Health monitoring of cultural heritage using ambient and forced vibrations

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Abstract

In this paper, the main results of a campaign of experimental dynamic tests involving three important monuments of Rome, the Colosseum, the Traian Column and the Aurelian Walls are presented. The structural dynamic response due to ambient excitation and to impact force tests was investigated. The damage risk due to the vibrations induced by road and railway traffic was assessed according to international standards. Natural frequencies and mode shapes were determined and compared to numerical ones, which were obtained by a finite element model. Measuring the evolution of these quantities, which are representative of the structural conditions, allows for health monitoring of monuments.

Keywords: dynamic characterization, ambient vibration, health monitoring.

1 Introduction

Health monitoring of cultural heritage is a topic of outstanding importance in the world over, especially in Italy, where ancient monuments are exposed both to the seismic hazard and to vibrations due to human activities, such as traffic-induced soil vibrations. The excitation due to the passage of vehicles on roads, railways or subways, propagates from the source to the buildings, provoking people annoyance and functionality problems to sensitive equipments or structural damage, particularly in historical buildings. Here, old materials and low level of structural integrity make vibrations to produce an increase in damage. In this paper, the main characteristics of these phenomena are outlined, emphasizing the key parameters, the awareness of which can be helpful to identify possible remedial measures; these actions may concern the source of vibrations, the
propagation or the receiver. Three main aspects can be highlighted: how road or rail vehicles generate a dynamic load on the underlying soil, how vibration propagates in the soil and how buildings respond to traffic-induced vibrations. The attention is focused here only on the last topic with reference to some relevant monuments in Rome.

The response of buildings to dynamic excitation depends both on the spectral content of the excitation and on the building modal characteristics (natural frequencies and mode shapes). Thus vibration measurements can be used to identify the dynamical properties of the structures [1] and, consequently, to estimate some mechanical parameters related to their structural integrity [2, 3]. If these kinds of measures are repeated in a framework of a structural monitoring programme, the reduction of structural integrity can be revealed over time.

This paper reports the main results of an experimental dynamic investigation on the Colosseum, the Trajan Column and the Aurelian Walls, which represent typical cases of historical buildings exposed to traffic vibrations. The experimental observations had two major objectives calling determining the nature and the extent of vibration response levels, and obtaining experimental natural frequencies and corresponding mode shapes. These parameters are extremely useful in order to update a finite element model that fits experimental results. In health monitoring this model may be used to predict modifications in structural properties, such as stiffness decay.

Two kinds of tests were performed: ambient vibration and impact force. Firstly, the potentially negative effects of traffic-induced vibrations were checked by comparing the response level to the limits fixed by national and international technical standards [4 - 7]. The measurements were then analysed in order to determine experimental modal parameters, which were compared to those obtained by the finite element models. Observing the evolution of these dynamic characteristics over time is a fundamental step for a monitoring activity.

2 Vibrations due to road and rail traffic

Figure 1a shows a simplified sketch of the phenomenon. Circled numbers refer to the main aspects to be considered. The main difference between road traffic and rail traffic is the interaction (item 1) between vehicle and road or rail-sleepers system. Beginning with road traffic, the vehicle wheels follow the rough surface of the pavement and transfer the vibration, filtered through the shock absorbers, to the vehicle cabin. The dynamic response of the vehicle produces a dynamic load on the road foundation (item 2). This dynamic load is usually described with stochastic approaches. In the case of rail traffic (Figure 1b), each wheel, moving on the track, transmits in sequence the axle load on the sleepers; the track bends under the load and, also in an ideal situation of irregularity-free contact between track and wheel, a dynamic load is generated; this depends both on train velocity and sleepers spacing. This load (characterized by frequencies under about 10 Hz) can be described with deterministic approaches. A high-frequency disturbance, due to wheel-track irregular contact, is added to the previously low-frequency load; this disturbance is usually described with
stochastic approaches. Also in this case the dynamic response of the vehicle produces a dynamic load on the permanent way (item 2). Following the propagation of vibration (Figure 1a), the dynamic load is filtered by the road foundation and transmitted to the soil, in which elastic waves are generated (item 3). The soil filters and transmits the vibration to the building foundation (item 4). Finally, the vibrations transmitted by the foundation propagate to the structural and non structural elements of the building (item 5).

In the case of road traffic, the pavement roughness and the dynamic properties of the vehicle shock absorbers play a fundamental role. In the case of rail traffic, the key parameter is the shape irregularity of the wheels. Another key parameter common to both road and rail traffic is the vehicle speed.

Awareness of the phenomenon features suggests some remedial measures. For road traffic, the maintenance conditions of the road pavement strongly influence the level of vibrations transmitted to the soil: poor conditions of the road pavement can imply an increment of one order of magnitude in the vibration amplitude at the building foundation level. Furthermore, the design of the vehicle shock absorbers has the aim of improving the passengers’ comfort and ensuring the adherence, rather than minimizing the environmental disturbance. For rail traffic, careful vehicle wheels maintenance can help to reduce the vibration disturbance. Other measures common to both road and rail traffic are: vehicle speed reduction, introduction of vibration isolation materials between road foundation and soil, trenches in the soil (very expensive and not effective at low frequencies) and building isolation (very difficult for existing buildings or incompatible for cultural buildings).

![Figure 1: Sketch of the phenomenon: (a) vibration induced by road or rail traffic; (b) interaction between train, track and sleepers.](image-url)

3 Test description and aims

The vibration tests were performed on three important Roman monument: the Colosseum, the Traian Column and the Aurelian Walls. These monuments are characterized by a strong exposure to vibrations due both to road and underground line traffic.

The first aim of the experimental measurements was evaluating the vibration severity in order to assess the vibration damage risk. However, the structural dynamic response to known or unknown inputs can also be employed to
investigate the system real behaviour. This kind of dynamic characterization is called modal analysis and is aimed at obtaining a mathematical description of the structural behaviour by means of an experimental estimate of natural frequencies and mode shapes. The linearity hypothesis is considered valid because of the small displacements involved.

The comparison and correlation between the experimental modal parameters and those predicted by a finite element model enable us to identify the possible causes of the discrepancies between predicted and measured properties. In particular, the obtained information might be related to the actual health conditions of a structure: lower natural frequencies with respect to those predicted by the finite element model may indicate stiffness decay; anomalous mode shapes may point out an independent motion of structural parts due to major cracks. A monitoring activity should be based on the periodical repetition of the measurements, in order to point out eventual reduction of structural integrity.

Accelerometers are used to measure the dynamic response. The most detailed measurement campaign was performed on the Colosseum. In Figure 2 the instrument location are indicated by the arrows. Radial accelerometers were employed on seven sections, using a total of 42 measurement points. Triaxial sets were employed only at sections 32, 39, 47, at the base and at level L1, L2, L4. Due to the very low expected frequency range for natural modes (0.5 – 3 Hz), a measuring time of about 40 minutes was chosen for each setup, in order to capture enough periods of low frequency modes and to have statistical robustness. To get further experimental evidence on the estimates, impact vibration tests were also performed on the columns, exciting the structure by an instrumented hammer and estimating Young’s material modulus by the transient response.

Figure 2: Accelerometer locations on the Colosseum.
Figure 3 shows the accelerometer locations on the Traian Column. One triaxial set was put at the base. Horizontal components in two orthogonal directions were measured on the remaining points.

On the Aurelian Walls a simple scheme was adopted, with three accelerometers located on the top of the walls and one on a pillar measuring horizontal accelerations. One triaxial set was also put at its base (Figure 3).

4 Assessment of the traffic vibration damage risk

Relating the vibration severity in terms of a kinematic quantity such as peak acceleration or velocity to damage effects is not straightforward. In general, the reference parameters used by technical regulations to evaluate damage effects on buildings are the values of the velocity components, measured both at foundation and at roof levels. These values must be compared to reference values from technical standards in order to estimate if the vibration level can be considered high enough to induce structural and non structural damage. In the investigations performed, velocities were obtained through integration of the measured accelerations.

The general content of the Italian code UNI 9916 [5] is in agreement with the international regulation ISO 4866 [4], which is often cited as a reference. The ISO does not explicitly fix any maximum velocity value: it simply defines ranges of displacement, velocity and acceleration that “may cause concern”. On the other hand, the UNI mentions the indications given by the DIN [6] and BS 7835 [7]. The DIN, in cases of buildings having an historical or archaeological importance and for short-term vibrations, defines the allowable maximum velocity component limits at the ground level as 3 mm/s for frequencies lower...
than 10 Hz and 10 mm/s for frequencies higher than 100 Hz; 8 mm/s is the limit for the horizontal component at roof level. In the case of long term vibrations, only the horizontal velocity limit at the roof level is fixed with a value of 2.5 mm/s.

When observing the signals recorded during the tests, no specific short term excitation source was identified, therefore only the limitation concerning long term vibrations was taken into consideration.

On the Traian Column, the highest level of excitation was found to be the vertical component at its base. However, the velocity spectrum both at the base and at the top of the column is largely lower with respect to the DIN limitations, as shown in Figure 4.

The signals recorded on the Colosseum were analysed in order to calculate the acceleration root mean square values and maximum values. It was observed that circumferential acceleration is smaller by one order of magnitude than vertical and radial components, while these two are of the same order. Furthermore, the radial acceleration rms and maximum values increase when passing from the ground to the roof level, whereas vertical components maintain the same order. The highest rms value is 0.00179 m/s² and the highest acceleration peak recorded is 0.1 m/s². This value falls in the low range of those values that may cause concern, according to the ISO (0.02-1 m/s²). In fact, also in this case, the velocity spectrum remains distant from DIN limitations (Figure 4).

On the Aurelian Walls, the maximum rms velocity value is 0.0075 mm/s and the maximum is 0.107 mm/s. This falls near the low range of those values that may cause concern according to the ISO (0.2-50 mm/s). When analysing the velocity spectrum, the vibration level maintains itself under the DIN limitation, as shown in Figure 5.

In conclusion, the traffic vibration level was ascertained to be rather low with regard to its potentially damaging effects on the buildings: the vibrations cannot be considered responsible for the poor health status of the monuments investigated.

![Figure 4: Mean FT of the velocity.](image-url)
Dynamic characterization

The dynamic characterization, based on a frequency domain analysis of the response, implies the evaluation of natural frequencies and mode shapes.

The Traian Column represents a very peculiar case in archaeological heritage because of its slenderness. In fact, historical buildings are generally massive and very articulated structures and many close natural frequencies are expected. The Traian Column data were analysed by means of the software package Artemis® [12]. The first four natural frequencies and modal shapes were identified (Figure 6). The first two modes are contained respectively into two orthogonal planes and, analogously, the third and fourth mode shapes. The mode shape couples 1-3 and 2-4 strongly resemble those of a cantilever beam. However, the frequency sequence does not exactly fit the ratios of the cantilever.

On the Colosseum, the first five natural frequencies and mode shapes were identified by the simple method of peak-picking on the power spectral density. Table 1 shows the experimental values \( f_e \) of these frequencies, that are concentrated in a small range of 0.6 Hz of amplitude. It may be observed that the experimental values of the natural frequencies are approximately half of the frequencies \( f_a \) predicted by the finite element model, which are also reported in
Table 1. This result is strongly related to another experimental result obtained by transient tests, i.e. the wave propagation velocity of compression waves $c_p$. The experimental estimate of this parameter is half of its analytical value, calculated with the same material mechanical properties assumed in the finite element model and derived by the literature. Since natural frequencies and wave propagation velocity exhibit the same dependence on Young’s modulus $E$, updating of this parameter in the finite element model brings the numerical and experimental results into agreement. However, it must be noted that Young’s modulus has to be reduced by 75% to tune numerical and experimental results. This means that global structural stiffness is much lower with respect to those initially derived by assumptions based on local mechanical properties. Figure 7 and Figure 8 depict the first and second numerical and experimental mode shapes identified by means of the ambient vibration tests. A good agreement is observed between the finite element model and the experimental results: the mode shapes are bending modes involving the external wall and are substantially the same. Analogous tests were already performed in 1985 by ENEA, the Italian Agency for new technologies, energy and environment [8]. These tests did not involve the part of the external wall where the first and second mode shapes are localized, therefore these were not determined. However, the first natural frequency (1.46 Hz) identified in [8] matches our third mode.

The identification of the modal parameters was carried out only for the Traian Column and for the Colosseum. In fact, the peak frequencies observed in the spectrum (2 - 3.5 Hz, Figure 9) of the Aurelian Walls are higher with respect to those expected. This might be due to the great longitudinal extension of the walls, where loose interaction of waves with boundaries prevent the arising of standing waves involving the whole structure.

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Figure 7: FEM model: first and second mode shapes.
Figure 8: First and second experimental mode shapes.

Figure 9: PSD of the Aurelian Walls.

6 Conclusions

The importance of health monitoring of historical buildings has increased in the last years because of the renovated interest in the preservation of cultural heritage. In this paper, the dynamic response of the Colosseum, the Traian Column and the Aurelian Walls was investigated in order to assess the damage vibration risk due to ambient vibration and to determine a dynamic characterization. The vibration level was found to be lower with respect to the limits fixed by international standards, therefore at present it can not be considered responsible for the decay of the health conditions. For two of the three monuments considered, the fundamental dynamic properties, i.e. frequencies and mode shapes, are determined; for the Aurelian Walls only general characteristics of the dynamic response have been obtained due to its extension. It is believed that the results obtained might be useful in the framework of a monitoring programme. A possible modification of the dynamic properties revealed by forthcoming measures might indicate a decay of the health conditions.
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