The 2018 Structures Congress (Structures18)
Songdo Convensia, Incheon, Korea, August 27 - 31, 2018

Dynamic Test Based Model Calibration of an Existing R.C. School Building

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ABSTRACT

This paper deals with the dynamic tests carried out on a school building seismically retrofitted with an innovative system that uses external steel dissipative towers. Before the retrofitting, ambient vibration tests were carried out with the aim of evaluating the modal parameters of the building including the contribution of non-structural components to the global dynamic behavior of the structure. In particular, the contribution of non-structural components plays fundamental role in structural design because neglecting the infills in finite element models can produce macroscopic errors that may compromise the capacity of the models to predict the structural response of the structure when used for design purposes, such as for seismic retrofitting projects. In this context, the calibration of the finite element models (f.e. models) through experimental measurements plays a fundamental role in ensuring that the models reproduce with sufficient reliability the real behavior of the structure. After the building retrofitting, ambient vibration measurements were repeated to verify that variations in modal properties of the building, evaluated at very small input energy level, are in accordance with those expected from the numerical model. Furthermore, snap-back tests of the building were performed at different load levels to assess the dissipative capacity of the new structural system at greater input energy level.

1. INTRODUCTION

Recent seismic events have underlined the importance of introducing innovations in the structural design of buildings both from the point of view of technologies aimed at

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reducing the incoming seismic energy, and from the point of view of the modelling of non-structural elements and the calibration of the finite element models (f.e. models.). In particular, the design criteria, up to the last years, have always been set on the Ultimate Limit States (ULS); therefore, the finite element modelling included only the structural elements such as beams and column (frame structure) completely excluding the stiffening contribution given by non-structural elements such as internal partitions and external infill walls. However, the 2016 Central Italy earthquake showed that we cannot disregard the influence of non-structural elements on the global behavior of the structure in the presence of seismic actions; both from an economic point of view and from a construction safety point of view. In fact, the damage/collapse of both external and internal infill walls causes, especially for strategic buildings, considerable economic loss due to both temporary interruption of services and costs for reconstruction/repair/retrofitting of the building. This important aspect was highlighted by the new seismic classification of buildings, presented in the D.M. No. 65 of 7/03/2017 (Ministero delle Infrastrutture e dei Trasporti, 2017). Furthermore, neglecting the infills in f.e. models. can produce macroscopic errors that may compromise the capacity of the models to predict the structural response of the structure when used for design purposes, such as for seismic retrofitting projects.

In this context, the calibration of the finite element models, based on dynamic identification, plays a fundamental role in ensuring that the f.e. model. reproduce with sufficient reliability the real conditions of the structure (Turek et al., 2007; Ivanovic et al., 2000; Dunand et al., 2004)). In the last decades considerable efforts have been made by researchers in the development and improvement of methodologies to identify the dynamic properties of civil engineering structures by means of experimental tests. Various testing techniques can be used which differ for various aspects, such as equipment, time-consuming, costs, and dynamic input. Depending especially on the input amplitude, some methods allow the investigation of the dynamic response of buildings only in the elastic range, other both in the elastic and inelastic range. Among those of the first class, one of the most attractive methods of measuring the dynamic characteristics of real buildings is the ambient vibration testing which uses natural vibrations (e.g. micro tremors, wind, anthropic activities noise) without requiring any artificial input action. The advantages of this method are that small, light, and very portable instrumentation are required and that tests can be carried out without disrupting the service of the building. On the other hand, the method requires the use of specific low noise accelerometers capable of measuring very low amplitude vibrations. Because of the low amplitude range of the ambient vibrations (10-5 g), dynamic characteristics evaluated with this method may be different from those obtained from strong-motion (> 0.1 g) records due to non-linear effects. To evaluate the dynamic characteristics under higher amplitude, different tests can be performed such as the stepped and sweep sine test, the release test (snap-back or free vibration test) or vibration tests induced by blast loading.

This article illustrates the results of ambient vibration tests performed on the Benedetto Croce high-school of Avezzano before and after the seismic retrofitting of the building and the results of the snap-back test carried out after the structural works. The modal parameters obtained from the tests are compared with those obtained from the f.e. models of the structure.

2. DESCRIPTION OF BUILDING AND RETROFITTING SYSTEM

The High School B. Croce in Avezzano town, not far from L'Aquila (Italy), is a 4-story r.c. building constructed in the 60's, which needed to be seismically retrofitted to meet the recent Italian seismic regulations (Ministero delle Infrastrutture e dei Trasporti, 2008). The innovative system "Dissipative Towers" (Balducci, 2005) was adopted to carry out retrofitting works without interrupting the activities inside the building, which is composed of 3 main 4-story blocks (A, G, and D) placed around a 1-story block (C-AM) Gioiella, 2017). Other two 1-story blocks (B and D) are located laterally to block D. Fig. 1 shows a plan view of the entire building with the dissipative towers, while Fig. 2 illustrates sectional elevations of the block A.

In particular, this paper deals with the retrofit of just block A; this has a plan dimension of about 13 x 48 m, in transverse (y) and longitudinal (x) direction, respectively. The first floor is located about 1.3 m above the ground level, the interstorey height is 3.5 m and the last floor has a medium height of about 1.5 m. The concrete frame structure has 2 spans of 6.6 m and 2.8 m, respectively, in the transverse direction and 12 spans of 3.9 m in the longitudinal direction. Columns have 300 x 600 mm cross sections, with the greater dimension oriented in the transverse direction, beams carrying vertical loads have 300 x 600 mm cross sections whereas secondary beams have 300 x 450 mm or 450 x 160 mm cross sections.

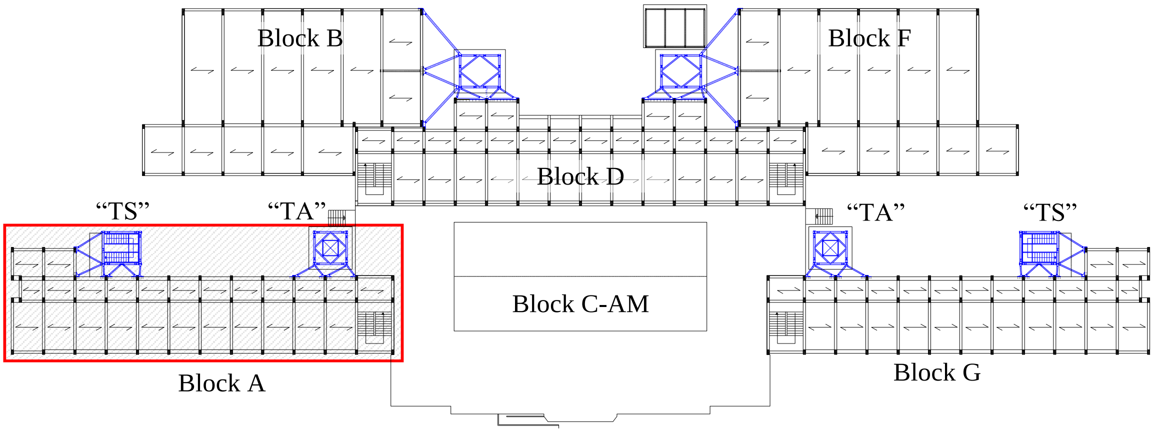


Fig. 1 First floor plan view

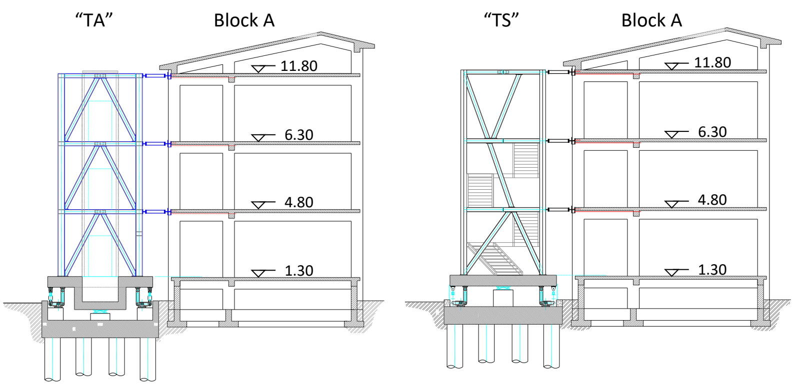


Fig. 2 Sectional elevations of block A with dissipative towers in the transverse direction

3. DYNAMIC TESTS

Two different dynamic tests were carried out on the building under study; ambient vibration tests before and after retrofitting and snap back test after retrofitting. The environmental vibration tests were performed on blocks A and G to obtain the modal parameters of the actual construction and snap-back tests only on block A to identify changes in the dynamic properties of the building as a result of the retrofit works.

3.1 Ambient Vibration Tests

The ambient vibration tests are carried out with the aim of determining the modal parameters of the structure in its real operating conditions. In particular, the modal parameters determined before retrofitting can be used for the calibration of the f.e. model at the base of seismic retrofitting projects, while the modal parameters determined after the seismic works can be assimilated to a sort of test to check that the building actually has the dynamic response expected.

The ambient vibration tests were carried out using a 24-bit data acquisition system connected to 14 low-noise servo-accelerometers by means of coaxial cables. Four different tests were performed by varying the sampling frequency (from 250 to 1000 Hz) and the time of acquisition (from 1 to 20 minutes). Three accelerometers per floor were positioned: two sensors, measuring along two orthogonal axes (transverse and longitudinal), were placed in the same point at a side of the building while the third, measuring along the transverse direction, was located in the opposite side of the building, far from the first two, to better catch the rotational component of the floor. Other two sensors were placed at the ground floor. Fig. 3 shows the position of accelerometers for tests performed before retrofitting (Roia et al., 2013).

As can be seen, for the measurement point 1 information has been obtained both in the longitudinal direction and in the transverse direction of the building, the measurement point 2 instead only in the transverse direction. Modal parameters of the building are obtained from recorded signal with Matlab routines (MathWorks, 2009) implementing the SSI-Cov procedure for the operational modal analysis. In Table 1 the frequencies, the relevant damping ratios and percentage difference between the measurement before and after retrofitting are listed. Fig. 4 shows modal shape before and after retrofitting.

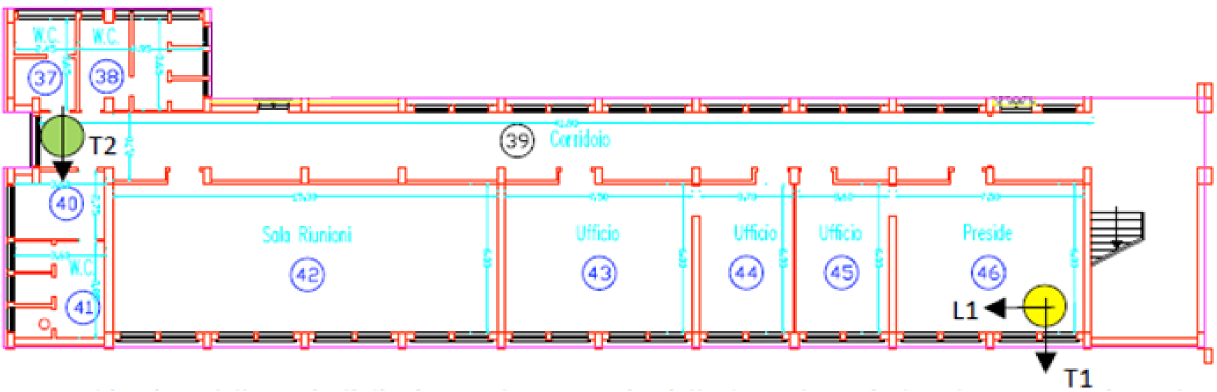
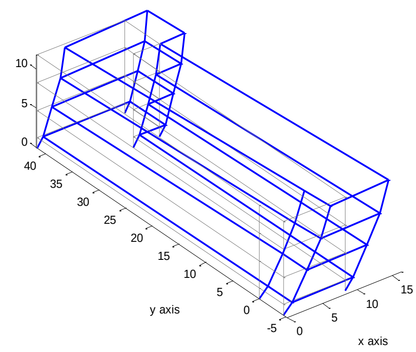
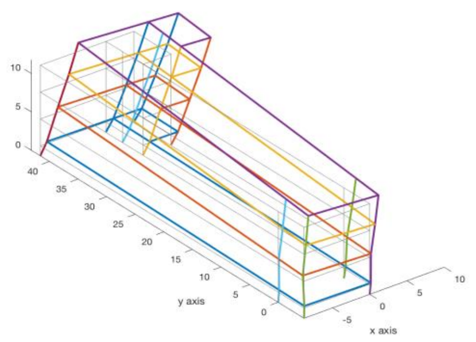
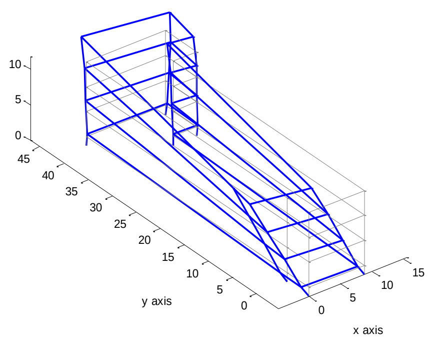
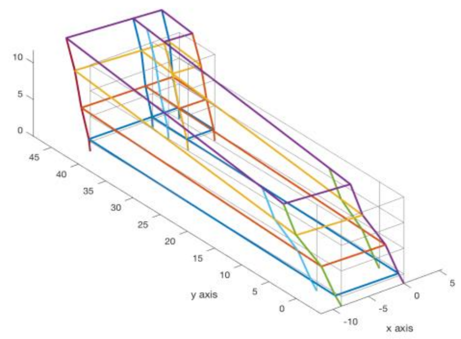
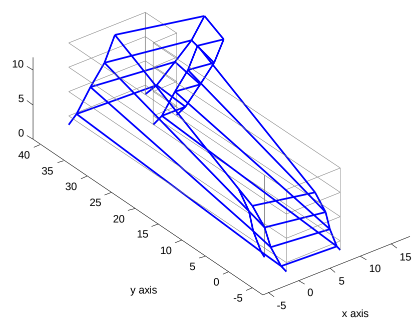
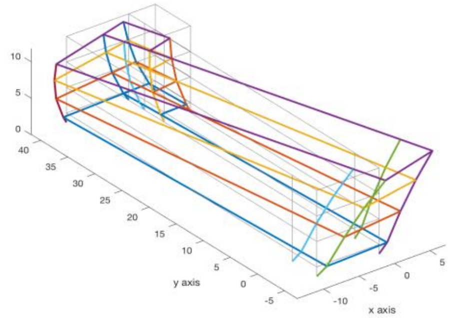


Fig. 3 Points and directions of measurement, at building floor

Table 1

Mode	Before Retrofitting		After Retrofitting		Percentage Frequencies Difference [%]	Mode type
	Frequency [Hz]	**Damping ratios [%]**	**Frequency [Hz]**	**Damping ratios [%]**		
1	5,23	2,88	5,42	3,60	3,51%	1st transversal
2	5,58	2,52	5,70	2,45	2,11%	1st longitudinal
3	6,26	3,22	6,50	2,92	3,69%	1st rotational
4	10,37	1,97	10,18	2,32	1,87%	in-plane distortional

Before Retrofitting	After Retrofitting
	
1st transversal f=5,23 Hz	1st transversal f=5,42 Hz
	
1st longitudinal f=5,58 Hz	1st longitudinal f=5,70 Hz
	
1st rotational f=6,26 Hz	1st rotational f=6,50 Hz

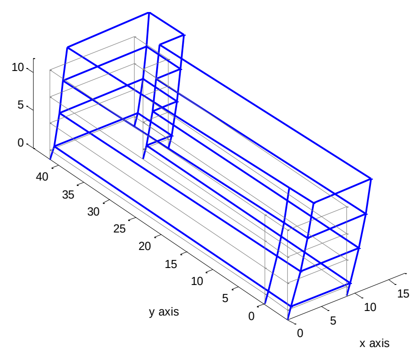
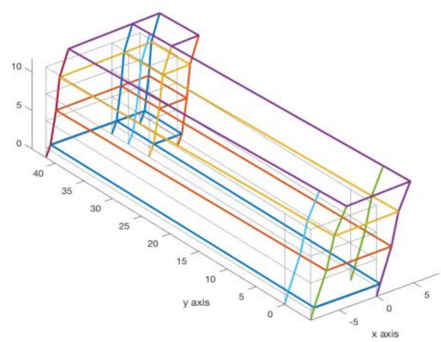
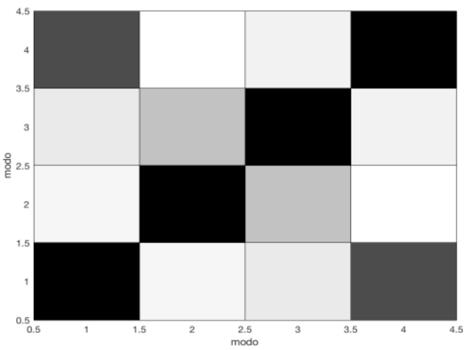
	
in-plane distortional f=10,37 Hz	in-plane distortional f=10,18 Hz

Fig. 4 Modal shapes before and after retrofitting

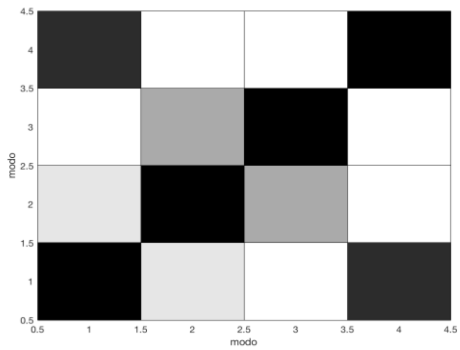
The first three natural frequencies are quite close to each other and can be associated to the first two translational modes (in longitudinal and transverse directions) and to the rotational mode; the fourth natural frequency is higher and corresponds to an in-plane distortional mode .

The results of the autoMAC matrix for dynamic tests carried out before and after retrofitting are shown below (Fig. 5), and finally, Fig. 6 shows the MAC matrix between modal shapes determined before and after retrofitting.

As we can see from the autoMAC matrix the experimental modal forms are quite decoupled therefore they represent the first 4 proper modes of the structure. Except for the first and fourth modes, among which we could note a certain dependence due, in this case, to problems of spatial aliasing. In fact, the fourth modal shape results in bending in the plane and it would have been impossible to be able to catch it with the test configuration adopted. While the results of the MAC matrix between the modal forms before and after retrofitting show a good correlation as evidence of the fact that the dissipative towers do not significantly modify the dynamic behavior of the structure.



(a)



(b)

Fig. 5 AutoMAC Matrix: (a) Before Retrofitting; (b) After Retrofitting

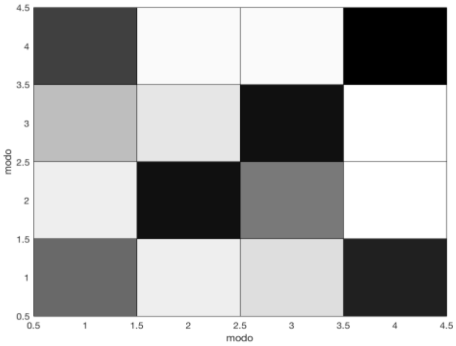


Fig. 6 MAC Matrix between modal shape obtained before and after retrofitting

3.2 Snap-back Tests

The snap-back tests are carried out with the aim of evaluating the dynamic response of the structure for large amplitude vibrations or, in the specific case, to verify the effectiveness of dissipative towers in terms of dissipation, thus increasing the input energy (Roia et al., 2013).

The snap-back test was carried out varying the maximum load applied. In this context only the results obtained with the maximum load value (188 t) is shown. The load was applied in a quasi-static manner by means of 2 Dywidag ϕ47, placed horizontally and anchored to the last floor; these bars were connected to the top vertex of a triangular steel truss pinned to ground at the one vertex at the base and pulled by 2 hydraulic jacks at the remaining vertex (Fig. 7a). For the snap-back test, once the release load was reached, the truss was blocked with a dog-bone shaped steel plate (Fig. 7b) and the quick release was obtained by cutting the steel plate with a blowtorch.

The measuring chain consisted of a 24-bit data acquisition system with 12 channels, 9 uniaxial piezoelectric accelerometers, 4 displacement transducers (2 dynamically and 2 statically sampled) and coaxial cables. Three accelerometers per floor (excluding the ground floor) were positioned by adopting the same configuration of the ambient vibration tests. Two displacement transducers per tower were placed near the dampers at two corners of the base plate of the tower, and positioned vertically.

Fig. 7 Loading system: (a) triangular steel truss; (b) hydraulic jacks and dovetail shaped steel plate

Considering that the displacement of the central point of the base plate is null and assuming that the plate behaves as a rigid body, the rotation of the tower base can be simply deduced from the vertical displacement component of two points of the plate.

From the free decay of accelerations the natural frequencies and damping ratios can be estimated. In particular, the frequencies are obtained by making a linear regression of the crossing times of the decay function. The results are shown in Table 2.

Table 2

N. of peaks	2	4	6		8	10	12	14	16	18	20	22	**Final**
Test_1	4.98	4.87	4.88		4.97	4.93	4.97	5.01	5.05	5.06	5.08	5.08	**5.20**

4. COMPARISON BETWEEN EXPERIMENTAL AND ANALYTICAL RESULTS

4.1 Before Retrofitting: Calibration

A finite element model was developed using the SAP2000 code (SAP2000, 2009) to represent the building before retrofitting. The structural elements such as beams, columns and plates, are modeled with elastic elements of beams and shells type. In order to better reproduce the real behavior of the structure at the time of the experimental dynamical tests, the f.e. model of the building also contains non-structural elements whose stiffness cannot be neglected for very low inputs. The light walls were modeled with equivalent connecting rods and the external walls are modeled with shell elements and the stiffness contribution given by non-structural components of the floors is appropriately taken into account when defining the shell elements of the floor.

The geometry is obtained from design drawings and technical surveys, while the properties of the materials are estimated by an experimental characterization, for concrete, from the technical literature, for the external masonry, and by dynamic tests previously carried out for the characterization of the internal infill panels. The concrete module used is the dynamic one, estimated around 1.1-1.2 Ec, in this specific case, the value of the concrete module that allows to reproduce at best the real dynamic behaviour of the building has been obtained through an iterative procedure and is equal to about 1.12 Ec. In addition, considering the variability of masonry, the elastic modulus was modified step by step to optimize the model, trying to capture the four natural frequencies experimentally identified. The properties of the materials obtained from the iterative calibration procedure of the model are summarized in Table 3.

The vibration frequencies and the relevant mode shapes are evaluated by means of an eigenvalue analysis. Table 4 shows values of resonance frequencies obtained with ambient vibration test and with f.e. model and the relative percentage difference, Fig. 9 shows the first four mode shapes obtained with the f.e. model and the corresponding frequencies. The comparison between experimental and numerical values of natural frequencies shows a good agreement. It is interesting to note that from the MAC results, modes 1 and 4 seem very similar to each other and not linearly independent. This is due to the fact that the measuring points are insufficient to catch the difference between the two modes due to in-plane flexural deformation of the floor. To appreciate this behavior at least one more sensor should have been placed at the center of the floor, measuring in transverse direction.

Materials	E [N/mm^2]
Concrete	27500
External Infills	3850
Light Longitudinal Walls	243850
Light Transversal Walls	327250

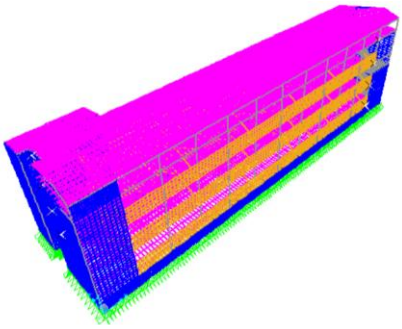
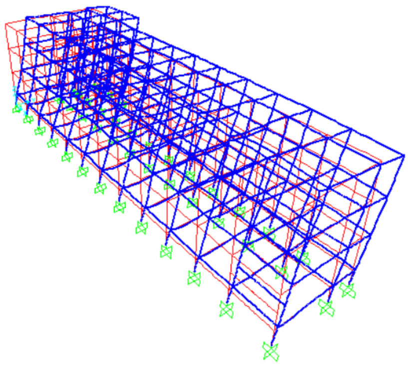


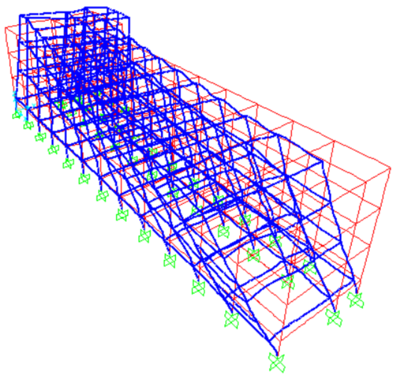
Fig. 8: (a) Table 3 Material properties; (b) f.e. model before retrofitting

Table 4

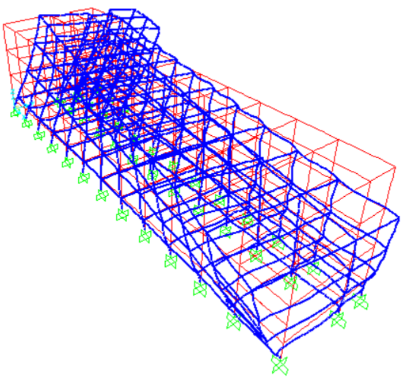
Mode	Experimental		Analytical	Percentage Frequencies Difference [%]	Mode type
	Frequency [Hz]	Damping ratios [%]	Frequency [Hz]		
1	5,23	2,88	5,26	0,57%	1st transversal
2	5,58	2,52	5,59	0,24%	1st longitudinal
3	6,26	3,22	6,11	2,52%	1st rotational
4	10,37	1,97	10,32	0,50%	in-plane distortional



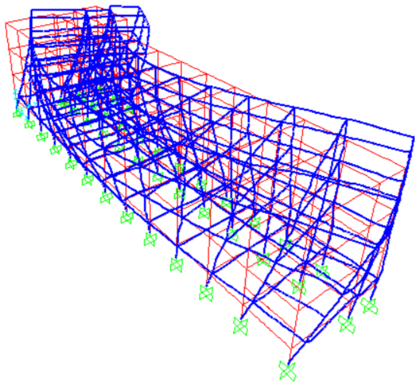
1st mode f=5,26 Hz



2nd mode f=5,59 Hz



3rd mode f=6,11 Hz



4th mode f=10,32 Hz

Fig. 9 Modal shapes obtained with f.e. model before retrofitting

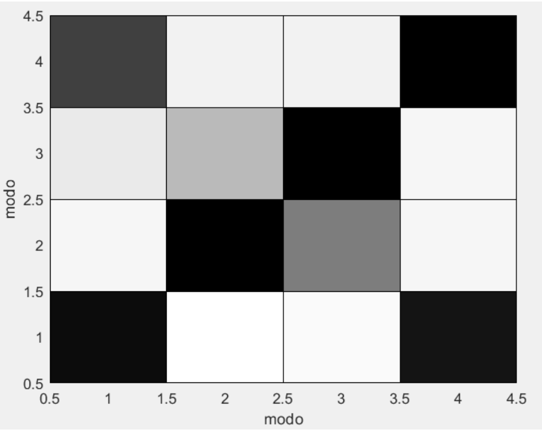


Fig. 10 MAC matrix of the modal displacements obtained with the experimental tests and with the f.e. model before retrofitting

4.2 After Retrofitting

The model f.e. model has the same characteristics of the model calibrated as a result of the ambient vibration test carried out before the retrofitting, with the addition of dissipative towers.

Table 5 shows values of frequencies obtained with ambient vibration test and with f.e. model and the relative percentage difference, Fig. 11 shows MAC matrix of the modal displacements obtained with the experimental tests and with the f.e. models. The comparison between experimental and numerical frequencies shows a good agreement.

Table 5

Mode	Experimental		Analytical	Percentage Frequencies Difference [%]	Mode type
	Frequency [Hz]	Damping ratios [%]	Frequency [Hz]		
1	5,42	3,60	5,57	2,91%	1st transversal
2	5,70	2,45	5,75	1,02%	1st longitudinal
3	6,50	2,92	6,55	0,87%	1st rotational
4	10,18	2,32	10,56	3,74%	in-plane distortional

5. CONCLUSIONS

Ambient vibration tests before and after retrofitting were performed on the structure under study. In particular, before retrofitting with the aim of evaluating the modal parameters of the structure in its real operating conditions and being able to perform the calibration of the finite element model at the basis of the adjustment project. After retrofitting with the aim of carrying out a sort of test to check that the dynamic response of the real structure is the expected one. The comparison of the results of the ambient tests before and after retrofitting shows a slight decrease in the vibration frequencies; the dissipative building-tower system is less rigid than the initial one, and a good correspondence of the modal forms before and after the retrofitting, as evidence of the fact that the dissipative towers do not significantly modify the dynamic behavior of the structure. The calibration of the finite element model through experimental modal parameters has had a good outcome, the percentage differences between the analytical and experimental model frequencies are very low, and the modal forms show good agreement except for an apparent interdependence between the first and the fourth way for reasons of spatial aliasing. The snap-back test is carried out with the aim of evaluating the dynamic response of the structure for large amplitude vibrations or, in the specific case, to verify the effectiveness of dissipative towers in terms of dissipation, thus increasing the input energy. Numerical simulations of the snap-back tests are currently under study.

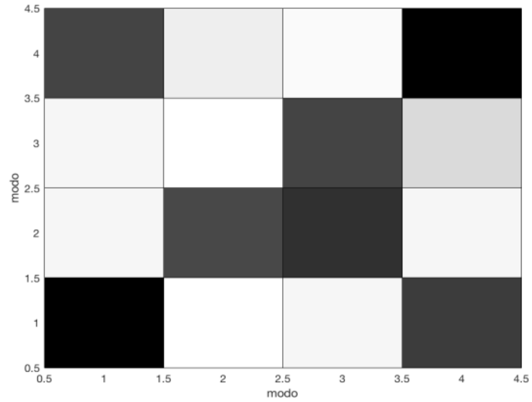


Fig. 11 MAC matrix of the modal displacements obtained with the experimental tests and with the model FEM after retrofitting

REFERENCES

S.S. Ivanovic, M.D. Trifunac, M.I. Todorovska, Ambient vibration tests of structures - A review. ISET J. Earthq. Tech., 37(4), 165-197, 2000.

F. Dunand, J.E. Rodgers, A.V. Acosta, M. Salsman, P.-Y. Bard, M. Çelebi, Ambient vibration and earthquake strong-motion data sets for selected USGS extensively instrumented buildings, Open-File Report 2004-1375, 2004

M. Turek, C. Ventura, S. Guerrero, Ambient vibration testing and model updating of a 44-storey building in Vancouver, Canada, 25th International Modal Analysis Conference, Orlando FL, USA, Paper 250, 2007.

A. Balducci. Dissipative Towers. Application n. EP20100747238 20100831, WO2010EP62748 20100831, International and European classification E04H9/02 – Italian concession n° 0001395591, 2005

MathWorks, MATLAB, version 7.9 (R2009b), The MathWorks Inc., Natick, Massachusetts. 2009.

SAP2000 advanced (v14.1.0) Static and dynamic finite element analysis of structures, Berkeley, CSI Computer & Structures, Inc., 2009.

D. Roia, F. Gara, A. Balducci, L. Dezi, “Dynamic tests on an existing R.C. school building retrofitted with “dissipative towers”, ICOVP 2013.

L. Gioiella, A. Balducci, S. Carbonari, F. Gara, L. Dezi, “An Innovative Seismic Protection System for Existing Buildings: External Dissipative Towers”, WCEE 2017.

Ministero delle Infrastrutture, D.M.14.01.2008, Nuove Norme Tecniche per le Costruzioni, G.U. n.29, 04.02.2008 (in Italian).

Ministero delle Infrastrutture e dei Trasporti, D.M. No. 65 of 7/03/2017 (in Italian).