1.

Small Amplitude Vibration Measurements of Buildings Undamaged, Damaged, and Repaired After Earthquakes

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Ambient vibrations provided the means to measure dynamic properties of reinforced concrete undamaged buildings, damaged and repaired after the destructive earthquakes of February 24,1981,in the major area of Athens and in Central Greece. Each fundamental period is given as function of the number of stories, the height of the building, the dimensions of its plan and the percentage of shear walls. The shape of the deformation of the vertical centerline and the associated percentage of critical damping resulted also from the measurements, which in addition proved that for the damaged buildings the vertical centerline presents a discontinuity at the level where the damages are concentrated.For the repaired buildings this line becomes smooth.

INTRODUCTION

Ambient vibrations having a small amplitude,arise from many disturbances of the environment, such as wind, distant waves of the sea, influence of the sun, distant storms, various microtremors of the Earth crust, traffic and the various vibrations caused by the activities of man.

These disturbances have a wide range of frequencies, thus many normal modes of structures can be excited by them. Exploiting these inherent small amplitude vibrations of buildings, their fundamental period and the deformation of their vertical centerline can be determined. The method applied for the determination of damping differs either at the stage of data reduction or at the stage of measurements - particularly at the excitation of the structure for the production of free vibrations. In the present measurements the latter excitation is carried out by specially trained, one or two, men.

Modern earthquake resistant regulations take into account the fundamental period of the structure to determine earthquake loads. The deformation of the vertical centerline in the fundamental mode is important for the determination of the distribution of lateral earthquake loads with height. Damping is also important to determine the structure's earthquake response.

The degree of deterioration or damage of a structure may,to a certain extent, be determined by field measurements of its vibrations. Changes in the predominant periods of vibration as well as discontinuity along the

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height in the deformation of the vertical centerline arise from discontinuity of stiffness, which in most cases is due to damage of either the structural system, secondary elements (mainly partitions) or both.

The dynamic characteristics (fundamental periods, modal shapes and corresponding damping values) of a building depend on many factors, the most important of which are:

(1) The particular structural system, that is the vertical (columns, shear walls), the horizontal (beams, slabs) elements and the way they are connected.

(2) The material of the structural system, that is concrete, steel, brick, stone etc. and/or a combination of these.

(3) The mass of the building and how it is distributed in height and plan.

(4) The geometry of the building (height, dimensions of the plan) and the various irregularities, if any, in height and plan of the various stories.

(5) The infill panels and non structural elements of the building, their construction and attachment to the structural system.

(6) The particular kind of soil as well as the type of foundation (isolated footings, shallow foundation, stiff or deep foundation).

(7) The age of the building, the quality of maintenance and the level and duration of its vibrations due to its use and its environment.

(8) The extent, location, and severity of damage along the height and plan of the building and the damaged elements (slabs, beams, columns, shear walls, infill panels) importance.

(9) In case of repair, alteration, or strengthening, the kind, the extent and material of repair in relation to the kind, the position and the percentage of existing failures.

(10) The amplitude of the vibration of the building during measurements in relation to previously experienced amplitudes.

The last factor is particularly important, since the amplitude of the vibration relates directly to the prior stress level and the degree of yielding which in turn directly influences the response of the structure, through intensely nonlinear behavior. For the same reasons the results of field measurements only have meaning for corresponding amplitudes of vibration. For the buildings discussed below the materials are in their linear range, strains being too small to develop nonlinear properties.

During the earthquake response of a building its dynamic characteristics change abruptly enough and its model for the analysis should be changed accordingly, as shown schematically in Figure 1. For small amplitude translations where there are only compressional stresses at the level of foundation, one may consider the frame fixed at its base, Figure 1b,which coincides with the typical way of analysis; for translations of a greater amplitude, however, where tensional stresses are created at the level of foundation, the frame must not be considered as fixed at its base and the model for the determination of the member forces, displacements etc. becomes complicated, Figure 1c,1d.

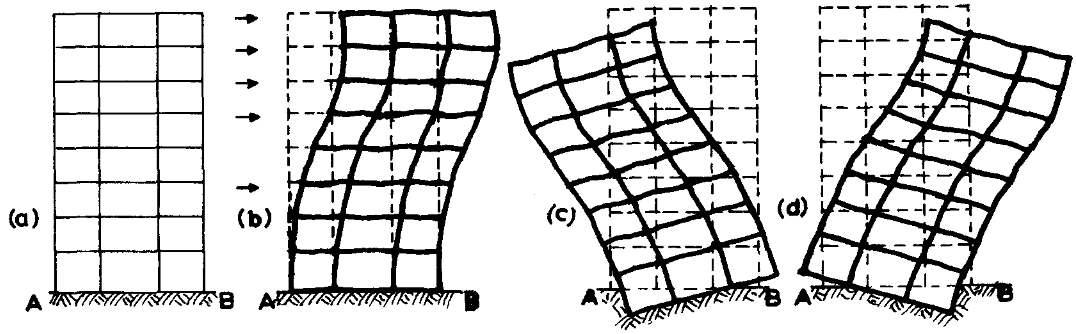

FIGURE 1. The amplitude of the translations of the stories affect not only the behavior of the members (linear-non linear) but also the model of the structure: (a) elevation of a typical frame; (b) for small amplitudes the frame may be considered as fixed at its base - the typical model for analysis; (c),(d) a magnified and exaggerated response of the frame during a strong earthquake which produces tensional vertical stresses at the foundation level.

If the analysis includes soil structure interaction, particularly with a non linear soil response, the stresses and strains computed will certainly be closer to reality, however the computational difficulty is substantially increased. Clough and Huckelbridge (1977) found that the stress in structures not fixed at their base during strong earthquakes is smaller than that calculated with the hypothesis of fixed base.

The dynamic characteristics of the structures to which the various earthquake resistant regulations refer should differ depending on the particular method of analysis that will be applied; for example, for the method of equivalent static load the fundamental period should most probably correspond to some mean value of those that the structure will exhibit during its earthquake response. Notwithstanding this fact the relations used by most regulations for the calculation of the fundamental period are to a great extent based on small amplitude vibrations similar to those that are reported herein.

The shape of the deformation of the vertical centerline due to horizontal translations of the floor diaphragms is influeced by the above mentioned factors, mainly, in order of importance: (8),(9),(4),(5),(1), (6),(3),(2),(7) and (10). Damping is influenced by the following factors, again mentioned in order of importance: (10),(2),(8),(9),(5),(7),(1),(6), (3) and (4).

With all these comments and with several reservations as far as the mean values are concerned (due to the small population of each case) the results of the measurements follow.

NOTATION

In the text the various symbols used have the following meaning, unless otherwise noted each time the symbol is used.

A: cross-section of cantilever (m^2)
B: width of building perpendicular to the considered direction of vibration (m)
β_i: regression coefficient
D: length of building along the considered direction of vibration (m)
E: modulus of elasticity of the material (MPa)
E(f): expected value of f
ζ: damping ratio
G: modulus of elasticity in shear (MPa)
H_o: height of building from its foundation level (m)
H: height of building above ground level (m)
I: moment of inertia of cross section (m^4)
K: mean value of story indices (KNm^{-1}) (story index=sum of stiffness of the columns of the story under the shear building hypothesis)
k: cross section form factor
m: mass distributed along the height of the structure (kgm^{-1})
M_k: lumped mass at the k-th level (kg)
N: number of stories above ground level (not necessarily the foundation level)
ν: Poisson's ratio
ρ: ratio between the cross section of the shear walls and the sum of the cross sections of shear walls and columns, mean value of the different stories
ρ': ratio between the cross section of the shear walls whose lenght is along a particular direction and the area of the plan of the building, mean value of the different stories
r: correlation coefficient
σ: standard deviation
T_f: fundamental period of structure for deformation in flexure (sec)
T_i: i fundamental period of structure (sec)
T_s: fundamental period of structure for deformation in shear (sec)
ω_n: circular frequency of the n mode (sec^{-1})

INSTRUMENTS USED FOR THE MEASUREMENTS, METHOD OF MEASUREMENT AND METHOD OF DATA REDUCTION

Two systems were used to measure and record the vibrations of buildings depending on the particular needs and the availability of transportation.

The first system, Figure 2, is a one-channel VM-1 (Vibration Monitor-1) by Kinemetrics;it has an integrated amplifier system, a thermal pen recorder and low pass filters. The electromagnetic accelerometer EM-4, from the same manufacturer, with a maximum sensitivity of 10^{-2}g is used as pickup. The second system, Figure 3, is a four-channel VSS-1(Vibration Survey System) by Kinemetrics with SS-1 (Ranger Seismometer) electromagnetic velocity transducers, and a separate signal amplifier which has integration and differentiation circuits as well as a series of low pass filters all

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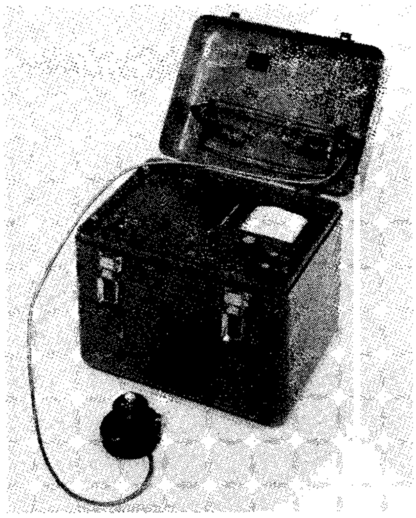

FIGURE 2. The one-channel "Vibration Monitor VM-1" by Kinemetrics

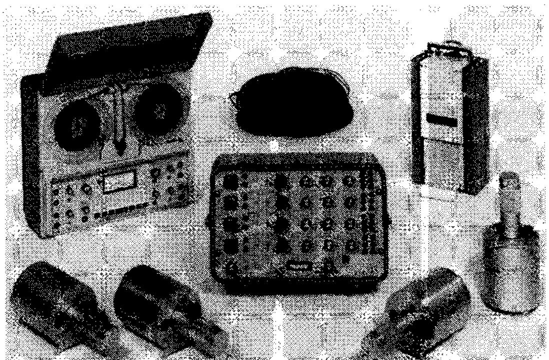

FIGURE 3. The four-channel "Vibration Survey System VSS-1" by Kinemetrics

Photos courtesy of Kinemetrics/Systems

integrated in the instrument SC-1 (Signal Conditioner). The signals are recorded on analog magnetic tape (FM) recorder and light beam oscillograph.

The selection of positions and directions for the tranducers in the building along the height and in the plan depends on the direction of the vibrations to be measured and on the discontinuities of stiffness and distribution of mass, in height and plan, as well as the extent and kind of damage and/or the repair and strengthening.

Torsional vibration around a vertical axis is likely for each building in addition to translation along its two main axes. For the determination of these vibrations, measurements were taken at various levels of the building and along its two main axes. For example, for a building of N stories without discontinuities, vibration measurements were taken at the following levels:

(1) At the top story; measurements of ambient vibrations and free vibrations after excitation with the "man power" technique, in order to find damping.

(2) At intermediate stories, the choise of which depended on the total number of stories N. This measurement was to determine whether the period of vibration was constant along the height of the building and for determining the deformation of the vertical centerline of the building along the height, and

(3) On the ground and along the three directions - length, width and vertical - inside and outside, but near the building plan, in order to determine the degree of soil structure interaction.

For building with an open first story (termed "Pilotis") measurements were also taken on the first story level to determine the deformation of the vertical centerline of the building.

The instruments used are very sensitive: they can clearly record accelerations of the order of 10^{-5}g (receiver 10^{-2} g and amplifier 10^{-3}). This sensitivity is necessary since the vibrations measured were mainly of very small amplitude.

For measurement of translational vibrations of the buildings, the transducers were placed at each level in such a position as to avoid the influence of torsional vibrations. The center of rotation was chosen as such a position. This is the best selection that can be made even though it is not free of torsional motions a multi - story building. This is due to: a) the difficulty in locating a purely translational point and b) the influence of the other stories. The measurements were taken along the two main axes of the building. It must be noted that the "vertical centerline" of multi-story buildings is not always a straight, vertical line, although its deformation from equilibrium is presented as if the centers of gravity were on a vertical line.

The measurements were taken at times specially chosen so that the movement of people in the buildings, the traffic and the wind were minimized. Care was taken in all the measurements so that there would be control of the variability of the vibrations. The vibrations recorded were only those that were permanent and not due to temporary causes. This is of particular importance in cases where only one recording channel was used and two consecutive measurements were separed by a time interval. The use of the low pass filters was very important in facilitating measurements and distinction of the fundamental period from other periods.

When the buildings were cracked, the number of points where measurements were taken was incereased in the vicinity of the cracks. A difficulty was encountered here, since the center of rotation (known from the data of the design and from the drawings) was considerably moved and not easy to calculate.

The "zero crossing" method of K.Kanai (1961) was used for data reduction, according to which the sample of the measurements must be 120 sec. The analysis was done by hand and by a small, portable programmable calculator. The histogram of the time intervals between two consecutive zero crossing points of the vibration curve was calculated for the 120 seconds of the record. The reader is refered to Mouzakis (1980) for the determination of the second fundamental period, as well as for the computational procedure. The mean period and its standard deviation were found next. For the calculation of the damping the "man power" method was used, that is the excitation of the building by means of the inertial force exerted by one or two persons pushing against the building trying to follow the needle of the recorder. The damping ratio was calculated from the following free vibration of the building according to the relation:

$$\zeta = \frac{1}{2\pi n} \ln \frac{x_n}{x_o} \qquad (1)$$

The damping determined by the above method is of a rather small importance since it generally refers to small amplitudes of vibration and the friction damping (Coulomb damping) that is certainly developing during the earthquake response of structures is not observed and therefore not considered in this calculation.

The procedure results in the reduction of the field data to the following items, that are of particular interest:

- Basic information about the use of building in plan and along the height,its age,exposure to previous disturbances, etc.
- Data about the geometry of the building (number of stories,plans and sections with the positions and the dimensions of the parts of the structural system as well as of the infill panels), the materials and the degree of completion of the building when the measurements took place.
- Data about the soil.
- The lowest periods of the building along the two main directions the plan with the corresponding maximum amplitudes.
- The maximum simultaneous amplitudes of deformation of building and along the two horizontal directions of the plan as well as the maximum vertical amplitudes of ground and building in selected points of building and ground.
- The damping in each direction, with the corresponding amplitude.
- Data about the climatic conditions, the traffic and generally the conditions of the environment and the use of the building during measurements.

CLARIFICATION OF SOME OF THE TERMS AND SYMBOLS USED

The number N corresponds to the number of levels of the building and is equal to the number of degrees of freedom of motion in each direction. When there is a mezzanine with peripheral beams it is also considered as a story.

Depending on the dynamic deformation curve, vertical cantilevers with distributed mass and constant stiffness (cross section that does not change along the height) are either shear (s) or bending (f) cantilever beams.

SHEAR CANTILEVER BEAM

The circular frequencies, $\omega_{s,n}$ of the various normal modes n, are given by the following formula:

$$\omega_{s,n} = (2n-1)\frac{\pi}{2H}\sqrt{\frac{kG}{\rho_1}} \quad (\mathrm{sec}^{-1}) \quad , \; n=1,2,3,\ldots \tag{2}$$

where H: the height of the cantilever beam, in meters, from its base to its free end

k: cross section form factor according to Blevins (1979); it is equal to

$k=6(1+\nu)/(7+6\nu)$ for circular cross section

$k=10(1+\nu)/(12+11\nu)$ for rectangular cross section

where ν is Poisson's ratio

ρ_1: the mass density of the material (kg m^{-3})

The period of free vibration of the normal modes of shear cantilever beam is independent of the area and the moment of inertia of the cross section of the cantilever.

The following relations are also valid for shear cantilever beam: $\omega_{s,2}=3\ \omega_{s,1}$, $\omega_{s,3}=5\ \omega_{s,1}$.

BENDING CANTILEVER BEAM

The circular frequencies of the various normal modes are given by the following formulae:

$$\omega_{f,n}= \frac{a_n}{H}\sqrt{\frac{EI}{m}} = \frac{a_n}{H}\sqrt{\frac{EI}{\rho_1 A}} \quad (\mathrm{sec}^{-1}), \tag{3}$$

$$a_1=3.516, \; a_2=22.034, \; a_3=61.696$$

where H: the height of the cantilever beam, in meters, from its base to its free end

ρ_1: the mass density of the material (kg m^{-3})

The period of vibration of the normal modes for the case of bending cantilever depends on the cross section of the cantilever (area and moment of inertia).

The following relations are also valid in the case of bending cantilever beam:

$\omega_{f,2}=6.28\ \omega_{f,1}$, $\omega_{f,3}=17.6\ \omega_{f,1}$

OTHER CLARIFICATIONS

The terms length (D) and width (B) used are not related to the stiffness of the buildings but refer to the longer and the smaller dimension of their plan respectively; therefore, when the longer dimension of a building is mentioned, this does not necessarily mean that along this direction the building has its maximum stiffness. In the case of a square plan, these terms lose their meaning. The separation of measurements into measurements along the length and measurements along the width proved to be of rather small importance in this analysis. It has only been observed to be important when the greater the dimension along one direction the more the building tends to have shear behavior along this particular direction, in relation to the other direction where the dimension of the building is smaller.

All the buildings measured had reinforced concrete load bearing systems. The vertical elements of these load bearing systems were columns or shear walls or combinations of both.

In the present investigation as shear walls are considered those vertical structural elements which are strained and stressed in their plane mainly in shear, having a cross section of minimum dimensions 1.00X0.20 (m^2). The shear walls taken into consideration were only those having their own foundation; deep horizontal beams and walls supported by columns were therefore excluded.

BUILDING CLASSIFICATION AND DESCRIPTION

A total of 110 buildings were measured. A file is maintained in the Laboratory for Earthquake Engineering of the N.T.U. of Athens for most of these buildings, with the basic structural drawings, photographs, and information about damage and repair.All these buildings are free standing, have a rectangular plan and are of reinforced concrete.About 90 of these buildings are located in the central area of Athens. The dynamic properties of these buildings were measured before the destructive earthquakes of February-March 1981 which struck Central Greece. For more information about these earthquakes, as well as about the damages to engineering structures, building code and practice, see the relevant reconnaissance EERI/NRC report by Carydis et al (1982). After these earthquakes , measurements were made for about 25 damaged buildings (a few in central Athens area, coinciding with the previously measured buildings, and the most in the epicentral region, not measured before). Only 20 of these buildings could be measured after their repair.

The measured buildings were classified in nine categories according to their use as it is briefly presented in Table 1.

Files are maintained for each of these buildings: the location, the code number according to use, the number of stories above and below ground surface, the height above ground, the depth of foundation, the floor area, the dimensions of the plan, a destription of the structural system, the material of partitions and the ratio ρ (see notation) for both of the main

TABLE 1. CLASSIFICATION OF BUILDINGS ACCORDING TO THEIR USE

Code	Use of Building	No of measured buildings
A	Apartments with an open and free of use first story (on "pilotis")	34
B	Apartments on "pilotis" and a mezzanine	4
C	Apartments with brickwall partit.all over the height	40
D	Offices all over the height	17
E	Offices with a mezzanine	8
F	Apartments with shops at the first story	2
G	Offices with shops at the first story	1
H	Hotels	2
I	Hospitals	2
	Total	110

directions of the plan. For damaged buildings brief data is kept about the kind and extent of damages, based on a damage classification presented in Table 2; for repaired buildings, a brief description of the repair and the extent of its complition when measured, it is also given,Laios (1982).

TABLE 2. DAMAGE CLASSIFICATION

	DAMAGES:	SIMPLE CRACKING (a)	EXTENDED CRACKING (b)	SEPARATION (c)
1	Infill walls	1a	1b	1c
	DAMAGES:	SIMPLE CRACKING (a)	LOCAL DISORGANIZATION (b)	DISCONTINUATION (c)
2 Horizontal elements	1 Beams	21a	21b	21c
	2 Slabs	22a	22b	22c
3 Vertical elements	1 Columns	31a	31b	31c
	2 Short Columns	32a	32b	32c
	3 Walls	33a	33b	33c

All buildings were classified in three major groups with respect to the continuity of their stiffness and mass along the height, after the measurements were completed:

(1) Buildings with continuity of stiffness and mass and a bare structural system (no columns "planted" on beams, small or no variation of the height of the stories and the dimensions of the vertical and horizontal elements of the structural system from story to story, small or no variation of the plan of the stories). These are office buildings or buildings for multi-story shops and

parking. There are very few or no partitions that may add stiffness and/or mass to the structural system. In this category the buildings of codes D,E and G are included.
This group is named "office buildings".

(2) Buildings with apparent continuity of their stiffness and mass with many infill walls (brickwalls in all stories as for example in apartment buildings). Any discontinuity of both stiffness and mass of the structural system should be small, compared to that of brickwalls, or other relevant partitions. In this category the buildings of codes C and I are included.

This group is named "apartment buildings with constant stiffness".

(3) Buildings with stiffer and heavier upper stories compared to the first story. This discontinuity of their stiffness and/or mass may be due either to the structural system (columns or walls planted on beams of the first story, walls supported on columns of the first story, higher first story compared to upper stories, smaller cross sections of columns and beams of the first story compared to those of the upper stories, reduction of the plan of the first story) and/or to the infill walls (considerable reduction of infill walls in the first story, as for example in the case of apartment buildings whose the first story is an open space or shops). The coexistence of both these reasons of discontinuity is very common. In this category the buildings of codes A,B,F, and H are included.
This group is named "apartment builidngs on pilotis".

With the discontinuity of stiffness obvious for cracked buildings, in order to facilitate comparison, such damaged buildings were classified in the same groups as they would have been if the building was without damage.

PRESENTATION OF RESULTS OF MEASUREMENTS OF UNDAMAGED AND DAMAGED BUILDINGS

Following the method of data reduction described earlier, the mean period and its standard deviation, the deformation shape for each one of the lowest modes of vibration, as well as the mean value of the damping for each building were subject to further processing. The latter one was carried out only to those measurements which presented very small errors. The criterion set was the standard deviation of the corresponding period (first and second mode) of each building to be less than 0.02 to 0.03 sec.

The method of processing and the results obtained are given in this section.

UNDAMAGED BUILDINGS

Relation Between Period and Number of Stories or Height of Building.
A linear relationship between the mean fundamental period T as calculated previously and the number of stories N, or the height H of the building, was computed, for the case of measurements before the earthquakes

(undamaged buildings). This has the following form:

$$T=a_1N+b_1 \quad \text{or} \quad T=a_2H+b_2 \qquad (4,5)$$

For all buildings that were measured and for the buildings included in each of the above defined three groups, the values of a_1,b_1 and a_2,b_2 of Eqs. 4 and 5 were found by use of a least squares regression analysis. The resulted relationships between mean period and number of stories, the corresponding Figure number (4 to 7) for the respective regression lines and their correlation coefficients r are given in Talbe 3.

TABLE 3. RELATIONSHIP BETWEEN MEAN FUNDAMENTAL PERIOD AND NUMBER OF STORIES N (undamaged buildings)

Building Group	Relationship	r	Corresp. Figure No
All Buildings	T=0.043N+0.107	0.782	4
Office Buildings	T=0.045N+0.207	0.786	5
Apartments with constant stiffness	T=0.032N+0.145	0.750	6
Apartments on pilotis	T=0.049N+0.028	0.923	7

The relationship between mean period and building height are given in Table 4.

TABLE 4. RELATIONSHIP BETWEEN MEAN FUNDAMENTAL PERIOD AND BUILDING HEIGHT (undamaged buildings)

Building Group	Relationship	r
All Buildings	T=0.012H+0.131	0.785
Office buildings	T=0.013H+0.216	0.783
Apartments with constant stiffness	T=0.011H+0.144	0.570
Apartments on pilotis	T=0.013H+0.107	0.732

It follows from the comparison of relationships shown in Figures 6 and 7 that the constant term of the first relation (Fig.6) is considerably larger than the one of the second relation (Fig.7). This constant term must represent the influence of the soil. This means that the influence of the soil is far larger in an apartment building with constant stiffness (and more stiff building) than in a pilotis building, which has a more flexible first story. This conclusion was expected, since the period of vibration of a completely stiff building is approximately the same with the period of vibration of the ground, Carydis (1972).

Results on Modal Shapes and Damping

The ratio of the period of the first normal mode to the period of the second normal mode was estimated to be approximately equal to three. This means that apartment buildings without pilotis can - with a good approximation - be considered as shear cantilever beams with distributed mass and stiffness. However, for office buildings the ratio of the period of the first normal mode to the period of the second one is considerably higher than three and quite often is approximately equal to 6.3 for

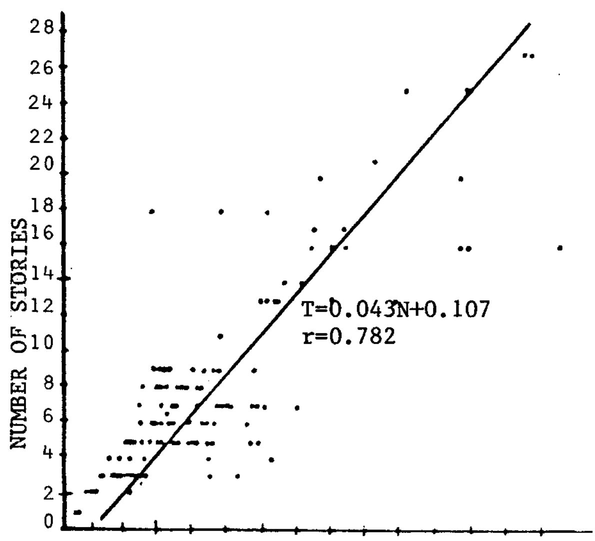

FIGURE 4. Relationship between fundamental period and number of stories for all undamaged buildings.

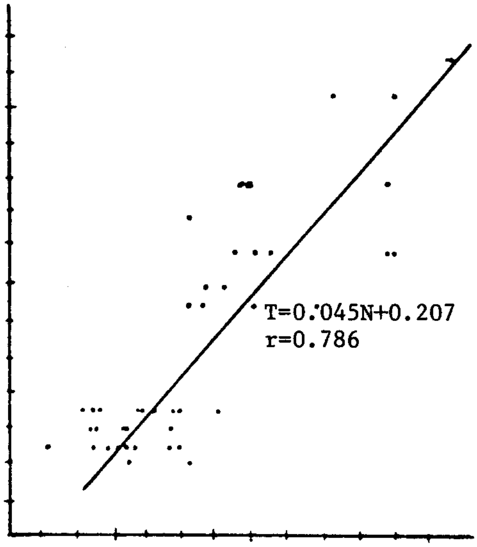

FIGURE 5. Relationship between fundamental period and number of stories for undamaged office buildings.

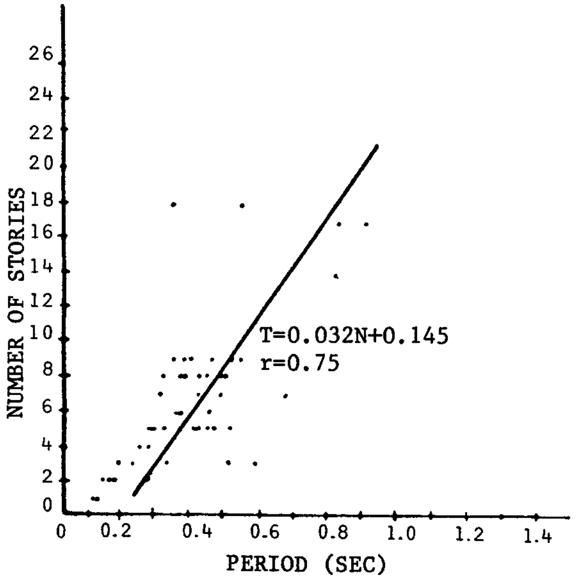

FIGURE 6. Relationship between fundamental period and number of stories for undamaged apartment buildings with constat stiffness.

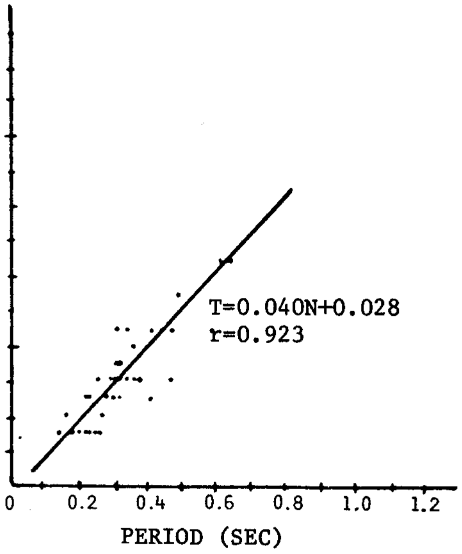

FIGURE 7. Relationship between fundamental period and number of stories for undamaged apartment buildings on pilotis.

oscillation along the small direction of the building, which means that some slender office buildings behave clearly like bending cantilever beams.

For each of the mentioned three groups of buildings, the mean value of the first and second normal shapes were calculated. Each one of these shapes was normalized (with a unit displacement at the top), and the respective comparison among the three groups is given in Figure 8.

It was measured that the acceleration and displacement in the second normal mode of some apartments on pilotis were larger at the second story than at the top one. The behavior, however, of this group of buildings resembles, due to the stiffness discontinuity in the first story, that of another building with damages in its first story, Matsushima and Carydis (1969).

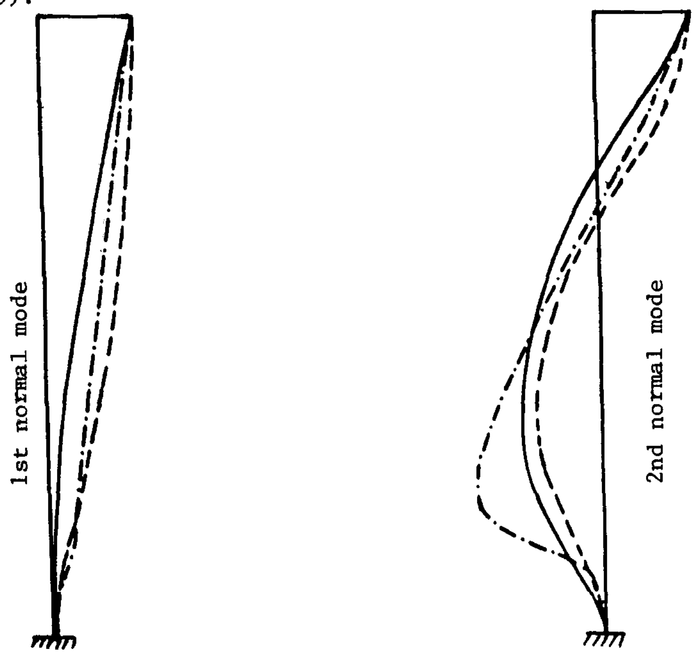

FIGURE 8. Comparision of the first and second modal shapes among the three groups of buildings:
——— Office buildings
—·—·— Apartment buildings on pilotis
——— Apartment buildings with constant stiffness

The measurements of the ambient vibrations were performed also on the ground, around and near the plan of each building, the pickups were placed at the vertical and horizontal direction. From the measurements on the ground it was verified that building and foundation soil constitute an integrated system of vibration and therefore of response to the earthquake. It has been observed that the vertical vibration of the ground near the "long" and the "short" side of the building, almost coincided (in phase and frequencies) with its horizontal vibration along the "short" and "long" axis respectively. This concidence was more accurate in the case of soft ground and buildings with almost constant stiffness. In some cases in which the ground water table was quite high, the horizontal vibrations on the ground were very much reduced, instead, the vertical ones were more pronounced.

The vertical vibrations of structures are of great interest, particularly in cases of measurements taken near the columns having their own foundation. It appeared that from a certain height upwards, the vertical vibrations of the buildings were not directly related to the vertical vibrations of the soil, this however can be explained by the transmissibility of vibrations of each buildings.

Finally, as far as the damping is concerned it was observed that the younger the building the higher the damping ratio, which may be due to the fact that the materials and the member connections are still young and have suffered no fatigue due to the use of the building (e.g. separation of infill walls from load bearing system, small fissures and cracks due to the previous deformational history of the building). This means that with larger amplitudes, than the ones that the structure has already experienced, new damping mechanisms will be activated and the observed damping will be higher. The value of damping found here by the application of the "man - power technique" was less than 3% in all cases.

Relation Between Period, Heigh of the Building, Dimension B and Shear Walls Ratio ρ for All Apartment Buildings.

The following statistical models were used for this correlation:

$$T_i=\beta_o H_i^{\beta_1} B_i^{\beta_2} (H_i+\rho_i B_i)^{\beta_3} 10^{e_i} \qquad i=1,2,\dots,n \tag{6}$$

$$T_i=\beta_o (H_i/B_i)^{\beta_1} (1+\rho_i)^{\beta_2} 10^{e_i} \qquad i=1,2,\dots,n \tag{7}$$

$$T_i=\beta_o (H_i/\sqrt{B_i})^{\beta_1} (1+\rho_i)^{\beta_2} 10^{e_i} \qquad i=1,2,\dots,n \tag{8}$$

$$T_i=\beta_o H_i^{\beta_1} B_i^{\beta_2} 10^{e_i} \qquad i=1,2,\dots,n \tag{9}$$

where n is the number of the sample, $E(e_i)=0$ and $E(e_i e_j)=\delta_{ij}\ \sigma^2$. From the above relations (6) up to (9) it follows that:

$$\log T_i=\log \beta_o+\beta_1\log H_i+\beta_2\log B_i+\beta_3\log(H_i+\rho_i B_i)+e_i \qquad i=1,2,\dots,n \tag{10}$$

$$\log T_i=\log \beta_o+\beta_1\log(H_i/B_i)+\beta_2\log(1+\rho_i)+e_i \qquad i=1,2,\dots,n \tag{11}$$

$$\log T_i=\log \beta_o+\beta_1\log(H_i/\sqrt{B_i})+\beta_2\log(1+\rho_i)+e_i \qquad i=1,2,\dots,n \tag{12}$$

$$\log T_i=\log \beta_o+\beta_1\log H_i+\beta_2\log B_i \qquad i=1,2,\dots,n \tag{13}$$

Using the regression method, the following regression lines were determined:

$$T_i=b_o H_i^{b_1} B_i^{b_2} (H_i+\rho_i B_i)^{b_3} \qquad i=1,2,\dots,n \tag{14}$$

$$T_i=b_o(H_i/B_i)^{b_1}(1+\rho_i)^{b_2} \qquad i=1,2,\ldots,n \qquad (15)$$

$$T_i=b_o(H_i/\sqrt{B_i})^{b_1}(1+\rho_i)^{b_2} \qquad i=1,2,\ldots,n \qquad (16)$$

$$T_i=b_oH_i^{b_1}B_i^{b_2} \qquad i=1,2,\ldots,n \qquad (17)$$

where b_o,b_1,b_2,b_3 are unbiased estimators of β_o,β_1,β_2, β_3 respectively.

Particularly for a sample n=66 it follows, from relation (14) that:
$\log b_o=-1.3452 \rightarrow b_o=0.045$, $b_1=0.8827$, $b_2=-0.1096$, $b_3=-0.1083$

From relation (15) it follows that:
$\log b_o=-0.58614 \rightarrow b_o=0.259$, $b_1=0.4856$, $b_2=0.1429$

From relation (16) it follows that:
$\log b_o=-0.99741 \rightarrow b_o=0.101$, $b_1=0.745$, $b_2=-0.185$

From relation (17) it follows that:
$\log b_o=-1.33384 \rightarrow b_o=0.046$, $b_1=0.7727$, $b_2=-0.1242$

Then, the regression lines are defined by the following relations:

$$T=0.045\ H^{0.883}\ B^{-0.110}\ (H+\rho\beta)^{-0.108} \qquad (18)$$

$$T=0.259(H/B)^{0.486}\ (1+\rho)^{0.143} \qquad (19)$$

$$T=0.101(H/\sqrt{B})^{0.745}\ (1+\rho)^{-0.185} \qquad (20)$$

$$T=0.046\ H^{0.773}\ B^{-0.124} \qquad (21)$$

Several methods for selecting the best regression relationship have been used. All of them, however, do not necessarily lead to the same conclusions. The residual mean square estimates the variance σ^2, and an objective method consists in choosing the relation with the lowest residual mean square. As such, relations (6) and (9) were found. Relation (9) is finally chosen instead of (6) because it is simpler, although relation (6) has a slightly lower residual mean square. The proposal for all apartment buildings is relation (21).

DAMAGED BUILDINGS

First, second and higher modes of vibration (period and shape) as well as the percentage of damping were measured for each of the 25 buildings studied after the earthquakes and are kept in NTU files. There are also sketches and description of damages according to the classification in Table 2. Each of these buildings is identified with a number 1 to 25. For example, a front view of the damages along one direction of buildings No 1 and 11 are shown in Figures 9b and 10b respectively, Laios (1982). In Figures 9 and 10 appear also the first and second modes along the "Long" and "Short" direction of the building.

It must be noticed here that some modes of higher order appeared in some damaged regions of the buildings, parts of buildings showed a rigid body response. Torsional vibrations also appeared and the measurements became cumbersome and time consuming besides the risks involved, since the buildings were evacuated due to their damages.

Fundamental Periods

The damaged buildings had high values (double, as an average) of their fundamental periods compared to similar undamaged buildings measured earlier by the same instrument in the area of Athens. The regression analyses for the relation between mean fundamental periods and number of stories showed low correlation coefficients. The extent of damages in the buildings considered in this regression analysis are of class (b) (see Talbe 2). It was found for apartment buildings with constant stiffness:

$$T=0.077N+0.109 \qquad r=0.489 \tag{22}$$

And for apartment buildings on pilotis:

$$T=0.038N+0.399 \qquad r=0.496 \tag{23}$$

The fundamental periods of the damaged buildings are certainly related to their stiffness before the earthquake, however, they are even more related to the damage of their load bearing system, as well as of their infill panels.

For apartment buildings on pilotis the percent increase of the fundamental period of the damaged buildings is calculated, by means of a regression analysis to be:

$$T\%=-6.97N+153.16$$
$$r=-0.329$$

This implies that maximum damage for this series of earthquakes (near field effect, high frequency content of ground motion) appears in low rise buildings, while for buildings of $N\approx153/7\approx22$ stories there should be little damage.

It was found that buildings with damage to several stories (in beams, columns, walls, slabs and infill masonry) have higher fundamental periods than buildings with damage of higher degree (deterioration etc.) but concentrated in a few particular points. The second fundamental period is not considerably increased, and therefore it is reasonable to assume that lowrise buildings of 4-6 stories were not excited at the second normal mode by these earthquakes, hense the participation of that normal mode,in the earthquake stresses considered, was small.

Modal Shapes

It was found that the shear cantilever beam model does not represent very well buildings with damage over the height and many cracks in slabs and beams. The same is valid for buildings with considerable damage to the infill walls extending to a great height. Buildings with damage to only a few vertical elements satisfactorily follow the shear cantilever beam model. These conclusions follow from the ratios of the fundamental periods of the first normal mode to those of the second normal mode and from the shape of deformation of the vertical centerline resulting from measurements at various levels, Laios (1982).

The zero crossing point as well, as the maximum of the horizontal deformation of the vertical centerline which corresponds to the second modal shape, are always found at lower positions than those of buildings without damage. The maximum appears near the area of damages. The ratio of this maximum amplitude divided by the amplitude of the top may be even larger than 2:1. It was observed that this ratio is usually larger in the direction of the longer of the two sides of the building. Some examples are presented in Figures (9a,c) and (10a,c), while the damages along the two directions of each building are almost equal.

Damping

The damping of these buildings does not seem to have changed very much from that of undamaged buildings. This is reasonable since the amplitude of the present measurements is small. Therefore,the results of the measurements of damping are of a rather limited value. The present values of damping (up to 3%) are valid for a future earthquake only if the amplitudes caused by that earthquake are smaller than those which caused the cracking of the building in a previous loading stage. Finally, there seems to be an intense nonlinearity in the values of the damping of cracked buildings.

In cases where many brickwalls have collapsed, the amount of energy absorbed by the remaining brickwalls was small, which explains the very small percentage of damping found - obviously for these small amplitudes of vibration.

MEASUREMENTS IN REPAIRED BUILDINGS

DESCRIPTION AND CLASSIFICATION OF REPAIRS

The various techniques that may be applied for the repair of a structure may or may not cause an increase of the stiffness of the repaired elements or of the total stiffness of the structure.There are techniques which do not cause an increase of the stiffness of the elements:

- Epoxy glues
- Replacement by elements of equal stiffness
- Addition of strengthening elements without virtual increase of the initial stiffness (e.g.flexible strengthening elements of metal)

As well as techniques that do increase stiffness:

- Concrete mantle or increase of dimensions
- Addition of new stiffening elements

The repairs may cause a change of the deformation of the vertical centerline of the structure (due to an increase of the stiffness of only some stories) or creat eccentricities if more stiff elements are eccentrically placed in the plan.

RESULTS

The various measurements taken after repair to find their influence on the stiffness gave rather consistent results. It was found, generally, that the fundamental period decreased considerably, for all the measured buildings. Where strengthening was also performed, the fundamental period was lower than for the respective undamaged building as is expected.

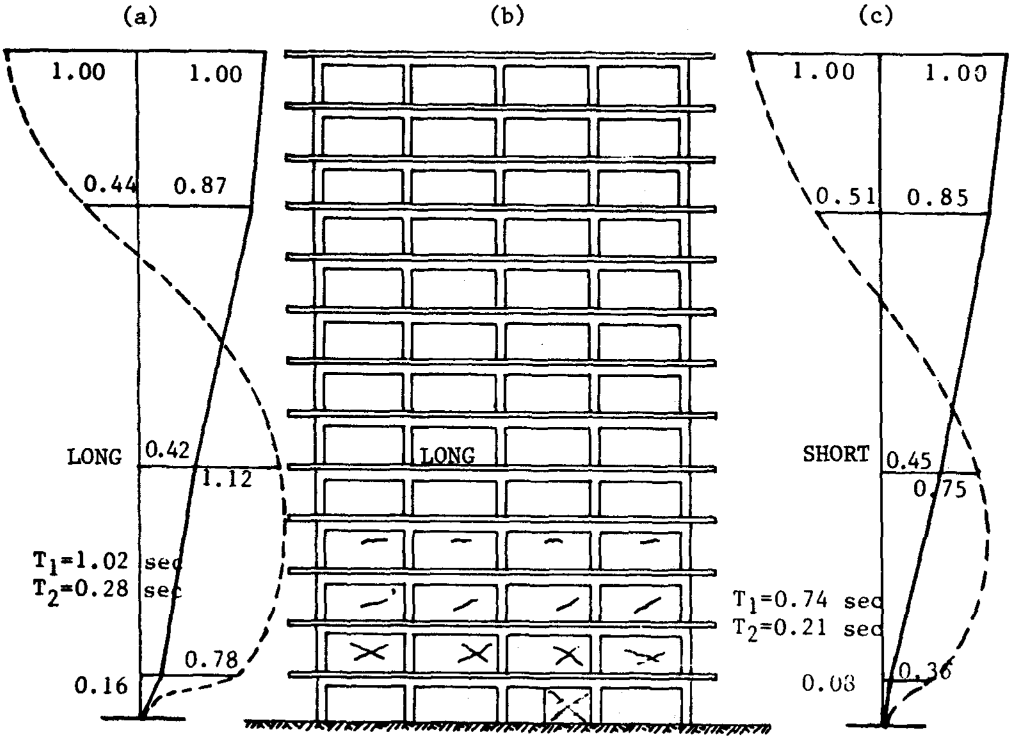

FIGURE 9. First and second normal modes of the damaged building no 1

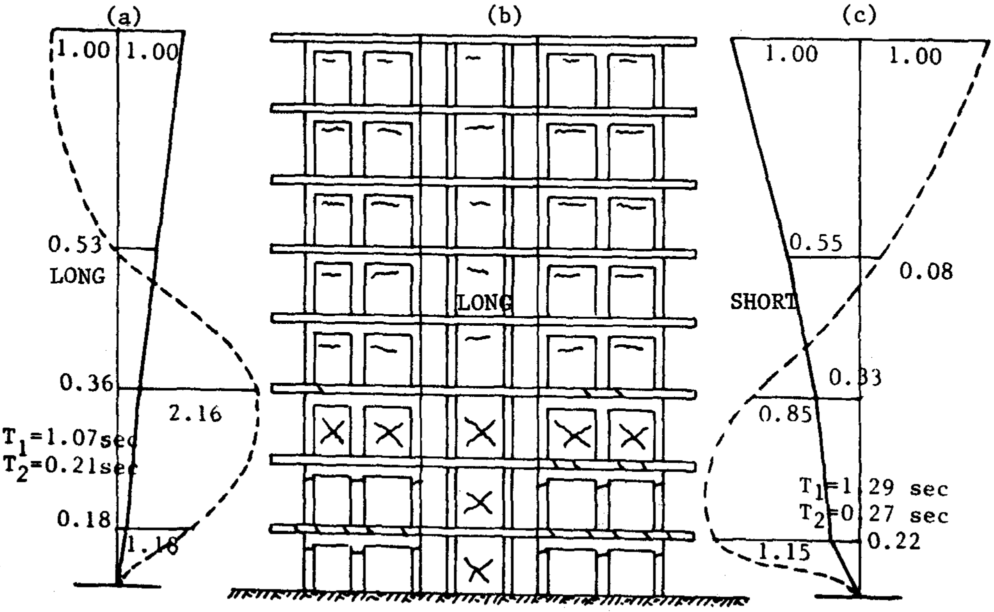

FIGURE 10. First and second normal modes of the damaged building no 11

The vertical centerline was shaped like that of the undamaged case, as it is schematically shown in Figure 11, when the repairs were simple, that is without adding stiffening elements at isolated stories.

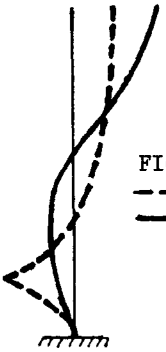

FIGURE 11. Second modal shape
- - - Damages in the lower story
—— After repair

It was observed that in some buildings on pilotis,and after the repair done with considerable strengthening of the two only lower stories, the deformation line along the height shows a singularity point at the third story. This means an increase of stresses at that particular point. There is a high possibility of damage at this point in a potential future earthquake.

CONCLUSIONS

Undamaged broad apartment buildings behave like shear cantilever beams, while slender office buildings behave like bending cantilever beams. The best expression for the fundamental period of apartment buildings is given by $T=0.046\ H^{0.773}\ B^{-0.124}$. The fundamental periods of damaged buildings are considerably increased, the large increase coinciding with low lise buildings for the case of the earthquakes considered. Higher rigid body modes appear in some parts of the buildings above the damaged level. The deformation of the vertical centerline of the damaged buildings shows a singularity in the level where the damages are concentrated. The repairs restored the periods and the modal shapes to the undamaged case. When buildings were strengthened with stiffening elements placed at some stories only, the deformation of the vertical centerline shows a discontinuity at the levels where these stiffening elements stop (top and bottom side of the element).

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