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Summary

Some leaded windows have been subjected to a series of sonic bang response tests using a specially developed explosive simulated bang. The tests covered a range of bang pressures and durations. Results show that the likelihood of damage to leaded windows by normal sonic bangs is very small.

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* Replaces R.A.E. Technical Report 69282—A.R.C. 32 663.

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1. Introduction

Some concern has been expressed regarding the safety of leaded windows, particularly stained glass windows, with the possible advent of civil supersonic flying over this country. This concern arises not only because leaded windows are more costly than plain glass windows, but also because many of them have great historical and antiquity value, and are indeed priceless and irreplaceable.

It was decided therefore to investigate the response behavior of leaded lights to the sonic bang. The information gathered from the experiment could then be used, in conjunction with a theoretical consideration of the relationship between window resonances and bang duration, to develop some criteria whereby the vulnerability of leaded lights in general could be assessed.

In order to have control over the excitation, the tests were done utilising a specially developed explosive simulation of the sonic bang, but it is expected that the results can be applied to the case of real sonic bang excitation.

2. Significance of Bang Duration in Relation to Window Natural Frequency

The amplitude of vibration of a window excited by a sonic bang must depend somewhat on the relationship between bang duration and window natural frequency. This subject is dealt with analytically by Crocker,[1] who considers the effect of an *N*-wave force input on a simple spring/mass system. It is shown that a maximum dynamic magnification factor of more than 2 can occur when the duration of the exciting waveform is about 0·87 of the system's natural period. Dynamic magnification factor is defined as, the greatest dynamic displacement normalised by the displacement produced by a static force which is equal to the peak dynamic force. Similarly, maxima of approximately 2 occur when the duration approximates a whole number multiple of the system period. However, these factors are much reduced if the damping of the system is taken into consideration when the bang duration is several times the natural period. In the case of leaded windows tested so far, natural periods of vibration are in the range 20 to 50 ms, which is short compared with the predicted approximate 300 ms duration of a Concorde sonic boom. Also, typical leaded windows have dampings which are $3\frac{1}{2}$ to 6 per cent of critical damping. At these ratios of bang duration to window period, and at these dampings, the amplitude of vibration induced by the first or bow shock of a sonic bang dies away before the arrival of the stern shock. The effect of a sonic bang on a normally constructed leaded window can therefore be considered as that which would be produced by two shocks well separated in time, and windows would not, therefore, be susceptible to any significant extra stressing such as might occur if their natural frequencies and the duration of a sonic bang were better matched.

3. Experimental Approach

Current laboratory work on the vulnerability of leaded windows to sonic bang damage attempts to correlate the likelihood of bang damage with the type of construction and state of repair of the windows. In connection with this, two types of damage are being considered and consequently both are included in this experiment. Firstly there is that which could be caused by a single bang, or a very few bangs, of sufficient intensity. This could possibly be in the form of glass breakage or isolated separation between the glass and lead components. Secondly there is a possibility that a large number of weaker bangs could produce a gradual and progressive deformation of the lead strips, resulting in a bowing of the window and loosening of the glass/lead joint, making the window less weatherproof. The bang programme for the experiment was planned so that these two effects could be studied.

4. The Simulated Sonic Bang

The pressure waveform simulating a sonic bang in these tests was produced by an explosive line charge developed by E.R.D.E.[2] Such charges are ideally suited for the generation of long duration pressure waveforms because, when observed along the charge axis, the pressure wave duration from a charge of length L must be of the order L/C where C is the speed of sound. It is thus only necessary to choose the length in order to obtain any required duration. It then remains to determine the required distribution of explosive to produce the specified shape of waveform. Three simulants have been developed by E.R.D.E. to achieve this and they were used in these tests. The nominal durations were 40 ms, 100 ms and 200 ms respectively. Their pressure waveforms are shown in Fig. 1, and these may be compared with some typical real sonic bang waveforms given in Fig. 2.

The simulant waveforms are not perfect, but they represent the best for structural response work from sonic bang simulants developed so far. One disadvantage of the simulant is that the second shock is not as good as the first for a thorough investigation into the significance of bang duration in relation to window natural frequency. Another disadvantage is the noise or ripple which is superimposed on the waveform. The noise seems to be greater when the pressure measurement point is nearer to the charge. It also varies with another unknown factor which may be an atmospheric effect.

The presence of the noise means that care must be observed when relating the measured peak pressure of the N-wave to the response of a structure. Webb and Warren[3] introduce the concept of the 'effective pressure rise' when describing the intensity of a sonic bang. The effective pressure rise is here defined as the equivalent ideal N-wave pressure rise and is obtained by extending the essentially straight, sloping line between the bow and stern shocks back to the point of onset of the bow shock. More recently, Warren[4] has suggested a more rigorous treatment of the pressure signature, arriving at essentially the same quantity and calling it 'effective overpressure'. Values of effective overpressure are shown next to the recorded peak pressure measurements in the tables of results. It is the effective overpressure which should be considered in relation to window response. Validity of this method of quoting pressure rise for this Report was confirmed by the analysis of 15 nominal 1 lb/ft^2 (48 N/m^2), 200 ms simulated sonic bang pressure recordings. Peak pressure measurements showed a coefficient of variation of 19·3 per cent, while analysis by the effective overpressure method produced a figure of 7·3 per cent.

The pressure levels quoted for the simulant are those measured by a microphone mounted near the building but sufficiently far away that the building did not greatly modify the signals received. They correspond to sonic bang pressure levels for a condition near the ground in the open, which is the condition generally used in specifying the intensity of a sonic bang.[5] On the window the initial peak pressure is doubled owing to reflection from the window itself.

5. Description of Windows

The leaded windows used in the tests are shown in Fig. 3. The windows having mainly rectangular or rhombic panes were in good condition except for a few cracks in the glass which had probably occurred in handling. The window with random-shaped panes which is shown on the left hand side of Fig. 3 was in poor condition. It had probably been exposed to weather for many years as the glass/lead joints had deteriorated to such an extent that the window rattled when tapped and it was obviously more flexible than the other windows. The plain glass window was included in the array so that its vibration response to bangs could be compared with that of the similar sized leaded window which is next to it, and so that glass stresses could be compared between these two windows.

The plain window was of 32 oz glass which is about 0·15 in (0·38 cm) thick and which would generally be used for a window of this size. In the adjacent leaded window the larger central panes were of 24 oz glass which was about 0·1 in (0·25 cm) thick, while the edge panes were of 32 oz glass.

The leaded windows were supported by steel saddle bars of 0·375 in (0·95 cm) square section. The ends of these were firmly fixed into the window frames and wired to the lead strips of the windows in the conventional manner. It was considered that saddle bars generally made a considerable contribution to the strength of leaded windows, and therefore if this contribution could be found, it would be useful. One of the saddle bars associated with the weakest window, the window on the left of Fig. 3, was therefore purposely omitted, so that the vibration of the window at that point could be compared with the vibration of the conventionally supported part of the same window.

The windows were fixed by a wood beading into a strong timber frame that was fitted into a brick building (Fig. 4) which was specially erected on a test site at R.P.E. Westcott (Fig. 5). The building protected the instrumentation associated with the tests and also ensured that the windows were subjected to the pressure wave on one side only. The explosive charge which was used to produce the sonic bang simulation was suspended from a line of steel posts which can also be seen in Fig. 5.

6. Instrumentation

Glass strains, window accelerations and displacements, and bang overpressures were measured.

Semi-conductor-type strain gauges, which have a high gauge factor, were used in conjunction with battery-powered pre-amplifiers to reduce power frequency interference at low strain levels. Half-bridge energising circuits were sufficient as only dynamic strains were required.

Window accelerations were measured by sub-miniature piezo-electric accelerometers coupled to battery-powered charge amplifiers. As the accelerometers weighed only 2·8 g, the mass could be neglected in comparison with the mass of the window.

Dynamic window displacement measurements were made with a capacitance-bridge-type, non-contacting Wayne–Kerr vibration meter. A Wayne–Kerr electronic micrometer, which operates on the same principle, was used to measure the static window displacements. Only these two channels of displacement-measuring equipment were available but they could be switched easily from one window to another.

Bang pressure waveforms were monitored by Bruel and Kjaer type 4131 one-inch capacitance microphones.[6] They were used in conjunction with frequency modulation amplifiers and the frequency range of the system was that of the microphone capsules alone. The time constant of the microphone pressure leak system had been specially increased to more than 6 seconds by the manufacturer, so that they were easily capable of following waveforms of duration 200 ms without distortion. The upper frequency limit of the microphones was about 3 kHz. Type 4134 half-inch microphones which may be used for higher pressures but which have reduced sensitivity were used with the same amplifiers for the higher intensity bangs. Microphones were calibrated with a Bruel and Kjaer Pistonphone which is easily used in the field and is an accurate sound pressure level calibrator for sensitivity adjustments.[6]

Signals from the various transducer systems were recorded on an Elliott 16-channel FM tape recorder having a 0 to 10 kHz bandwidth together with a timing signal from an oscillator for frequency comparison. The ecorded information was replayed at one eighth of recording speed on to a UV galvanometer recorder. In addition, pressure waveforms were recorded on an oscilloscope/Polaroid camera combination, so that pressure levels and waveforms could be checked instantly.

7. Programme

The programme consisted of a total of 25 bangs. In the first 10, bang intensity and duration were varied so that the effect of changes in these two parameters on the dynamic behaviour of the various types and condition of windows could be measured. Bang intensity was varied by changing the distance between the charge and the test building. The remaining 15 bangs were all of the same intensity and duration, and in this part of the programme the static displacement of the centres of the windows relative to their frames was measured after each bang, so that any evidence of bowing due to continued bang exposure could be examined.

Before the tests, the windows were carefully examined for glass cracks and the positions of these were noted.

8. Results and Observations

8.1. Strain Measurements

The positions at which glass strains were measured are shown in Fig. 6, and the measured peak strain values are shown in Fig. 7. The suffix *V* or *H* to the strain gauge position numbers indicates the orientation, vertical or horizontal, of the strain measurements axis. In Table 1, peak strain measurements have been abstracted from the general results, and averaged and normalized to an overpressure of 1 lbf/ft^2 (48 N/m^2) so that it is possible to compare strains at similar positions on the leaded and plain glass windows, for the three durations of bangs.

The table shows that strains are roughly the same at the centres of the leaded and plain glass windows, but that, at the edges, strains are much lower in the leaded window.

From this observation it might be concluded that a leaded window of this type is less likely to break than a plain window of equivalent size, when subjected to a sonic bang. This particular leaded window however is rather a special case in that the glass panes are mostly rectangular and those at the edge have a high aspect ratio. The consequent extra flexibility at the edge may account partly for the very much lower glass strains in that area in the plain glass window. It may be that in the type of leaded window having random shaped pieces of glass, glass strains would be higher than in the sample which has been tested. Further tests could be designed to discover if this were so. Also, glass fracture is not the only way in which a leaded window could fail when subjected to sonic bangs. Failure could be due to permanent deformation of the lead, showing up as bowing of the window or localized separation between glass and lead. This type of failure is dealt with in Section 8.6.

With regard to absolute values, the maximum strain that was measured on the leaded window for 200 ms bangs having an effective overpressure of about 0·7 lbf/ft^2 (34 N/m^2) was 20 micro-strain. If Young's modulus for glass is taken to be 10×10^6 lbf/in^2 (Ref. 7), this is equivalent to a stress of 200 lbf/in^2 ($0{\cdot}014 \times 10^8$ N/m^2). The bending strength of glass depends very much on composition, but the minimum figure which is quoted is for silica glass[8] which has a bending strength of about 10,000 lbf/in^2 ($0{\cdot}69 \times 10^8$ N/m^2). It has been suggested that the strength could be half of this for ancient glass or for glass which has been stressed for a long period. Nevertheless in this test, it would appear that the bang intensity could be increased by a large factor before glass breakage would be expected in this type of window.

8.2. Acceleration Measurements

The positions at which window accelerations were measured are shown in Fig. 8 and the peak accelerations calculated from the recordings are shown in Fig. 9. As was stated in Section 4, pressures entered in the tables of results correspond to sonic bang pressures for a condition near the ground in the open. Where structural acceleration measurements are being made, high frequency components of the exciting force contribute largely to the response of the structure. It is therefore important to note that the high frequency components of the bang pressure wave, i.e. the initial peak pressure, would be doubled in amplitude at the window surface because the wavelength of such components would be small compared to the size of the building.

Window accelerations have been measured in this experiment so that they can be compared with similar measurements made in other experiments. For instance, Crawford[9] has measured cathedral window accelerations which have been caused by the cathedral noise environment such as organ playing, bell ringing, traffic etc. The measurements made here therefore will be of value in comparing the window vibration produced by such noise environments with that produced by sonic bangs for damage probability assessment.

It was seen from analysis of the records that the accelerometers had, as expected, responded mainly to the high frequency components of the excitation, namely the initial peak pressure rise, and the recordings could not be used for substantiating the low frequency vibration amplitudes measured with the displacement gauges. The existence of these high frequency components is an interesting feature of the measurements and they may be themselves an important factor in the development of fatigue damage of a window structure excited by a sonic bang. In this connection therefore laboratory fatigue tests on leaded windows should aim at demonstrating the relative damage effects of high and low frequency vibration.

8.3. Dynamic Displacement Measurements

The positions of the window displacement transducers are shown in Fig. 10. In Fig. 11 are shown the peak displacements measured, the frequency of vibration of the windows and the percentage of critical damping estimated from the decaying window response. Only one channel was available for displacement measurements, and because of variations in the bang waveform, vibration amplitude comparisons between the various types of windows cannot be made as accurately as multi-channel recordings would allow. Nevertheless it is possible to obtain from these few results a feel for the order of displacement expected of leaded windows subjected to sonic bangs.

To a limited extent the effects of the three durations of bangs on a particular window (displacement transducer position 2c) can be compared with each other and with Crocker's theoretical dynamic magnification factor based on the positive duration measured from the pressure recording. In Table 2, initial peak window displacements (called 'greatest maximum during N-wave' by Crocker) have been abstracted from the general results, and averaged and normalized to a 1 lbf/ft^2 (48 N/m^2) bang pressure. The duration of the positive phase of the N-wave has been measured from the oscillograph pressure records in Fig. 1, and the natural frequency of vibration of the windows estimated from the bang response recordings.

From this table it appears that the displacement is more nearly proportional to $f\tau$ (or to the duration of the N-wave) than to the dynamic magnification factor. This clearly cannot be generally true, otherwise an infinitely long N-wave (or step function of pressure) would produce infinite amplitude. Therefore this table cannot be used for linear extrapolation to predict the effect of a 300 ms Concorde bang on these windows. If, however we fit Crocker's 'greatest maximum during N-wave' curve to the displacement due to the 200 ms bang, then we can extrapolate on the curve to show that a 300 ms 1 lbf/ft^2 (48 N/m^2) bang would produce a peak displacement of 0·047 in (0·12 cm). This is the worst case, and if a Crocker curve were fitted to either of the other two bang durations, then it could be shown that the deflection due to a Concorde-type bang would be much less than this. Two reasons why the displacements produced by the three durations of bangs do not bear a closer relationship with the theoretical dynamic magnification factor can be suggested. Firstly, the simulated sonic bang pressure waveforms may not be sufficiently similar to each other or to the idealized N. Secondly, as will be shown in Section 8.6, leaded windows exhibit a high degree of Coulomb damping and the peak amplitude excited by the bang would depend on the window's 'at rest' position before the bang. This effect would tend to be averaged out if a larger number of measurement samples were taken.

In the case of the 100 ms and 200 ms bangs there is no evidence from the recorded vibrations of the windows to show that negative displacement peaks, termed 'greatest minimum during *N*-wave' by Crocker, are any larger than the initial or positive displacement peaks shown in the tables of results. This is probably due to the high inherent damping of leaded windows. Analysis of one of the bang recordings showed that a 40 ms bang produced a negative displacement peak which was slightly larger than the positive peak on a window whose natural period was close to the bang duration, which is the case where the dynamic magnification is theoretically greatest. This was not considered worth pursuing however, as the pressure waveform of the 40 ms bang in particular is very far from the ideal *N*.

Little can be said about the effects of the bangs on windows of different sizes and conditions in relation to Crocker's theory, as the windows would naturally have different static stiffnesses and the effect of static loading on the windows has not been measured. It is hoped to do static stiffness tests on leaded windows in the laboratory.

8.4. Effect of Saddle Bars

Leaded windows are generally stiffened by being wired to regularly spaced metal saddle bars which are themselves attached to the window frame. When the windows were installed for the purposes of these tests, they were attached to $\frac{3}{8}$ in (0·95 cm) thick square section saddle bars which were firmly wedged in the wooden framework. This is the minimum stiffening that would be expected in practice. To find out what contribution the saddle bars made to the stiffness of the window, a bar was removed at position 4 (Fig. 10). A comparison between the deflection caused by the bang at that point and the deflection at position 5 on the same window where the bar was retained showed that removal of the bar caused the deflection to be doubled. It would therefore obviously be necessary to ensure that the fixings of the bars and the wire attachments are maintained in good condition if the risk of damage is to be minimised.

8.5. Effect of Wind

It was fortunate that, during these tests, at least one very windy day was experienced. It enabled the window vibration due to the simulated sonic bang to be compared with that due to wind. At measurement position 4 for instance, a 200 ms bang produced an average peak deflection of 0·027 in (0·069 cm) per 1 lbf/ft^2 (48 N/m^2) effective overpressure, whereas the wind, which was estimated to be gusting up to 40 knots (21 m/s) produced a maximum deflection of 0·012 in (0·030 cm). In connection with this it should be remembered that, while the vibration due to a bang would be over in a fraction of a second, that caused by the wind would continue for as long as the wind lasted.

8.6. Effect of Repeated Bangs

It had been suggested that a large number of sonic bangs might result in a permanent deflection or bowing of a leaded window, thus spoiling its appearance and perhaps even reducing its mechanical strength and weatherproof quality.

An electronic micrometer was therefore fixed to the window frames and the static displacement of the centre of the window from an arbitrary position relative to the frame was measured after each bang (bangs 5 to 25). The bangs were mostly 200 ms and a nominal 1 lbf/ft^2 (48 N/m^2), but bangs 5 to 10 were of higher intensity as shown in the tables of vibration results (Figs. 7, 9 and 11). Measurements were made at the same transducer positions (Fig. 10) as for the dynamic displacement tests.

The results are shown in Figs. 12 to 16. The points are the positions in which the window settles after it has finished vibrating. Where two unconnected points are shown in the same vertical line it indicates that there had been a temporary halt in the bang programme, and the displacements were then measured again immediately before the next bang. What must be looked for in the results is an upward or downward trend in the points, indicating a progressive displacement of a window or 'creep'. No such trend appears on the scale used for the diagrams and if there is any trend it is obviously very small compared to the scatter of the points.

The scatter could be due either to (a) random inaccuracy of the instrumentation or measuring technique, (b) inherent friction or plasticity in the lead and glass assembly of a window, (c) looseness between a window and its frame or (d) random movement of the timber framing produced by weather or the bangs. There is a curious similarity of scatter pattern between measurements made at positions 4 and 5 (Figs. 15 and 16). Since these positions are on the same window, scatter is more likely to be due to window or frame behaviour than to inaccuracies of the measurement method. There is also some pattern similarity between positions 1 and 2 (Figs. 12 and 13), one of which is on the plain glass window, therefore the scatter cannot be caused simply by the properties of a lead and glass structure or to looseness of the window in its frame. Only the inadequacy of the supporting timbers is left, and it is significant that windows having displacement transducers 1 and 2 are separated by a common timber which may have moved slightly with each bang.

Before the commencement of the experiment it was not known what the order of creep might be. These preliminary results show that the creep is so small that if it is to be investigated further, the method of supporting the window specimen and the displacement gauge must be much more sophisticated than has here been used.

The test could be supplemented by the use of a shock-tube-type of bang simulator such as Blunderbuss[10] in which a very large number of bangs, of correct pressure although not of correct sonic bang duration as yet, can be produced easily and quickly under laboratory conditions.

At the conclusion of these tests the windows were again inspected for damage. No further cracks had appeared and it was considered that the condition of the windows was as good as when the tests commenced.

9. Conclusions

The windows described in this Report have been subjected to a total of 25 explosive simulated sonic bangs, the maximum overpressure being 5·0 $\mathrm{lbf/ft^2}$ (240 $\mathrm{N/m^2}$). The windows, one of which was in poor condition before the tests, were in no way damaged by the bangs. Tests showed that bangs caused lower strains in the glass of a leaded window than in a plain glass window of the same size. After subjecting them to 25 bangs, the windows did not appear to have suffered any cumulative and permanent distortion. The latter effect requires to be investigated further however, and will require a prolonged and very searching test.

The windows were found to have high inherent damping. It follows that their susceptibility to extra damage due to coincidence effects between typical sonic bang durations and window natural period is very low.

It is suspected that the vulnerability of a leaded window to sonic bang damage can increase if the condition of the saddle bars and attachment wires is neglected.

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TABLE 1
Comparison of Micro-Strain

	Window centre				Window edge			
	Horizontal		Vertical		Horizontal		Vertical	
Gauge position	2*H*	6*H*	1*V*	5*V*	3*H*	7*H*	4*V*	8*V*
Leaded or plain	*L*	*P*	*L*	*P*	*L*	*P*	*L*	*P*
Bang duration 40 ms	16	24	9·6	8·2	1·2	9·6	3·8	13
Bang duration 100 ms					0·9	11		
Bang duration 200 ms	31	34	12	11	3·1	23	4·7	15

TABLE 2

Nominal bang duration (ms)	Duration of positive phase τ (s)	Natural frequency f (Hz)	$f\tau$	Dynamic magnification factor	Measured displacement (in)	Measured displacement (cm)
40	0·025	18	0·45	1·1	0·011	0·028
100	0·034	18	0·61	1·3	0·018	0·046
200	0·080	18	1·45	1·65	0·043	0·112

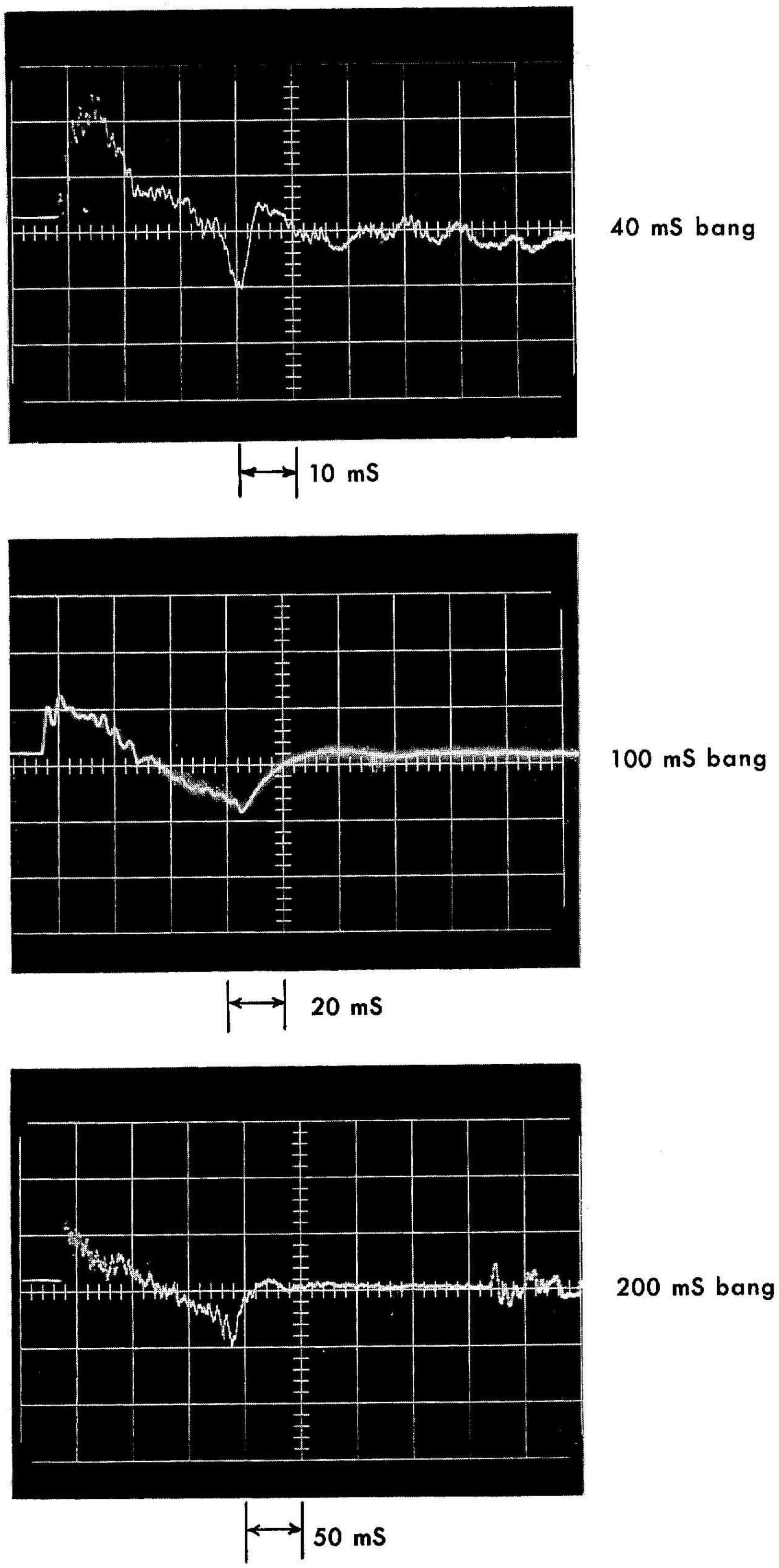

FIG. 1. Simulated sonic bang waveforms.

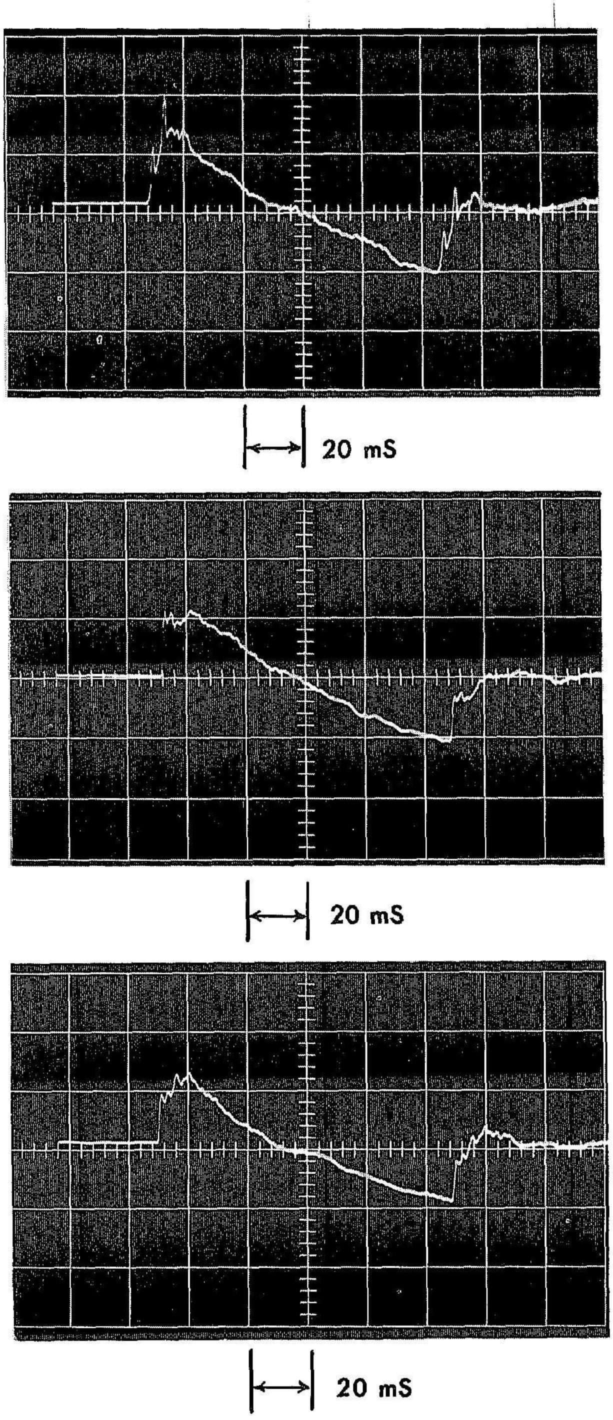

FIG. 2. Real sonic bang waveforms.

FIG. 3. The leaded window array.

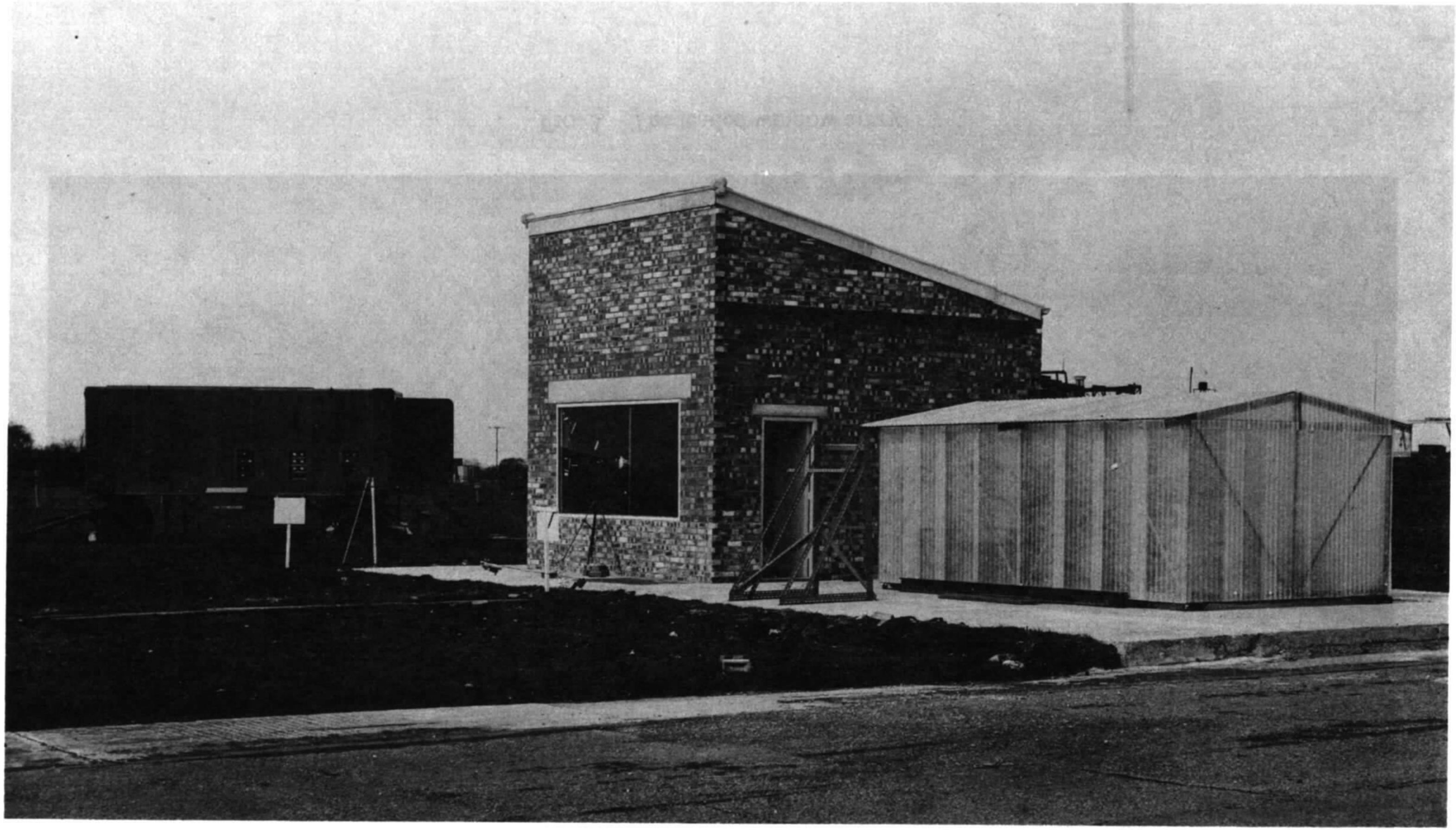

FIG. 4. The test building.

FIG. 5. The test site.

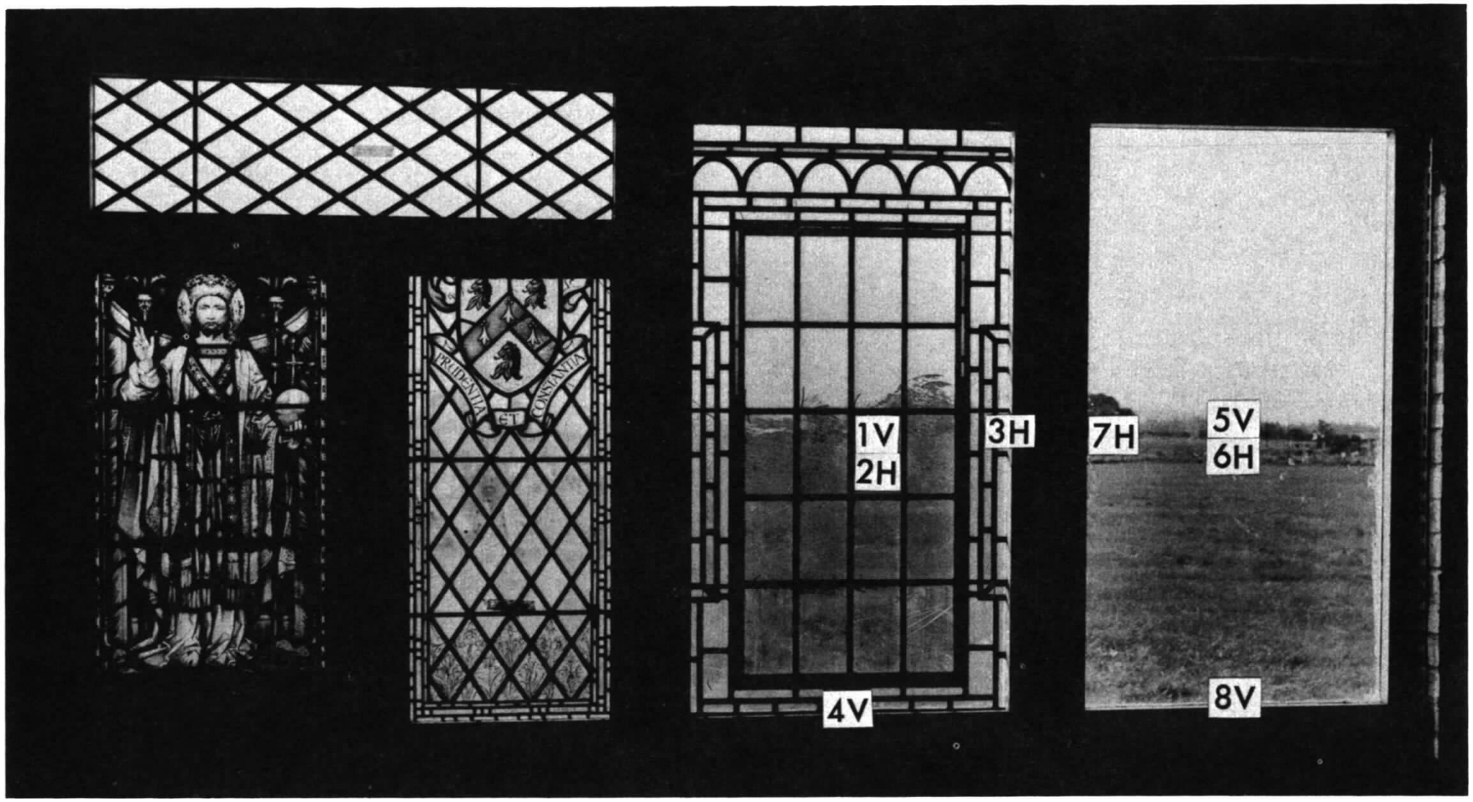

FIG. 6. Strain gauge positions.

Bang No	Nominal bang duration ms	Nominal peak pressure		Measured peak pressure		Effective overpressure *		Strain gauge position							
								1V	2H	3H	4V	5V	6H	7H	8V
		lbf/ft^2	N/m^2	lbf/ft^2	N/m^2	lbf/ft^2	N/m^2	Peak strain x 10^6							
1	100	1·0	48	1·2	58	1·16	56			1		8	20	12	8
2	40	1·0	48	1·6	77	1·64	79			2		12	40		21
3	200	1·0	48	1·3	62	0·72	35			1		8	20	12	10
4	40	1·0	48	1·6	77	1·76	84			3		16	40		24
5	100	2·0	96	2·4	115	2·08	100			2			32	24	16
6	200	2·0	96	3·0	144	1·04	50			2			40	24	16
7	200	3·0	144	3·2	153	1·20	58			2			32	16	13
8	200	4·0	192	4·0	192	1·20	58			2				35	
9	200	4·0	192	3·4	163	1·52	73	16	40	2	9			32	
10	40	4·0	192	5·0	239	5·00	239	48	80	5	19			48	
11	200	1·0	48	1·8	86	0·72	35	10	20	4	8			18	
12	200	1·0	48	2·0	96	0·60	29	8	16	2	6			16	
13	200	1·0	48	1·6	77	0·68	33	6	20	2	6			16	
14	200	1·0	48					8	16	2	4			14	
15	200	1·0	48	1·8	86	0·68	33	8	20	2	4			14	
16	200	1·0	48	2·0	96	0·68	33	8	20	2	4			17	
17	200	1·0	48	1·3	62	0·72	35	8	16	2	3			16	
18	200	1·0	48	1·6	77	0·60	29	8	16	2	3			16	
19	200	1·0	48	1·2	58	0·60	29	8	16	1	2			13	
20	200	1·0	48	1·2	58	0·60	29	8	20	2	3			16	
21	200	1·0	48	1·4	67	0·60	29	8	20	2	1			12	
22	200	1·0	48	1·5	72	0·64	31	8	20	2	1			14	
23	200	1·0	48	1·2	58	0·72	35	8	20	2	1			16	
24	200	1·0	48	1·2	58	0·64	31	8	20	2	3			16	
25	200	1·0	48	1·2	58	0·68	33	8	20	2	2			16	

* See section 4

FIG. 7. Leaded and plain window peak strains.

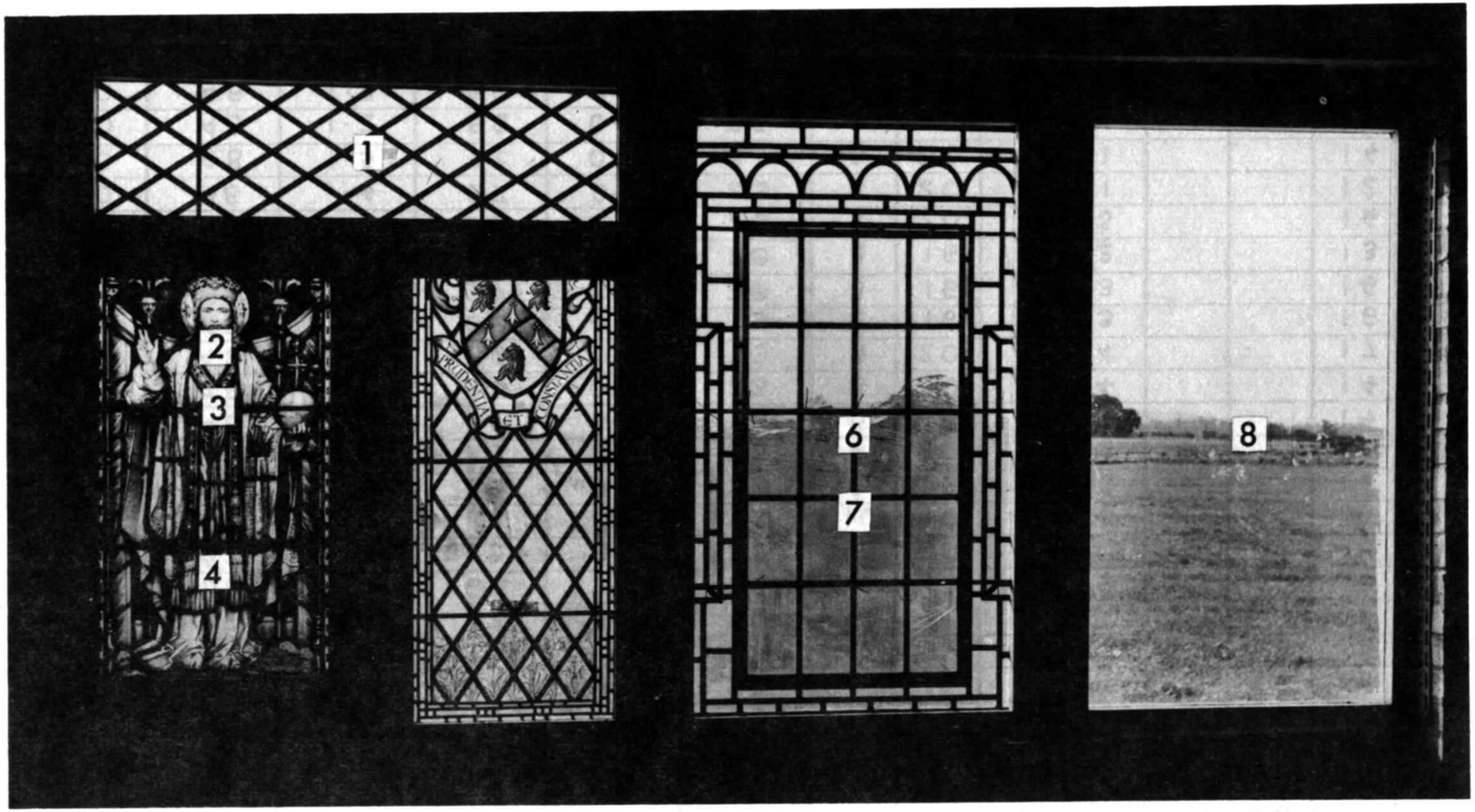

FIG. 8. Accelerometer positions.

Bang No	Nominal bang duration ms	Nominal peak pressure		Measured peak pressure		Effective ✻ overpressure		Accelerometer position						
								1	2	3	4	6	7	8
		lbf/ft^2	N/m^2	lbf/ft^2	N/m^2	lbf/ft^2	N/m^2	Peak acceleration in g units						
1	100	1·0	48	1·2	58	1·16	56		0·9	0·9	1·4		1·6	2·0
2	40	1·0	48	1·6	77	1·64	79		0·9	2·0	1·8		2·0	3·4
3	200	1·0	48	1·3	62	0·72	35		0·9	0·9	1·4		2·4	2·0
4	40	1·0	48	1·6	77	1·76	84	0·9	0·8	1·6	1·6	1·2	1·6	3·6
5	100	2·0	96	2·4	115	2·08	100	2·8	1·6	1·6	1·6	1·9	1·6	3·2
6	200	2·0	96	3·0	144	1·04	50	1·9	1·9	1·6	2·2	2·4	2·8	3·2
7	200	3·0	144	3·2	153	1·20	58	2·9	1·9	1·9	1·9	2·6	1·3	3·5
8	200	4·0	192	4·0	192	1·20	58	3·2	2·6	2·6	3·2	3·2		4·8
9	200	4·0	192	3·4	163	1·52	73	3·2	3·2	2·4	2·4	4·0	4·8	4·0
10	40	4·0	192	5·0	239	5·00	239	3·2	1·9	3·2	3·2	3·5	6·4	
11	200	1·0	48	1·8	86	0·72	35	1·6	1·2	1·6	1·6	2·5	2·4	4·0
12	200	1·0	48	2·0	96	0·60	29	1·2	1·2	1·6	1·6	1·6	1·6	4·0
13	200	1·0	48	1·6	77	0·68	33	1·2	1·4	1·6	1·6	1·6	1·2	4·0
14	200	1·0	48					1·2	0·9	0·8	1·4	1·6	1·3	3·2
15	200	1·0	48	1·8	86	0·68	33	1·6	1·6	1·6	2·0	3·4	3·2	4·0
16	200	1·0	48	2·0	96	0·68	33	2·4	1·6	2·4	2·4	3·2	2·6	4·0
17	200	1·0	48	1·3	62	0·72	35	1·6	1·2	1·4	1·4	1·8	2·4	1·9
18	200	1·0	48	1·6	77	0·60	29	1·2	0·8	0·8	1·2	2·4	2·4	2·4
19	200	1·0	48	1·2	58	0·60	29	0·8	0·8	1·2	1·2	3·2	3·6	3·2
20	200	1·0	48	1·2	58	0·60	29	1·6	1·6	1·2	1·6	2·5	3·2	2·5
21	200	1·0	48	1·4	67	0·60	29	1·4	0·8	0·8	1·4	1·4	1·4	1·6
22	200	1·0	48	1·5	72	0·64	31	1·0	1·0	1·3	1·6	1·8	2·0	2·9
23	200	1·0	48	1·2	58	0·72	35	0·8	0·8	0·9	1·4	2·0	2·0	2·4
24	200	1·0	48	1·2	58	0·64	31	0·8	0·8	1·2	1·3	1·4	2·4	1·6
25	200	1·0	48	1·2	58	0·68	33	0·8	0·8	1·0	1·0	1·6	2·4	3·2

✻ See section 4

FIG. 9. Leaded window peak accelerations.

FIG. 10. Displacement transducer positions.

Bang No	Nominal bang duration ms	Nominal peak pressure		Measured peak pressure		Effective overpressure *		Measurement position	Peak displacement		Percentage of critical damping	Resonant frequency Hz
		lbf/ft²	N/m²	lbf/ft²	N/m²	lbf/ft²	N/m²		in	cm		
1	100	1·0	48	1·2	58	1·16	56	1	0·023	0·058	2	28
2	40	1·0	48	1·6	77	1·64	79					
3	200	1·0	48	1·3	62	0·72	35	2C	0·037	0·094	6	18
4	40	1·0	48	1·6	77	1·76	84	2C	0·019	0·048	6	18
5	100	2·0	96	2·4	115	2·08	100	2C	0·037	0·094	6	18
6	200	2·0	96	3·0	144	1·04	50	2C	0·03	0·076	6	18
7	200	3·0	144	3·2	153	1·20	58					
8	200	4·0	192	4·0	192	1·20	58					
9	200	4·0	192	3·4	163	1·52	73	4	0·037	0·094	5½	26
10	40	4·0	192	5·0	239	5·00	239	4			5½	26
11	200	1·0	48	1·8	86	0·72	35	4	0·019	0·048	5½	26
12	200	1·0	48	2·0	96	0·60	29	4	0·019	0·048	5½	26
13	200	1·0	48	1·6	77	0·68	33	5	0·009	0·023	4	26
14	200	1·0	48					5	0·009	0·023	4	26
15	200	1·0	48	1·8	86	0·68	33	3	0·006	0·015	3½	32
16	200	1·0	48	2·0	96	0·68	33	2C			6	18
17	200	1·0	48	1·3	62	0·72	35	2C			6	18
18	200	1·0	48	1·6	77	0·60	29	2C	0·03	0·076	6	18
19	200	1·0	48	1·2	58	0·60	29	2L	0·002	0·005	6½	18
20	200	1·0	48	1·2	58	0·60	29	2R	0·008	0·020	6	18
21	200	1·0	48	1·4	67	0·60	29	2R	0·007	0·018	6	18
22	200	1·0	48	1·5	72	0·64	31	2R	0·007	0·018	6	18
23	200	1·0	48	1·2	58	0·72	35	2R	0·007	0·018	6	18
24	200	1·0	48	1·2	58	0·64	31	3	0·004	0·010	3½	32
25	200	1·0	48	1·2	58	0·68	33	3	0·004	0·010	3½	32

* See section 4

FIG. 11. Leaded and plain window dynamic displacements.

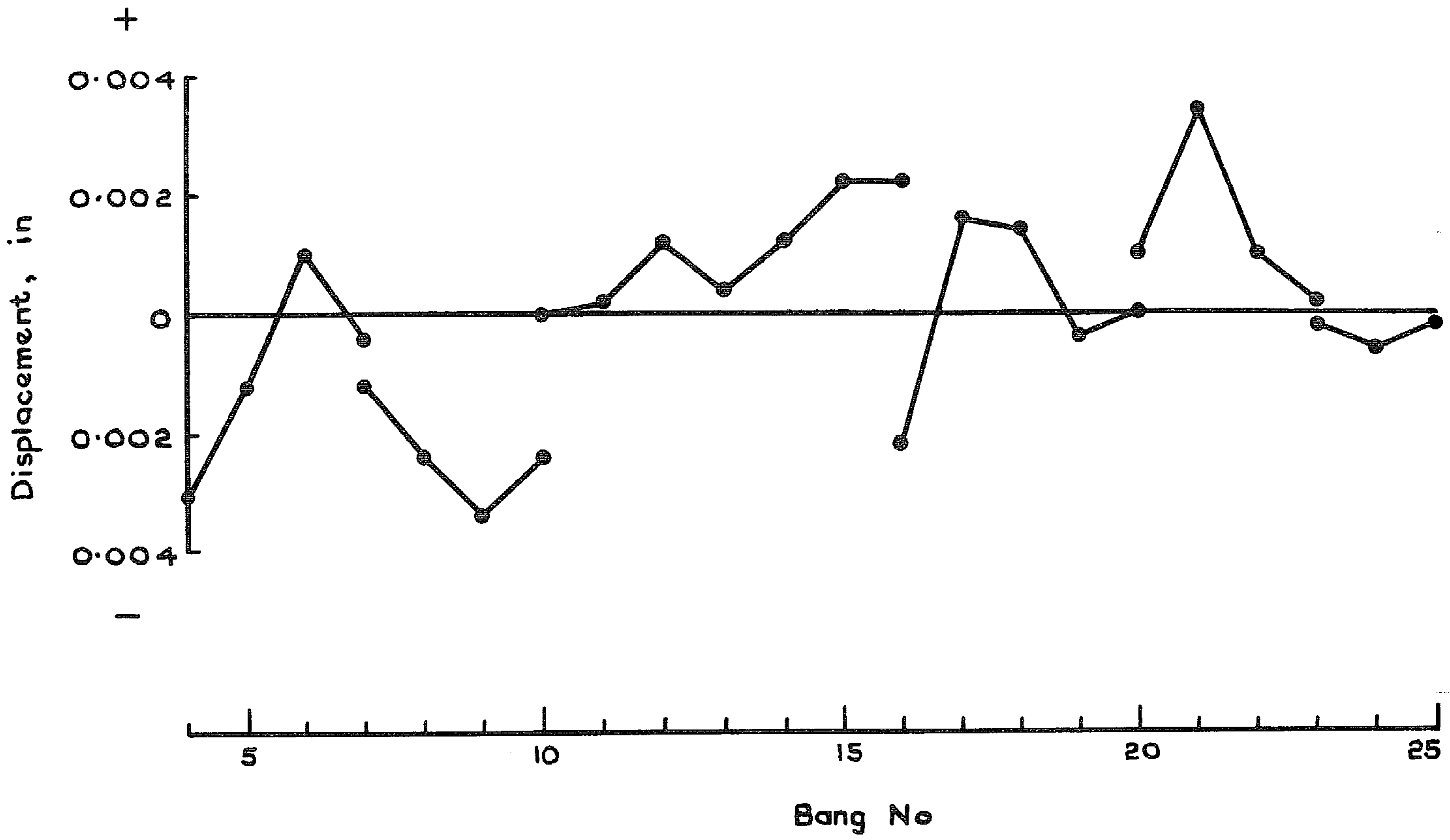

FIG. 12. Static displacement, position 1.

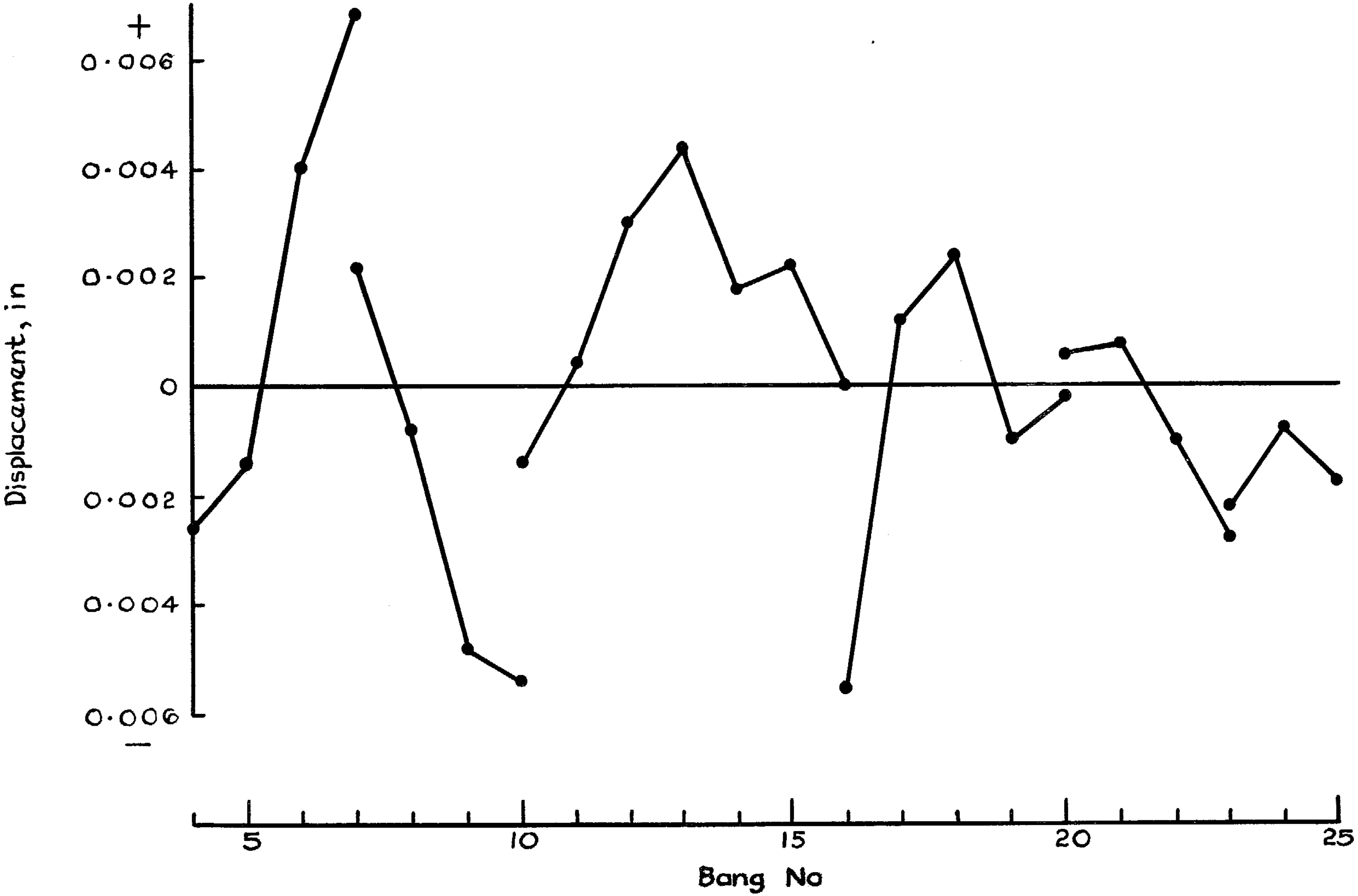

FIG. 13. Static displacement, position 2c.

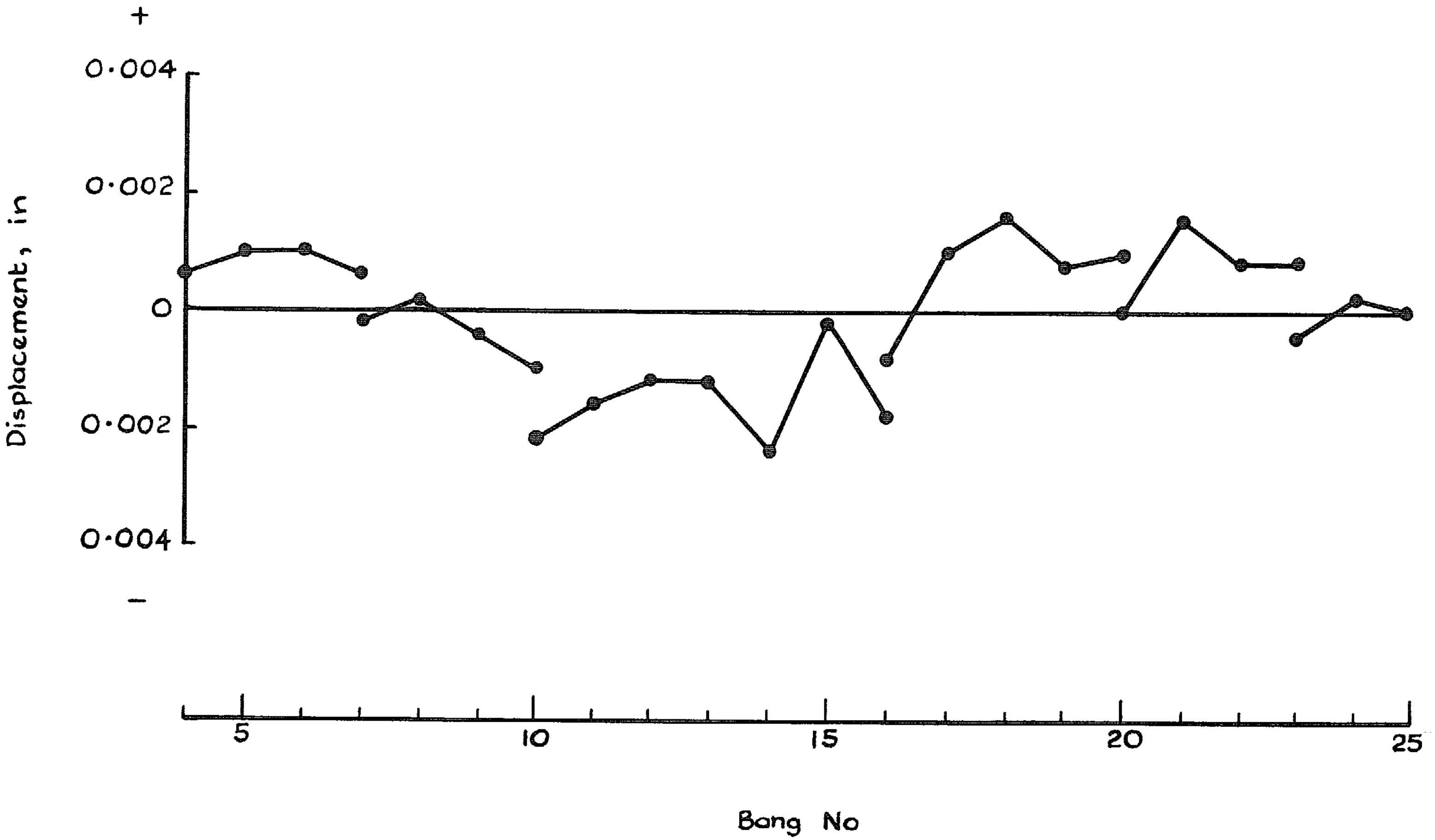

FIG. 14. Static displacement, position 3.

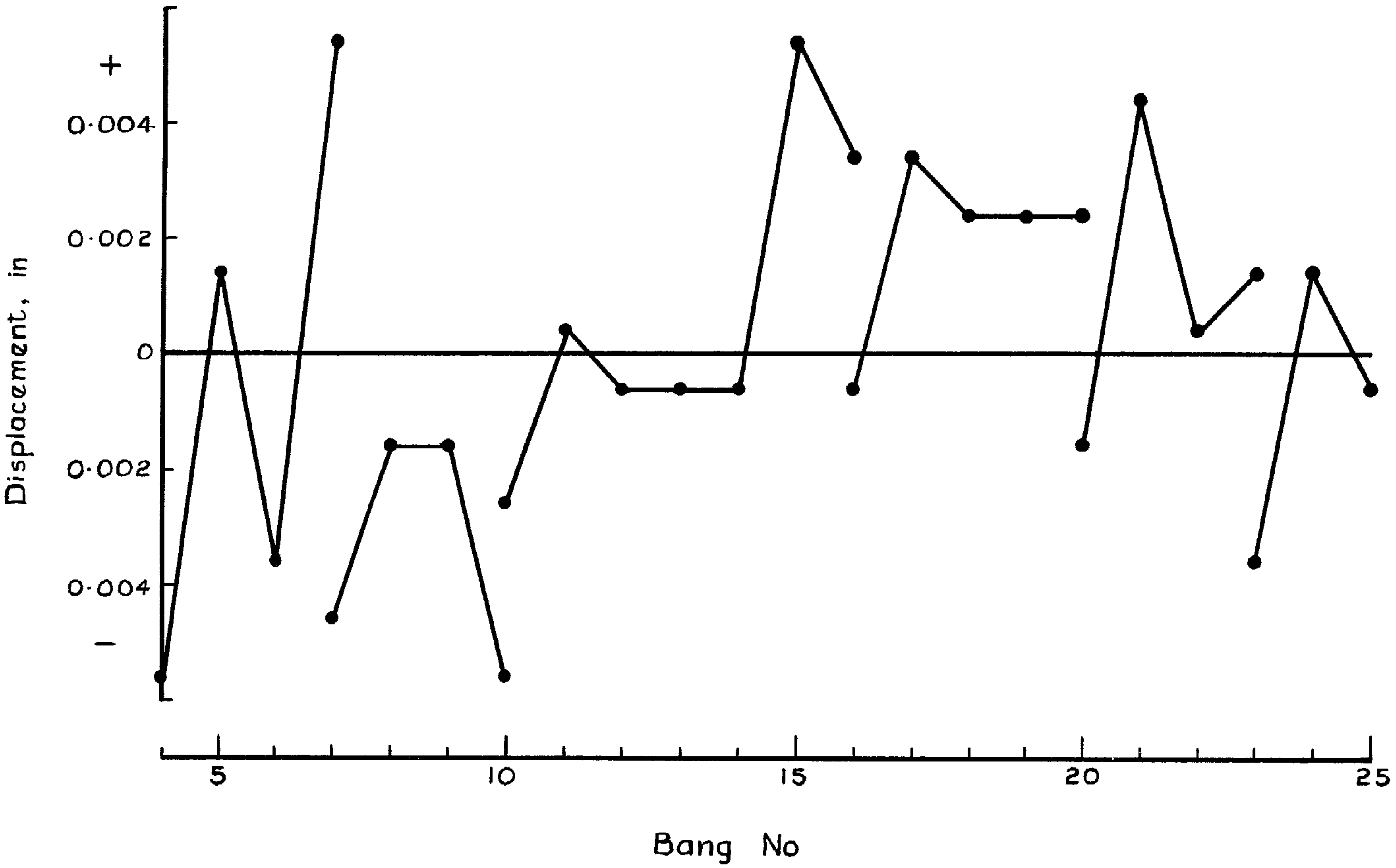

FIG. 15. Static displacement, position 4.

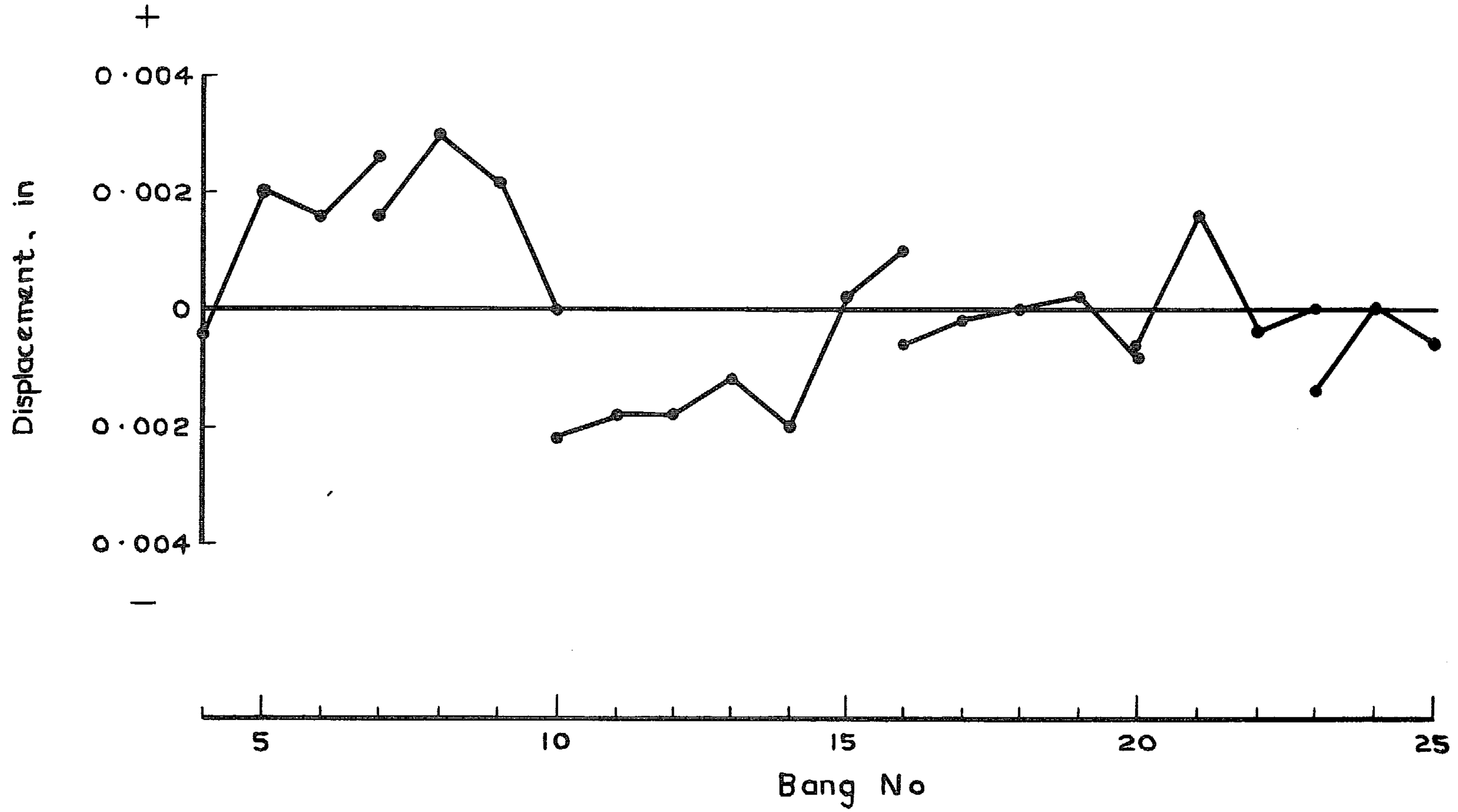

FIG. 16. Static displacement, position 5.

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