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Blasting Vibrations and Building Damage

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Building vibration and building damage resulting from blasting operations were studied in a series of experiments on expendable buildings. Sixty charges ranging from 0·3 lb to 1 600 lb were set off at distances of 3ft to 300ft from the buildings under study. For this range the primary evidence of damage was in basement walls. Observations were made of vibration displacement, velocity, acceleration and strain of the building structures. The results supported previous conclusions that particle velocity is the most useful indicator of the onset of damage.

THE relation between blasting operations and building damage is often a subject of argument when blasting is done in the vicinity of buildings. Until recently, however, there has been a dearth of published information relating conditions of blasting to reliably documented damage. Accordingly it was decided a few years ago that a systematic study should be made, using carefully controlled blasting in the vicinity of expendable buildings. An earlier paper[1] described experiments made in the St. Lawrence Seaway area in 1958. The present study, a continuation of the same project, reports on further experiments and reviews other available evidence on blasting vibrations and building damage.[2,3]

At about the time the St. Lawrence study was being completed the results of a similar project were reported by Langefors, Westerberg and Kihlstrom.[4] Although the two studies were conducted independently and in different types of soil, approximately the same vibration level was found for the onset of damage. It is also noteworthy that although most of the primary observations were particle displacement or acceleration, it was concluded in both studies that particle velocity was the most useful parameter, since the onset of damage was related to the same velocity amplitude for a wide variety of soil, structural and blasting conditions. Since this conclusion was based on inferences from complicated records of acceleration and displacement it seemed advisable to repeat the experiment, measuring velocity directly. This was the primary purpose of the new work. Various other improvements in instrumentation have contributed also to a more precise determination of the damage threshold. Most attention was directed toward basement walls since the previous work indicated that the first evidence of damage usually occurred there.

The new project was carried out in a region being levelled for use as a head pond for a hydro-electric plant at Carillon Falls on the Ottawa River. Several buildings earmarked for demolition were made available by the Quebec-Hydro Power Commission and the Hydro-Electric Power Commission of Ontario. The buildings selected were houses between thirty and seventy years old. The older houses were founded on glacial till consisting of sand with a large proportion of fair sized boulders; the newer buildings were founded on or very close to hard limestone bedrock overlain by a similar glacial till. The type of construction, particularly of the basements, varied with the age of the building. For all except one house of frame construction and one of stone masonry, the superstructure was 9in to 12in brickwork. The newer houses had solid concrete basements, whereas the older ones had basements constructed of uncut stones and mortar up to a thickness of 28in in some places. Apart from minor cracks, which were carefully documented prior to blasting, the houses selected were in fairly good condition with regard to masonry, brickwork, concrete and plaster. Foundations and footings, chimneys and roofs also were in good condition. Fig. 1 shows one of the houses studied.

Fig. 1—One of six buildings used in Carillon studies

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DAMAGE CRITERIA

Damage to houses can vary from hairline plaster cracks to complete structural failure. For purposes of discussion three categories of damage, identical with those in the previous study, will be used. These are defined as follows:

(1) The threshold of damage is indicated by the lengthening of old cracks, formation of hairline plaster cracks, dislodging of loose mortar, concrete, brickwork or plaster.

(2) Minor damage, an extension of the threshold of damage, consists of superficial damage not likely to weaken the structure. This may include new cracks in brickwork or concrete, or permanent opening of old cracks and the loosening or removal of mortar, plaster or concrete from previously sound walls.

(3) Major damage, a degree more severe than minor damage, results in a serious weakening of the structure. This may include extensive cracking and permanent separations in walls, either caused directly by the vibration or indirectly because of settlement.

EXPERIMENTAL PROCEDURE

A typical series of operations on a particular wall or part of a wall started with a combination of charge and distance corresponding to about half the predicted damage threshold. The charge was then increased and a second observation taken at the same distance. Keeping the charge the same, distance was decreased until damage was produced. The wall was inspected after each shot. Vibration levels observed from the first shot dictated the form of the next one and the sensitivity settings of the recording apparatus. Thus a series of three or four shots was involved in each threshold determination. Charges and distances were chosen so as to determine the damage threshold for a wide range of these parameters.

In order to reduce the number of variables to a manageable experiment, explosive charges were all of the same type of powder, DuPont 60% special gelatin, mostly in 17 lb sticks 5in in diameter. Shots had a good collar, 10ft where possible, and were well tamped to minimise fly rock and air blast. For shots up to 5 lb, 8in by $1\frac{1}{4}$in sticks of the same material were used. Column charges in single holes were used wherever feasible. When a larger shot was required the pattern was arranged so that a minimum area of ground was used, with the holes 8ft to 9ft apart in an approximately circular area. Shots were detonated with instantaneous caps throughout the survey. A total of sixty shots were fired, varying from 0·3 to 1 600 lb at distances from 3ft to 300ft.

DAMAGE OBSERVATION TECHNIQUES

Several types of observation were used to detect and assess damage. A close visual inspection for existing damage was made and photographs were taken before and after test shots to record damage. Strips of paper cemented over old cracks were used as indicators or "telltales" of movement (Fig. 2) and the lengths of cracks were noted. Plumb bobs and precise level measurements were employed in some of the buildings for indicating permanent deformation or settlement.

Vibration observations were made with various types of transducers, which were connected through appropriate amplifiers to the galvanometers in a multi-channel recording oscillograph. Particle velocity was measured by means of a moving-coil transducer with a natural period of 2·5 sec (MB, Type 120). Acceleration was measured with Statham accelerometers (Types A5 and A501) in which the active elements are resistance strain gauges that modulate a carrier voltage. The over-all system, comprising accelerometers, amplifiers and recorder galvanometers had a frequency response from zero to an upper limit varying from 100 c/s to 370 c/s, depending on the accelerometer used. Since the system operated down to zero cycles/sec, it was easily calibrated in terms of the earth's gravitational field by inverting the transducer and obtaining a deflection corresponding to 2*g*. Displacement records were obtained in two ways: by electrically integrating the output of a velocity-sensitive transducer, and by using a differential transformer to measure displacement of a one-second pendulum system. Strains in the wall surfaces were measured with resistance strain gauges of 6in gauge length.

The recording oscillograph employed direct-writing photographic paper, which produced records a few seconds after each blast. The information was thus immediately available for planning subsequent shots. Pick-ups were attached to mounting brackets screwed to the wall under test and were usually grouped as close together as possible in order to define the motion of a specific part of the wall. A typical installation is shown in Fig. 3, which also shows a crack produced by one shot.

All three components of motion were examined in the earlier tests, but the traverse component (relative to the blast direction) was later abandoned since it adds little to the information gained from longitudinal and vertical components. Attention was concentrated on velocity and acceleration, with secondary emphasis on strain and displacement. Peak-reading velocity meters were also used much of the time to compare this relatively simple instrumentation with the detailed records. The traditional falling-pin gauge was also set up for most shots.

WAVEFORMS

The form of typical disturbances is illustrated in Figs. 4 to 6. The first of these shows longitudinal and vertical components of velocity and acceleration for the same blast, all observed on a basement wall, together with a velocity measurement from a stake driven into the ground beside the building. Generally the acceleration and velocity records were quite different, as in this case, although point-to-point differentiation of the velocity curves demonstrates that the corresponding records are consistent. Velocity curves are usually the simplest, consisting of a well-defined initial pulse followed by a quickly damped wave-train. Acceleration records are frequently complicated by sharp pulses of short duration followed by a slower wave-train. Velocity records obtained from stakes in the ground generally agreed reasonably well in waveform with the basement records, but amplitudes were usually larger.

Fig. 5 shows records for two different

Fig. 2—Paper "telltales" used for indicating movement of old cracks. Second "telltale" was applied after first was partially torn.

1. Crack caused by blasting. 2. Strain gauges. 3. Velocity transducers. 4. Accelerometer.

Fig. 3—Stone basement wall showing typical transducer installation. Note that the crack produced by a test blast passes through two strain gauges

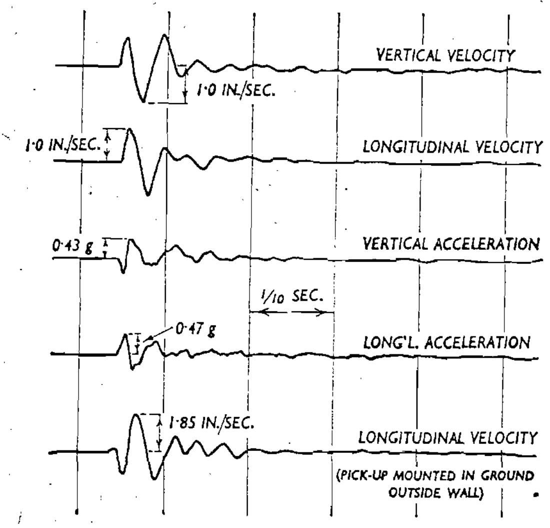


Fig. 4—Typical velocities and accelerations from a 100 lb charge at 300ft fired in rock. Transducers mounted on a concrete basement wall

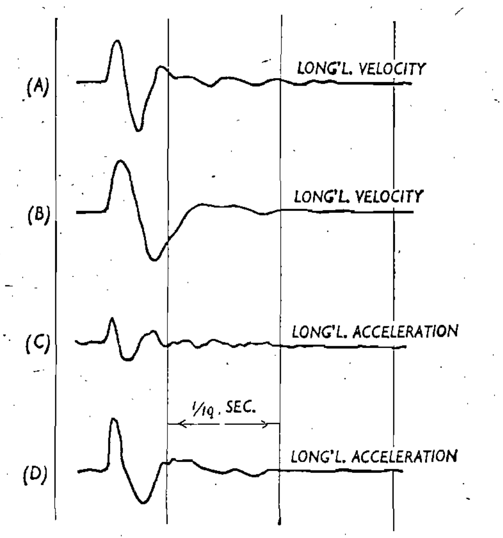


Fig. 5—Comparison of waveshape for different charges at same distance. Traces *A* and *C*, 100 lb at 300ft. Traces *B* and *D*, 600 lb at 300ft

charges at the same distance. This illustrates the general observation that the duration of the initial pulse (and usually of the whole disturbance) is longer for increased charge. This is further illustrated by Fig. 6, which shows the brief disturbance produced by a very small charge (at short distance).

VIBRATION LEVELS VERSUS DAMAGE

Of particular interest is the threshold of damage, and a study of this formed the main objective of the present work. As was noted in previous studies, damage was observed more consistently in basements than in other parts of buildings. This applied particularly to the threshold of damage and minor damage. For shots remote from the buildings, where the wavefront affects the building as a whole, typical cracks are usually related to the junctions of walls and to weak areas such as the corners of doors and windows. For the most distant shots (200ft to 300ft), damage was observed in the superstructure as well as in the basement. For closer shots the effects are localised in the region of the basement wall nearest the shot. In some of the St. Lawrence studies of buildings founded on waterlogged sand and clay the primary failure was in the underlying soil; in these instances the damage produced by blasting took the form of settlement, with the usual cracking and vertical dislocation of foundation sections. Perhaps it is worth noting that there is nothing characteristic about these early evidences of damage that identifies them specifically with blasting vibrations rather than with the other stresses to which buildings are subjected.

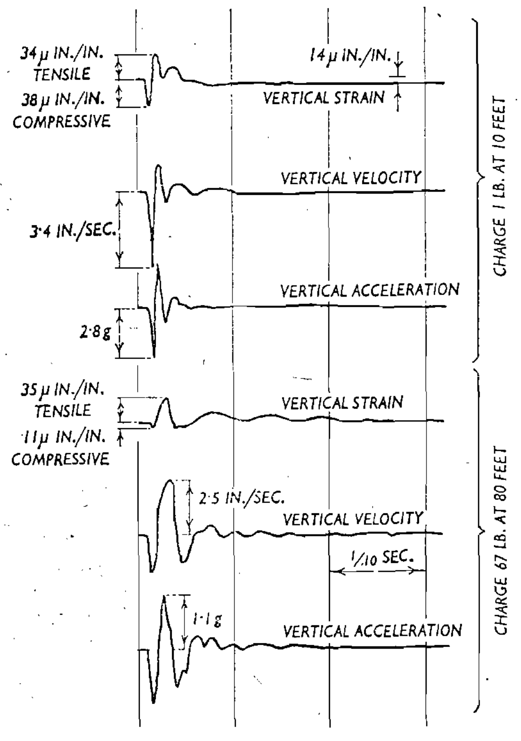


Fig. 6—Typical velocities, accelerations and strain for close and distant shots. Transducers mounted on concrete basement wall

Figs. 7 and 8 show plots of the longitudinal and vertical components of particle velocity and acceleration for the walls observed in each series of shots. The symbols used show the gradation in each series from no damage to threshold, minor and major damage. It will be seen that, of the four plots, the longitudinal velocity results show the most uniformly defined transition for the whole family of tests. Vertical velocity is also reasonably good, although there is some scatter relative to the corresponding longitudinal components. This is best seen in Fig. 9, where the correlation between horizontal and vertical velocities is shown.

The acceleration results show somewhat more variation from series to series in all transitions. In part this may be due to difficulties in interpreting the acceleration records, which were frequently dominated by

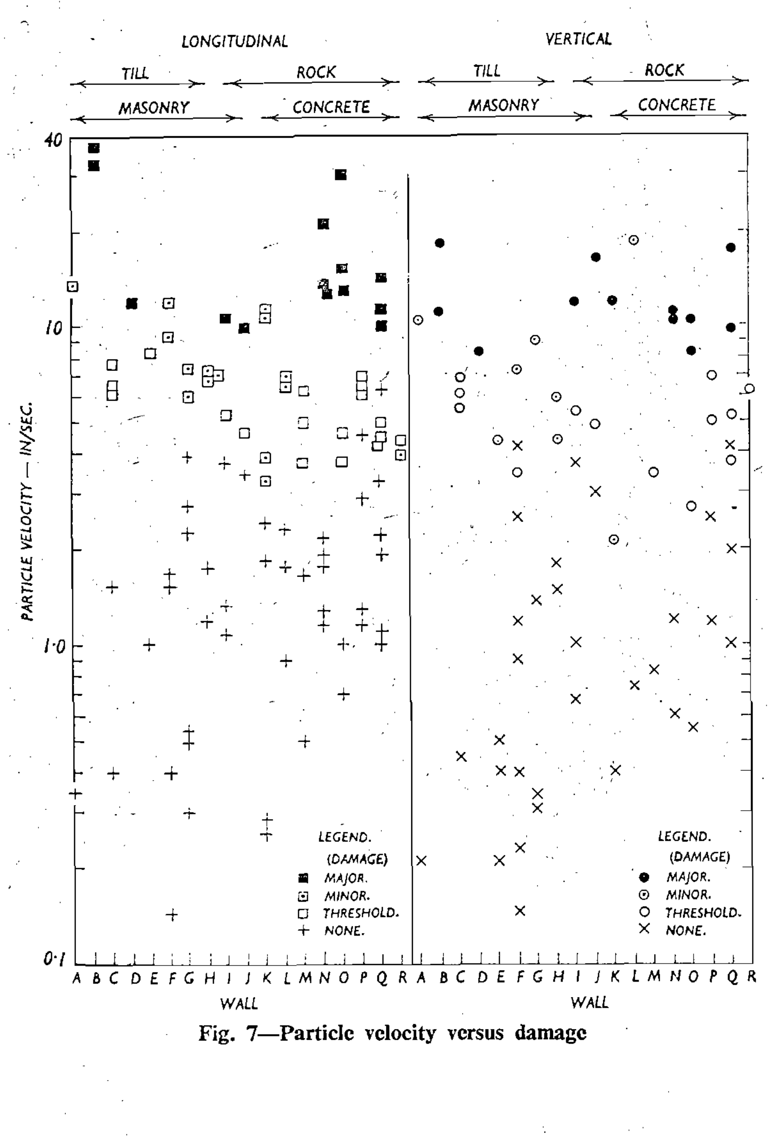


Fig. 7—Particle velocity versus damage

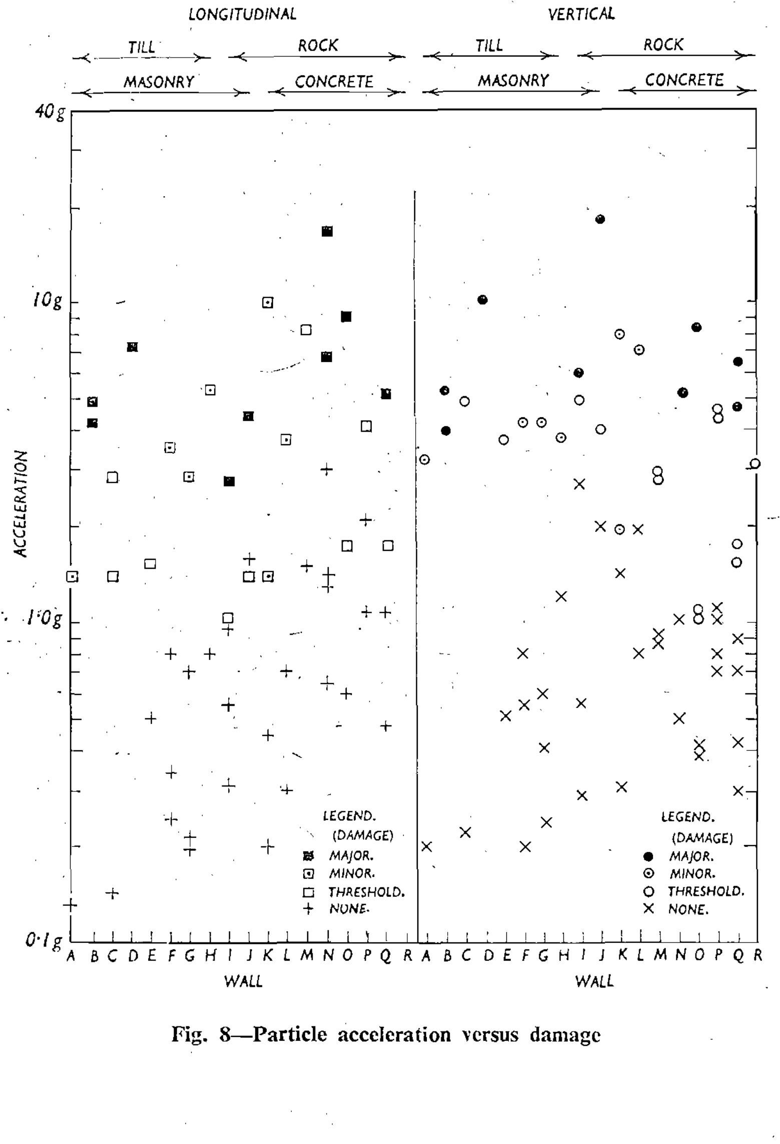


Fig. 8—Particle acceleration versus damage

Technical Contributors Section (*Continued*)

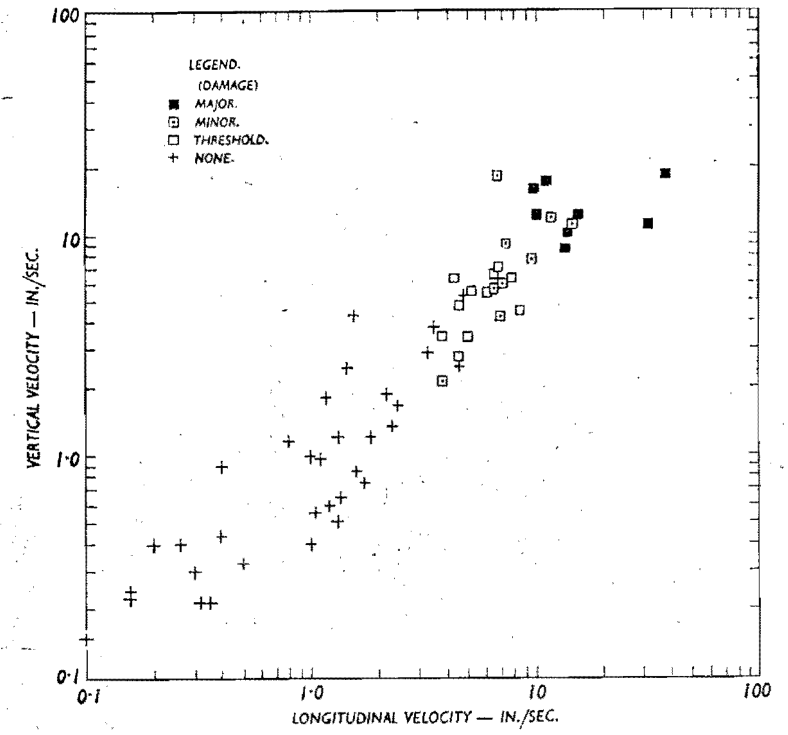


Fig. 9—Longitudinal velocity, vertical velocity and damage

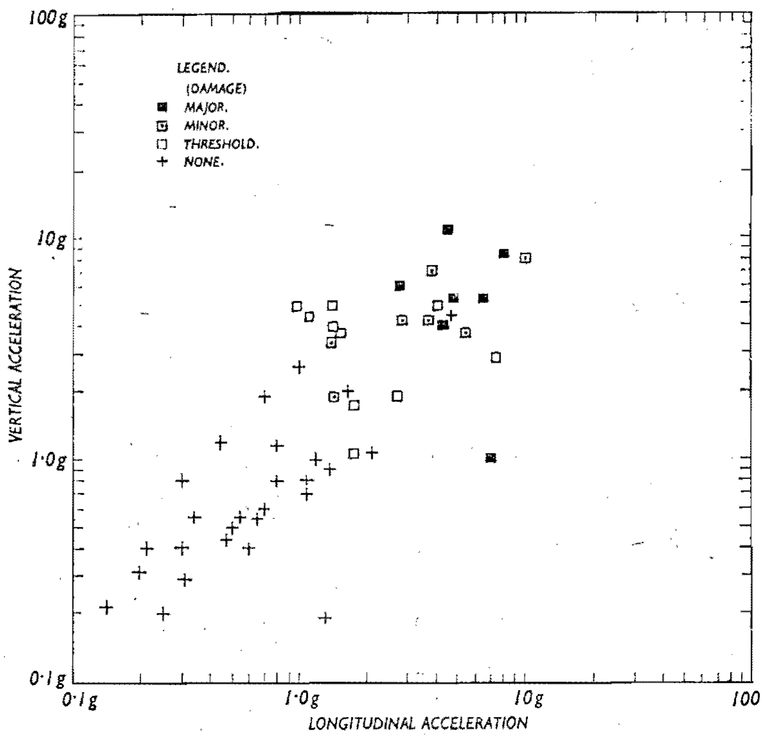


Fig. 10—Longitudinal acceleration, vertical acceleration and damage

a very fast initial impulse; the frequency content of these fast impulses may approach the limits of the measuring system. The correlation between horizontal and vertical acceleration (Fig. 10) is somewhat more erratic than for velocity.

One may conclude from these observations that for vibration in till and rock the longitudinal velocity in basement walls is the best single criterion of damage. A minimum threshold value appears to be about 3in/sec. There is slight indication, most evident in the longitudinal velocity plot, that the damage threshold for massive masonry basements in till is higher than for modern concrete basements on rock. (Unfortunately there were only a few observations that distinguish separately between the types of soil and foundation). This observation is consistent with the St. Lawrence work, all done on massive stone basements, in which a minimum threshold value of about 4in/sec was obtained. The earlier work differed also, however, in that some free ground vibration measurements were used, and these now appear in many instances to be higher than measurements in the basement structure itself. The earlier work of Langefors, *et al.*, indicated a damage threshold in rock of 4·2in/sec.

The St. Lawrence study indicated that in certain soils (waterlogged sand and clay) the horizontal component of vibration was anomalously low. To protect against this possibility it would be desirable to measure both components, at least for some exploratory shots, and to take the larger of the two as the criterion, using the above threshold value. The minimum threshold for acceleration, slightly less suitable for general application, would be an acceleration of 1g. Again an exploratory check of horizontal and vertical components should be made to guard against unusual soil conditions.

STRAIN OBSERVATIONS

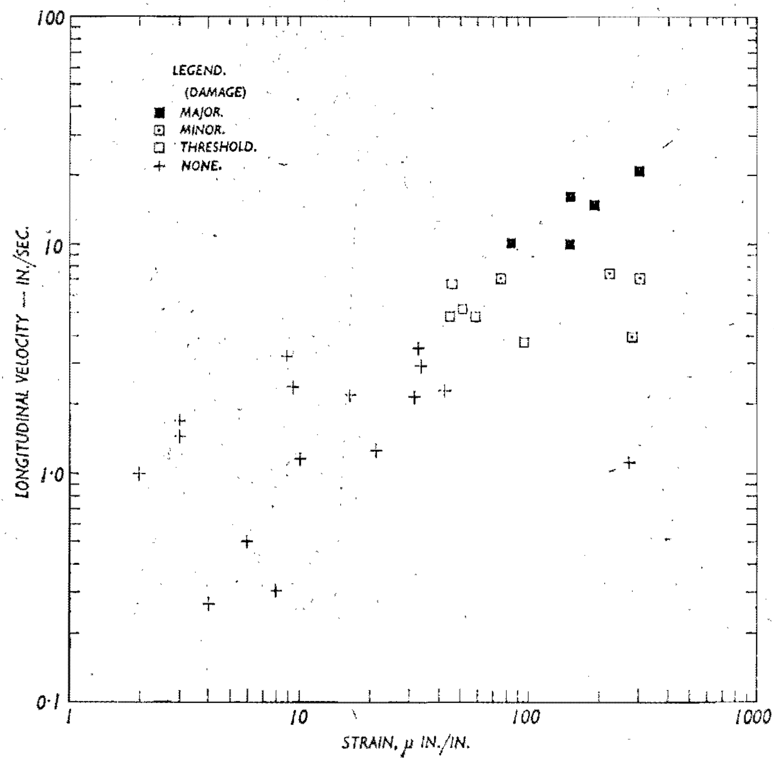
In the hope of throwing some light on the damage mechanism in basement masonry walls, strain measurements were made on the surfaces of some walls near the other vibration transducers. Gauges were mounted both horizontally and vertically, but were of course transverse to the direction of the blast. A careful comparison was made of the waveforms of velocity, acceleration and strain; there was no consistent pattern of resemblance that would identify strain exclusively with either of the vibration parameters. The problem is illustrated by Fig. 6, in which there is a close resemblance among all three records.

As another approach, the amplitudes of corresponding components of strain with velocity and acceleration were plotted. These show that the correlation between maximum horizontal strain and maximum longitudinal velocity is slightly better than between the other variables. The resulting scatter diagram for this case is shown in Fig. 11. Clearly these observations do not greatly illuminate the problem of basement damage. A further study in a laboratory simulation of the problem is planned. The strain measurements might themselves be examined as an index of damage. Fewer observations are available, but it would appear (Fig. 11) that damage is likely to occur with strains above about 40 microinch/in.

THE FALLING-PIN GAUGE

The falling-pin gauge used in these studies consisted of six steel pins $\frac{1}{4}$in in diameter, ranging in length from 6in to 18in. They were arranged on a carefully levelled base plate, each contained in a large-diameter

Fig. 11—Longitudinal velocity, strain and damage



tube to minimise the effect of wind and prevent one falling pin from disturbing the rest.

As originally conceived the pins were thought to vary in sensitivity with length, so that by noting the length of the shortest pin that fell one could presumably deduce the maximum amplitude of vibration. It can be shown, however, that both the amplitude and the exact waveform of the disturbance are factors in causing the pin to fall. Hence, there is no simple predictable correlation between pin lengths and their sensitivity to blasting vibrations.

In the present study the gauges were set up on the basement floor as close as possible to the location of the other instruments. The results are given in Table I. It may be observed that no pins fell when vibration levels were below the damage threshold. The damage threshold is not perfectly established; but in five of the seven threshold observations some or all of the pins fell. In all cases of minor and major damage some or all of the pins fell. When only some of the pins fell their lengths appeared quite randomly selected.

Table I.—*Distribution of Pin-Gauge Observations versus Damage Observations*

Fallen pins	Damage			
	None	Threshold	Minor	Major
None	8	2	0	0
Some	0	3	3	2
All	0	2	0	5

Propagation Relations

The amplitude of vibration produced in a structure by a blast depends not only on the size of charge and its distance from the structure but on several other parameters that are more difficult to define. There are variations related to the coupling of charge and medium: for example, charges set in dry unconsolidated material appear to produce less vibration than charges placed in rock or well consolidated soil.

Attenuation with distance similarly may depend on the mode of propagation and on dissipative and dispersive effects in the medium. For the present study, in which most of the distances are only a few multiples of the source depth, an approximation of spherical propagation might be expected. This would lead to attenuation at a rate somewhat greater than 1/(distance) assuming some dissipation in the medium. For greater distances there might be a transition to surface wave propagation, which would suggest a decreased attenuation rate, but this decrease would probably be compensated for by increased dispersion. Occasionally, though not in the present study, large attenuations related to discontinuities in the propagation path may occur; these cannot be predicted by any propagation law.

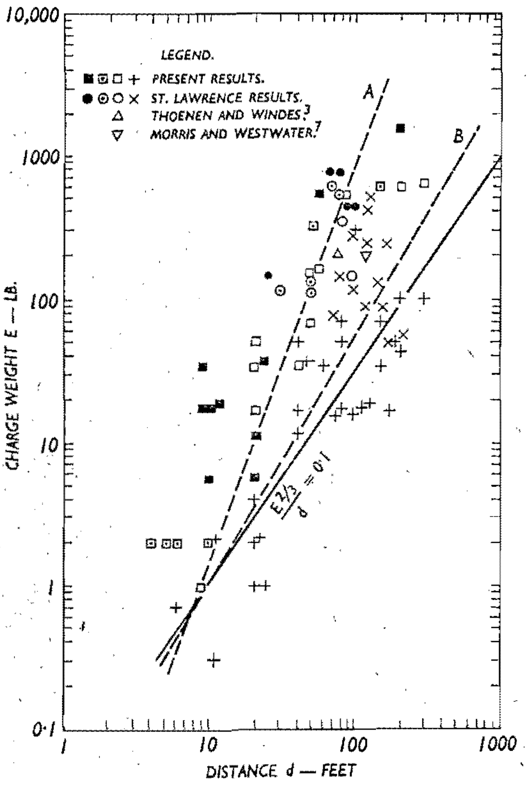
Finally, the vibration transmitted to the structure will depend on the elastic properties of the medium relative to the structure. As an extreme example it was noted in these experiments that vibration of the free ground surface was sometimes as much as double the corresponding measurements in a basement wall at the same range.

To minimise the effects of these extraneous variables in studies of the charge and distance relationships, the procedure was to compare shots set off in the same general terrain and measured at the same observation points. The variation of amplitude with distance was studied by comparing pairs of shots employing the same charges at different distances. Similarly the variation with charge was investigated by comparing different charges at approximately the same distance.

Assuming that for a pair of shots the amplitude varies as $(d_2/d_1)^m$ and $(E_1/E_2)^n$ where d_1, d_2 and E_1, E_2 are distances and charges respectively, the best values of m and n were sought. These were found to be $m=1\cdot 6$, with a standard deviation of 0·11 and $n=0\cdot 71$ with a standard deviation of 0·07. Initially the acceleration and velocity results were treated separately, but the differences were not found to be statistically significant.

Various other charge relationships have been reported. For studies of quarry blasts, Thoenen and Windes[3] found that amplitude was proportional to $E^{2/3}$. Habberjam and Whetton,[5] measuring amplitudes of first peaks rather than maximum amplitudes, found a proportionality to $E^{0\cdot 805}$. O'Brien[6] shows that seismic amplitudes should be directly proportional to the weight of charge, but that high frequency components vary as $E^{1/3}$ for very large charges. The St. Lawrence study indicated an $E^{2/3}$ law, and the work reported here reinforces it; this is in agreement with Thoenen and Windes and midway between O'Brien's two values of $E^{1\cdot 0}$, and $E^{1/3}$.

In the foregoing sections it has been shown that there is a well-defined level of vibration at which building damage begins, and a reasonable correlation between vibration amplitude, explosive charge and distance. It is of interest to examine directly the relationship of damage, charge and distance. The available information from this and other studies,[3,7] is shown in Fig. 12. Calculations for E and d versus vibration level suggest that the most probable damage threshold curve should be given by $E^{0\cdot 71}/d^{1\cdot 6}$=constant. Carrying the calculations one stage further, the most probable slope (in the logarithmic scale of Fig. 12) is 2·25, with a standard deviation of 0·27. Assuming that this standard deviation is indicative of the variations that can arise in practice, one might infer that 95% of such variations will be within plus or minus twice the standard deviation. Curves A and B in Fig. 12 have slopes corresponding to these limits. Their position has been adjusted to fit the region of uncertainty in which both damage and no-damage observations occur. Curve B might be taken as a safe limit for estimating charge and distance in the absence of vibration information.



The area between curves A and B represents region of uncertainty in which damage may or may not occur. Curve B, or the simpler approximation $E^{2/3}/d=0\cdot 1$, are recommended as safe limits for blasting operations

Fig. 12—Distance versus charge weight showing damage

For comparison the still lower solid line corresponds to the relation $E^{2/3}/d=0\cdot 1$, which was proposed as a safe limit in the St. Lawrence report. It might be regarded as a simpler and slightly more conservative rule than the new derivation.

Comments on Multi-Delay Blasting

The common practice of using small time delays between individual charges in a large blast has two virtues. Properly designed, it can improve the efficiency of the blast and the precision of the results, and can reduce the maximum vibration amplitude. Generally it is safe to assume that the resulting vibration amplitude is slightly greater than the value to be expected from the largest individual charge. (A factor of 1·5 would be a conservative rule.) Langefors, Westerberg and Kihlstrom[4] have been successful in designing blasts so that vibrations from successive charges interfere with one another and produce reduced amplitude in a particular direction. The precision timing required for such an operation is not ordinarily warranted, but in restricted quarters it may be a practical technique.

Procedure for Controlling Blasting Operations

This discussion will be based on a consideration of single or simultaneously fired charges. When a sequence of delayed charges is used an equivalent charge of 1·5 times the largest single delay should be assumed.

In the absence of vibration information the recommended procedure is to use the safe limit given by curve B (Fig. 12) or the simpler formula $E^{2/3}/d=0\cdot 1$ (where E is the charge in pounds and d is the distance in feet). Either of these criteria should give adequate protection against the worst combination of terrain factors that is likely to occur. If vibration levels can be measured, advantage can be taken of conditions actually existing at the site. Following an initial calibration shot, which might be designed according to the safe limit curves, adjustments can be made to the charge and distance to bring the vibration velocity up to 3in/sec. In most cases the simple expression $A=CE^{2/3}/d$ will be an adequate rule if calculations are being made for greater distances. To calculate for smaller distances a somewhat steeper variation (with distance) should perhaps be assumed (e.g. amplitude proportional to $d^{3/2}$). There is always the danger in working smaller distances that a major discontinuity exists in the propagation path; thus the vibration amplitude might rise suddenly if the blasting operation were to cross this discontinuity. Hence, for critical blasts it is advisable to do calibration shots at shorter, rather than longer distances.

The traditional falling-pin gauge has proved to be a fair indication of the damage threshold. As the pins do not fall until the threshold is actually reached, however, it appears that a direct inspection for damage (before and after the event) would be equally useful. Consequently, they seem to have little application, except possibly by a building owner, to provide corroborative evidence.

Peak Reading Velocity Meter

In recent years blasting vibrations have typically been monitored by displacement- or acceleration-measuring instruments. As it now appears that the most suitable index is velocity, it is desirable to devise a method of measuring this quantity directly. Although one can, in principle, derive velocity from the other quantities, it is rather difficult in practice because of the complexity of the usual wave and the frequency limitations of the available instruments.

A relatively simple system tested during this study consisted of a velocity transducer (MB 120) connected to a peak-reading meter (General Radio Type 1556B—Impact Noise Analyser). The latter instrument is one of several developed as attachments for sound level meters and retains the peak reading of an impulsive disturbance for several seconds so that an operator can read it. Both transducer and meter respond down to about 5 c/s. Readings obtained with this system correlated closely with other recorded observations and are, in fact, incorporated in the results. The merit of the system lies in the relative simplicity and portability of the equipment. Although the instrument gives only peak amplitude, with no details of waveforms, these are not needed for routine monitoring purposes.

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Inert Gas Generator for Control of Fires in Large Buildings

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A brief description is given of the principles on which an inert gas generator, based on a jet engine, may be designed. A summary is given of tests carried out using a generator which can produce gases containing down to 7% oxygen at rates of 30 000 ft³/min to 50 0000ft³/min and high expansion foam at rates of up to 20 000 ft³/min. The tests were carried out using two quite different buildings: (1) a barn-like single-storey building of volume 250 000 ft³; and (2) a set of basements of volume 300 000 ft³. The tests in (1) showed that inert gas could extinguish flames first at roof level and then throughout 90% of the volume of the building within ten minutes and that dilution with more than half its own volume of air did not significantly affect its performance. The tests in (2) showed that both gas and foam could travel in quantity through narrow corridors and doors to fill rapidly a set of basements. Firemen could operate reasonably efficiently in many of the atmospheres produced in the buildings; however, the atmospheres produced by gases containing 10% oxygen and less in the basements were too hot for this purpose. The implications of these findings are examined. It is suggested that an appliance of this kind could be usefully employed in the majority of fires where monetary loss is high (greater than £10 000) and the ways of using the appliance at fires of different kinds are indicated. It is suggested that an improved appliance should be developed for use by firemen to gain experience, and for use eventually at actual fires.

THE suggestion that a jet engine might be used to generate and move gases on a scale sufficiently large to fight fires in large buildings, arose out of a review of the problem of smoke in fire-fighting.[1] From time to time, fires which are difficult to fight because of the presence of dense, hot smoke occur in unventilated premises like large basements; examples are the fires at Covent Garden in December, 1949, and at Smithfield in January, 1958. There were objections to the use of the conventional portable fans available for artificial ventilation because their capacity was too low, and their use might have increased the intensity of a fire and possibly also the total amount of smoke produced. It was thought that not only was it necessary to fill the premises with a transparent gas, but that this gas had also to reduce the combustion or the rate of formation of smoke by the fire. It was suggested that such a gas could be produced in quantities sufficiently large for the purpose (10^4–10^5 ft³/min) by a mobile appliance based on a jet engine.[2] A preliminary study of the potentialities of such an appliance indicated that a mobile appliance which could produce an unlimited supply of inert gas at a rate of 50 000ft³/min might not only be useful in the comparatively few fires where dense smoke is the main problem, but also in a substantial proportion of the much larger number of fires in buildings that led to high financial loss. Following this, after consultation with the National Gas Turbine Establishment the latter was asked to design and develop an experimental device for appraisal by the Joint Fire Research Organization. This device was delivered in 1960 and a number tests have been carried out since then to assess its potential usefulness. A summary of these tests and the conclusions reached so far are presented here.

EXPERIMENTAL APPARATUS

A highly simplified diagram of the inert gas generator is shown in Fig. 1. The raw materials for the process are fuel, air and water. The combustion of fuel in the engine itself reduces the oxygen content of the air passing through the engine to 17% to 18% and increases its temperature to about 400°C. The gas then passes into an after-burner where more oxygen from the air is burnt out and the temperature further increased. This gas then passes through a humidification section where water is injected as a spray and is evaporated. The evaporation of water spray reduces both the gas temperature and the oxygen concentration and results in a large flow of gas of low oxygen concentration at a temperature of approximately 100°C.

The oxygen concentration of the outlet gas may be controlled within a wide range by varying the amount of fuel burnt in the engine and in the afterburner. Some control over the outlet temperature of the gas may also be obtained by varying the amount of water spray used in the humidification section although, beyond a certain input of water, the function of the water would be to cool the gas rather than humidify it. The gases are also ejected from the apparatus at a high velocity. This fact may be used to entrain into the outlet gas a large volume of air from the surrounding atmosphere before the gases are injected into the delivery duct and thence into the building; this air entrainment allows further control of the oxygen concentration, and temperature of the gas. Some quantitative relationships for these processes have been given elsewhere.[3]

The apparatus built by the National Gas Turbine Establishment was based on a "Viper" jet engine and was designed to produce a gas containing 7% oxygen at a

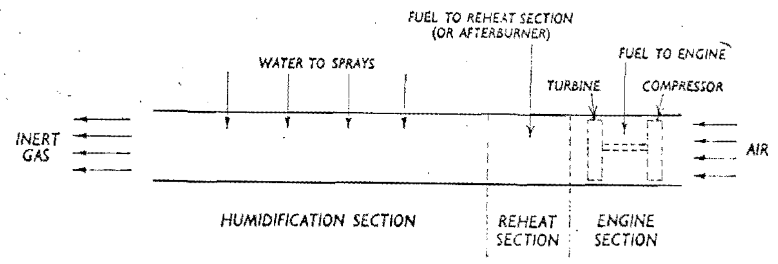

Fig. 1—Diagram of inert gas generator

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