TRANSPORT AND ROAD RESEARCH LABORATORY
Department of Transport

RESEARCH REPORT 146

TRAFFIC VIBRATION AND BUILDING DAMAGE—
TRRL PAPERS PRESENTED AT ACOUSTICS '87

Papers presented at the Institute of Acoustics Conference, Acoustics '87 at Portsmouth Polytechnic, 14-18th April 1987

Edited by G R Watts

The views expressed in this Report are not necessarily those of the Department of Transport

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TRAFFIC VIBRATION AND BUILDING DAMAGE—
TRRL PAPERS PRESENTED AT ACOUSTICS ’87

ABSTRACT

Four papers were presented at the Institute of Acoustics conference, Acoustics ‘87, that together describe a recent TRRL study in which the possible link between traffic induced vibrations and building damage was examined by exposing an unoccupied house to simulated traffic vibrations. The background and reasons for carrying out this piece of research are also given.

The papers were:

Traffic vibration and building damage by P M Nelson and G R Watts

Monitoring the effects of simulated road traffic on a test house—experimental method by R A Hood and C Marshall

Monitoring the effects of simulated road traffic on a test house—results by C Marshall and R A Hood

Response of building elements to simulated traffic vibrations by G R Watts

PREFACE

In 1985 a study was planned by TRRL to investigate the effects of traffic induced vibrations on buildings. The background to this work, including the reasons for carrying out further studies, are given in Paper 1 in this Report. Towards the end of 1985 Travers Morgan Planning under contract to TRRL began an experiment which involved monitoring the effects of simulated traffic vibrations on an unoccupied dwelling. This was completed in the spring of 1986 and during this period the building was exposed to the equivalent of many years of relatively high levels of traffic vibration. Throughout the test period the condition and movement of the building and surrounding soil were monitored and vibration measurements taken. Paper 2 describes the building and vibration sources and the methods employed to monitor the building and soil. Paper 3 presents the main results and conclusions of the study and finally paper 4 gives details of the way in which the building responded to the vibration sources.

The session at which these papers were presented was chaired by Dr H G Leventhall of W S Atkins Ltd. Dr Nelson and Dr Watts are members of the Vehicles and Environment Division at TRRL. Dr Hood and Mr Marshall are consultants from Travers Morgan Planning.
ABSTRACT
Evidence mainly of an anecdotal nature indicates that vibration generated by road traffic can give rise to both architectural and more major structural damage to buildings. This fear or perception of damage has caused considerable concern to both the occupiers of buildings located near to traffic as well as more general concern expressed by such bodies as the Civic Trust and the Histic Buildings and Monuments Commission.

Unfortunately, despite the widespread concern, there is little evidence of a substantive nature which can be used to either support or reject these perceptions. Buildings will become damaged by a range of natural processes and by other vibration-related but non-traffic sources and there remain considerable difficulties in isolating and defining the contribution of traffic vibration to the overall damage occurring in buildings.

This paper reviews the evidence for the perception of traffic vibration and damage in buildings, suggests possible damage mechanisms worthy of further study and outlines an appropriate research methodology.

1 INTRODUCTION
Previous studies at the Transport and Road Research Laboratory on the subject of traffic vibration have concentrated on examining the causes of building vibration and the overall disturbance caused by vibration (Martin et al 1978, Martin 1978, Watts 1984). During the course of these studies it has become apparent that numbers of people who experience some form of traffic vibration in their homes consider that this can, or already has, caused damage to their property. Increases in allowable vehicle weights may have tended to intensify the degree of concern (Civic Trust 1970, Armitage 1980).

While there is plenty of evidence of damage to buildings, there is little evidence linking traffic vibration to this damage and since traffic vibrations are generally very low, it has become common practice to place the blame for observable building damage on a wide variety of natural causes which cause substantially higher stress levels in structures than traffic vibration. While this argument would seem plausible, it does ignore the possibility that fatigue damage could occur as a result of long term exposure either to low level stress reversals or to a combination of such reversals and high static stresses in the structure. It is also possible that, on some soils, traffic vibration could cause compaction or soil movement beneath the foundations leading to settlement and damage, or at least to high static stresses.

This paper briefly reviews the reasons why new research on traffic vibration has been started at TRRL and gives an outline of experiments which are being carried out to gain a better understanding of the problem.

2 THE EVIDENCE AGAINST TRAFFIC RELATED VIBRATION DAMAGE
2.1 SOURCES OF TRAFFIC VIBRATION
Traffic can cause vibrations in building by two separate processes:
1. Low frequency sound waves generated at vehicles exhausts can couple into the structure via windows and doors causing different elements of the building to vibrate.
2. Forces generated by vehicles passing over the road surface profile can generate vibration in the ground which then propagates along the ground surface and through the underlying soil to reach the building foundations.

The low frequency sound waves of importance have frequencies centred on the fundamental exhaust frequencies of heavy duty diesel powered lorries (ie the range 50-100 Hz). Even when heavy lorries travel close to buildings and where the sound pressure levels are high, the forces induced in the structure are small. Nevertheless these forces can give rise to perceptible vibration, particularly, in the lighter and more flexible parts of the structure such as windows and suspended floors. In addition, poorly fitting windows can be made to rattle or buzz as a result of low frequency noise excitation which can be annoying to the occupants. Vibration generated in the floors by low frequency noise will depend upon the mass and stiffness of the structure and the frequency of the noise as well as the dimensions of the room which can give rise to standing wave effects. Again, while these vibrations can, on occasions, be detectable and can give rise to disturbance, the stresses induced in the floor, its support and the adjoining walls are small and generally lower than the levels caused by normal household activities such as opening and closing doors or the operation of domestic appliances.

Ground vibrations generated by traffic do not generally become perceptible unless the nearby road is in a poor condition, usually exhibiting irregularities in the surface such as a poorly filled trench or pothole. Vehicles passing over the surface irregularity produce impulsive forces in the road whose decay characteristics depend upon the resonant frequencies of the suspension and tyre (ie the wheel hop frequency) and the damping characteristics. For many vehicles, the suspension frequencies lie in the range 10-20 Hz which means that even for low vehicle speeds, the surface irregularity may produce relatively high dynamic loads over several metres of the road. The dynamic loads depend mainly upon the type of vehicle, its suspension and speed but typically the ratio of dynamic axle load to static axle load would be 1.5 to 2.0 with a possibility of an impact factor rising to 3 on occasions (Leonard et al 1974). The dynamic load imparted to the surface may, therefore, be as high as 10-20 tonnes given the current axle loads permitted on UK roads.

However, despite the large forces resulting from this dynamic loading the average vibration levels generated in the ground alongside the road are usually quite low (ie less than 100 mm/s²) although distinctly perceptible under some conditions. Figure 1 shows an example of vibration recorded in the ground at a distance of 6.9 metres from a large road surface irregularity during the passage of a two-axle lorry. The first major peak represents the impulse generated by the first axle (static load = 5.94 Mg) as it passes over the irregularity followed by three further peaks. This is then followed by the impulse generated by the second heavier axle (static load = 9.70 Mg) and further peaks decreasing according to the damping characteristics of the suspension and tyres on the vehicle and the response of the road structure and the soil beneath. In general a maximum of three or possibly four major peaks may be generated by the passing of each axle. On a three or more axled vehicle, impulses occur more rapidly and interference between vibration waves often result in fewer observed peaks per axle. For example, at this site, a 5-axle vehicle was observed to produce 11 major peaks.

2.2 DAMAGE CRITERIA

A great deal has been written about the levels of vibration which could give rise to damage in buildings. While it is unlikely that a precise and universally acceptable set of criteria will emerge, the consensus would appear to suggest that the levels required to cause even minor damage to structures are generally much higher than the levels generated by traffic. In addition, it should be borne in mind that damage criteria have, not unnaturally, tended to be of a conservative nature. For example, the original German Standard DIN 4150 (1938) gave limits which are generally regarded as over cautious. The Standard was revised in 1984 and provides some relaxations from the original limit values as well as providing different criteria for different frequency ranges (Deutsches Institutfuer Normung 1984). Table 1 summarises the recommendations for peak particle velocity for transient shaking.

The various recommendations and criteria for prevention of damage are borne out by the results summarised in Figure 2 which is a compilation of vibration from sources which have been related to damage (Steffens 1971), vibration from various sources which has not caused damage (Steffens 1971), and vibration from traffic (Whiffin and Leonard 1971). In each case the vibration level was measured on a structural element, for example, a foundation, wall or floor. It would appear that the onset of damage occurs at a particle velocity of about 10 mm/sec which is substantially above the average or RMS levels generated by road traffic.
TABLE 1
Guide values for peak velocity during transient shaking (DIN 4150)

<table>
<thead>
<tr>
<th>Structure Type</th>
<th>&lt;10 Hz</th>
<th>10-50 Hz</th>
<th>50-100 Hz*</th>
<th>Top storey on wall at floor level (all frequencies)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offices and industrial premises</td>
<td>20</td>
<td>20-40</td>
<td>40-50</td>
<td>40</td>
</tr>
<tr>
<td>Domestic houses and similar constructions</td>
<td>5</td>
<td>5-15</td>
<td>15-20</td>
<td>15</td>
</tr>
<tr>
<td>Other building sensitive to vibrations</td>
<td>3</td>
<td>3-8</td>
<td>8-10</td>
<td>8</td>
</tr>
<tr>
<td>Foundations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top storey on wall at floor level</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*At frequencies higher than 100 Hz a higher guide value is allowable.

3 THE EVIDENCE FOR TRAFFIC RELATED DAMAGE

3.1 POSSIBLE DAMAGE MECHANISMS

While it would appear that for most materials in buildings, the levels of vibration from traffic are too low to cause direct failure, it is important to realise that the vibration velocities known to occur at the roadside may have little relation to the vibration levels that propagate into nearby buildings. Propagation of vibration into soil and rock is very complex, involving the interaction of both shear and compressional body waves which propagate with different phase velocities. The influence of boundaries within the soil structure can also give rise to reflections, refractions and scattering and associated interference effects. The presence of a surface introduces a third wave type, the Rayleigh wave, which travels at a lower phase velocity than the compressional body waves and is potentially more damaging to structures since the wavelength is relatively small. In addition this wave is confined to a wavelength or so of the surface and is, therefore, subject to relatively low spreading losses. The excitation of a building structure is also very complex and will greatly depend on the response characteristics of the different building elements. In many cases, resonance of the floor will occur at frequencies in the range 10-30 Hz which is consistent with the suspension frequencies of heavy vehicles. Because of this the amplitude of vibrations of floors or ceilings can be four or five times that of the building foundations.

It is also important to realise that characterising vibration by an RMS average in, say, the vertical direction does not always indicate its true significant or damaging potential. Many previous measurements of traffic vibration have been carried out near roads with smooth surfaces and often RMS vibration levels have been recorded. Recently a study of traffic vibration (Watts 1987b) at kerbsides and in buildings close to significant road surface irregularities has recorded peak levels of well in excess of 100 mm/sec². It can be seen, for example, in Figure 1 that the peak particle velocity of the vertical direction waveform recorded close to the road was 286 mm/s². If this...
TABLE 2
Peak acceleration and dominant frequency by site

<table>
<thead>
<tr>
<th>Site</th>
<th>Vehicle producing vibration</th>
<th>Max depth of surface irregularity (mm)</th>
<th>Position</th>
<th>Peak acceleration level (mms⁻²)</th>
<th>Dominant frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5 axle artic</td>
<td>32</td>
<td>Facade*</td>
<td>75</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Floor**</td>
<td>175</td>
<td>12/74</td>
</tr>
<tr>
<td>B</td>
<td>2 axle rigid</td>
<td>75</td>
<td>Facade</td>
<td>130</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Floor</td>
<td>164</td>
<td>12.5</td>
</tr>
<tr>
<td>C</td>
<td>3 axle cement mixer</td>
<td>28</td>
<td>Facade</td>
<td>110</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Floor</td>
<td>114</td>
<td>12.5</td>
</tr>
<tr>
<td>D</td>
<td>4 axle rigid</td>
<td>23</td>
<td>Facade</td>
<td>42</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Floor</td>
<td>78</td>
<td>25.5</td>
</tr>
<tr>
<td>E</td>
<td>Double decker bus</td>
<td>15</td>
<td>Facade</td>
<td>57</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Floor</td>
<td>96</td>
<td>24</td>
</tr>
</tbody>
</table>

*Near foundations at the facade fronting the main road.  
**In the middle of the living room.

occurred on a lightly damped soil and near a building it could produce vibrations in the structure which equal or exceed the published thresholds for architectural damage. The highest level recorded at the kerbside in this recent study was over 1200 mm/s². Table 2 lists the peak acceleration levels recorded in buildings close to surface irregularities.

The highest level recorded in the hard structure of these buildings was 130 mm/s² (site B), which according to the data given in Figure 2 is approaching the levels at which vibration damage begins to occur.

While some doubts must, therefore, be directed at the observation that traffic vibration does not exceed damage thresholds in all circumstances, a further and more widespread concern is the possibility of fatigue damage occurring as a result of continuous exposure to low levels of vibration over a long period of time. It is worth noting that buildings located alongside busy roads may be exposed to many millions of cycles of fluctuating stress from traffic each year and so the number of repeat loadings can be very high over the expected life of a building and some fatigue, therefore, a distinct possibility. Furthermore, the possibility must be considered that damage may be caused by a 'trigger' effect whereby an already weakened component may fail at an earlier stage than would have occurred in the absence of traffic vibration. In addition to these direct causes of damage, it is also possible that damage occurs indirectly as a result of vibration aided compaction of soils beneath the foundations of buildings. Such assisted settlement, if occurring, could lead to progressive damage of buildings, particularly if the foundations settle at different rates in relation to the vibration stresses occurring in the soil. For example, vibration levels will generally be higher at the front of the building than at the rear. Buildings which are at greatest risk from settlement are those constructed without proper foundations on poorly consolidated soils. Differential settlement has been suggested as a reason why several larger churches and medieval cathedrals apparently lean towards the nearest heavily trafficked road (Crockett 1966), however, it is not possible with the available data to substantiate these claims.

3.2 PERCEPTIONS OF VIBRATION DAMAGE

It is quite clear that despite the evidence that traffic vibration does not produce stresses in structures which are large enough to cause damage directly, large numbers of people believe that it does. There is considerable anecdotal evidence, and the numbers of complaints and claims received by both the Departments of Transport and of the Environment as well as by the local authorities provide further evidence of this widespread view. In addition, there is more substantive evidence taken as part of a recent survey at fifty sites (Watts 1984) where residents were interviewed about their perceptions and concerns with vibration. At each site some thirty residents from different households were interviewed (ie a total of some 1500 interviews). The percentage of respondents who noticed traffic vibration in their homes is summarised in Table 3.

It can be seen that a large proportion observed windows and doors rattling and buzzing and perceived the floor shaking or trembling. Table 4 lists the percentage of residents who reported various types of damage thought to be caused by traffic vibration.
In addition it is necessary to determine and assess the type of damage occurring and to relate this to the mechanisms of damage which have been suggested.

No single experiment can be expected to yield all the answers to the questions raised. Furthermore, the techniques of assessing and measuring damage in buildings have yet to be developed for this application. It was, therefore, considered necessary to design and to develop appropriate techniques as part of a feasibility study with the hope that this would give an early indication of the extent of the problem and would give further guidance on the design of a second stage of experimentation.

Three different experiments were proposed:

1. **A fatigue study to be carried out on an unoccupied dwelling using simulated traffic vibration inputs.** The objective would be to isolate traffic vibration effects from other long term "environmental" effects and, in particular, to determine the levels of traffic vibration needed to cause damage of any classification in buildings, the location of this damage and the relative importance of ground and airborne vibration on the total damage caused.

2. **An assessment to be carried out using occupied dwellings in order to establish clearly whether excess damage due to traffic vibration occurs in real environments.** In this case the objective would be to compare the structural quality of buildings exposed to heavy traffic flows and high levels of vibration with essentially identical buildings located in a quiet area away from the traffic. Again techniques would need to be developed for assessing damage in occupied dwellings.

3. **An examination for evidence of trigger damage to be carried out in buildings located alongside a road in which traffic flows were about to increase.** A sample of buildings could be studied before and after the increase in traffic flow.

At present the first experiment to study damage mechanism using simulated traffic vibration on a test house has been completed and the results are reported here. The second experiment to study damage in occupied houses is in progress.

Hood and Marshall (1987) describe the experimental method used to study the test house and Marshall and Hood (1987) and Watts (1987a) describe the results. It should be noted that very little damage was recorded in this house despite the fact that the simulated vibration levels were at the extreme end of the range observed in practice.

---

**TABLE 3**

Percentages of respondents who noticed various vibrations (all sites combined)

<table>
<thead>
<tr>
<th>Vibration effect</th>
<th>Percentage noticing effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows or doors rattling or buzzing</td>
<td>62.2</td>
</tr>
<tr>
<td>Floors shaking or trembling</td>
<td>29.5</td>
</tr>
<tr>
<td>Ornaments rattling or buzzing</td>
<td>15.7</td>
</tr>
<tr>
<td>Traffic causing the bed to shake</td>
<td>13.6</td>
</tr>
<tr>
<td>Muffled sensation in the ears or fluttering in the chest</td>
<td>18.9</td>
</tr>
<tr>
<td>Feeling vibration in the air</td>
<td>30.2</td>
</tr>
</tbody>
</table>

---

**TABLE 4**

Percentages of respondents reporting damage thought to be caused by road traffic (Watts 1984)

<table>
<thead>
<tr>
<th>Damage reported</th>
<th>Percentage reporting damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof tiles falling or moving</td>
<td>31.6</td>
</tr>
<tr>
<td>Cracks in plaster on walls or ceilings</td>
<td>25.8</td>
</tr>
<tr>
<td>Cracks in brickwork</td>
<td>10.0</td>
</tr>
<tr>
<td>Cracked windows</td>
<td>19.9</td>
</tr>
<tr>
<td>Subsidence</td>
<td>13.7</td>
</tr>
<tr>
<td>Damaged foundations</td>
<td>7.6</td>
</tr>
</tbody>
</table>

A significant proportion reported minor damage such as cracked plaster or tiles falling off the roof while, surprisingly, 14 per cent reported that subsidence had occurred which could lead to more serious forms of damage. While it is clear that people do tend to overstate the evidence of traffic vibration damage, and the responses should, therefore, not be taken as evidence, by itself, of a significant effect, the data does provide a further reason, coupled with those given in the previous section for developing further research on this topic.

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**4 EXPERIMENTAL DESIGN CONSIDERATIONS**

Any research method has to overcome the very difficult nature of the problem. Damage from traffic vibration is likely to be slow acting, if occurring at all, in some cases requiring many years to develop into measurable effects. There are also many natural causes of damage and so the research method must be capable of isolating the vibration damage component from the many other factors which are acting simultaneously.
5 CONCLUSIONS

While, in general, the levels of traffic induced vibration in buildings are too low to cause damage directly, little is known about the possibility of long term exposures causing fatigue in parts of the structure or of the potential for traffic vibration to cause buildings to subside by compacting the soil beneath the foundations. Further research on these topics is currently being carried out at the Transport and Road Research Laboratory.

6 ACKNOWLEDGEMENTS

The work described in this paper forms part of the programme of the Transport and Road Research Laboratory and the paper is published by permission of the Director.

7 REFERENCES


PAPER 2
MONITORING THE EFFECTS OF SIMULATED ROAD TRAFFIC VIBRATIONS ON A TEST HOUSE—EXPERIMENTAL METHODS
by R A Hood and C Marshall (Travers Morgan Planning)

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1 INTRODUCTION

An experiment which was carried out under contract to the Transport and Road Research Laboratory was designed to investigate the effects of road traffic vibrations on house structures. An empty property was acquired and subjected to simulated groundborne and airborne traffic vibration. Adjacent to the vibration source, six test foundation strips were constructed and subjected to varying dead loads. Dynamic behaviour, movement and damage, in both the main structure and the foundation strips were closely monitored throughout the experiment. This paper describes the simulation and monitoring techniques employed. Further details are given in Hood and Marshall (1987). The reasons for carrying out the experiment are given in Nelson and Watts (1987).

2 EXPERIMENTAL ARRANGEMENT

The general layout of the site is shown in Figure 1. The test structure comprises a pair of semi-detached houses, approximately 80 years old, constructed of brickwork in lime mortar. The test foundation strips each consisted of 'H' shaped area of mass concrete surmounted by brickwork. They were arranged in two rows approximately three and six metres from the vibration source respectively. Loading was arranged to provide ground bearing pressures of half, one and two times that under the main structure in each set of three strips.

Trial pits were dug on the site before and after the simulation, to assess ground conditions and to evaluate soil densities. This work was conducted in order to assist in interpreting any settlement of the structure which occurred. The investigation showed the soil to be a loose to medium dense uniform sand, with a lightly cemented layer at a depth of approximately two metres. It was calculated that if the soil above the cemented layer were to densify during the experiment to optimum density a settlement of between 10 mm and 20 mm would result.

3 COMPUTER SYSTEM

This experiment called for a considerable amount of generation, collection and analysis of electrical signals. For these purposes, a CED Laboratory Interface linked
to a BBC microcomputer was employed. This system is capable of fast analogue to digital and digital to analogue conversion of signals on up to 16 channels.

For the simulation of airborne vibration, the system was operated using an inverse Fourier transform technique to generate a waveform of any chosen frequency content.

For vibration monitoring, data was captured on 12 channels from 4 geophone arrays. Analysis software was developed during the experiment. Facilities developed included: production of waveform amplitude envelopes, fourier analysis of waveforms and cross correlation of waveforms, permitting accurate assessment of wave speed.

4. SIMULATION

Building vibrations are generated by road traffic by two separate mechanisms. In simple terms, tyre contact with irregularities in the road surface leads to groundborne vibrations; engine and exhaust noise produces airborne vibrations. For this study, these two vibration sources were simulated independently of each other.

4.1 GROUNDBORNE VIBRATIONS

Monitoring of building foundations close to main roads has indicated that the groundborne component of traffic-generated vibration typically has the following characteristics:

- **Frequency** — in the range 5 to 30 Hz. The predominant frequency in any particular case depends upon the nature of the vehicle suspension and its loading.
- **Pulse duration** — up to a few tenths of a second, depending upon vehicle and number of axles.
- **Maximum amplitude** — the vertical component of vibration in building foundations adjacent to uneven road surfaces frequently exceeds 1 mm/s. Figures of 2-3 mm/s have been recorded in a few instances.

Simulation was achieved using a geophysical surface vibrator. This equipment is capable of vibrating the ground surface with verticle impulses of a selected duration and frequency. A suitable interface was required between the vibrator plate and the soil, both to prevent local soil failure, and to ensure that the passage of vibrations into the ground realistically modelled the effect of a lorry on a road pavement.

It was decided that this would be best achieved by the construction of a small area (5 m x 5 m) of flexible road pavement close to the structure under test, on which the vibrator would be mounted. The road pavement was built to withstand 7 million axles in accordance with the DTP Specification for Road and Bridge Works.
The waveform generated by the vibrator had the following characteristics (measured on the adjacent house foundations):

- **Fundamental Frequency**: 12-13 Hz
- **Pulse duration**: approximately 1 second, including rise and fall. The waveform typically included 8 reversals at peak amplitude which is broadly equivalent to 4 heavy goods vehicle axles.
- **Maximum amplitude**: 2.5 mm/s (vertical component)

Figure 2 compares the waveform produced by the vibrator with a typical roadside measurement of a heavy goods vehicle.

In addition to the generation of pulses as described above, the vibrator was used on a number of occasions to generate a waveform of continuously varying frequency, such that the dependence of response on frequency could be determined. These “frequency sweeps” ranged from 80 Hz to 10 Hz in a period of about 15 seconds.

### 4.2 AIRBORNE VIBRATIONS

Noise is generated by traffic over a wide frequency range. However, significant structural excitation only results from low frequency noise (up to about 200 Hz). Noise throughout this range is generated by vehicle engines and exhausts. For the large diesel engines fitted to heavy commercial vehicles vibration levels often peak in the 50–80 Hz region.

Simulation of airborne vibration was achieved by mounting four 18” Celestion loudspeakers in the wall of a high sided refrigeration lorry, parked adjacent to the house facade. These were powered by a 500 watt amplifier. The signal to the amplifier was provided by the CED 1401 Laboratory Interface.

Initially the system was used to generate a broad band signal, ranging in frequency from 0 to 200 Hz, and peaking in the 50–80 Hz range characteristic of heavy goods vehicles. Signal amplitude was monitored in the space between the vehicle housing the loudspeakers and the house facade. The signal was pulsed such as to produce a noise level of 110 dB during pulses and 100 dB between pulses.

The resulting vibration levels were lower than had been expected even in the window adjacent to the loudspeaker system. The broad band signal was replaced with a single frequency source at the resonant frequency of the window (27 Hz). In this way an “upper bound” experiment was carried out. The window vibration levels achieved were the highest possible for the particular noise level (110 dB). Therefore it could reasonably be assumed that they would equal or exceed any produced by traffic.

The pulse length used for the majority of the experiment was 2 seconds and the passage of approximately 500,000 vehicles was simulated.

### 5 VIBRATION AND NOISE MONITORING

Vibrations were monitored using four 3-dimensional arrays of geophones. Signals were recorded and analysed using the CED Laboratory Interface. The availability of fast data capture and extensive analysis made it possible to gain considerable understanding of how the structure was responding to the vibration stimulation. In all, vibration response was measured at 82 locations on the structure, 7 on the test foundations strips, and 10 elsewhere.

Noise was monitored using three systems: a B & K Sound Level Metre Type 2208; a CEL Environmental Noise Analyser Type 162 and CEL Level and Waveform Recorder Type 160. Noise levels were analysed using third octave band filters, and a Fourier analysis undertaken using the CED 1401.
Measurements were undertaken of noise level and character within the structure due to groundborne and airborne vibration sources, and an assessment was made of fenestration attenuation. The main measurements are described below:

(i) Response of structure to vibration simulation
With the vibrator operating normally, measurements were taken at 20 locations on the outside of the structure, and 9 locations internally. The purpose of this experiment was to assess the dynamic response of the main structural elements to the vibration. By assessing how the groundborne pulse moved through the structure, likely areas of stress concentration were identified. The excitation of floors and walls by the groundborne vibrations resulted in low-frequency noise within the houses. Noise levels were measured in all the front rooms with the vibrator alone operating, and a fine frequency analysis was performed. Noise and vibration levels in response to the airborne vibration source were similarly monitored.

(ii) Response of floor joists to groundborne vibrations
Subjective response of house occupants to vibration is often associated with the fact that suspended floors can amplify vibrations. Measurements were carried out to assess the dependance of floor response on the frequency and amplitude of vibration to which it was subjected.

(iii) Vibrations due to normal use
The response of different parts of the structure to such activities as slamming doors and running down stairs was measured in order to put the traffic-generated vibrations into context. The levels of noise and vibration in the structure due to external sources (primarily traffic) prior to the start of the experiment were also measured.

### 6 MONITORING OF MOVEMENT

As well as monitoring dynamic behaviour, a number of techniques were employed to monitor changes in the condition of the structure during the course of the experiment. Methods were used to assess movements of the structure, movements within the soil underlying the structure and changes in the pattern of cracking. Details of individual techniques are given below.

All measurements of movement were carried out simultaneously on a series of selected dates. The following table lists the amount of vibration exposure which had occurred at each measurement stage:

<table>
<thead>
<tr>
<th>Measurement Stage</th>
<th>Number of vibrator pulses completed</th>
<th>Percentage of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.</td>
<td>20,000</td>
<td>2</td>
</tr>
<tr>
<td>3.</td>
<td>42,000</td>
<td>5</td>
</tr>
<tr>
<td>4.</td>
<td>85,000</td>
<td>10</td>
</tr>
<tr>
<td>5.</td>
<td>164,000</td>
<td>19</td>
</tr>
<tr>
<td>6.</td>
<td>317,000</td>
<td>36</td>
</tr>
<tr>
<td>7.</td>
<td>568,000</td>
<td>63</td>
</tr>
<tr>
<td>8.</td>
<td>888,000</td>
<td>100</td>
</tr>
</tbody>
</table>

### 6.1 LEVEL SURVEY

In order to assess whether any heave or settlement was occurring, levelling stations were installed at 36 locations on the structure. These were levelled using at Wild N3 level and an Invar staff, with which it was possible to resolve movements in the foundations of ±0·3 mm.

### 6.2 MOIRE PHOTOGRAPHY

To determine whether or not any differential movement was occurring within the structure, the N. P. L. system of high resolution Moire photography was employed (Birch and Forno 1982). Specially prepared paper printed with a fine grid of lines was attached to the front facade of the house and photographed with a modified 35 mm camera. When two negatives produced on different dates were overlaid, interference fringes were produced which related to movements of the structure. By this technique, differential movements in the plane of the facade were resolved to 0.2 mm.

### 6.3 CRACK SURVEY

During the preparation of the houses for the experiment, all wallpaper and ceiling finishes were removed. This revealed very extensive existing cracking in the plaster. Due to the extent of the cracking, it was not possible to accurately measure and monitor every crack. Instead, 40 existing cracks in various locations were selected and monitored for movement with a Demec gauge. In addition, the location of every significant crack was recorded on a plan or elevation of the relevant facade. On each measurement day, an inspection was carried out, and any further cracking recorded.

### 6.4 SOIL MOVEMENTS

The level survey was intended to measure settlement of the structure. Such a settlement could develop by three mechanisms:

1. Settlement directly under the vibrator pad extending to the soil beneath the structure.
2. Soil densification below the house footings.
Soil particle movements, perhaps without change in density, within a "log-spiral" zone under each footing. A log spiral is the curve along which a failure surface would typically develop within the soil. Slight shearing along such a surface could lead to settlement.

In order to assess which mechanism was responsible for any observed settlement and to corroborate the results of the level survey, two techniques were employed for monitoring movements within the soil.

(i) Electrolytic levels

Electrolytic levels measure change in inclination. For this study, six such levels were positioned at intervals along each of two horizontal boreholes. The boreholes were about one metre below ground level. Borehole locations are shown on Figure 1. Soil movements were calculated by integrating the measured inclination changes. This technique was developed at the Building Research Establishment (Cooke and Price 1974) but has never previously been used in a sand deposit. We assessed the accuracy of the system to be better than ±0.1 mm.

(ii) Magnetic Extensometers

Magnetic Extensometers consist of a series of magnets embedded in the soil, a plastic guide tube, and a probe. The probe is passed up and down the guide tube in the soil and detects null points in the magnetic fields. This enables relative vertical movements within the soil to be deduced. For this study, systems were installed and operated by Soil Instruments Limited, Uckfield, Sussex. The accuracy claimed for the system was ±0.1 mm. Four extensometers were installed, each to a depth of 4 m (see Figure 1).

By using the above techniques the degradation of a building due to the effects of road traffic noise have been studied. The results of this work are given by C Marshall in a subsequent Paper (1987).

7 ACKNOWLEDGEMENTS

The authors of this report are employed by Travers Morgan Planning. Work reported herein was carried out under a contract placed on them by the Transport and Road Research Laboratory. The views expressed are not necessarily those of the Department of Transport.

8 REFERENCES


MONITORING THE EFFECTS OF SIMULATED ROAD TRAFFIC VIBRATIONS ON A TEST HOUSE—RESULTS

by C Marshall and R A Hood (Travers Morgan Planning.)

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Abstract

This paper describes the results from an experiment studying the effects of road traffic vibrations on buildings. A vacant house founded on loose sand was subjected to simulated traffic vibration over a period of four months. During exposure to vibration, the dynamic behaviour of the structure was monitored in several locations. At regular intervals, a number of techniques were employed to measure long term movements in the structure and the underlying soil. In addition any damage that occurred was measured. In the paper the results of the experiment are presented. Possible damage mechanisms are postulated in the light of the small amount of damage actually recorded. Distinction is made between the effects of airborne and groundborne vibration and between trigger and fatigue damage. Conclusions are drawn regarding risks of building damage from traffic induced vibration.

1 INTRODUCTION

An experiment which was carried out under contract to the Transport and Road Research Laboratory was designed to determine whether simulated traffic vibration caused damage to a specimen house and if so, what damage mechanisms were involved. The structure selected for the study comprised a pair of semi-detached houses, approximately 90 years old, founded on a loose to medium dense sand. Vibration simulation was split into two parts. Airborne vibration was simulated by a loudspeaker system, mounted in the side of a lorry and connected to a computer. Groundborne vibration was achieved using a geophysical vibrator which impacted the ground.

The aim of the work was to assess whether road traffic vibration caused damage to houses. In order to make this assessment, four types of monitoring were carried out. These comprised a site investigation, a structural survey, a programme of vibration monitoring, and periodic measurements of movement and damage. Full details of the techniques employed are provided in the previous paper (Hood and Marshall 1987). Further results on the response of building elements to the simulated vibrations are given in Watts (1987).

2 VIBRATION MONITORING

2.1 RESPONSE OF STRUCTURE TO GROUNDBORNE VIBRATION

The vibrations of the front facade of the structure in vertical and radial directions, with respect to the vibrator were studied. The peak levels measured are plotted on Figure 1.

On the foundations the vertical component attenuates with distance approximately in accordance with an inverse square root function. The pattern is mirrored at eaves level with some amplification, which is probably associated with the reduced dead load. This
smooth response is unlikely to have introduced any severe stress concentrations into the structure.

The radial component demonstrates a very different pattern of behaviour. On the foundations, no significant attenuation is present. At eaves level, vibration peaks at either end of the structure, with a drop in level towards the middle. This pattern suggests that the main transmission of energy is taking place through the foundations.

At eaves level there is a large change in radial vibration level between the end of the structure and the adjacent measuring position. The restraint afforded by the chimney is probably a major cause of this. Such a sudden change in vibration level is likely to be associated with stress concentration.

Figure 2 plots the time taken for the wave front to reach each geophone station against distance from the vibrator. This shows radial component to be travelling approximately 25 per cent faster than the vertical component.

Measurements were also undertaken on individual structural elements. The end wall of the structure was found to be vibrating at up to 11 times the amplitude measured on its foundation. New cracks were observed internally both on this wall and at the adjacent wall/ceiling joint.

2.2 RESPONSE OF STRUCTURE TO AIRBORNE VIBRATION

The airborne vibration source gave a noise level of 110 dB(A) outside the window and 92 dB inside. A peak vibration response of 131 mm/s was measured on the window pane adjacent to the noise source. However, the highest vibration level resulting elsewhere within the structure was less than 2.5 mm/s (in a suspended floor). Response of the house foundation was negligible. No damage was recorded. Since the simulation of airborne vibration was devised as a 'worst case', we conclude that in general any damage resulting from this source would be superficial. For even slight damage to occur, stress concentrations would probably have to be present prior to exposure.

3 MONITORING OF MOVEMENT

3.1 LEVEL SURVEY

Some scatter occurred in the results of the level survey, limiting its accuracy to approximately 0.3 mm. Within this range no detectable settlement or heave occurred at any time during the experiment.

3.2 INTERFEROMETRIC PHOTOGRAPHY

This technique showed a lateral movement of 0.4 mm in one small area of the house facade. However, the resolution of the system is only ± 0.2 mm, rendering this result only just significant.
3.3 CRACK SURVEY
A small amount of additional cracking of plaster occurred during the experiment, mostly at wall/ceiling junctions. Of the 40 existing cracks surveyed for movement, only 5 showed a sustained change in width exceeding 0.1 mm. First floor ceiling crack patterns are shown on Figure 3.

3.4 SOIL MOVEMENTS
Although a settlement of 22 mm was recorded within the soil under the vibrator pad, little movement was evident beneath the house foundations. Figure 4 shows the movements recorded by one of the electrolevel strings. In contrast, settlements in the range 1–11 mm were measured on the test strips. The pattern of these settlements is shown on Figure 5.

All six test strips tilted to some degree. In each case, two levelling stations were monitored. The settlements measured are tabulated below:

**TABLE 1**

<table>
<thead>
<tr>
<th>Strip ref</th>
<th>Vibration Level Ratio</th>
<th>Near edge to vibrator (mm)</th>
<th>Far edge from vibrator (mm)</th>
<th>Settlement Ratio (max/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>2.0</td>
<td>14.0</td>
<td>7.0</td>
<td>2.0</td>
</tr>
<tr>
<td>A2</td>
<td>1.2</td>
<td>2.1</td>
<td>2.4</td>
<td>1.1</td>
</tr>
<tr>
<td>A3</td>
<td>0.6</td>
<td>1.6</td>
<td>1.9</td>
<td>2.7</td>
</tr>
<tr>
<td>B1</td>
<td>1.2</td>
<td>1.4</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>B2</td>
<td>1.3</td>
<td>1.4</td>
<td>1.7</td>
<td>1.2</td>
</tr>
<tr>
<td>B3</td>
<td>2.0</td>
<td>1.4</td>
<td>1.2</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Note: Dead Load and Vibration Level ratios are absolute values divided by corresponding values on house foundation.
3.5 FINAL SITE INVESTIGATION

At the end of the experiment, a second site investigation was conducted, to assess the density of the soil beneath the vibrator, the house foundation and the test foundation strips. In all locations, the measured densities fell within the range assessed for the site prior to the simulation. (See Figure 6).

4 SUMMARY OF POSSIBLE DAMAGE MECHANISMS

The following mechanisms for vibration-related damage to buildings are suggested:

(i) Compaction or migration of soil resulting in differential settlement and damage.

(ii) Damage to structural elements due to high local vibration levels. This could occur either as 'trigger damage' or as a fatigue effect.

(iii) Damage due to changes in structural stiffness or mass, leading to sudden changes in vibration level.

(iv) Damage to plaster at wall/ceiling joints due to vibration of floor and ceiling joists.

(v) Roof damage, due to high vibration amplitude in rafters.

(vi) Damage to windows and surrounding plaster due to airborne vibration.

5 DISCUSSION

5.1 SOIL MOVEMENTS

Very little movement of the test structure or the underlying soil was recorded despite a potential for up to 20 mm of settlement by densification of the soil.

The test foundation strips, however, did settle, by varying amounts. No soil densification was recorded anywhere on the site. It therefore appears that the vibration levels being generated were insufficiently high to densify this particular soil.

The settlement under the test foundation strips appeared to be associated with localised rotational movements within the soil. The main structure was unable to undergo similar movements due to the difference of scale. A shearing plane beneath one of the test strips would be contained within the top layer of loose uncemented sand. For part of the house to rotate in a similar fashion, soil mobilisation would be necessary to a greater depth.

There may be other circumstances in which settlement of a full sized structure might occur. These are summarised below:

(i) Different soil types eg saturated sand, soft clay or peat.

(ii) Other ground conditions, eg no cemented layer.

(iii) Different structural conditions. Individual footings of the test house were unable to rotate due to the restraint afforded by the structure. Had any single facade been poorly supported, localised rotational settlement might have occurred.
5.2 MOVEMENTS WITHIN THE STRUCTURE

The most significant movements within the plaster (new cracks or movements in existing ones) occurred in the end wall of the house facing the vibrator, and in ceilings close to the chimneys. The overall level of damage was very slight. It is probable that in a normally decorated house, none of the damage recorded would have become evident.

The slight movements which did occur appear to have been as a result of a fatigue effect since they appeared relatively late in the simulation period. No ‘trigger damage’ was recorded in the experiment. This may have been due to the extensive cracking which already existed, which would have relieved any stress concentrations within the plaster.

6 CONCLUSIONS

This study involved an extensive and wide ranging series of experiments. However in drawing conclusions from the work the particular characteristics of the site must be borne in mind as they will have had a considerable effect upon the results recorded.

Damage to buildings caused by road traffic vibrations will, in our opinion, result from: differential settlement in the underlying soil; trigger damage, or fatigue effects. In this experiment only the last of these three mechanisms was observed, and the resulting damage was limited to slight cracking of plaster. Bearing in mind the particular site conditions and the limited damage actually observed the following conclusions can be drawn:

(i) Airborne vibration from traffic is unlikely to lead to structural damage. Windows and nearby plaster under stress could be damaged by trigger mechanisms though none were generated during this study.

(ii) It is unlikely that structural damage would result directly from traffic vibration except in cases where settlement or trigger damage occurred.

(iii) The test structure suffered no ‘trigger’ damage. In a house with less extensive plaster cracking the risk of vibration induced trigger damage to plaster would be greater. We consider that structural damage is highly unlikely to result from this mechanism.

(iv) Differential settlement had been predicted prior to the experiment, but none was actually recorded. This appears to have been a function of the particular conditions existing on the site. Other soil types and geometries exist in which differential settlement would be more likely, and under such circumstances some damage might result. Even on a soil such as that at the test site, it is possible that settlement might have been observed due to localised rotational movements had the facades of the structure been less well tied together.

(v) Previous work in the field of vibrations and buildings suggests that maximum nuisance to occupants is caused by rattling windows and vibrating floors. The vibration monitoring work undertaken during this experiment showed that these effects are not directly related to vibrations in foundations and walls. Therefore an increase in traffic related nuisance does not necessarily imply an increase in the risk of damage. In our view, for any risk of damage to exist at all due to traffic induced vibration, considerable nuisance would have to be present.

7 ACKNOWLEDGEMENTS

The authors of this paper are employed by Travers Morgan Planning. Work reported herein was carried out under a contract placed on them by the Transport and Road Research Laboratory. The views expressed are not necessarily those of the Department of Transport.

8 REFERENCES


ABSTRACT

A test house was subjected to simulated groundborne and acoustically coupled vibrations as part of a programme of research into the effects of traffic induced vibrations on buildings. This paper describes the response of the structure to this exposure and to energetic activity within the house and to actual vehicles travelling on the road near the front facade.

The response of the house was monitored using triaxial geophone arrays and strain gauges. The geophones allowed the calculation of the peak particle velocity (PPV) in three directions. Strain gauge measurements were used to determine the amount of movement taking place at significant cracks in the plasterwork. Measurements of PPV were taken on floors, internal and external walls, ceilings and windows at various levels throughout the building.

Results showed that the building responded strongly to the simulated groundborne vibration which produced PPVs in excess of 10 mm/s in an upper floor. Responses to acoustically coupled vibrations were generally lower and localised near the source. Maximum crack movements occurred close to the groundborne vibration source. Displacements were small with maximum amplitudes less than 50 microns.

1 INTRODUCTION

An unoccupied dwelling was subjected to simulated groundborne and airborne vibrations as part of a programme of research into quantifying the effects of traffic induced vibrations on buildings. This paper describes the response of the structure to this exposure in terms of peak particle velocity and crack movements.

The building consisted of a pair of semi-detached houses approximately 80 years old built on medium to loose sand. The groundborne vibrations were produced by a geophysical vibrator located approximately 2 m from the side wall at the right hand side of the building. Levels were adjusted so that the peak vertical velocity at foundation level was in the range 2.5-3.0 mm/s. This is at the extreme end of the range of peak velocities measured in buildings close to large roadside irregularities during the passage of heavy vehicles [Watts 1987]. The driving frequency was adjusted to approximately 13 Hz which is within the range found in practice and produced a relatively large response in the structure. Figure 1(a) and (b) show the time history and frequency content of a typical pulse. The house was exposed to 880 000 pulses simulating the effect of over 3.5 million goods vehicle axles.

![Fig. 1 Vertical particle velocity at foundations adjacent to vibrator](image-url)
Airborne vibrations were produced by four Celestion speakers mounted in the sides of a lorry parked close to the left hand side of the front facade. The speakers were driven by a 500 W amplifier and the signal was generated by a CED computer. A broad range of frequencies were first produced in order to simulate general traffic noise but it was found that the various building elements vibrated at a very low level. Tests showed that resonances in the ground floor window and floor could be excited by a narrow range of frequencies centred in the 25 Hz third octave band (figure 2). The peak level was adjusted to approximately 110 dB producing an exposure which was considered to have a damage potential at least as large as that produced by heavy goods vehicles passing close to the facade under the worst operating conditions. The pulse length selected was 2 seconds and the passage of approximately 500 000 such vehicles was simulated.

2 INSTRUMENTATION AND ANALYSIS

Measurements of particle velocity were made in three orthogonal directions using long travel geophones (sensitivity 27 mV/mm/s). These were attached using either Plaster of Paris or steel angle brackets. The signals were conditioned using a bank of operational amplifiers the input impedance of which was adjusted to give a level frequency response in the range of interest i.e 5-100 Hz. The signals were recorded on a FM tape recorder and time and frequency domain analyses were carried out using a Hewlett Packard digital signal analyser, computer and plotter. Time domain analysis allowed the particle velocities in three directions and the corresponding resultant to be plotted and maximum values computed. Cross correlation of signals from separated geophone arrays was employed to determine the propagation velocity of both compression and shear waves. Linear fourier transforms were computed at a resolution of 0.39 Hz and used to establish the principal frequency components and associated harmonics. Sound recordings were made with a ½ inch microphone and third octave analysis was carried out using a Bruel and Kjaer digital third octave analyser. Crack movements were measured using a TML strain gauge which allowed movements of 1 micron to be resolved.

3 RESPONSE TO GROUNDBORNE VIBRATIONS

Investigations showed that the response of the building to groundborne vibrations was complex. This was partly due to the fact that the building was not subject to plane waves since the vibrator was positioned only 2 m from the side wall. In addition the forcing frequency was not purely sinusoidal since it included a number of significant harmonics (see figure 1(b)). As expected it was found that suspended wooden floors and ceilings were among the building elements.
showing the greatest response. Triaxial measurements were made in the middle of floors, on roof joists and on the floor of the cellar. Figures 3(a) and (b) show the variation of vibration level between the various measurement positions. There is a clear trend of increasing level with height for both vertical and radial components which is likely to be due to the decreasing dead load and restraining influence of the ground and changes in the mass and stiffness of the suspended floors. Although vertical levels decay rapidly with horizontal distance, radial and transverse components do not. It appears that vertical shear waves are more greatly influenced by the damping in the underlying soil. Levels on the external brickwork of the front facade followed broadly similar trends although absolute levels differ.

The highest levels were recorded in the first floor room adjacent to the vibrator where the most obvious damage to the building occurred. This was limited to a number of hairline cracks in the lath and plaster walls and ceiling and a small piece of loose plastic was dislodged. No structural damage had occurred. Figure 4 shows a plan of this room which is labelled A in figure 3(a). Numbers 1 to 9 and labels a to f refer to geophone and strain gauge monitoring positions respectively. Tables 1 and 2 list the peak velocities and crack movements that were recorded. It can be seen from table 1 that the highest levels occurred on the window pane and in the middle of the ceiling. The vibration level on the chimney breast (position 5) was substantially less than on the opposite wall (position 2) and this was probably due to the high mass and stiffness of this structure. These vibrations were in phase and because of the difference of velocity (4.1 mm/s) a maximum displacement of 50 microns was expected across the ceiling on each cycle. Strain gauge measurements showed that virtually all this movement was accommodated at two cracks (d and f) one of which had developed during exposure (see table 2). These were the highest measured crack movements in the building.

4 RESPONSE TO AIRBORNE VIBRATION

Table 3 lists the peak levels of vibration in rooms most affected by the airborne vibrations (see figure 5).

The linear sound pressure levels measured at a height of 1.2 m above the middle of the ground and first floor rooms were 98.6 and 89.5 dB respectively. The ground floor responded poorly due to the restraining influence of brick sleeper walls under the joists. The peak level on the suspended floor above was nearly 2.5 mm/s due to the fact that its natural frequency was close to the driving frequency. The highest level of over

<table>
<thead>
<tr>
<th>Measurement position</th>
<th>Axis of measurement</th>
<th>Peak velocity (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Middle of wall</td>
<td>Transverse</td>
<td>2.85</td>
</tr>
<tr>
<td>2. Middle of wall</td>
<td>Radial</td>
<td>7.17</td>
</tr>
<tr>
<td>3. Middle of wall</td>
<td>Transverse</td>
<td>6.46</td>
</tr>
<tr>
<td>4. Lower pane in window</td>
<td>Transverse</td>
<td>41.53</td>
</tr>
<tr>
<td>5. Middle of chimney breast</td>
<td>Radial</td>
<td>3.10</td>
</tr>
<tr>
<td>6. Middle of ceiling</td>
<td>Vertical</td>
<td>19.37</td>
</tr>
</tbody>
</table>
TABLE 2
Peak crack movements

<table>
<thead>
<tr>
<th>Measurement position</th>
<th>New/old crack</th>
<th>Axis of measurement</th>
<th>Peak displacement (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Near middle of wall</td>
<td>New</td>
<td>Vertical</td>
<td>4.0</td>
</tr>
<tr>
<td>b. Wall near floor</td>
<td>Old</td>
<td>Transverse</td>
<td>9.1</td>
</tr>
<tr>
<td>c. Wall close to ceiling</td>
<td>Old</td>
<td>Vertical</td>
<td>16.4</td>
</tr>
<tr>
<td>d. Ceiling</td>
<td>New</td>
<td>Radial</td>
<td>20.5</td>
</tr>
<tr>
<td>e. Wall close to ceiling</td>
<td>Old</td>
<td>Vertical</td>
<td>16.3</td>
</tr>
<tr>
<td>f. Ceiling</td>
<td>Old</td>
<td>Radial</td>
<td>28.4</td>
</tr>
</tbody>
</table>

Table 3 shows the peak vibration levels due to noise source. 130 mm/s was produced on a ground floor window pane. This was expected since the source was adjusted to obtain resonance. Comparing levels at points 3 and 4 on opposite sides of a wall it can be seen that the lath and plaster responded more to airborne vibration than the much stiffer brickwork. Vibration levels produced by the acoustic source in other rooms were barely perceptible unlike the levels produced by the vibrator. For example the level on the chimney breast in the adjacent room was only 0.18 mm/s.

5 RESPONSE TO DOMESTIC ACTIVITY AND TRAFFIC

Household activities such as heavy footfalls and slamming doors can produce very large vibrations especially on the floors and ceilings close to the source. To determine the extent to which this vibration reaches the external brickwork triaxial geophone arrays were placed 4 m above the ground and at foundation level (positions 8 and 9 in figure 4). Vertical impulses to the floors were generated by jumping from a stool placed in the middle of the ground and first floor rooms. Horizontal impulses were provided by slamming the bedroom door on the first floor and the door to the side entrance on the ground floor.

From table 4 it can be seen that the largest resultant levels were produced by slamming doors and that the levels recorded at 4 m were always greater than at foundation level. It was expected that a vertical impulse on the ground floor would have relatively little effect because of the presence of sleeper walls under the joists.

To gauge the effects of traffic, a two axle lorry laden close to the maximum permissible axle loads was driven.
TABLE 4
Peak resultant vibration levels resulting from activities

<table>
<thead>
<tr>
<th>Activity</th>
<th>Location</th>
<th>Foundations (position 9 in figure 4)</th>
<th>4 m above ground level (position 8 in figure 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jumping from stool</td>
<td>Position 6 in first floor room</td>
<td>1.26</td>
<td>3.64</td>
</tr>
<tr>
<td></td>
<td>Position 7 in ground floor room</td>
<td>0.35</td>
<td>0.72</td>
</tr>
<tr>
<td>Slamming door</td>
<td>In first floor room</td>
<td>1.04</td>
<td>5.68</td>
</tr>
<tr>
<td></td>
<td>Outside door in ground floor room</td>
<td>3.12</td>
<td>7.04</td>
</tr>
</tbody>
</table>

past the site at various speeds. At the highest speed achievable, perceptible vibrations were generated as the vehicle crossed a sunken manhole cover 27 m from the measurement point. The peak resultant vibration was 0.32 mm/s at the foundations (position 9). On the first floor the highest level recorded (1.18 mm/s) was near the point closest to the irregularity (position 3). The highest recorded level at the foundations produced by general traffic was 0.66 mm/s.

6 CONCLUSIONS

The whole building responded relatively strongly to simulated groundborne traffic vibrations and vibration levels in the suspended wooden floors and ceilings on the first floor adjacent to the vibrator were among the highest recorded. Although these vibrations were very noticeable, and would be unacceptable to most occupants, crack movements were relatively small, the largest peak displacement being only 28 microns. It should be noted that changes in temperature and moisture content in walls and ceilings are known to produce movements much greater than this [Building Research Station 1966, Dowding 1985]. Acoustically induced vibrations were only perceptible in rooms close to the noise source and levels were generally below those produced by the vibrator despite the extreme nature of this simulation. Domestic activity such as slamming doors produced peak vibration levels in the hard structure of the building comparable to those produced by the groundborne vibrations. Vehicles passing the site produced relatively small but measurable vibrations, greater response being noted on the first floor.

7 ACKNOWLEDGEMENTS

The study formed part of the programme of research of the Vehicles and Environment Division of TRRL. The assistance of Mr Godfrey is gratefully acknowledged. The test house and vibration sources were prepared by Travers Morgan Planning under contract to TRRL.

8 REFERENCES

