
Dd. 505715 K5 10/73

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