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Evaluation of traffic-induced vibrations in historic buildings: the case of the 'Galleria Vasariana' in Florence

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Abstract

Vibrations induced by urban bus lines in the "Galleria Vasariana" in Florence were measured, to assess the disturbance for the construction, recently interested by the explosion which damaged also the "Uffizi" museum. In order to design a new damping pavement for the road nearby the construction, a model of generation and propagation of traffic vibrations was developed and its effectiveness was verified through comparisons with recorded experimental data. The numerical model permitted the correct dimensioning of the damping pavement, in order to attenuate the vibration frequencies which revealed most dangerous for the conservation of the historical building.

1 Introduction

Protection from traffic-induced vibrations may be very important for building conservation, especially in the case of the historical heritage; in this case, in fact, architectural damage assumes the same importance than structural damage, due to vibrations that can affect a structure causing additional stress to be superimposed on existing concentrations, thus triggering off a failure. In the case of the Galleria Vasariana in Florence (see Figure 1), effects of the recent explosion, which affected also the "Uffizi" museum, added to the existing causes of damage, so that it became very important to accurately evaluate the level of traffic-induced ground vibration in the vicinity of the roadway along the Galleria, named "Lungarno Archibusieri".

Effects that traffic-induced vibrations may cause in buildings have been the subject of many studies, most of which have concluded that vibration levels are generally insufficient to produce structural damage. However, most of these studies has been carried out on building of modern construction and they have disregarded to distinguish between structural and architectural damage.

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For historic buildings, on the contrary, it was found very important to investigate any link that might exist between vibration levels arising from road traffic and the deterioration of the construction [1].

Vibrations are mainly generated by fluctuations of wheel contact loads, when vehicles travel over road surface irregularities. According to Whiffin and Leonard [2] and Watts [3], irregularities of the order of 20 mm in amplitude can cause peak particle velocities in the ground of up to 5 mm/s, and at this level severe "architectural damage" may occur in buildings. Crockett [4] also claims that lower levels of ground vibration can cause architectural damage by triggering off stress movements within masonry constructions. Watts [5] underlines that ground vibration is of greatest concern to heritage buildings when they are exposed to relatively high levels of traffic vibration.

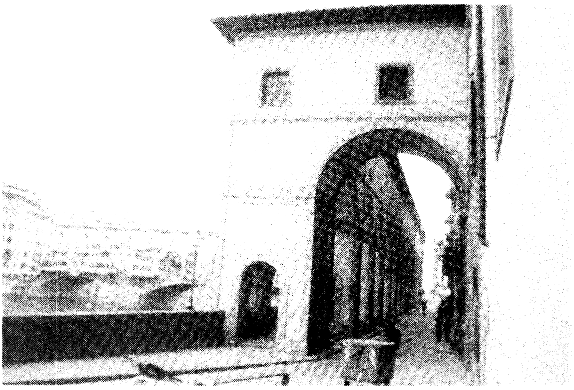

Figure 1: The "Galleria Vasariana", near "Ponte Vecchio" in Florence

2 Damaging induced by ground vibrations

Several points have to be considered when interpreting the contribution of vibrations to building damaging, as introduced in the following.

- Damage in historical buildings may be normally induced by various factor as differential settlement of foundations, expansion and contraction cycles due to changes in temperature, shrinkage of materials, stress concentration, wind and snow actions, change in humidity, and natural deterioration of materials.
- There is a need to differentiate between "structural" and "architectural" damage. Structural damage should be considered as the type which would affect the function or the use of a structure. Architectural damage, such as the cracking of plaster or other brittle materials, is more annoying than dangerous and begins at a much lower level of motion than structural damage. An area subjected to architectural damage from a given source may be 100 to 1000 times larger than an area subjected to structural damage.
- The role of people in interpreting damage: emotional factors may lead to magnify any claimed damage by several orders of magnitude.

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- Any criterion should take into account all buildings in a reasonable state of repair: in establishing a realistic threshold, the weakest structure is in fact the one which determines the threshold for any given set of conditions.

The role of vibration in causing damage have to be examined against this background. Vibrations can affect a structure or part of a structure in three ways:

- "direct damage", when relevant traffic-induced vibrations are generated, capable of inducing direct failures;
- "fatigue damage" due to the repetition of minor level stresses, induced by cycles of vibration. In this case the damage is due to accumulation of single effects during the time.
- "triggering"; Whiffin and Leonard [2] suggest that the "triggering" effect is likely to be the most important effect of vibration from traffic. Due to the concentrations of stresses which occur naturally, there is a high probability that, with the increasing number of heavy goods vehicles, vehicle vibrations will coincide with a peak stress and will cause damage.

Despite the distinction above, it is generally very hard to fix the most reliable value of threshold for the various kinds of damage [1, 4].

3 The evaluation of traffic induced vibration

A numerical model was developed by the Authors to evaluate the level of traffic induced vibration [6]. Results from the model were accurately verified through comparisons with direct measurements performed in the same conditions of traffic assumed in the model, obtaining in this way a satisfying validation of numerical results, as showed in Fig. 2, where S_v represents the spectral density function of vibrations velocity.

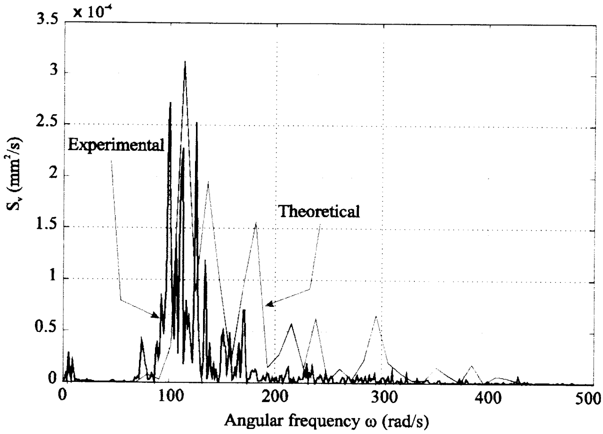

Figure 2: Comparison between theoretical and experimental results

In evaluating results in Figure 2 it is important to point out the peculiar range of frequency in the phenomenon of traffic-induced vibrations (1÷40 Hz) and the range in which the spectral density peaks of vibration velocity converge (8÷25 Hz).

A further comparison regarded the value of greatest vibration velocity directly measured, as peak-to-peak quantity, from vibrometer graphs, which resulted in V_{max} = 0.266 mm/s. The maximum vibration velocity, as a peak value, was derived from the numerical model through a probabilistic analysis as performed in [7]; in this way, a value of spectral answer $V_{T,P}$ was obtained, representing the value that in the period T has probability P not to be trespassed; such value, for P = 90%, resulted in V_{max} = 0.130 mm/s, corresponding to a peak-to-peak value of 0.260 mm/s thereby furnishing a further validation of the numerical model.

4 The insulation of buildings from ground vibrations and minimization of damage

Once the numerical model for the evaluation of traffic-induced vibrational levels was setup and verified, the same model was utilized in evaluating reliable methods to reduce vibrations at the building foundation level. From a general point of view, the problem can be faced up in several ways, as introduced in the following.

- "Building insulation" - Such solution generally does not reveal appropriate for historical buildings. This insulation method better applies to new buildings, through a specific planning of intervention.
- Roadway insulation - This solution insulates directly the noise source; in this case benefits regard both buildings and the environment. For ground vibrations, the reduction of the input force at the source is generally the way to reduce undesired vibrations. Despite this kind of insulation is generally expensive for road-traffic, there are many examples of such interventions, most of all about railway and subway.
- Transmission reduction - The mitigation of vibrational levels during their transmission implies necessarily the intervention on characteristics of the ground between the source of vibration and the building to protect. A way of vibrations control is to construct trenches between the vibrational source and the building, along the roadway or along the building. Trenches act as a barrier to vibrations and can therefore reduce transmission through the soil. To obtain maximum performance, the impedance of the fill material used in the trench should be as low as possible so that energy is reflected rather than transmitted towards the affected building. Although such trenches have been widely investigated, the consensus of opinion is that the method is of little value practically, as the trench has to be fairly deep and kept open throughout the life of the building. Barkan [8] suggested that the depth of the trench should be at least equal to a third of the wavelength of the vibration (thereby 5 m deep for a 20 Hz vibration and a velocity of propagation of 300 m/s) but others [9] found that a trench must be at least as deep as the wavelength of surface waves in the ground in order to achieve effective insulation.

The transfer function H_{ff} from the force applied to the pavement to the force applied to the ground, related to the road damping superstructure schematized with the one-degree-of-freedom system in Figure 4, has the following expression:

$$H_{f_tf} = \frac{F_m + F_a}{e^{j\omega t}} = \frac{kx + c\dot{x}}{e^{j\omega t}} = \frac{k + cj\omega}{-M\omega^2 + j\omega c + k} \qquad (1)$$

The basic property of this function is that when $\omega > \sqrt{2k/M}$ it results $\left|H_{f_tf}(\omega)\right|^2 < 1$, thereby an attenuation of ground forces is achieved. So the aim of the design was to set a system with a natural frequency considerably inferior (about 2 times to have guarantee of an efficacious insulation) to the peculiar frequency to insulate .

An effective damping behavior was designed through the setting of the bearings installed between the two firm structures and the evaluation of the mass of the upstanding pavement. The bearing elements utilized in the design are "*Matel and Matel G*" (Figure 5) produced by "*Pirelli Antivibration Systems*", disposed in piles with dimension of mm 120 × 220 in plan and 128 mm high (four elements for each pile, see also Figure 3) . With these elements and the appropriate setting of the pavement mass, the transfer function H_{ff} in Figure 6 was obtained, resulting for $\omega > 56.55$ rad/s ($f > 9$ Hz) a value $H_{ff} < 0.14$, corresponding in this way to a considerable reduction of forces applied to the ground.

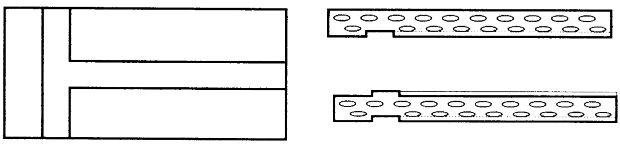

Figure 5: Adopted bearings

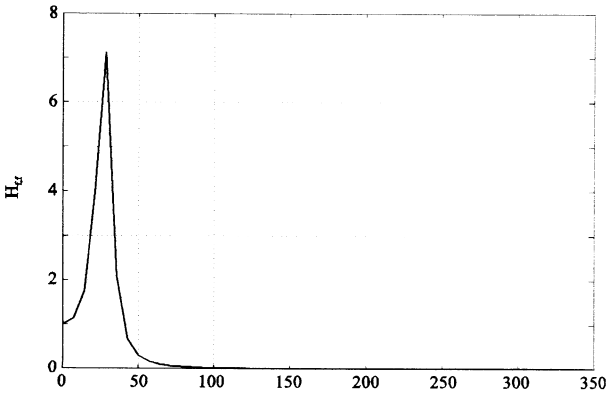

Figure 6: Frequency response function from force applied to the pavement to forces applied to the ground

5 Road damping pavement design

Basing on the analysis in the preceding paragraph, a road damping pavement was designed for "Lungarno Archibusieri", to protect the "Corridoio Vasariano" from traffic-induced vibrations caused by biggest-mass vehicles such as urban and tourist buses.

Examples realized till now to isolate roads from the environment, consist in the installation of elastic bearings between two firm structures, as in Figure 3, the first directly subjected to traffic loading (the road pavement), while the second laying directly on the road-superstructure on the ground [10].

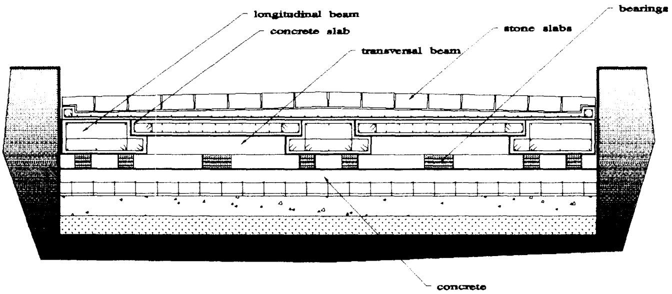

Figure 3: Road damping pavement

Benefits of the damping pavement were evaluated through the numerical model developed, simply including a further filtering element. The structure in Figure 3 can in fact be schematized with a model consisting of a Hookean elastic spring with elastic constant k put in parallel to a viscous linear organ with constant of viscosity c, that is able to exercise a resisting force proportional to the velocity (Figure no 4); parameters k and c depend on the stuff that is placed between the two firm structures.

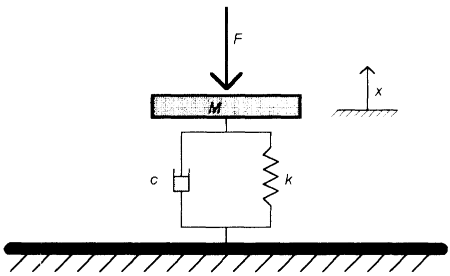

Figure 4: model of the road damping pavement

For design purposes, the generation model has been hypothetically set off on sampled road irregularities at axial speed increased of 10% with respect to the legal speed (thereby 55 km/h). Corresponding to the higher vehicle speed, spectral density peaks about vibrational velocity of ground particles at foundation level don't suffer important shifts in frequency, but the relating content increases of one order of magnitude. The value of maximum vibrational velocity was is in this case evaluated in $V_{max} = 0.278$ mm/s.

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A good working action of this kind of design can be pointed out when comparing the trends of the spectral densities about vibration velocity and the values of maximum vibration velocity in both the cases of usual road superstructure and of the designed damping road superstructure. Effects of the damping pavement make values of the spectral density go from a 10^{-3} order of magnitude (see Figure 7) to 10^{-5} (see Figure 8), while the value of maximum vibrational velocity is reduced by more than 6 times, from V_{max} = 0.278 mm/s to V_{max} = 0.0438 mm/s.

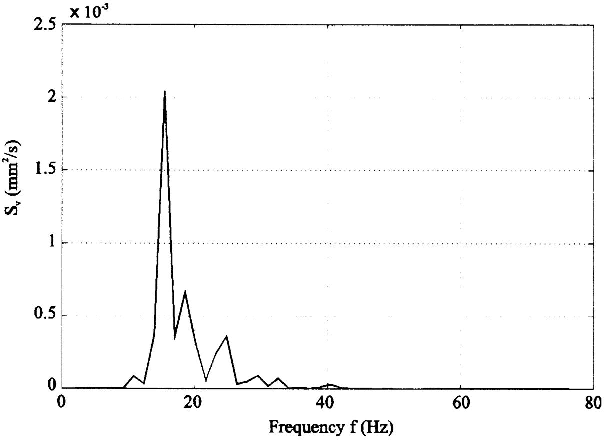

Figure 7: Power spectrum of the velocity for ordinary road pavement

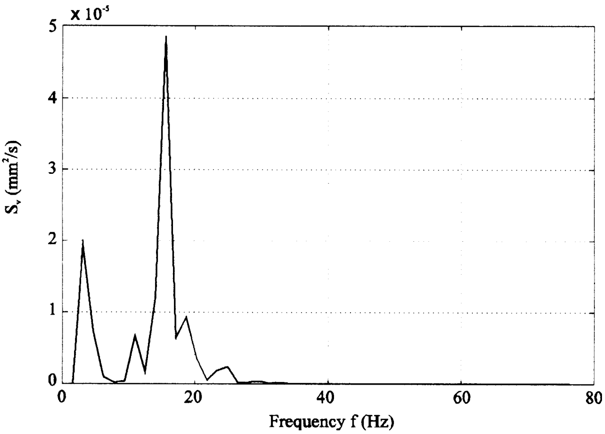

Figure 8: Power spectrum of the velocity for damping road pavement

Conclusions

A computational method to predict levels of ground vibration induced by urban bus lines traffic was developed and employed to design a damping pavement in order to preserve an historical construction from damaging. Comparisons with experimental measures demonstrated the developed model suitable to predict the motion induced from traffic in the vicinity of the construction. The same tool was then utilized to determine the design characteristics of the damping structure in order to obtain an effective reduction of the vibration level, through the setting the mass of the paving and the stiffness of elastic bearings in order to cut the most dangerous frequencies of traffic vibrations.

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