1683

ANALYSIS OF 3-D VIBRATIONS OF THE BASE ISOLATED SCHOOL BUILDING "PESTALOZZI" BY ANALYTICAL AND EXPERIMENTAL APPROACH

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SUMMARY

The results obtained by experimental dynamic ambient and forced vibration tests, as well as from the 3-D finite element analyses on a base-isolated structure are presented and discussed in this paper. Since the isolators of the structure were placed 30 years ago, one of the goals of these investigations was to discover whether the isolators have been affected by aging, i.e., whether there has been a change of the dynamic characteristics of the structure.

First of all, the school building is described and the characteristics of the bearings are given. Then, the results obtained by means of the ambient and forced vibration technique are presented. Based on these tests, some of the necessary characteristics of the isolators to be used for formulation of the 3-D mathematical model of the school were obtained.

Described is the mathematical model that is used in the analyses for obtaining of the fundamental frequencies and mode shapes (fixed and isolated model). The results from these analyses are also presented in this text. Finally, the results obtained analytically and experimentally are analysed and discussed.

INTRODUCTION

The primary school "Pestalozzi" in Skopje, built in 1969, is the first building in the world for which natural rubber isolators were used for its protection against strong earthquakes. [4,5,6] Since the isolators on which the school is placed are more than 30 years old, a project is currently being carried out jointly by IZIIS (Institute of Earthquake Engineering and Engineering Seismology, University "St. Cyril and Methodius", Skopje, Republic of Macedonia) and EERC (Earthquake Engineering Research Center at the University of California at Berkeley) to evaluate the state of the isolators after passing of so many years. [2]

The behaviour of the school building under the effect of strong earthquakes shall be analysed by using a 3-D mathematical model that shall include all the present characteristics of the isolators. To accurately formulate this model, it is necessary to consider the effect of aging of the isolators, i.e., define their present stiffness characteristics and equivalent damping. For the purpose of defining the mentioned characteristics, experimental laboratory tests of two isolators taken from the foundation of the school building "Pestalozzi" are planned to be performed. [2] To define the dynamic characteristics, in-situ, ambient and forced vibration tests were performed obtaining thus the fundamental and some of the higher frequencies and the corresponding mode shapes for the three orthogonal directions of the school building. [3,4] Two torsional modes of vibration and equivalent damping for all the measured mode shapes were also defined.

A 3-D mathematical model of the school building and the bearings was formulated in order to analytically define the dynamic characteristics of the structure. The discretization of the structure was done by using shell finite elements, while the bearings were modelled with spring elements. In addition to the fundamental shapes of vibration, higher vibration modes were also obtained analytically. Comparison between the experimental and analytical results was done.

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The results from the ambient and forced vibration tests, as well as from the 3-D finite element analyses of the school building "Pestalozzi", are given in the subsequent text.

DESRIPTION OF THE BUILDING

The building which is subject of the investigations, i.e., the primary school "J.H. Pestalozzi" in Skopje was donated to Skopje by the Swiss Government after the catastrophic earthquake of July 26, 1963. The school building consists of several units of different number of stories and outline. The base isolation system has been applied only for the main school building, while the other units are founded in the classical way.

The main school building consists of a ground floor and two stories. The proportions of the stricture at plan are 11.0 m / 61.5 m, while its height is 10.0 m. It represents a reinforced concrete box system. The bearing wall system is composed of shear walls with a thickness of 0.18 m, while the floor slabs are 0.20 m thick. The building has a strip foundation forming a beam grid, which is sufficiently rigid to sustain all the effects from the upper structure without heavier deformations. Along the edges of the building, there is a seismic gap with a width of 0.3 m. The gap is covered with reinforced concrete plates.

The structure is base isolated by its placement on special rubber bearings incorporated between the foundation structure and the first floor slab. (Fig.1) [8] There are a total of 54 bearings made of natural rubber, with a square shape, a side of 0.7 m and a height of 0.35 m. Each bearing transfers an axial force amounting to approximately 455 kN. The Swiss firm HUBER-SUHNER from Zurich produced the rubber bearings. The isolators do not contain reinforcing steel plates. They are fabricated by gluing together several rubber layers. The vertical stiffness of such bearings is therefore not much greater than the horizontal one. In addition to the negative effect of the low vertical stiffness of the bearings on the possible rocking motion, there is another disadvantage of these bearings, which is the occurrence of large lateral deformations of the rubber bearings due to dead load effects. [1]

Figure 1. Rubber bearings placed between the strip foundation and the building

DYNAMIC TESTING OF THE PRIMARY SCHOOL "J.H. PESTALOZZI"

Dynamic testing of the main (isolated) school building was performed by application of two independent testing methods:

Ambient vibration method - This method was used for fast obtaining of preliminary results on the dynamic characteristics - resonant frequencies and mode shapes of vibration of the tested structure. The vertical vibration of the structure obtained by this method was used as a referent one since the vibrators used for the forced vibration tests cannot induce vertical displacements.

Forced vibration method - This method was applied to define some characteristic vibrations of the structure in both horizontal directions as well as the torsional one.

To define the *damping coefficients*, two methods were used: (1) half-power bandwidth (frequency-response) method and (2) logarithmic decrement (time-response) method.

The dynamic characteristics of the building were obtained for the state of reinforced concrete plates being removed from the seismic gap and free motion of the isolated building in all directions was enabled. [3,4]

Fig. 2 displays the plan of the second storey of the structure with marked measuring points and position of vibration exciters by which it was excited during the forced vibration tests.

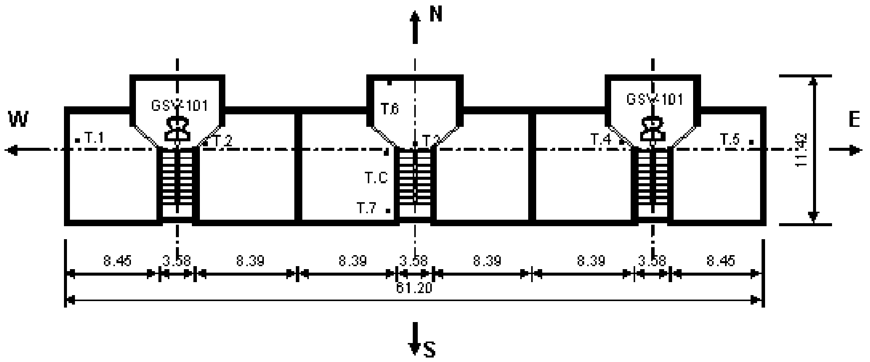


Figure 2. Plan of the second storey of the tested structure with presentation of measuring points and position of the two vibration exciters

Results From the Tests Performed by Applying the Ambient Vibration Method

To define the resonant frequencies of the structure in both orthogonal directions - transverse (N-S) and longitudinal (E-W), and the vertical one, four Range Seismometers, Model SS-1 produced by Kinemetrics from USA were used as sensors. Seismometer was placed in the central part of the structure, at the level of the second storey, at point "C" (Fig. 2). Seismometers were placed at the ends of the structure (measuring points 1 and 5) and also at the level of the second storey to define the resonant frequencies of the torsional vibration. The Fourier amplitude spectra corresponding to the torsional vibrations of the structure were obtained by combining the signals from both seismometers.

Fig. 3 shows the Fourier amplitude spectra recorded on the structure in the corresponding directions of vibrations from which the resonant frequencies were defined. For such defined resonant frequencies of the structure, the corresponding mode shapes were obtained. However, these and the mode shapes obtained by other measurements are not presented in this paper due to lack of space.

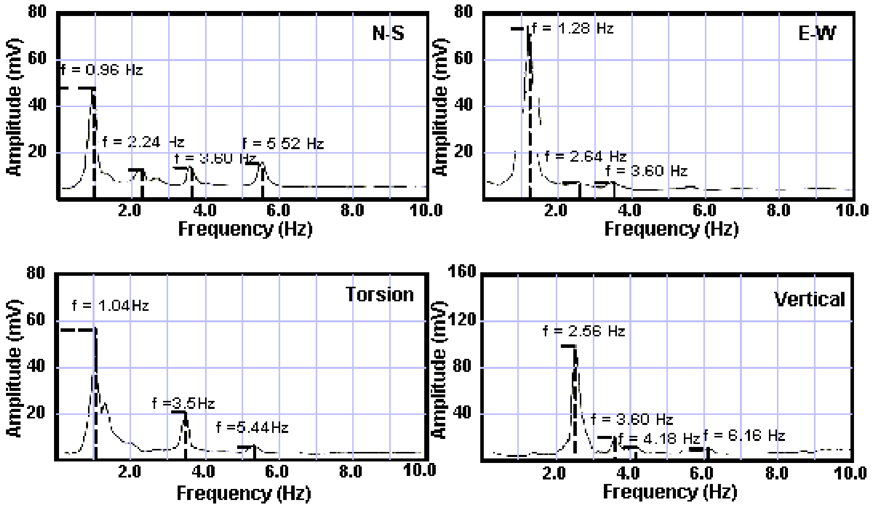


Figure 3. Fourier amplitude spectra on the isolated building recorded with the ambient vibration method

Results From Tests Performed by Using the Forced Vibration Method

In the process of testing, the resonant frequencies of the structure were first of all defined for both orthogonal directions (N- S) and (E-W) and then for torsion. The structural response to the generated excitation, while defining the resonant frequencies for the N-S and E-W directions, was recorded at several measuring points. The recorded responses at the points located in the midst of the structure (point "C" or point "3") were considered referent. The referent point for definition of the torsional resonant frequencies was point "5" on the east side of the structure. Based on the recorded amplitudes of the response of the structure to the generated excitations, the corresponding resonant frequency curves were established. (Fig. 4) Certain tests performed for definition of the same frequency were carried out by different excitation forces for the purpose of evaluating the relation between modification of the resonant frequency and the excitation intensity.

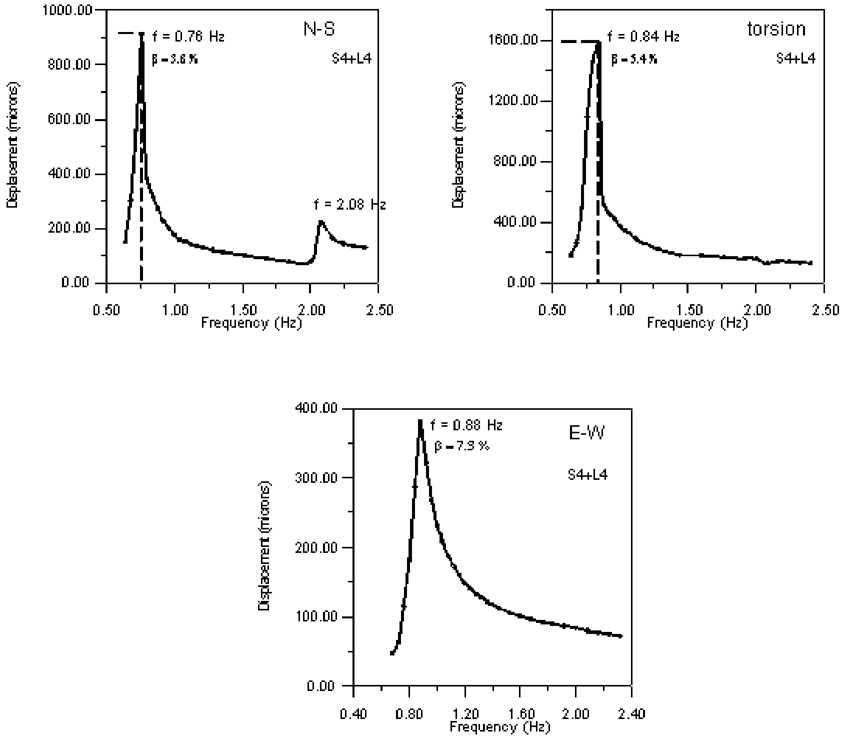


Figure 4. Resonant curves of the structural response obtained with the force excitation method

Due to the flexibility of the isolators, some of the mode shapes could quite well be excited and even visually observed. Therefore, apart from using accelerometers, which is the usual practice in performing these tests, displacement-meters (LVDT-s) were also used.

The frequency curves presented in Fig. 4 were established based on the recorded amplitudes of structural response to the generated excitations.

For such defined resonant frequencies, the corresponding mode shapes of vibration were also recorded.

3-D EIGENPAIR ANALYSIS

For both cases of support of the school building, the eigen values and the eigen vectors were computed. First, the fundamental vibrations of the school fixed at its base were computed. Then, the fundamental frequencies and the corresponding mode shapes of the school building placed on rubber bearings were obtained. The finite elements mesh for both analyses was the same.

Description of the Finite Element Model

The analyses of the mathematical model of the "Pestalozzi" primary school building has been done by means of the SAP2000® computer programme. [7] The structure itself has been modelled by a total number of 7189 "SHELL" elements. Due to the size of the model, the individual structural elements: floor slabs, bearing walls in both orthogonal directions, staircase slabs, parapet walls and alike have been modelled separately. Then the structure has been assembled as a whole by means of "welding" of the joints that share the same location. The rubber bearings supporting the structure have been modelled by a total of 54 "NLLINK" elements. These have been taken as one-joint grounded spring, and they are of the type of biaxial base isolators. During the analysis of this model, it has been necessary to solve 43596 equilibrium equations.

Such a refined model (with a large number of finite elements) was used because the generation of the mesh was not time consuming, as were also the analyses. Such a model is necessary for further analyses when the stress state in the walls is to be analysed.

Analysis of the School Building Model Fixed at its Base

This analysis was necessary to be performed because of two reasons: (1) the fundamental frequencies of the fixed structure had to prove whether the base isolation of the structure is justified; (2) this analysis had to prove whether rigid-structure approximation is possible for the performance of a simpler analysis.

Table 1 shows the eigen frequencies of the first fundamental modes of vibration obtained by this analysis.

Analysis of the School Building Model on Rubber Isolators

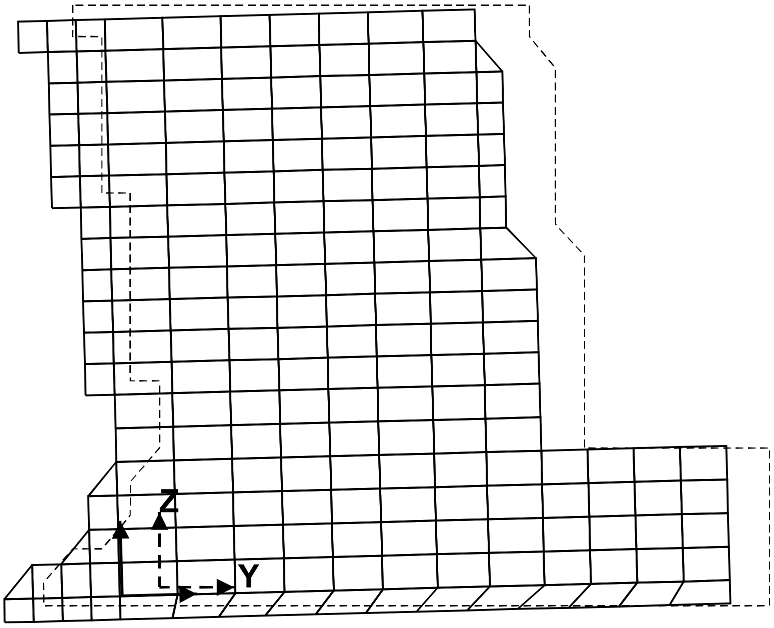
Precise determination of stiffness characteristics in lateral and vertical direction was not possible at present since force-displacement hysteretic loops of the installed rubber isolators were not available. Therefore, the approximate values of stiffness characteristics of isolators were obtained via the measured values of fundamental frequencies by using the following basic formula:

$$\sum_{i=1}^{54} k_{Bi} = \omega_B^2 \, M_{total}$$

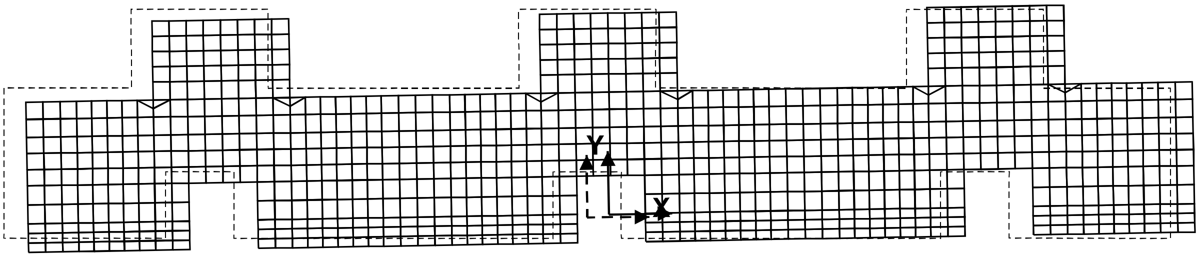
where: k_{Bi} - stiffness of i-th base isolator, ω_B - measured circular frequency of the base isolated building, and M_{total} - total mass of building structure and base isolators.

It is assumed that: (1) the structure is rigid (the fixed-base analysis (f_N-S = 12.97 Hz; f_E-W = 8.32 Hz did confirm this assumption), and (2) the mass is known (it can be computed from the given geometry and the bulk density of the concrete). However, it should be noted that the computation of the lateral stiffness in this way is partially compromised since the fundamental modes of vibration in both orthogonal directions are not purely translational, but there is also a rocking motion due to the low vertical stiffness of the isolators.

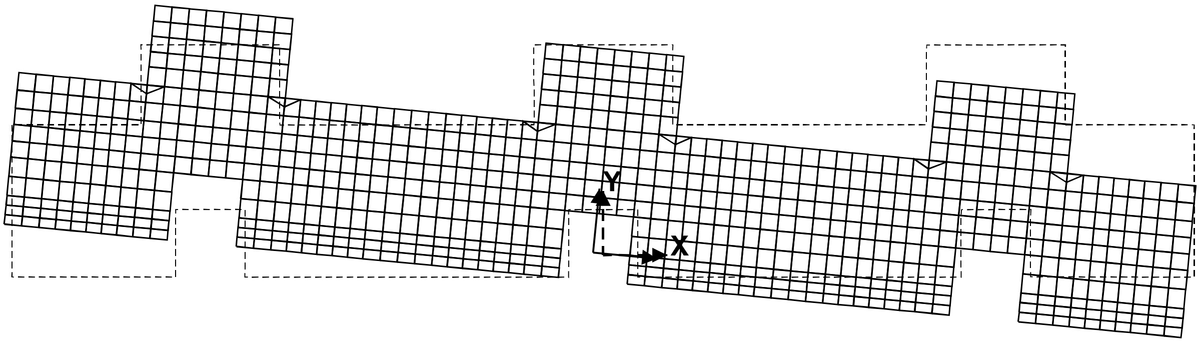
Table 1 shows the eigen frequencies of the first fundamental modes of vibration, while the characteristics mode shapes are presented in Fig 5.



a) Mode: 1, Period: 1.408 s, Frequency: 0.710 Hz, Dominant direction: N-S (transversal)



b) Mode: 2, Period: 1.167 s, Frequency: 0.857 Hz, Dominant direction: E-W (longitudinal)



c) Mode: 3, Period: 1.133 s, Frequency: 0.882 Hz, Dominant direction: torsional

Fig 5 Characteristics mode shapes of the base isolated building model

DISCUSSION OF THE RESULTS OBTAINED THROUGH THE EXPERIMENTAL MEASUREMENTS AND ANALYTICAL PROCEDURES

Based on the data obtained from the performed testing of the structure, the following is concluded:

The values of the frequencies of the fundamental vibration modes in certain directions when the plates covering the seismic gap are removed are: for transverse direction (N-S): f_1f = 0.76 Hz (forced vibration tests) and f_1a = 0.96 Hz (ambient vibration tests); for torsion: f_2f = 0.84 Hz (forced vibration tests) and f_2a = 1.04 Hz (ambient vibration tests); for the longitudinal direction (E-W): f_3f = 0.88 Hz (forced vibration tests) and f_3a = 1.28 Hz (ambient vibration tests) and for vertical direction: f_5a = 2.56 Hz (ambient vibration tests).

Apart from the fundamental vibration modes, some of the higher modes were recorded. The frequency of f_4f = 2.08 Hz represents the second natural frequency of the structure in the (N-S) direction, while f_6f= 3.20 Hz represents the second natural frequency at torsional excitation. The second natural frequency of the structure in the E-W direction is very close (almost equal) to the corresponding frequency at torsional excitation amounting to f = 3.20 Hz, i.e., f_7f= 3.28 Hz.

The recorded higher frequencies of f_8f = 3.44 Hz, f_9f= 5.28 Hz, f_12f = 5.92 Hz in the transverse direction and f_10f = 5.28 Hz in the longitudinal direction, i.e., f_11f = 5.52 Hz at torsional vibrations are associated with some of the higher mode shapes of vibration of the structure.

The frequencies and the corresponding damping measured by applying both methods are presented in Table 1.

Table 1

Mode		Experimental Testing				Analytical	
No.	Direction	Ambient	Forced vibration			Fix Base	Isolated
		f [Hz]	f [Hz]	Damping [%] hp*	Damping [%] ld**	f [Hz]	f [Hz]
1	first (N-S)	0.96	0.76	3.8	3.5	12.97	0.71
2	first (E-W)	1.28	0.88	7.3	6.3	8.32	0.86
3	torsion	1.04	0.84	5.4	3.0	-	0.88
4	vertical	2.56	-	-	-	-	1.87

*Half-power bandwidth method **Logarithmic decrement method

Analysing the recorded mode shapes, it can be said that the translatory components dominate over the first two modes of vibration of the school building (f_1f = 0.76 Hz, f_2f = 0.88 Hz).

Characteristic for the second vibration modes in E-W direction (f_4f = 2.08 Hz) and N-S direction (f_7f = 3.28 Hz) is the rocking motion which is more pronounced for the mode with a frequency of f_4f = 2.08 Hz.

The experimentally measured mode shapes and those obtained analytically clearly point to the fact that the modes, in addition to the translation component, contain also the component of a rocking motion.

The complex motions of the mode shapes result from the low vertical stiffness of the rubber bearings.

Since the fundamental modes for the two horizontal directions are not purely translatory (there are rotation components), their frequencies are not identical. There occurs a difference of 15.8% in the values of their frequencies.

The obtained results on damping presented in Table 1 point to similar damping obtained by both methods. The damping values lead to the conclusion that the internal damping of the bearing is small since the coefficients of viscous damping for the fundamental vibration modes are 3.5%, 3% and 6.3% of the critical one in the N-S and E-W directions as well as torsion respectively.

The fundamental frequencies of the fixed base model do justify the performed isolation of the building. However, the first modes of vibration for both orthogonal directions f_N-S = 0.76 Hz; f_E-W = 0.88 Hz obtained experimentally are far above the minimum frequency of f = 0.5 Hz which is necessary for the isolators in order that they be efficient.

The mathematical discretization and analysis of the isolated structure has successfully been done since there is a good correlation between the analytical and experimental values of the fundamental frequencies and their mode shapes. However, evaluation of the efficiency of the base isolation could be made in the final phase of this project when two isolators shall be taken off and the hysteresis curves obtained in laboratory conditions. The final analyses shall be performed by use of these curves and shall lead to obtaining of the base shear and the maximum displacements. From the laboratory testing on the taken off bearings and the analyses, one could further conclude whether the old bearings are necessary to be replaced by new ones or whether it is only necessary to add dampers for dissipation of the input energy from the earthquake.

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