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CONSIDERATIONS ON THE SEISMIC SAFETY OF HISTORICAL MONUMENTS

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ABSTRACT

The critical modes of failure experienced by monumental structures submitted to severe earthquakes are described, giving consideration to the feasibility of a quantitative estimation of the level of safety.

Some comments are made about the effects of different types of ground motion on monuments and about the quantification of the seismic action for the analysis of the structure.

The presentation is focused mainly on the types of structures common in the colonial monuments of Latin America.

KEYWORDS

Monuments, Seismic Performance, Safety Evaluation, Modes of Failure, Ground Motion, Monitoring.

INTRODUCTION

A great controversy exists about the criteria for the safety evaluation of historical monuments and about the techniques for preservation of their structural safety. The prevailing philosophy is that historical monuments do not lend themselves to sophisticated structural analyses and that decisions must be based on qualitative considerations regarding how much the original capacity has been affected by different factors, including earthquakes. The same philosophy states that any structural modification should be restricted at restoring the characteristics the structure initially possessed.

It must be recognized that the distrust about the validity of modern techniques for structural analysis, and specifically of those related to seismic design, derives from the misuse that has often been made of them by extrapolating procedures developed for modern structures, without proper consideration to the different nature of historical monuments. Nevertheless, in the last few decades great advances have been made in the understanding of the structural behavior of monuments and in the development of analytical methods suitable to their behavior.

The purpose of this paper is to highlight some relevant aspects of the structural safety of monuments in areas of significant seismic hazard, with specific reference to the problems of the structures typical of the colonial period in Latin America, and especially to those of Mexico City.

In early colonial times, at the beginning of the XVI Century, the afore mentioned monuments were mere transferences of the architectural styles, structural forms, materials and construction techniques that were common in Spain at that time. Progressively, though, they changed to adapt to differences in culture and in local conditions. By coincidence, most of the great colonial cities were set in areas of great seismic hazard (Mexico, Puebla, Oaxaca, Guatemala, Lima, Quito). Damages due to earthquakes as well as to fires, were rather frequent, thus several modifications were introduced to make buildings more apt to withstand seismic effects. The addition of strong buttresses and of closely spaced transverse walls, the increase in the size of walls and pillars, the reduction of the height and of slenderness of towers, constitute the most clear evidence of these changes.

In Mexico City, seismic problems are tied to those of subsoil. The huge and heavy colonial monuments have suffered great settlements causing distortions, inclinations, and large cracking in their structural members, that have greatly impaired their seismic safety. Seismic performance of colonial monuments can be considered in general as satisfactory, nevertheless, severe damage has occurred in some cases and the situation is becoming more critical as the age and the settlements affect the structural capacity of the constructions.

RELEVANT ASPECTS OF THE SEISMIC BEHAVIOR OF HISTORICAL MONUMENTS

The basic structural material for historical monuments is masonry, in several different kinds, from adobe or rubble joined with mud mortars, to stone sills and stone conglomerates with cementitious materials of good quality. Seismic problems in these monuments derive from the intrinsic weaknesses of masonry: its great weight and low tensile strength, frequently aggravated by deterioration due to weathering. An important aspect of the masonry used in monuments is its heterogeneity and the significant variations in its quality among different structural members and even within the same member. A critical aspect of masonry structures is the difficulty to give continuity to their structural members (among transverse walls and of the walls with the floors and roofs), as well as the difficulty to form stiff horizontal diaphragms capable of distributing inertia forces to the stiffest and strongest walls.

Among the many problems are of the seismic behavior of monumental masonry structures, the most relevant will be discussed in the next paragraphs.

The most severe, and rather frequent, mode of failure is the overturning of facade walls due to out-of-plane inertia forces and propitiated by the outward thrust of the roof (Fig 1). The situation is particularly critical in dome or vault shaped roofs. The failure starts with the separation of the wall from its transverse supports, then by its vibration as a cantilever of increasing length. Finally, the walls overturn or opens enough to produce the instability or loss of support of the roof which collapses.

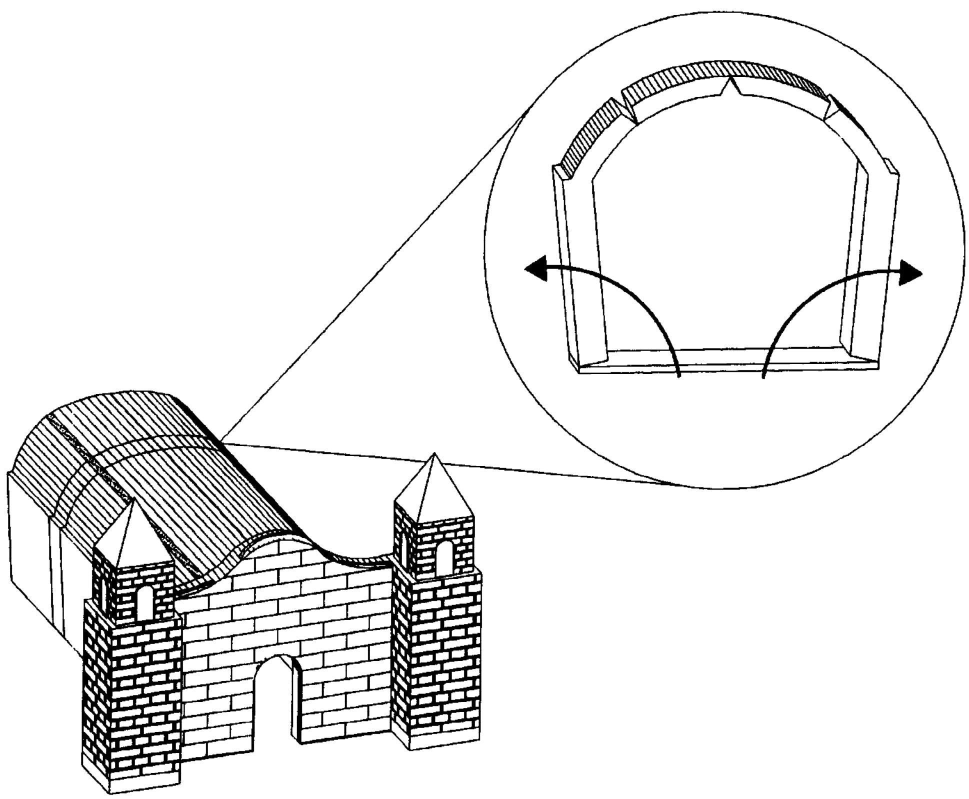


Fig. 1. Out of plane bending and overturning of long walls

The afore mentioned phenomenon is highly non linear, because of the loss of stiffness due to the progressive cracking and because it is essentially a problem of instability. For that reason it is not easy to perform an analytical evaluation. The checking of safety is commonly made by geometrical rules based on evidence of past performance of similar structures. These rules are commonly expressed in terms of maximum height-to-thickness or unsupported length-to-thickness ratios for the walls, like those proposed for a specific case in Table 1.

TABLE 1. LIMITS OF HEIGHT AND LENGTH OF WALLS FOR ADOBE HOUSES FROM ANALYTICAL STUDIES OF BAZAN *et al* (1978)

Type of roof (Weight in kg/m^2)	Zone of Highest Risk		Zone of Heavy Damage Risk	
	Unreinforced	With Collar Beam	Unreinforced	With Collar Beam
Light (50)	2.9	6.5	4.1	9.2
Intermediate (250)	2.4	5.5	3.4	7.7
Heavy (500)	2.0	4.7	2.9	6.6

Values in the table correspond to maximum H/t and L/2t ratios. Seismic Risk Zones correspond to the particular case of seismicity in Mexico.

H Wall height
L Unsupported wall length
T Wall thickness

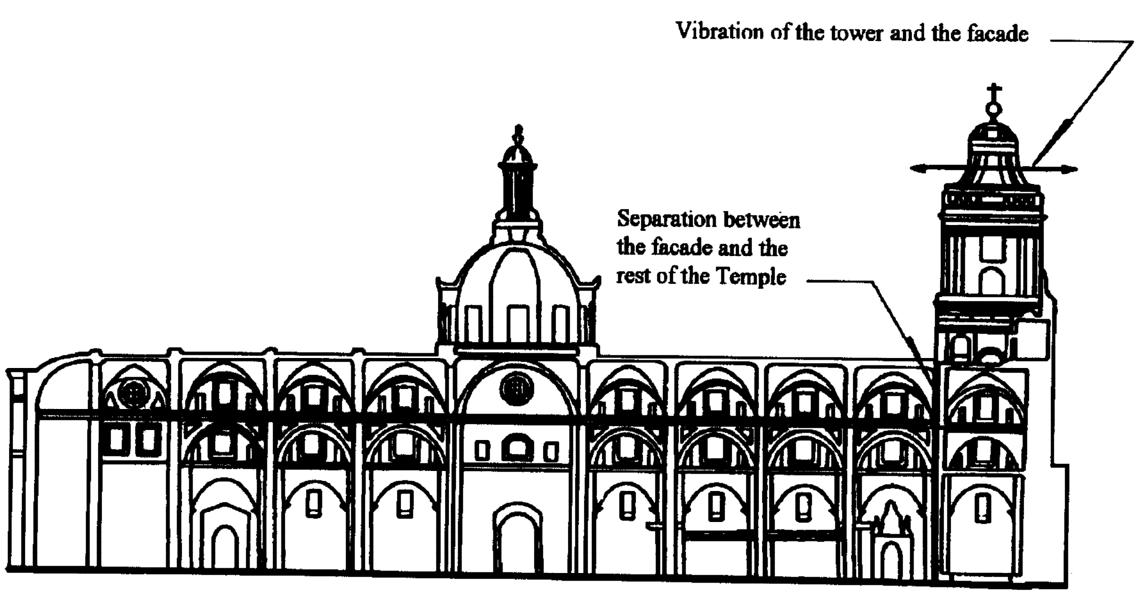


Fig. 2. Separation and possible overturning of the main facade of a temple (from Meli and Sánchez Ramírez, 1994)

Similar to the former case is the failure due to the overturning of facades of churches or palaces which were not well tied to the rest of the monument. Fig 2 shows a typical situation, where a heavy and tall facade can become unstable due to the inertia forces transverse to their plane. Roofs or intermediate floors do not provide proper restriction to the outward displacement of the facade. One of the most frequent measure of seismic retrofitting is to anchor the main walls to the rest of the structure by different procedures.

The simplest case of overturning is that of cantilever walls, posts or towers. This mode of failure is less frequent than commonly thought. The evaluation of safety against overturning, by applying equivalent statical lateral forces is overconservative, because it does not consider that the structure can hardly reach the lateral displacements needed to overturn, before the change of direction of the inertia forces produces the reversal of the direction of the motion.

Analytical models of the phenomenon should consider the opening and closing of the cracks, the possibility of sliding of the stones over the horizontal joints and the effect of the energy dissipation by the impact between the stones when the cracks close due to the reversal of displacements (Fig 3). Evidences of this kind of dynamic behavior are frequently observed in towers and free-standing columns, as lateral sliding and tortional rotations; nevertheless overturning failure only occurs in cases of extreme slenderness. The dynamics of systems of this type has been solved by Housner (1963) and computer programs for the analysis of complex structures with these characteristics are now available.

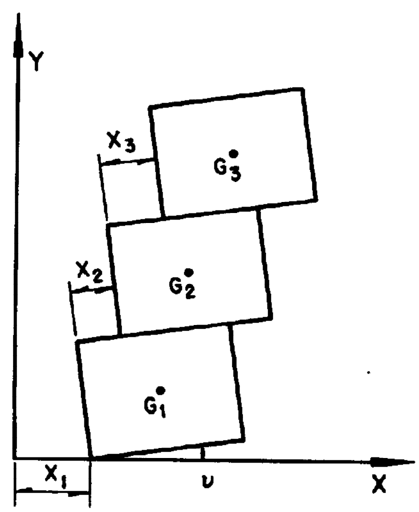


Fig. 3. Dynamic motion of a multiblock column

The failure due to shear forces in walls through diagonal cracking, is the case that more clearly lends itself to a quantitative evaluation of the seismic safety, through the equivalent static methods common for bearing wall structures, (Meli 1994). This mode of failure is not very frequent in monuments, though, because the great thickness typical of the monuments gives the walls a significant capacity to resist shear forces, even if their unit shear strength is low. The shear failure is commonly associated to walls with large openings, like the case of the walls of bell towers, where, even if their slenderness would suggest that bending would govern the failure, the most common cause of collapse is by shear, (Fig 4).

In most monuments which lack of proper floor and roof diaphragms inertia forces generated in the large masses at roof levels are directly transferred to the walls bearing each portion of the roof, regardless of the relative lateral stiffness of the resisting members. Large concentrations of lateral forces can arise in some walls. Furthermore, it must be taken into account that during the vibration of the structure tensile stresses arise in the roof that could generate large cracks, actually separating the structure in parts whose stability must be evaluated specifically. An example of this situation is shown in Fig 5. When the large vaulted structure vibrates in the transverse direction, tensile stresses produce a longitudinal crack on the vault; therefore, the left part of the structure, which is less stiff and strong, must withstand the inertia forces generated in the largest part of the roof. Similarly, the facade with its towers and buttresses can separate, due to the longitudinal vibration, from the rest of the structure which must withstand the inertia forces generated on it, and whose butresses do not contribute to the shear strength of the rest of the structure.

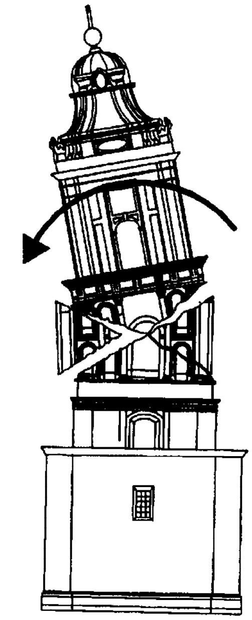


Fig. 4. Overturning of a bell-tower by shear failure through large openings

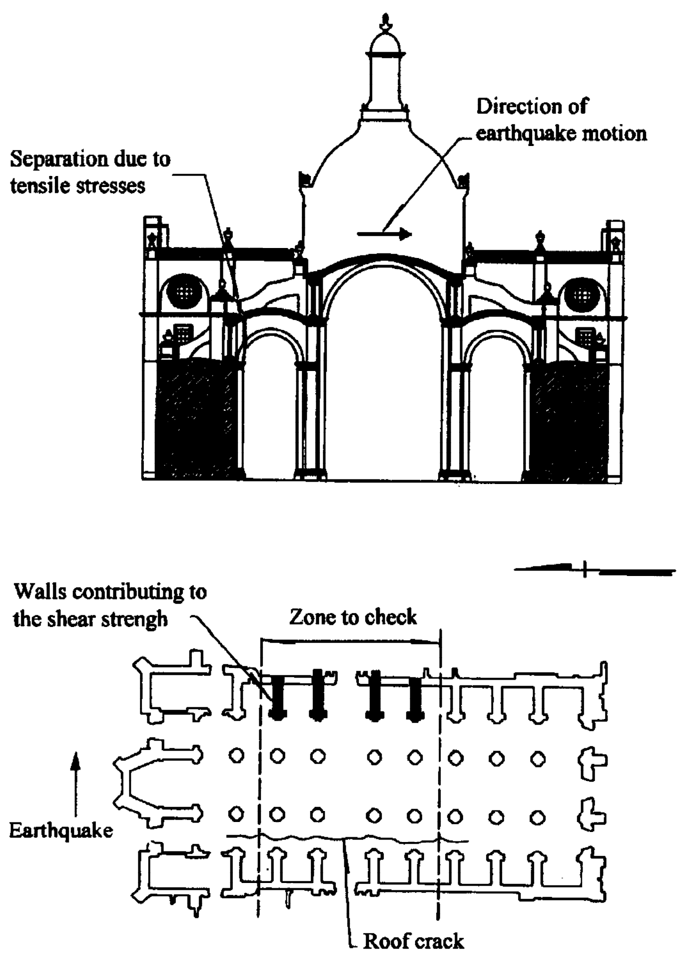


Fig. 5. Mechanism of the shear resistence of the central part of a vaulted temple

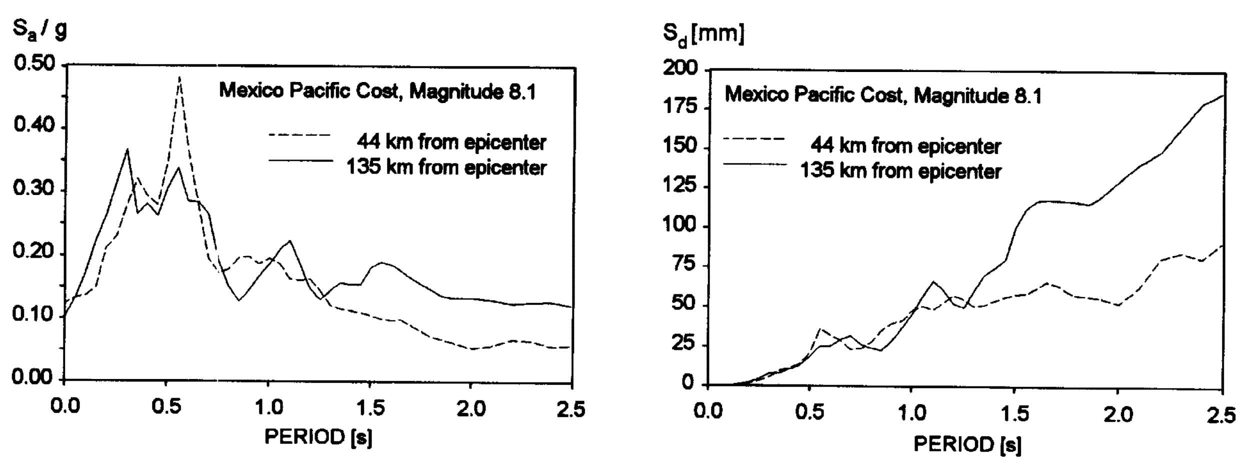
When deciding on how to define the seismic action for an analytical evaluation of the forces and displacements induced in a monumental structure, its many differences with modern structures must be kept in mind.

Code specified values of seismic coefficients and response spectra, along with their reduction factors for considering non linear behavior, have been defined mainly to produce structures similar to those whose performance under severe earthquakes has been considered as satisfactory. Values have been calibrated for modern buildings and they cannot be directly extrapolated to monumental structures.

In view of the uncertainties in the problem, simplistic methods for seismic safety evaluation are preferred, and in most studies of individual cases it is stated that equivalent static lateral forces have been used corresponding to base shear coefficients between 0.1 and 0.2, for zones of significant seismic hazard. Equivalent lateral forces are applied at the levels where masses are assumed to be concentrated, and a linear increase of acceleration with the height of the building is assumed.

The former approach can be accepted if the structure is modeled considering the specific features characterizing its dynamic behavior, like the absence of a stiff continuous foundation, in most cases, or like the lack of monolithism and the possibility of large amplification of the vibrations in parts of the structure which are drastically less stiff than the rest, as is the case in towers and parapets.

The characteristics of the ground motion expected at the site must be taken into account. The violent ground shaking experienced at sites which are near to possible epicenters, are characterized by very large accelerations, small displacements, high frequencies of vibration and, commonly, short duration. This type of shaking is particularly harmful for the shear failure of rigid parts of the structures and less critical for instability failures, because of its small displacements. In areas that can be subjected to the effects of large magnitude earthquakes with far epicenters, ground shakings are characterized by relatively small accelerations with low frequencies, long duration and rather large displacements, which can produce instability failures like the overturning of flexible parts of the structures, fall of the roofs and collapse of structural elements whose stiffness significantly deteriorates with the repetition of loads. The differences between the two types of shaking is illustrated in the comparison of the respective acceleration and displacement spectra, in Fig 6.



(a) Acceleration Response Spectra

(b) Displacement Response Spectra

Fig. 6 Response spectra of ground motions recorded on rock sites, nearby and faraway from the epicenter.

Particular attention must be given to the study of monuments founded on very soft soil, where great amplifications of the seismic waves occurs with critical effects especially on tall, flexible structures. The great weight and stiffness of the massive monumental buildings make it that a great portion of the energy that the ground motion tries to introduce into the structure is returned to the soil through radiation, giving rise to a drastic reduction of the shaking actually imposed to the structure.

An extreme case of this situation occurs at the historical center of Mexico City where the soil is constituted by very soft layers of clay, 30 to 40 m thick. In the free-field, due to the large magnitude earthquakes that are rather frequent in the Pacific Coast, more than 300 km away, very large ground motions occur. Nevertheless the motion at the base of monumental structures is significantly smaller, as it can be appreciated in Fig 7 which compares response spectra computed for the two cases in a particular site, (Ordaz and Meli, 1993).

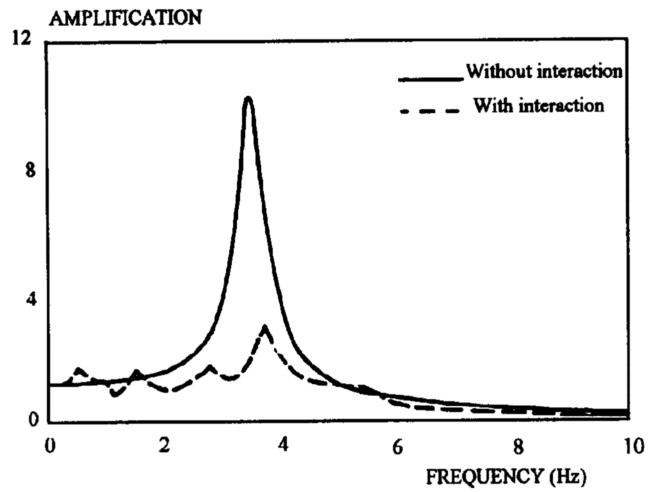


Fig. 7. Amplification of spectral accelerations with and without consideration of the ineteraction of the soil with a heavy colonial structure (from Ordaz and Meli, 1994

Historical monuments have performed well, in general terms, under the severe earthquakes which have affected Mexico City, even when modern and apparently more earthquake-resistant structures have suffered significant damage. This is due partly to the favorable soil-structure interaction mentioned above, and partly because the fundamental periods of vibration of these monuments are well below the prevailing long periods of the ground motion.

The seismic vulnerability of many monuments is increasing, nevertheless, because of the regional subsidence of the lake-bed area of Mexico City, which is caused by the extraction of water from the deep sand layers. The differential settlements, the inclination of the vertical structural members and the severe cracking increase steadily and reduce the safety against future earthquakes. These effects cannot be ignored in quantitative evaluations of the seismic response. On the other hand, the most effective way to restore the seismic safety these structures initially possessed, is by correcting the differential settlements and out-of-plumb of structural members, as well as by restoring the continuity among different parts of the structure.

EXPERIMENTATION, INSTRUMENTATION AND MONITORING

Even if the limitations of quantitative approaches to the evaluation of seismic safety of monuments are recognized, decisions at this regard will be more reliable if they are based on structural properties that are directly measured in the field.

For modern structures, the methods for design or for safety evaluation are based on assumptions and on mechanical properties which are derived from an extensive experimentation performed mainly in laboratories. For their nature, monumental structures do not lend themselves to laboratory experimentation, which is limited to the behavior of the simplest forms (arches, columns, walls). Most experimentation must be carried out directly on actual buildings.

In recent years, several techniques have been developed for in situ measurement of structural properties. These techniques are reliable and non-destructive, or only slightly destructive, like sonic tomography, thermography, endoscopy, rebound tests, core sampling, etc. The flat jack technique developed in Italy by ISMES is a particularly powerful tool for determining Young modulus and the state of stresses on the structure, (Rossi, 1990).

Additionally, sophisticated techniques for monitoring the behavior of monumental structures in terms of displacements, settlements, out-of-plumb and crack openings have been implemented in several monuments. In some cases they are complemented by automatic data adquisition systems which can be set to give alert signals when the response exceeds a selected threshold.

Instrumentation and monitoring of monuments for the determination of seismic response have been scarce. Nevertheless, they can be extremely useful.

One technique that is increasingly being used for modern structures and that can give significant information also for monuments is the ambient vibration test. High-sensitivity accelerographs, or seismographs, are placed in different setups on critical point of the structure, to measure the vibration caused by traffic, wind or microtremors. Averages of a large number of measurements are used to obtain general trends, while eliminating noise and effects of specific inputs. By spectral analysis of the signals, natural frequencies of vibration and modal shapes can be determined, along with correlations between vibrations of different parts of the structure.

When these measurements are repeated after several years or after a significant earthquake occurred, changes in dynamic properties can be detected, which can be consequences of damage or of degradation of the structure. Ambient vibration measurements must be interpreted with great care when used to assess the structural response to actual earthquakes. The amplitudes of motions and the levels of stresses imposed by ambient vibration are so small that the structural behavior remains essentially linear elastic and the effect of cracking and discontinuities in the structure is not completely reflected.

Much more representative of the earthquake response are the records obtained by permanent networks of accelerographs placed in critical points of the structure to measure its response to actual earthquakes. Results are much more difficult to obtain than in the former case, nevertheless it is important to count on at least a few instrumented monuments to try to derive general conclusions about the earthquake response of typical structures.

Mexico City is a particularly convenient place for seismic instrumention of monuments, because of the large variety of building types available, and because of the great number of significant seismic records that can be obtained. Due to earthquakes in the subduction zone of the Pacific Coast, on the average two events with itensity V or greater in the Modified Mercalli scale are recorded each year. The existance of a large network of ground motion instruments provides a useful reference for the interpretation of the results.

A small network of strong motion instruments is being installed in the Mexico City Cathedral. Its purpose is to determine the differences in the motion recorded at the base of the monument and that in the free-field nearby, as well as to measure the amplification of the motion at different points of the roof. These results are important for the estimation of the maximum acceleration that can be induced by severe earthquakes.

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