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# Dynamic behaviour of isolated buildings

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ABSTRACT: There has recently been a strong increase, in many countries, in the use of isolation devices to reduce the seismic effects on structures. In Italy two small buildings with the same characteristics have recently been built, one conventional and the other isolated by means of rubber bearings. After giving a general description of the two structures, the isolation system and the planned research activities to compare the dynamic behaviour of the two buildings, the paper presents the forced vibration tests for characterization of the dynamic properties of the two structures. The results reveal many interesting aspects and provide valuable information for the identification of interpretative models to process the data collected during monitoring of the two buildings, which is currently being carried out.

## 1 INTRODUCTION

Traditional earthquake design methodologies use high strength or high ductility to mitigate seismic effects (Housner, 1982). Except in certain special structures, high ductility is more usually called upon to assure the ability to withstand severe earthquakes. This approach nonetheless implies that, even in cases of low-medium intensity earthquakes, the yielding resistance may be exceeded and a structure will exhibit some damage, if only to non-structural elements.

An alternative design approach consists in the isolation of the base of a structure: this aims to reduce directly the seismic forces by decoupling the motion of the structure from that of its foundations (Kelly, 1985, 1990). Following satisfactory results obtained with new technologies for isolation devices (Derham, 1985, 1987; Thomas, 1982; Muhr, 1991), this approach is attracting considerable interest and is the subject of intensive research to expand its field of application. However, at present there are insufficient data available concerning the seismic behaviour of isolated structures, a fact that does little to increase the confidence of designers in adopting of this solution.

In Italy, as in other countries, a number of projects have been launched to study isolated buildings (Martelli, 1991). One that is particularly worthy of note concerns the construction of two buildings, one conventional and the other base-isolated (Di Pasquale, 1989; Vestroni, 1992). Apart from the foundation-isolation system, the two have identical geometrical and mechanical characteristics. A number of research activities have planned to study the behaviour of the isolated structure and to compare it with its conventional 'twin'. The experiments in question may be briefly summarized as follows:

a) monitoring of the vertical displacement of the isolated building
b) cyclic and dynamic tests on the isolation devices under alternate displacements and constant axial forces for different frequencies of excitation
c) forced vibration tests to assess the dynamic properties of the two structures
d) measurements of environmental vibrations
e) monitoring of vibrations.

Experiments (c) and (d) have already been concluded, (a) and (b) are in progress, while (e) has only recently been started.

The present paper describes the forced dynamic tests aimed at characterizing the two structures. Some results are presented concerning the general structural behaviour of the two buildings.

## 2 DESCRIPTION OF THE BUILDINGS

The two buildings are in Calabria (Italy), a region of high seismic activity. With the exception of the foundations and isolation system, the two structures are identical. The plan and elevation of both are shown in Figure 1. The buildings are low-rise structures with four storeys, three above and one below ground. The resistant structure is a spatial reinforced concrete frame, symmetrical in relation to the central transversal axis, while on the longitudinal axis the mass and stiffness centres are nearly but not quite coincident. The first interstory is stiffer than the others, as shear reinforced concrete walls were built along the whole perimeter. The isolation devices are underneath the first floor; beneath them is a rigid box structure that acts as foundation, while above them is a framed structure. This arrangement facilitates all activities linked to the

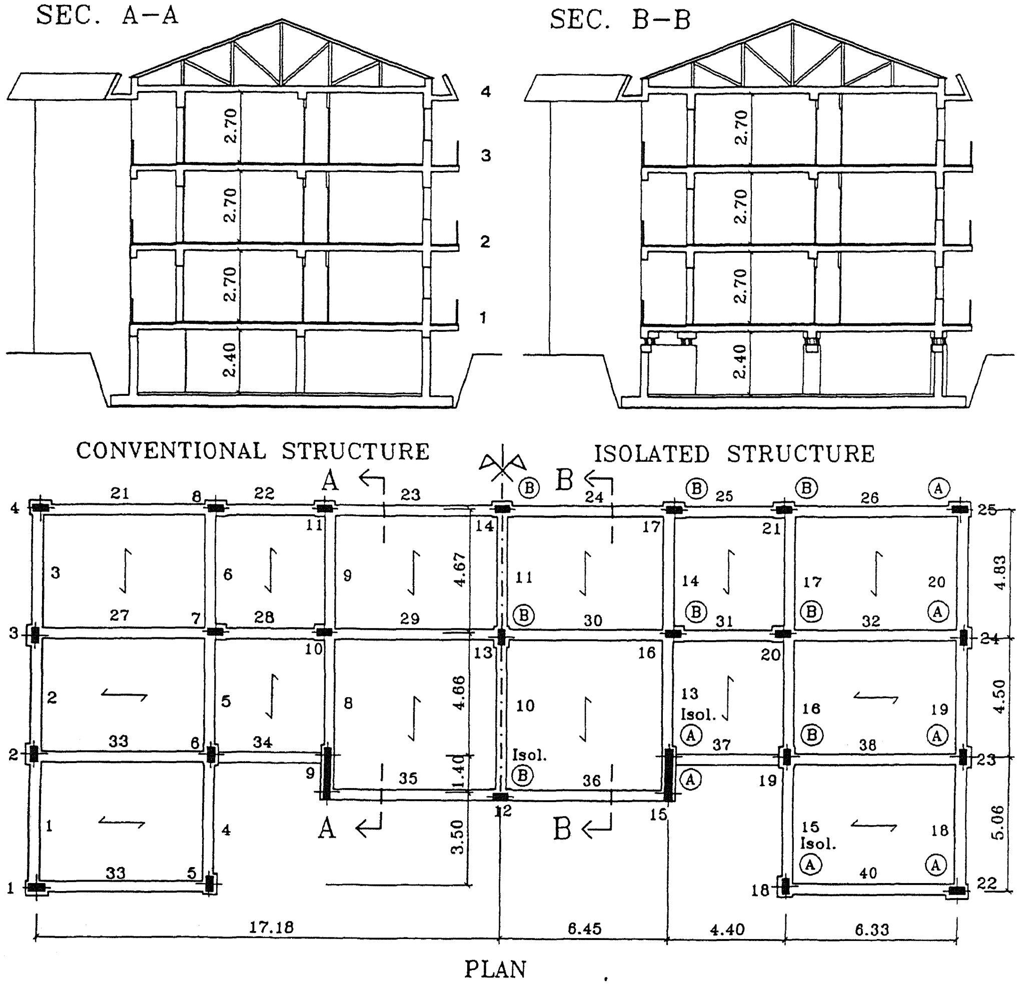

Figure 1. Plan and elevations of the isolated and conventional structures.

measurement of displacement, integrity checks of the devices and their replacement where necessary.

The isolation devices consist of hysteretic rubber bearings composed of rubber layers and steel shims (Figure 2) of two diameters, the larger for the interior columns and the smaller for the exterior columns, which carry a lower vertical load. The height of the bearings was designed to obtain fundamental periods of about 1.75 seconds.

At the time the dynamic tests were carried out the frames of the structures were finished but the buildings were not complete: neither had a roof and the flooring was not in place. In the conventional structure the external masonry walls and internal partitions were present, while the isolated structure had only the external walls.

## 3 EXPERIMENTAL INVESTIGATION

Forced vibration tests were carried out on both the conventional and the isolated buildings with the principal aim of characterizing their dynamic properties. The tests were performed by ISMES with its personnel and equipments.

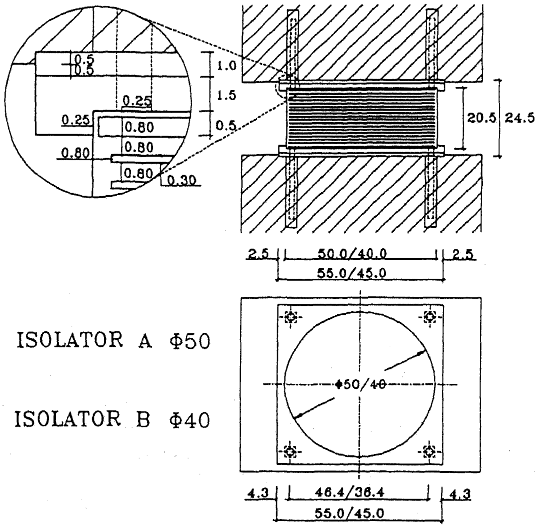

Figure 2. Geometrical characteristics of the rubber bearings.

The force was generated by means of a mechanical vibration exciter (vibrodyne), placed on the top floor of the building, capable to deliver sinusoidal forces within the frequency range 0.3–20 Hz up to a maximum value of 100 kN.

To extract the modal parameters of a system from the records of forced vibrations it is sufficient in theory to analyse the response associated with the resonances. Because their location is unknown, the driving frequency must be continuosly varied in the range in which the natural frequencies of the system may be expected. Moreover, any force is able to excite the motion in the resonant shape except those applied in the nodes of the modes.

The two buildings have an axis of symmetry in the Y direction while in the X direction the mass and stiffness centers do not coincide; the latter is also different at the isolator level with respect to the higher levels. Two eccentrical forces, V1 and V2 (Figure 3), were used parallel to the Y and X axes so as to move the structure in its translational and rotational modes. Since a preliminary analysis performed by a finite element model has shown that the translational and rotational modes are very close, a third excitation V3 was applied to the isolated building only, directed along the symmetry Y axis to acquire information on the symmetrical modes. Indeed, when a mechanical system exhibits repeated frequencies, identifiability of the associated modes requires the use of a number of excitations at least equal to the molteplicity of the frequency.

The analytical model was also used to select the position of V2 force, in such a way as to minimize the excitation of the first rotational mode of the isolated building, as in this case the response to three excitations would have been available and it was preferable to obtain a response close to a translational eigenvector. In any case, taking into account the weight of the vibrodyne, it was placed on a beam not far from a column, 10.85 m from the symmetry axis, and 0.75 m from the alignment 3 (Figure 3).

The mass centers are in the same position at each level, on the symmetry axis at a distance of about 1 meter from alignment 3, according to the assumption that the mass is evenly distributed over the whole floor. The center of stiffness, taken as being the point at which the application of an external force will produce a prevailing translational motion at the isolator level, is about 1.20 meter far off alignment 3.

The vibrations produced by the exciter were measured by 19 accelerometers (4 horizontal at each floor and 3 vertical on the top floor) and 11 seismometers (horizontal and vertical under the first floor); their positions and numbers are reported in Figure 4.

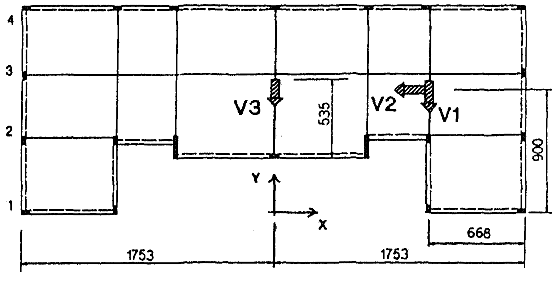

Figure 3. Positions of the external force.

On the basis of the results supplied by the analytical model, the frequency range investigated was 0÷20 Hz where the most important modes of the two structures are present.

The frequency of the force was increased slowly with small finite increments; when the response becomes stationary the average amplitude of the measured quantity (acceleration or velocity) was evaluated over five periods. The ratio between the i-th component of the response and the force $f_j$ gives the transfer function $H_{ij}$ (inertance or mobility).

For the conventional building, the inertance functions of components A1, A2, A13, A14 for excitations V1 and V2 are reported in Figure 5, while those of the isolated building relevant to excitations V1, V2 and V3 are reported in Figure 6.

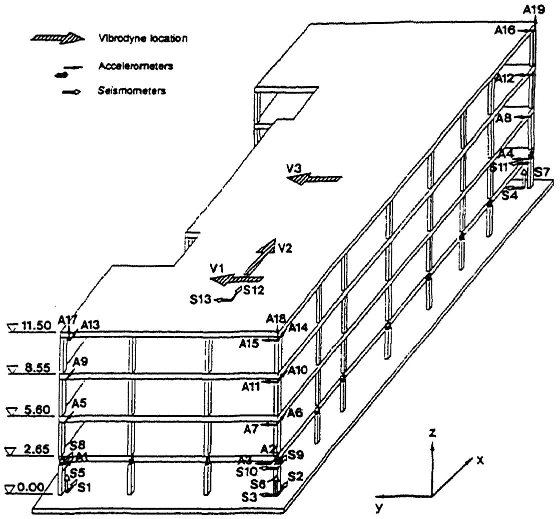

Figure 4. Locations of sensors.

## 4 RESULTS

A quick glance at the transfer functions shows that each curve exhibits few resonance peaks, thus confirming the occurrence of repeated or highly coupled frequencies. The analysis of the inertance functions of the conventional bulding reveals an higher number of peaks with respect to the isolated building, which means that the natural frequencies are close but not multiple. For example in the range 5.70 - 7.70 Hz it is possible to find on the curves obtained with both V1 and V2 at least three peaks relevant to the first three modes of the strucuture. Moreover, the curves appear more irregular even in the range of the first natural frequencies. The finite element models of the two structures give the first six frequencies, which were divided into two groups of three very close frequencies; the first group are relevant to the first longitudinal, transversal and rotational mode while the second group refer to the analogous second mode (Table 1). For the conventional structure the first X, Y and Φ modes have a frequency of around 6-7 Hz, while the second are around 15-18 Hz. By using for isolator stiffness the values obtained from tests performed on few devices, the model of the isolated structure shows closer values for the first three frequencies, around 0.85 Hz, and around 8 Hz for the others. The experimental transfer functions exhibit resonances just within the narrow ranges defined by the models.

Table 1. Frequencies of analytical models (Hz)

| | Conventional | | | Isolated | | |
|---|---|---|---|---|---|---|
| mode | X | Y | Θ | X | Y | Θ |
| 1st | 5.02 | 5.58 | 6.47 | 0.78 | 0.81 | 0.83 |
| 2nd | 14.6 | 16.6 | 18.6 | 7.90 | 8.73 | 9.79 |

The introduction of the isolation devices strongly reduced the first frequencies associated mainly with the deformation of isolators and shifted upwards the seconds, associated with deformation of the structure. Although the deformation values imposed during the tests were fairly small, the stiffness of the isolators was similar to the large deformation value and the frequency was well outisde the range where most earthquakes are very strong. Moreover, the ratio between a frequency of the second group and the corresponding frequency of the first was very high, around ten, which assured a high level of isolation.

The inertance functions for vertical components (A17, A18, A19) are also reported in Figures 5 and 6. In the isolated structure there is a higher vertical deformability but associated with the second modes, whose contribution in the seismic response is negligible. Instead the vertical components in the first modes is small.

As the frequencies are very close, it is not easy to determine the modal shapes, since every response is the product of similar contributions from more modes.

For the isolated structure the available results obtained from three different excitations facilitate their analysis.

The values at resonance of inertance functions relevant to the measured components allow to draw the deformed shape of the structure during the harmonic motion.
The shapes obtained with V1, V2 and V3 around 0.85 and 8.5 Hz are illustrated in Figures 7 and 8.

The response to V3 and V2 excitations defines two modal shapes fairly well, because in both cases the force acts along a line passing in the node of the rotational mode. Thus V3 excites the X-translational mode, and V2 the Y-translational mode (Figure 7b, c).

The V1 force excites two modes. Because the two frequencies nearly coincide, the deformed shape in Figure 7a could be considered as a modal shape, but it is not orthogonal to that of Figure 7c. By subtracting the latter, a nearly rotational mode is determined.

At the resonance around 8.5 Hz the situation is less clear than in the first group for at least two reasons: the modes are more coupled with similar values of X and Y components and local deformations are greater. In any case the typical shape of the second modes is still well defined. V3 makes it possible to determine the second transversal mode which now exhibits a small but appreciable horizontal motion, associated with floor distortion (Figure 8c). The deformed shapes produced by V1 and V2 are partly due to two modes that cannot easily be determined.

Based only on this approximate data processing, it is reasonable to suppose the existence of a prevailing X-translational 2nd mode and a rotational 2nd mode where the distortion of the floors is small. Thus the deformed shape of Figure 8b is the result of these two modes, while that of Figure 8a is due to a rotational mode and to the mode of Figure 8c.

The deformed shape of the conventional structure at the first three resonances under V1 e V2 excitation are drawn in Figure 9. In this case only forces eccentrically acting were used, but the determination of natural modes is easier since the frequencies are distinct though very close. The rotational component is great under V1, as expected, and under V2 too; this is due to an higher distance between masses and stiffnesses center in the conventional building and a greater distance of V1 from the last.

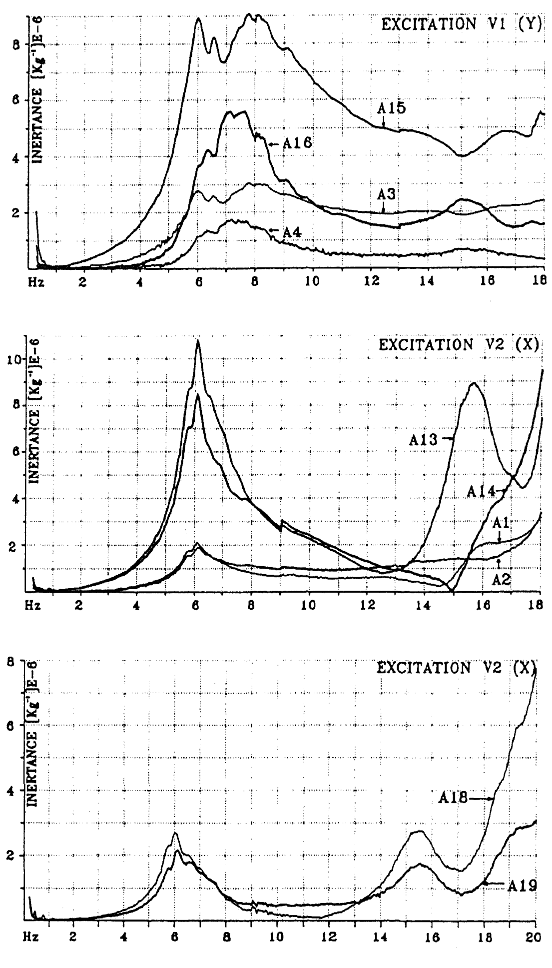

Fig. 5. Inertance functions of conventional building.

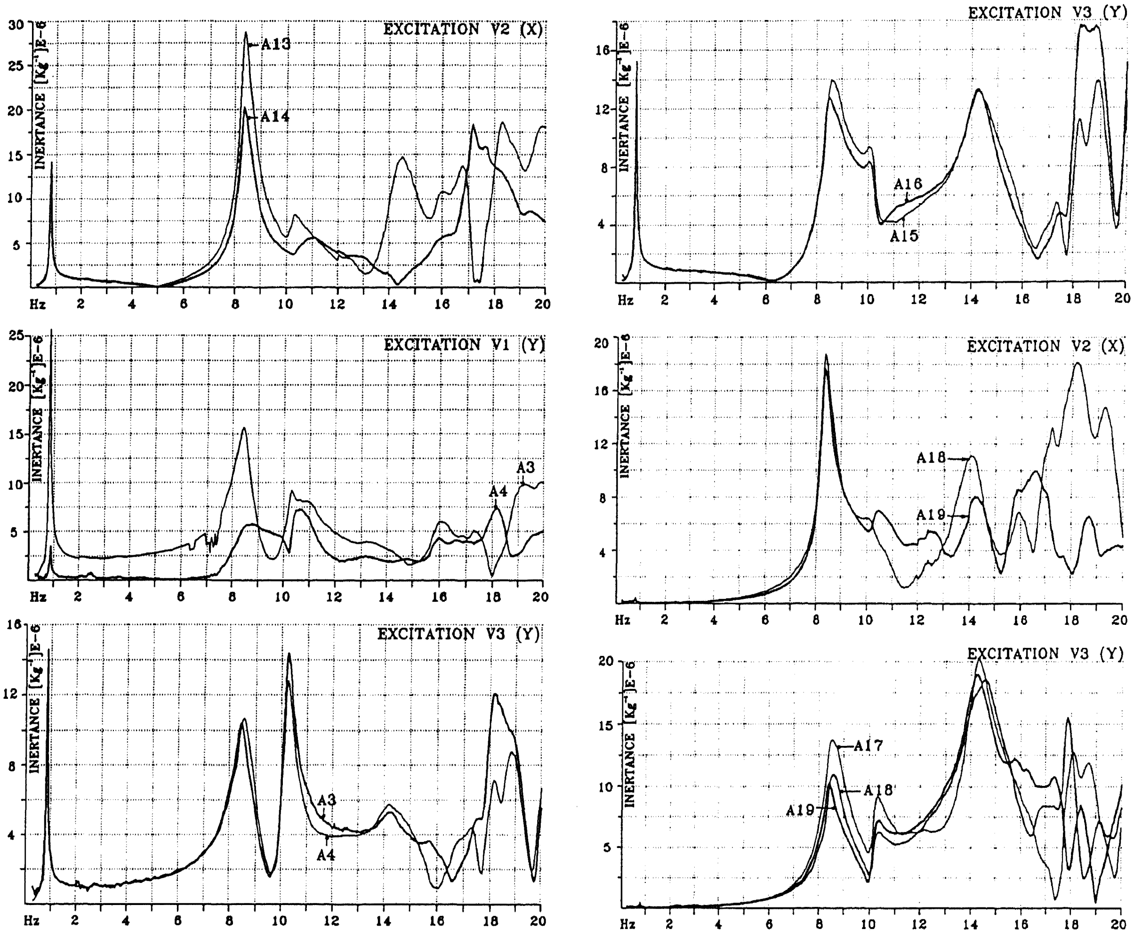

Fig. 6. Inertance functions of isolated building.

A simplified analysis of the shapes at resonance in the range 5.70 - 7.0 Hz leads to three modes: the first and the third are coupled with X and Θ components, translational the former and prevailingly rotational the latter, while the second mode is Y-translational. The higher modes appear quite complicated for the presence of strong coupling and the effect of local deformations.

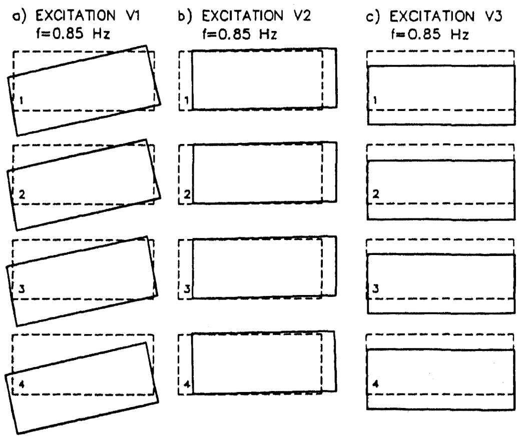

Fig. 7. Isolated building. Deformed shapes at 0.85 Hz.

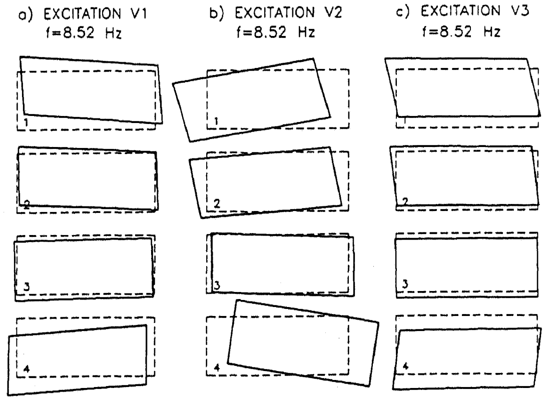

Fig. 8. Isolated building. Deformed shapes around 8.5 Hz.

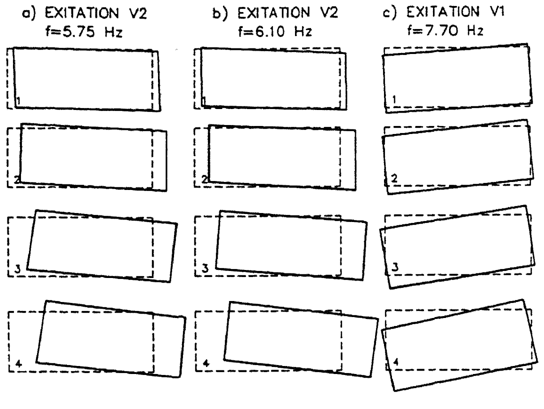

Fig. 9. Conventional building. Deformed shapes around 6-7 Hz.

## 5 CONCLUSIONS

The experimental tests performed on two similar structures, one conventional and the other isolated, were mainly devoted to the dynamic characterization of the two systems, necessary for the planned monitoring activities.

The preliminary analysis has already revealed certain aspects of the different behaviour of the two structures. Even for small displacements the stiffness of the isolators is such that the first frequency is lower than 1 Hz and thus is in the range where the earthquake is less powerful. The shape of the second modes of isolated structures confirms that their contribution, which mainly affects the deformation of structural elements, is practically negligible since it is almost orthogonal to seismic forces.

Both the conventional and isolated structures exhibit two groups of frequencies; the first group comprises the first three modes and the second comprises the second three modes. For the isolated structure the behaviour is more regular, on account of well defined characteristics of the isolation devices; for the conventional building the foundation flexibility is probably responsible for slightly unsymmetrical characteristics of the response.

Nevertheless, the presence of nearly multiple frequencies in the isolated structure raises difficulties in the interpretation of the experimental results and in the identification of modal parameters.

Further processing of the results will aim to determine modal models of the structural systems using more refined methods (Ewins, 1984; Capecchi, 1990, 1992), where the modal parameters are evaluated by the comparison of experimental and analytical transfer functions, taking into account all the modes in the frequency range considered. Subsequently, the modal quantities will be used for identification of a finite element model (Capecchi, 1992).

More detailed knowledge of the results of the vibration tests and the availability of reliable interpretative models allow better use of the data obtained during monitoring, which can also give information on the integrity of the isolation system.

## ACKNOWLEDGEMENTS

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## REFERENCES

Capecchi, D., Vestroni F., Antonacci, E. 1990. Experimental study of dynamic behaviour of an old masonry building. *9th Europ. Conf. on Earth. Eng.*, Moscow, 5, 247.

Capecchi, D., D'Ambrogio, W. 1992. Experimental modal analysis and damage detection of an old masonry building. *MECCANICA*.

Capecchi, D., Vestroni F. 1992. Identification of finite element models in structural dynamics, *Engineering Structures* (to appear).

Derham, C.J., Kelly, J.M., Thomas, A.G. 1985. Nonlinear natural rubber bearings for seismic isolation. *Nuclear Engineering and Design*, 84, 417.

Derham, C.J. 1987. The development and use of NR structural bearings for earthquake protection. *Rubber World*, vol. 195.

Di Pasquale, G., Vestroni, F., Vulcano, A. 1989. Inelastic response of an isolated structure. *Proc. of the International Meeting on Base Isolation and Passive Energy Dissipation.* Assisi.

Ewins, D.J. 1984. *Modal testing: theory and practice.* Research Study Press Ltd., U.K.

Fujita, T. 1991. Research development and application of seismic isolation systems in Japan. *Conf. on Earthquake Protection of Buildings*, Ancona.

Housner, C.W., Jennings, P.C. 1982. Earthquake design criteria. *EERI*, Berkeley.

Kelly, J.M. 1985. Aseismic base isolation: review and bibliography. *Soil Dyn. and Earth. Eng.*, 5, 202-216.

Kelly, J.M. 1990. Base isolation: linear theory and design. *Earthquake Spectra* 6, 2, 223-244.

Martelli, A., Di Pasquale, C., Sanò, T., Bonacina, G., Marioni, A. 1991. State-of-art on base isolation development in Italy. *Conf. on Earthquake Protection of Buildings*, Ancona.

Muhr, A.H., Thomas, A.G. 1991. Design of laminated elastomeric bearings for base isolation. *Conf. on Earthquake Protection of Buildings*, Ancona.

Thomas, A.G. 1982. The design of laminated bearings T. Proc. *Conf. on Natural Rubber for Earth. Protec. of Buildings*. Kuala Lampur.

Vestroni, F., Vulcano, A., Di Pasquale, G. 1991. Earthquake response analysis of nonlinear model of a base-isolated structure. *Conf. on Earthquake Protection of Buildings*, Ancona.

Vestroni, F. et al., 1992. Study of the behaviour of an isolated structure in Squillace (in Italian), *Report DISAT*, L'Aquila, Italy.