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Publisher's version / Version de l'éditeur:

Bulletin of the Association for Preservation Technology, 14, 1, pp. 2-10, 1982

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EFFECT OF VIBRATIONS ON HISTORIC BUILDINGS: AN OVERVIEW

by J.H. Rainer

ANALYZED

Reprinted from
The Association for Preservation Technology Bulletin
Volume XIV, No. 1. 1982, p. 2 - 10

DBR Paper No. 1091
Division of Building Research

Price \$1.00

OTTAWA

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RÉSUMÉ

Nous sommes entourés de vibrations. Une bonne part d'entre elles proviennent de la nature elle-même (séismes, vent, vagues, etc). Avec le développement de la technologie, les sources de vibration se sont multipliées et sont devenues gênantes pour les occupants des bâtiments modernes et surtout pour ceux qui ont le désir et le devoir de préserver les bâtiments anciens. Cette note décrit les effets qu'exercent sur les bâtiments anciens un certain nombre de sources de vibration courantes. Parmi celles-ci on trouve notamment: la circulation sur les routes et les voies ferrées, les vols supersoniques, les travaux, le sablage, les séismes. Cette note présente des cas particuliers d'étude et propose des remèdes lorsque le niveau de vibration est excessif.

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EFFECT OF VIBRATIONS ON HISTORIC BUILDINGS: AN OVERVIEW*

J.H. Rainer**

Introduction

Vibrations surround us, for nature provides its own vibration sources such as earthquakes, wind and ocean waves. With the advent of the technological era, vibration sources have multiplied and have become a concern to residents of modern buildings and to those whose task and desire it is to preserve historic ones. A number of common vibration sources (including road and rail traffic, sonic boom, construction vibrations, blasting and earthquakes) and how they affect historic buildings will be discussed in this paper. In addition, case studies and possible remedial action where vibration levels are deemed excessive will be reviewed.

The literature concerning vibration effects on historic buildings is not abundant, especially that relating to permissible and safe vibration levels, and conclusive studies of damage from vibrations are rare. This is not surprising when one considers the complex nature of the problem and the interrelation among the many environmental factors that cause deterioration of historic buildings. It is often impossible to separate vibration effects from the detrimental effects of atmospheric pollution on mortar and stone, wetting and drying, freezing and thawing, and other seasonal and daily dimensional changes caused by heating and cooling. Changes in the water table due to removal of moisture by trees or drainage works, with subsequent damage to foundations, etc., can also be a cause of distress for buildings.

Vibrations are most frequently blamed for deterioration of historic buildings while other detrimental effects are apparently ignored. This may be ascribed to the fact that the human being is very sensitive to vibrations and becomes alarmed at levels generally well below the danger level for most buildings.

Vibration effects on historic buildings are similar to those for ordinary buildings and structures, although some added complications and uncertainties may be encountered. These arise for the following reasons:

1. Historic buildings are generally older and may not be structurally sound.
2. Building materials and structural configurations differ from these in current use, so that modern criteria may not be applicable.
3. Both monetary and non-monetary values associated with historic buildings necessitate greater assurances against damage or failure.
4. Possible long-term effects from past and future exposure need to be addressed.

Experience gained from modern buildings can be used if modified to account for the above differences. Because a large number of unknown or non-quantifiable aspects are involved, the need for sound judgment is particularly great.

Traffic Vibrations

Vibrations arising from road and rail traffic and its effect on historic buildings have become a subject of concern in recent decades, in Europe as well as North America. Major traffic arteries pass near ancient cathedrals, castles and other structures that are hundreds of years old, so that many are subjected to constant, easily perceptible vibrations. Reports in the press in recent years have drawn attention to traffic restrictions in effect near the Colosseum in Rome and in other historic sections of European cities to prevent further deterioration of architectural treasures from traffic-induced vibrations.

The detrimental effects of traffic vibrations need to be viewed in perspective. If one examines competent old and new structures that are subjected to perceptible vibrations, using present methods of mechanics and theories of strength of materials, one comes to the conclusion that the additional dynamic loads imposed by traffic vibrations cause only a small fraction of the stresses already imposed by the structure's own weight, by wind forces and temperature changes. But frequently, the materials in the building have de-

* Presented at the Annual Conference of the Association for Preservation Technology, 29 September – 4 October 1980, Quebec City, Canada.

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TABLE 1
Suggested Effect of Traffic Vibrations on Masonry Buildings
(Adapted from Bata⁵)

Category	Average Acceleration, g (mm/s ²)	Location of Building	Traffic Density (veh/day)	Danger of Crack Origin
a	<0.005	on secondary road	—	none
b	0.005-0.010	>10m from main road	<2000	none in next few decades
c	0.005-0.010	near main road	>2000	probable in next few decades
d	0.010-0.020	near main road	>2000	probable in next 1 or 2 decades
e	>0.020	near main road	>2000	certain within next few years

teriorated and weakened, so that added stresses from low levels of vibration constitute a greater proportion of the available strength reserve and could therefore contribute to further deterioration and even cause eventual collapse. In other words, vibration effects could accelerate the process of deterioration initiated by other causes. As almost every building is subjected to different environmental effects and is at different stages of strength deterioration, a unified treatment of vibration effect cannot be expected to be successful and a case-by-case approach is necessary.

The effects of traffic vibrations on buildings, as for most other vibration problems, can be conveniently divided into three components: source, transmission path and receiver. This simplifies the consideration of cause and effect and subsequent discussion of remedial actions.

i) Vibration Source

Rolling wheels on an elastic or imperfect contact material generate waves that then propagate downward and outward. The principal variables that effect vibration amplitudes are vehicle speed and weight, type of vehicle suspension, roughness of the rolling surface, and the stiffness of the wearing surface and sub-base.

ii) Transmission Path

Waves generated at the source propagate outward through the ground. They are attenuated in the soil over distance and by material damping effect. Sometimes, however, they can be channelled in a certain direction, owing to layering of the soil, in such a way that there will be little attenuation or even some amplification. Soft and saturated soils transmit vibrations more readily than sandy, dry ones. While rock readily transmits vibrations, the small amplitudes generated and the high frequencies of the propagated waves usually pose little danger to a building's integrity.

iii) Vibration Receiver

For present purposes, the vibration receiver is the historic building under consideration and the occupants within it. After vibrations enter the building through the foundations, they may amplify by factors of from 2 to 5 in propagating to higher storeys. This will depend on the nature of the vibration (the frequency content) and the vibration susceptibility of the building component (beam, wall, floor, windows, etc.) as governed by the natural frequency and damping. Vibrations can induce secondary effects such as rattling of dishes or other furnishings, acoustic radiation from components and direct annoyance of the occupants.

Remedial Action

Unacceptably high vibrations can be reduced at the source, in the transmission path, or at the receiving end. The suitability of any one or a combination of these actions will depend on the circumstances that present themselves.

The vibration source can be treated as follows: traffic can be re-routed and thus eliminated altogether; heavy vehicles can be restricted; speed of vehicles can be reduced; surface irregularities (potholes, manhole covers, washboards, cobblestones, etc.) can be eliminated or minimized by road improvements or re-surfacing; stiffness of the road surface and its sub-base can be increased and isolation pads

over limited sections of a road can be installed¹; rails of subways or surface lines can be cushioned by rubber-like materials². Examples of cushioning can be found in the Washington and Toronto subways; the Paris and Montreal subways have adopted rubber tires and thereby reduced vibration and structure-born noise levels considerably.

Remedial measures applied to the transmission path include trenching between vibration source and building, followed by backfilling with a slurry; and piles or holes can be placed in specific geometric patterns between the source and the receiver³. These measures are generally difficult to carry out and are, perhaps, the least effective.

Vibrations arriving at and propagating through a building can sometimes be reduced by use of damping strips or tuned dampers; the resonance frequency and, therefore, the vibration behaviour can be changed by stiffening or bracing a component; or a building or component can be placed on flexible supports⁴. It is recognized, however, that although the latter is possible in principle and would be theoretically effective, placing an existing building on flexible supports is generally not practical.

Long-Term Effects of Vibrations

Although traffic vibrations may not cause deterioration in the short term, there is some concern about long-term effects on historic buildings. Two possibilities stand out as potential problem areas: building material fatigue and building foundation settlement.

Fatigue, as the name implies, is a "tiring" of the material when high loads are applied repeatedly. Strength decreases and failure can occur at load levels well below those that cause failure under only a few load cycles. For steel and concrete, fatigue behaviour is reasonably well-quantified, and strength reductions from 30% to 50% over millions of load cycles have been observed. For brick, mortar or stone, fatigue effects are not well known. A further complicating factor is the possible interaction of stresses from loads and vibrations and from other deteriorating factors such as chemical pollutants.

Following studies of vibration effects on historic buildings performed at the Technical University of Prague, Bata reported the collapse of a church in Hustokece, placing the blame directly on traffic⁵. The mortar is said to have pulverized and lost all adhesion to the stones. Vaults located near the roadway passing the Saint Thomas Church in Lesser Town of Prague have also exhibited cracks. On the basis of these and many other observations, the likelihood of cracking in masonry buildings have been estimated and is presented in edited form in Table 1. The team from the Technical University of Prague has also proposed a scale of reduction to the life of regular buildings, based on the effective traffic density⁶.

Other reports of the damaging effects of long-term exposure to vibrations are those of the Villa Farnesina in Rome⁷, where the fresco "Triumph of Galatea" by Raphael is said to have sustained numerous cracks. As a remedial measure, a 60-meter stretch of road in front of the villa was reconstructed on rubber isolation pads.

In Britain, Crockett has studied numerous old churches near roadways⁸. Distortions of the structures were found to

be more pronounced on the side near the road. It should be recalled that vibrations have been present there over many centuries, starting with the carts and wagons used in the Middle Ages. The vibrations are said to have caused fatigue in the stone masonry construction.

A second possible long-term detrimental effect of vibrations on historic structures could be the settlement of soils adjacent to roadways and buildings. Those constructed of masonry or stone are sensitive to small deformations, and differential local settlements of soil could cause cracking and initiate a process of progressive deterioration. Unfortunately, little is known in a quantitative way of the long-term compaction of soils from low vibration levels.

The foundation of the Palace of Art in Budapest is reported to have settled due to continuous exposure to vibrations⁹. Although other contributing factors are mentioned, such as the shallow foundation and the decomposition of an organic layer of soil, cracking of the walls is directly attributed to vibrations.

Whereas in these and other case histories, the influence of vibrations has been singled out as the major deteriorating effect on the structure, little direct evidence has been presented in support of this conclusion. Other possible damaging effects have apparently not been investigated or considered, or at least have not been reported in the literature. Thus, there is a lack of convincing documented evidence in support of the contention that long-term exposure to low, but nevertheless perceptible levels of vibration is detrimental to both old and new buildings that are competent structurally.

Sonic Boom

Sonic boom (or sonic bang as it is called in Britain) results from supersonic travel of aircraft. Damage to buildings, particularly historic ones, was under intensive study in the 1960's and early 1970's, but has now subsided since commercial supersonic aircraft have not proved to be economically viable. Military aircraft, however, still break the sound barrier and commercial supersonic transports may be revived in the future.

Sonic boom is characterized by a sudden pressure rise in the air, followed by a gradual drop to an equal and opposite pressure, forming a saw-toothed pulse¹⁰. The over-pressure effects considered here are those produced by supersonic aircraft flying at 10,000 metre elevation or higher.

Many studies have been carried out in Britain, France, the United States, Canada and other countries on the effect of sonic boom on buildings. Historic structures, such as cathedrals, have been studied intensively¹¹. It has been concluded that sonic booms can produce vibrations in cathedral vaulting, ceilings and windows that are an order of magnitude larger than those from organ playing, traffic or bell ringing; whereas in walls the vibrations produced are of magnitudes similar to those from traffic or bell ringing. Although these levels are smaller than the vibration levels that can cause damage to structurally sound buildings, their long-term effects are less certain; traditional stress analysis and fatigue theory, taking into account the number of cycles and duration of loading, indicate no substantial fatigue

1. Damage criteria for blasting vibrations.

effects on traditional structural materials such as masonry, steel and wood. How window glass and other brittle materials such as plaster are affected in the long term is somewhat uncertain, since the mechanism of repeated loading, or aging, is not well understood. In general, however, such brittle materials are the most vulnerable to sonic boom.

From other studies carried out on damage effects of sonic booms on buildings¹², the tentative conclusion has been reached that a cumulative damage level does exist for components of ordinary buildings (walls, ceilings). Plaster cracks in walls tend to be very fine and to close again after passage of the boom; the plaster would deteriorate with time by progressive cracking, although no evidence of damage might exist initially. Cracks first start in corners of openings that constitute stress raisers. Buildings with weakened materials, poor mortar or cracked walls could then expect further deterioration.

It follows from these and other studies on buildings that sonic boom causes vibration levels up to an order of magnitude larger than common vibrations from traffic, wind and bell ringing in church towers. Such levels are not considered detrimental to the durability of main structural elements, but they can produce damage to brittle components, such as plaster or glass, particularly at corners or cut-outs, where stress raisers exist.

Blasting Vibrations

Blasting vibrations differ from traffic vibrations in that they are generally of higher magnitude, of short duration, of higher frequency and of rapidly decaying amplitude. Vibrations from blasting are a fairly common disturbance for historic buildings since blasting is often employed on excavations for neighbouring building foundations, roads, underground services and subways.

Maximum permissible blasting levels for regular buildings have been determined from extensive series of con-

trolled tests¹³ and from field experience in many countries. For ordinary houses in the U.S. and Canada, a safe level of blasting for basement walls has long been 51 mm/s (2 in./sec.), measured normal to the wall (Fig. 1). For special construction and massive components, higher values have been used with success¹⁴. Sweden has adopted vibration levels of 75 mm/s (~3 in./sec.), based on their experimental results. Germany, on the other hand, has specified 30 mm/s

soil, as well as possible sensitive contents. Permissible values should then be established, based on specific circumstances. Some rather large variations of permissible vibration levels employed in past construction projects are illustrated in Table 4. During subway construction near St. Stephen's Cathedral in Vienna, vibration limits in the cathedral were prescribed barely above the human perception level¹⁷, whereas those in downtown Montreal¹⁸ were

TABLE 2
West German Vibration Criteria for Blasting
(DIN 4150 – September 1975)

Category	Building Type (abbreviated)	Permissible Velocity, V_R [mm/s]
1	houses & commercial buildings, structurally sound	8
2	well-braced structures with heavy elements, structurally sound	30
3	structures not in Category 1 or 2, under heritage protection	4

NOTE: $V_R = \sqrt{v_x^2 + v_y^2 + v_z^2}$ (see Table 3)

(1.2 in./sec.) for massive structures, with lower values for houses and historic buildings (Table 2). New criteria advanced by the U.S. Bureau of Mines (1980) for regular buildings are reproduced in Fig. 2.¹⁵

Various codes of practice recognize the special nature of historic buildings in stating permissible vibration levels. Table 3 gives a collection of these from a number of countries. As may be seen, the permissible values for blasting at the basement walls of structures are from five to ten times larger than those for ordinary buildings, but still five to ten times larger than the threshold of human perception given in Table 4. Blasting vibrations permissible for historic buildings might thus still be objectionable to inhabitants. A graphical presentation of various ranges of vibration levels is shown in Fig. 3, which has been adapted from Persson, et al¹⁶. The range of values for historic buildings is an order of magnitude smaller than the damaging level (Curve A) or the slightly lower permissible blasting level for the city of Stockholm (Curve B), but is an order of magnitude larger than the threshold of human perception (Curve C). No such national code values for historic buildings exist in Canada or the U.S., although some local jurisdictions, provincial or state authorities have adopted permissible levels for ordinary and special buildings.

Although these maximum permissible levels exist in codes, a thorough examination of the structure to be affected should be carried out, including its structural system, the condition of the building materials, the foundations and the

higher than the commonly accepted 51 mm/s (2 in./sec.) in North America. At the latter site, mainly massive, well-constructed buildings were involved.

Vibrations from other impact sources, such as pavement breakers and pile-driving operations, are similar in character to those for blasting¹⁹ and consequently, permissible vibration limits on buildings should be similar. Ferahian and Hurst reached this conclusion as a result of controlled experiments carried out on old houses in Winnipeg²⁰. A review of the state-of-the-art of construction vibrations has recently been presented by Wiss²¹.

Seismic Effects on Historic Buildings

In areas where seismic disturbances pose a potential threat, the vulnerability of historic buildings should not be overlooked. In North America, the seismic risk is particularly high on the Pacific coast. Somewhat lower, but nevertheless of potential destructive levels, is the seismic risk in the St. Lawrence valley, downstream from Quebec City. The Missouri region and the Charleston areas have also suffered large earthquakes in the past.

Historic buildings are frequently constructed of brick-work, stone or adobe, materials known to be vulnerable to seismic disturbances since they do not deform easily without rupturing. Past performance has demonstrated this clearly. The introduction of reinforcing having the ductile properties of steel, for example, would be desirable. Thus, modern

TABLE 3
Permissible Blasting Vibrations for Historic Buildings^{30,31}

Country	Code	Quantity Measured	Maximum Permissible Velocity [mm/s]
West Germany	DIN 4150 (1975)	v_R	4
East Germany	KDT 046/72	v_z	2 at <30 Hz 6 at 60 Hz 14 at 100 Hz
Switzerland	SN 640 312	v_{max}	8 at <60 Hz 8-12 from 60-90 Hz
Czechoslovakia		v_{max}	5
USSR & other East-Europe Countries		v_{max}	10 (frequent) 30 (occasional)
France	AFTES (Proposed)	v_R	hard soil soft soil 7.5 2.5 >10 Hz
ISO	ISO/IC 108/SC2 (Draft 1978)	v_R	3-5

NOTE: $v_R = \sqrt{v_x^2 + v_y^2 + v_z^2}$
 v_{max} = maximum velocity component
 v_z = vertical velocity component

masonry construction in seismic areas incorporates steel reinforcing rods, and the refurbishing of old buildings usually consists of introducing steel bars or wire mesh into the brick or stonework. A discussion of the effects of earthquakes on historic buildings and some recommendations for rehabilitation have been presented by Feilden and Alva²².

In assessing the need to strengthen historic buildings, one could attempt to satisfy the seismic requirements of present building codes such as the National Building Code of Canada or the Uniform Building Code and the ANSI Code in the United States. These are intended to provide a minimum level of public safety and a reasonable probability of survival in a major quake. Examples of this approach have been reported from California²³ where an adobe building from 1832, a brick storage warehouse built in 1929, and a more recent building from 1952 have been refurbished to conform to present seismic standards of the Uniform Building Code. Christoffersen, too, at the 1979 National Research Council Second Canadian Building Congress on the rehabilitation of buildings, reported on the experience of designers in applying the seismic provisions of the National Building Code of Canada to the restoration of brick row-houses in Vancouver²⁴. Both publications describe the difficulties that can be encountered. A major problem lies in determining the strength of existing masonry components and in tying the structure together so that the floor diaphragm and walls can act as a unit. To determine the

strength of brick walls, Fattal and Cattaneo²⁵ of the U.S. National Bureau of Standards, have suggested cutting out at least nine relatively large samples of brickwork and testing

2. Safe levels of blasting vibrations for houses using a combination of velocity and displacement.

TABLE 4
Vibration Limits for Subway Construction

City	Quantity	Maximum Permitted	Occasional	Continuous
VIENNA -St. Steven's Cathedral (Construction vibrations) ¹⁷	accel, g, mm/s ²	0.020	0.005	0.002
PRAGUE -(Blasting) ³¹	v _{max} , mm/s	10		
MONTREAL -University Interchange (Blasting) ¹⁴	v _{max} , mm/s	80		
Threshold of Human Perception (approx.) ³²	v _{max} , mm/s accel, g, mm/s ²			0.5 $\left\{ \begin{array}{l} 0.002 - 0.02 \\ (10 - 100 \\ \text{Hz}) \end{array} \right.$

them in the laboratory for strength properties. This may, however, be unacceptable for historic buildings, and development of improved in-situ methods would be desirable.

Localized examination of mortar strength and comparison with allowable stresses for masonry, offers a possible practical alternative²⁶.

A routine application of the seismic provisions of building codes to the rehabilitation of historic buildings may not always be appropriate for the following reasons:

1. The building code is drawn up primarily for new construction, which frequently differs from that used in the past. As a consequence, it may be difficult or impossible to adapt the stated requirements to the materials and structural configurations in historic structures.
2. The requirements of the code are so derived that under the "design earthquake" some damage can be expected; that is, cracks will appear in walls, glass is likely to break and façade damage will occur. The choice of the "design earthquake" inherent in code requirements is geared to the seismic risk of the area; it expresses the likelihood of occurrence of a certain size of quake. The design requirements in the code are then arrived at by considering aspects of safety for occupants and, possibly, the economics of replacement or repair of buildings. As the value and life expectancy of heritage buildings tends to be quite different from that of a regular apartment building, different criteria may be needed.

In view of the increased interest in preserving historic buildings, the seismic requirements in present building codes should be reviewed to determine their applicability to these types of structure and, where necessary, alternate guidelines should be developed for the use of the design professions. Useful principles of strengthening structures are contained in the seismic code of the U.S. Veterans Administration²⁷ for their existing hospitals and in the experience gained in California in strengthening old school buildings to resist earthquake damage²⁸. Further approaches to seismic rehabilitation are presented in "Build-

3. Ranges of permissible blasting vibrations.

ing Rehabilitation Research and Technology for the 1980's"²⁹. One challenge encountered in strengthening historic buildings is to find structurally effective solutions that are also acceptable from the point of view of preservation architecture.

Conclusions

Vibrations are one of many environmental factors that act on buildings and potentially reduce their lifetime. Because vibrations are readily perceived, they frequently take the major blame for deterioration. Before embarking on expensive remedies, however, the interrelation of the various factors of deterioration should be investigated and appreciated. Some are thermal problems from sun and interior heating, water and frost action, chemical changes in mortar or other building materials caused by atmospheric pollutants, organic action of bacteria on soil and rock materials, effect of trees on removal of soil moisture, and consequent settlement and de-watering as a result of changes in the water table.

Knowledge of vibration effects on historic buildings is rather incomplete, for the topic is one that encompasses many disciplines and is highly complex. No unifying approach exists for dealing with vibration problems on historic buildings, and a case-by-case approach should be followed. Guidelines can be obtained from previous case studies and permissible vibration levels can be prescribed in the codes of various countries.

Solutions to the following problems would be desirable:

1. long-term effects of vibrations on materials and, consequently, the criteria to be used in specifying allowable levels;
2. in-situ methods of determining strength of existing structural components;
3. practical remedial measures for cases where vibration levels are deemed to be excessive.

Vibrations will be a part of modern life to an ever-increasing extent, affecting historic buildings as well as new construction. It is hoped that some modern buildings will survive to become future heritage structures.

Acknowledgement

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

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