VIBRATION CONTROL OF STRUCTURES UNDER ENVIRONMENTAL LOADING

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ABSTRACT :

The present paper illustrates preliminary results of the project TELLUS STABILITA, an ongoing three-year project funded by the Italian Ministry of Research focusing on modern technologies to mitigate the structural damage caused by environmental dynamic loading. Innovative schemes for vibration control of civil structures have been assessed both analytically and experimentally. Two scaled steel multi-storey (2- and 4-storeys) frames were designed according to modern codes of practice for seismic and wind loads, respectively. Dynamic properties, i.e. modes of vibrations, natural frequencies, modal damping and generalized masses, of the sample structures were obtained by means of identification tests carried out with shaking tables. Such properties were used to calibrate refined finite element models used to simulate the response of the sample structures.

Two different innovative devices were utilized to control the dynamic response of the sample steel frames. A friction-damper employing piezoelectric actuation was designed for the two-storey frame. A reduced model of the friction-damper was assembled and tested under both static and dynamic loads. The results of the experimental tests were used to validate the numerical models utilized for the design of the damper and for setting-up the layout of the full scale device.

Magneto-rheological fluid dampers were employed for the 5-storey sample frame. Commercial type dampers were selected to control the vibrations of the frame; nevertheless, it was necessary to optimize such devices to achieve the structural performance target. A number of static and dynamic tests were conducted on magneto-rheological fluid dampers to validate the control performance estimated via numerical algorithms. The most suitable location of the dampers along the height of the sample frame was identified by using advanced genetic algorithms and modal parameters.

Extensive numerical analyses were carried out on the frames equipped with the friction damper and magneto-rheological devices. Those devices were found very effective in reducing the lateral drifts and accelerations of the sample frames.

Procedures to test the dynamic properties of structural systems with innovative vibration control devices are also outlined and the results of the performed tests on the 2- and 4-storey frames discussed.

Three full-scale tests are going to be performed on RC multi-storey frames for buildings. These frames are typical structures designed for gravity loads only; they have been retrofitted with buckling restrained braces. The systems will be subjected to reversal loads at increasing displacement amplitudes to identify the progressive collapse of the sample structural systems. These tests are carried out on site, thus also accounting for soil-structure-interaction.

KEYWORDS: Supplemental damping, vibration control, piezoelectric dampers, magneto-rheological fluid damper, buckling restrained braces, testing.

1. INTRODUCTION

The traditional seismic design of framed systems for buildings is based on the energy dissipation due to the inelastic response of structural members, e.g. beams, columns and braces. Capacity-design rules may thus be employed to size structural members to sustain large magnitude earthquakes without exhibiting significant damage. Additional rules are employed to limit large lateral deformations so that non structural damage is prevented. However, for a number of structures, e.g. critical facilities, the structure should have the requisite to behave elastically even under large earthquakes (e.g. Bozorgnia and Bertero, 2004). In so doing, innovative strategies to control the lateral deflections may be adopted. The present paper illustrates preliminary results of an ongoing large project dealing with the applications of innovative dampers and strategies to control the dynamic response of new and existing structures subjected chiefly to wind and earthquake ground motions.

2. OVERVIEW OF THE PROJECT

The project TELLUS STABILITA is a three year project funded by the Italian Ministry of Research aimed at assessing the viability of application of innovative strategies and devices to control the structural vibrations induced by environmental actions, e.g. wind, earthquake loading and traffic-induced vibrations. This is a research project with a total budget of about 7.5 million euros with matching funds from the University of Naples, Federico II and the Consortium TRE. It includes analytical and experimental work on a number of case studies and involves several shaking table tests on prototype structures, either in steel and RC, to evaluate the benefits of using innovative devices to enhance structural and non structural performance of building structures. In so doing, commercial magneto-rheological dampers (MR) manufactured by Lord Corporation (Figure 1) were selected to damp the vibrations in a typical slender frame (5-storey steel frame) under low magnitude long-distance earthquake ground motions or to control wind effects that may cause discomfort in the building occupants. An innovative friction-type damper was also designed, engineered and applied to a two-storey steel frame under moderate strong motions. Health monitoring of the sample structures was carried out through shaking table tests carried out at ENEA Laboratory of Casaccia, Rome, Italy. Different configurations of the frames were considered to estimate the optimal design parameters of the dampers and their effects on the structural response quantities.

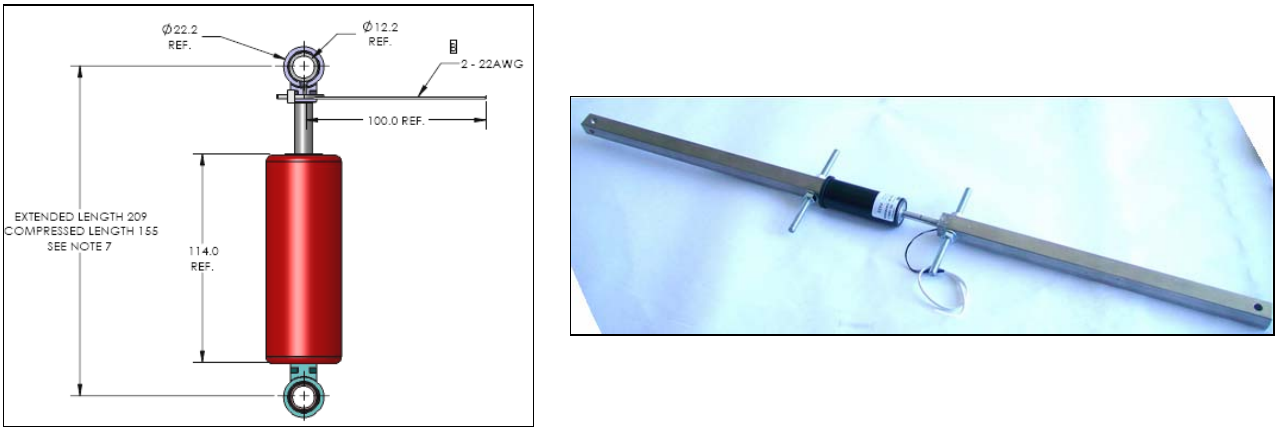

Figure 1 Magneto-rheological damper: layout (*left*) and close up of the device (*right*)

Two full-scale RC frames were selected for the applications of buckling restrained braces (BRBs), as those shown in Figure 2. The sample structures are representative of typical framed buildings designed for gravity loads only during the 60s. Two structures were tested as bare frame and retrofitted with BRBs to quantify the benefits of the application of these devices, if any. Comprehensive dynamic tests of the three RC structures was carried out on site and quasi-static cyclic pushover tests are going to be carried out on the full-scale tests.

3. SAMPLE STRUCTURES

Two sample steel frames were considered to assess the response of steel multi-storey frames under wind and earthquake ground motions at different limit states. Two- and five-storey scaled frames were designed and dynamically tested using the 6 degree of freedom shaking table at ENEA Casaccia, Rome, Italy. The two-storey frame has a rectangular plan layout (base B=3000mm and width W=2400mm); the interstorey height is 2000mm. The cross sections of the members are shown in Figure 3. The floor slabs employ composite steel and concrete deck (the sheeting is A55/P600 HI-BOND) with a total thickness of 100mm and can thus be assumed rigid for dynamic analyses. The mass of the first floor is 5032kg, while the second floor has a mass of 4993kg, which are compliant with the scale 1:2 of the structure. The two-storey structure was retrofitted with innovative friction dampers to mitigate the structural vibrations under environmental loading. The novel friction dampers were engineered, tested and then installed on the structure.

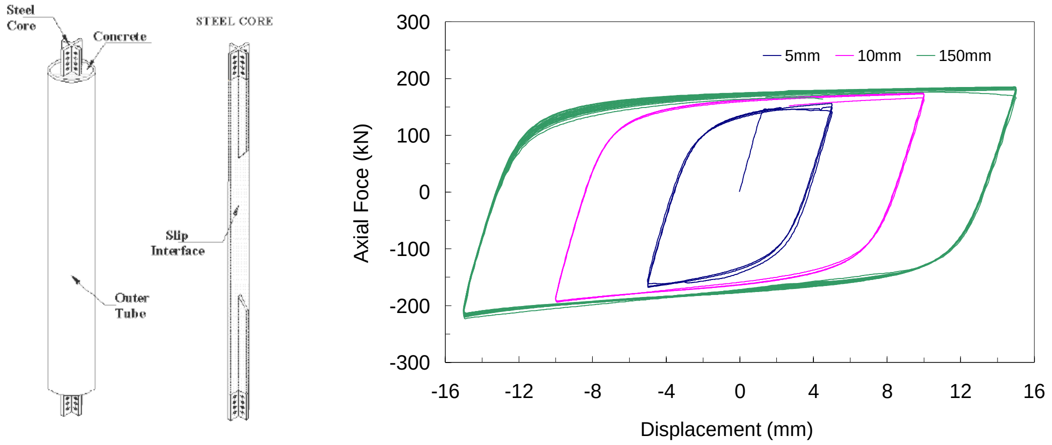

Figure 2 Buckling restrained brace: layout (*left*) and cyclic response (*right*)

The 5-storey frame employs rectangular hollow sections for columns (the cross sections are 40x40x2 mm) and beams (40x20x2 mm). The structure possesses a square plan layout (each side is 600mm); the interstoreys are 900mm. The mass of all but the top floor is 385.85 kg; the mass of the roof is 266.57 kg. This 1:4 scaled system can be assumed as representative of slender structures subjected to low-magnitude and long distance earthquake ground motions. The slenderness ratio (height-to-width) of the steel frame is 7.5. The dynamic response was assessed either with or without magneto-rheological dampers to estimate the benefits, if any, of such devices. The results presented herein are expressed in terms of accelerations because this response quantity is critical for operational limit states in slender structures. The dynamic properties of the steel frames were assessed through shaking table dynamic identification as discussed in Section 4.1.

Three full scale RC framed systems were also considered to investigate on the site of construction the effectiveness of BRBs as a retrofitting scheme of typical multi-storey frames designed for gravity loads only, i.e. with low lateral stiffness and resistance and without seismic details. The two bare RC frames are outlined in Figure 4, where the plan layout and the cross-sections are displayed. Such frames employ typical details of gravity load design, i.e. smooth bars, intermediate concrete compression strength, hooks and large spacing stirrups. They were designed according to the codes of practice and best practice available during the 60s, to simulate actual response of existing RC buildings. Such buildings were retrofitted with buckling restrained braces (BRBs) produced by FIP Industriale, in Italy (buckling restrained axial damper –BRAD- a patented-type brace). Two types of BRBs are employed in the bare RC frame at first and second floor; both BRADs exhibit maximum strokes of 20mm. They are connected to tubular pipe of diameter 80mm and a thickness of 72mm and 74mm, for the first and top floor, respectively. The yield force of the BRADs at base is F_y =75 kN, the maximum force is F_{maY} = 90 kN; the displacement is S_{maY} = ±15mm and the elastic axial stiffness k_{el} = 90 kN/mm. For the top floor, F_y = 40 kN, the maximum force is F_{maY} = 55 kN; the displacement is S_{maY} = ±14mm and the elastic axial stiffness k_{el} = 90 kN/mm. These devices were found to be very effective to fulfil code drift limitations at serviceability and collapse limit states, as further illustrated in Section 5.

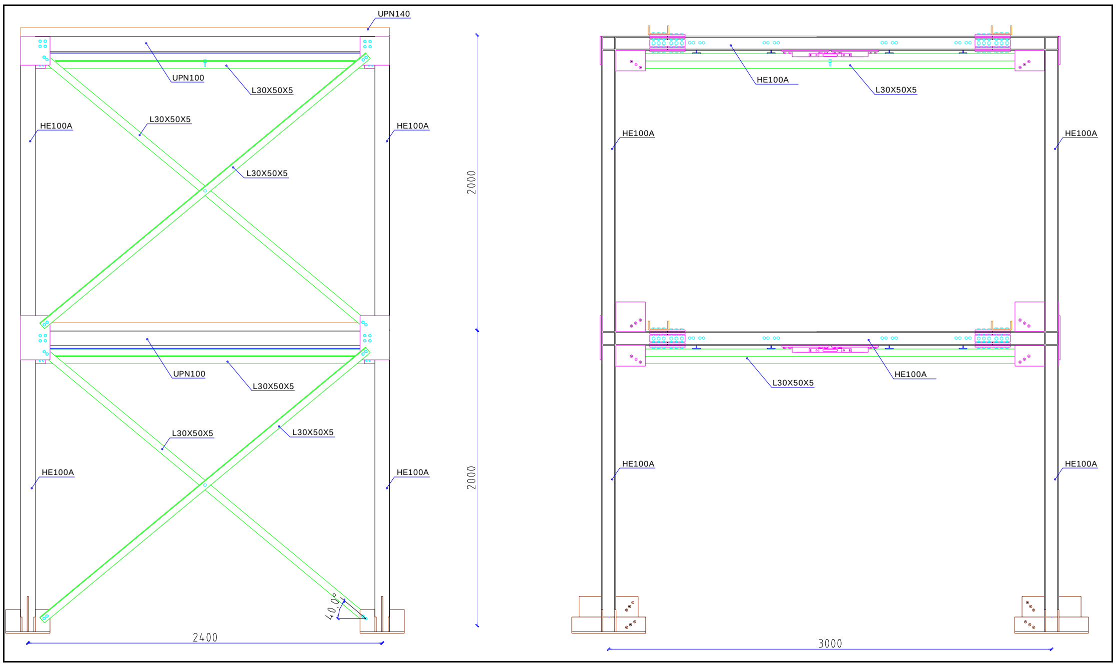

Figure 3 Cross-sections of the sample two-storey steel frame

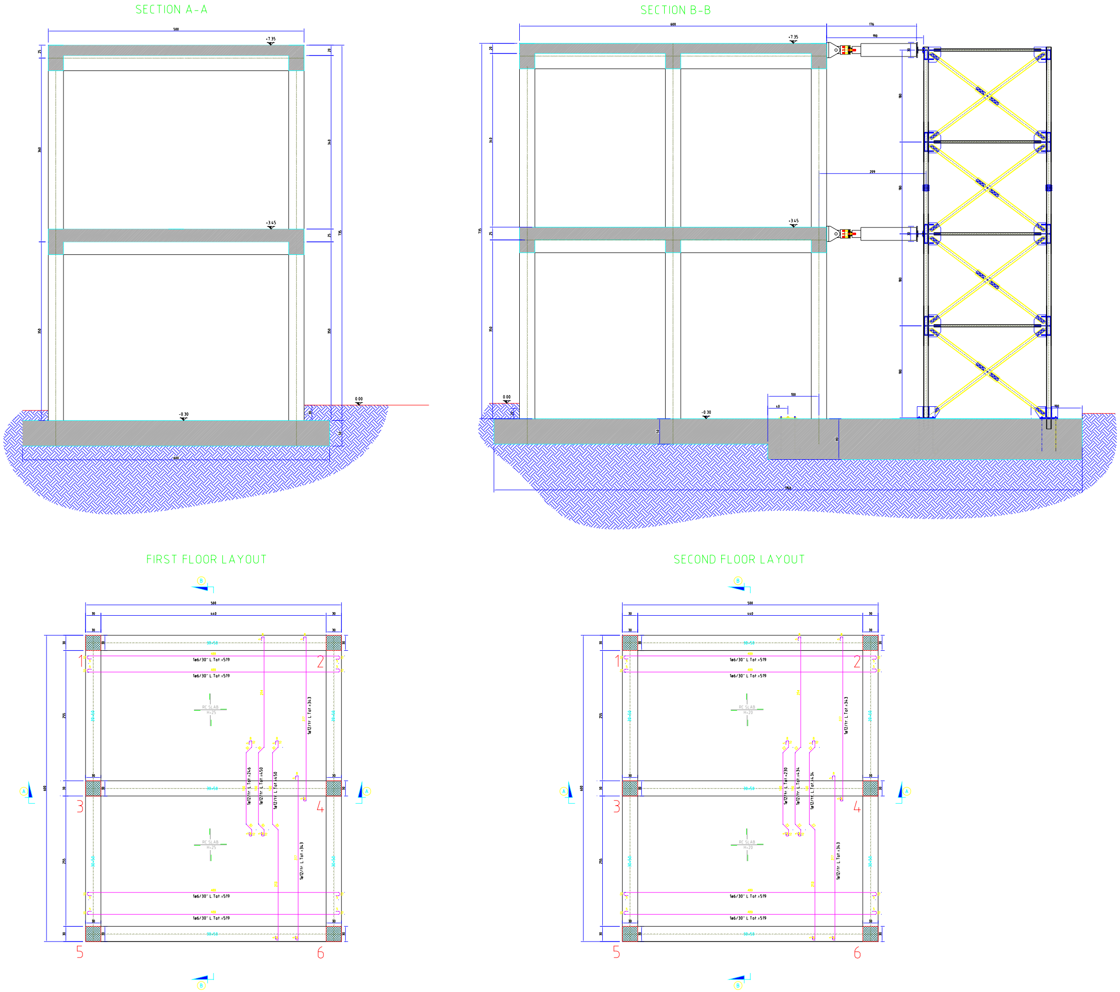

Figure 4 Cross-sections (*top*) and plan layouts (*bottom*) of the sample two-storey RC frame

The dynamic response of an existing RC three-storey frame with tuff-infills was assessed (Figure 5). The building does not comply with modern seismic codes of practice and hence a retrofitting scheme was designed. The adopted strategy consists of BRBs located along the perimeter of the building.

Figure 5 Existing RC framed building used a case study

The structures was subjected to an extensive screening from geometric and mechanical standpoints. A number of *in situ* tests were carried out to achieve a complete knowledge of the physical properties of the as-built system. Modal properties of the existing structure were determined and will be compared with those of the retrofitted structure. The effects of the infills was also estimated by computing the frequencies and the modal shapes.

4. EXPERIMENTAL TESTS

4.1. Dynamic properties

A comprehensive study was carried out both analytically and experimentally to identify the modal properties of the sample structures, both in steel and RC concrete. Experimental frequencies derived through dynamic identification on the shaking table are summarised in Table 1 for the steel two- and five-storey frames. The values of frequencies estimated through numerical simulations of the frames are also included. It is noted that the experimental values tend to be lower for the first and second modes in the low-rise steel frame compared with the analytical counterparts. Such differences are lower at higher modes. They can be related to the value of the pre-stress in the bolts of the connections. They were not fully known for the two-storey frames. The modal shape determined numerically matches the experimental one for both two- and five-storey systems.

Mode	**Description**	**F_E [Hz]**	**F_A [Hz]**
1st	Flexural, Direction X	1.74	2.42
2nd	Flexural, Direction X	5.89	8.62
3rd	Flexural, Direction Y	9.42	7.48
4th	Torsional	12.48	14.42

Mode	**Description**	**F_E [Hz]**	**F_A [Hz]**
1st	Flexural, Direction X	1.41	1.35
2nd	Torsional	3.17	3.40
3rd	Flexural, Direction X	4.43	4.68
4th	Flexural, Direction X	7.94	7.58
5th	Torsional	9.63	10.49
6th	Flexural, Direction X	11.5	11.6
7th	Flexural, Direction X	14.39	15.2
8th	Torsional	16.21	17.2

Table 1 Experimental (F_E) and analytical (F_A) frequencies of the steel two- (*top*) and five-storey (*bottom*) frames

On site tests with ambient noise and hammering impulsive tests were carried out on the RC framed buildings. The Fourier analysis of the tests carried out on the two-storey RC bare frame is provided in Figure 6 for ambient vibrations. The cross-spectra are relative to sensors located along orthogonal directions of the plan layout of the systems and highlight the fundamental frequencies of the system. The experimental and analytical frequencies are outlined in Table 2.

Mode	Description	F_{E1} [Hz]	F_{E2} [Hz]	F_A [Hz]
1st	Flexural, Direction X	3.15	3.15	3.15
2nd	Flexural, Direction Y	3.30	3.40	3.24
3rd	Torsional	4.75	4.75	4.30
4th	Flexural, Direction X	8.80	9.13	8.50
5th	Flexural, Direction Y	9.31	9.24	8.60
6th	Torsional	13.10	13.08	11.63

Table 2 Experimental (Ambient vibration F_{E1} and hammering F_{E1}) and analytical (F_A) frequencies of the RC two- storey frames

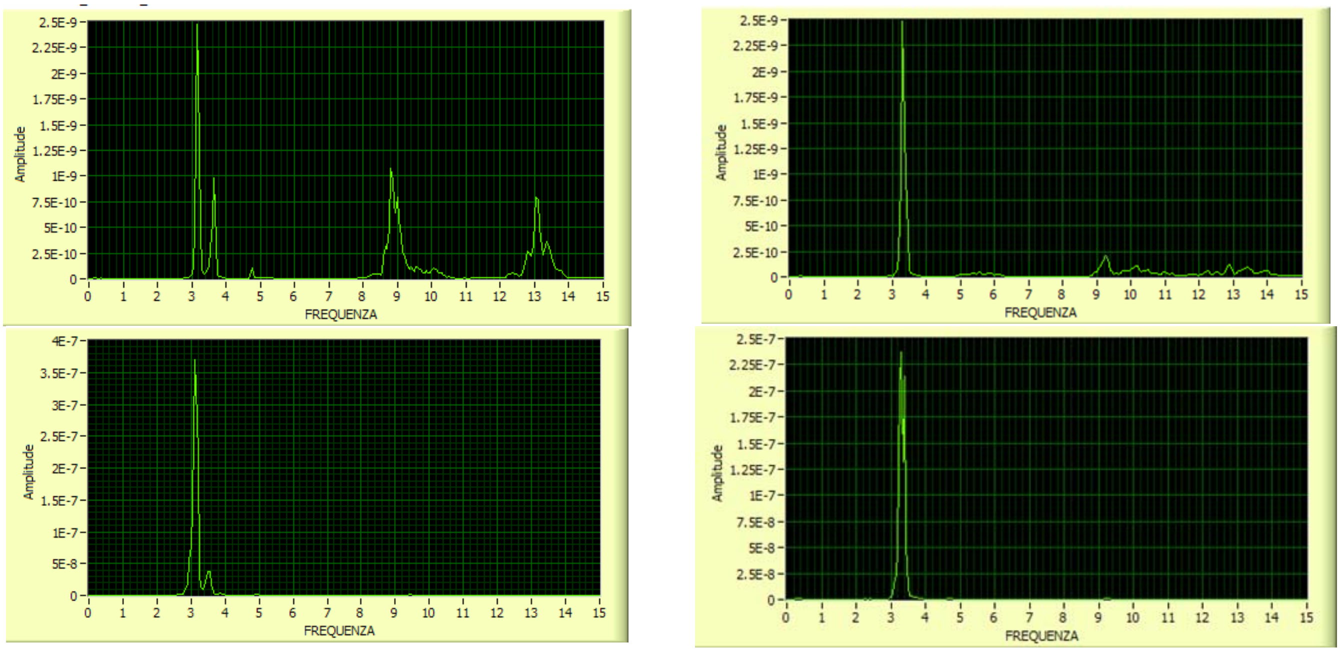

Figure 6 Cross-spectra for the sample frames: sensors located along X- (*left*) and Y-direction (*right*)

The modal response of the existing RC building structure was assessed with and without the presence of masonry infills. The frequencies and the modal damping are listed in Table 3.

		With Infills		Without Infills	
Mode	Description	F [Hz]	ξ [%]	F [Hz]	ξ [%]
1st	Flexural, Direction Y	4.52	3.23	3.32	0.91
2nd	Flexural, Direction X	5.11	2.45	4.05	3.49
3rd	Torsional	6.77	4.70	4.40	3.30

Table 3 Experimental frequencies (F) and modal damping (ξ) for RC three-storey frames with and without infills

The effects of the infills reduce the frequencies of vibrations for all modes. The reduction is, however, significant (about 60%) for torsional modes because the infills are located along the perimeter of the frames. The infills are beneficial to enhance the damping of the structure, thus should accounted to predict reliably the earthquake response of structures.

4.2. Response assessment

The response of the five-storey frame to the suite of selected earthquake ground motions was determined through linear modal transient analysis and large mass method. The modes used for the analyses are those computed through the experimental tests, as outlined in Table 4.

Mode	Description	Frequency [Hz]	Modal damping [%]
1^{st}	Flexural, Direction X	1.405028	1.90
2^{nd}	Flexural, Direction Y	1.405028	1.90
3^{rd}	Torsional	3.172985	0.92
4^{th}	Flexural, Direction X	4.433487	1.62
5^{th}	Flexural, Direction Y	4.433487	1.62
6^{th}	Flexural, Direction X	7.938655	0.73
7^{th}	Flexural, Direction Y	7.938655	0.73
8^{th}	Torsional	9.632010	0.73
9^{th}	Flexural, Direction Y	11.505080	0.36
10^{th}	Flexural, Direction X	11.505080	0.36
11^{th}	Flexural, Direction Y	14.392330	0.24
12^{h}	Flexural, Direction X	14.392330	0.24
13^{th}	Torsional	16.215250	0.56

Table 4 Numerical frequencies and damping for the steel five storey frames

The design target was the reduction of the maximum accelerations. Additional damping was introduced by magneto-rheological (MR) dampers. The location of the dampers was based on the mass participation, i.e. value of 4% was assumed for the damping. Hence, each device should have an equivalent damping equal to 10^5 N·sec/m; thus a MRD-1005-3 by Lord Corporation was employed as damper. The response of the MR dampers was evaluated experimentally in order to validate the characteristic curves provided by the manufacturer (Figure 7). The experimental tests on shaking table include: (i) dynamic response of the bare frame (without MR dampers), (ii) dynamic response of the frame with MR (non activated) and (iii) dynamic response of the frame with MR (activated at 0.5 Ampere).

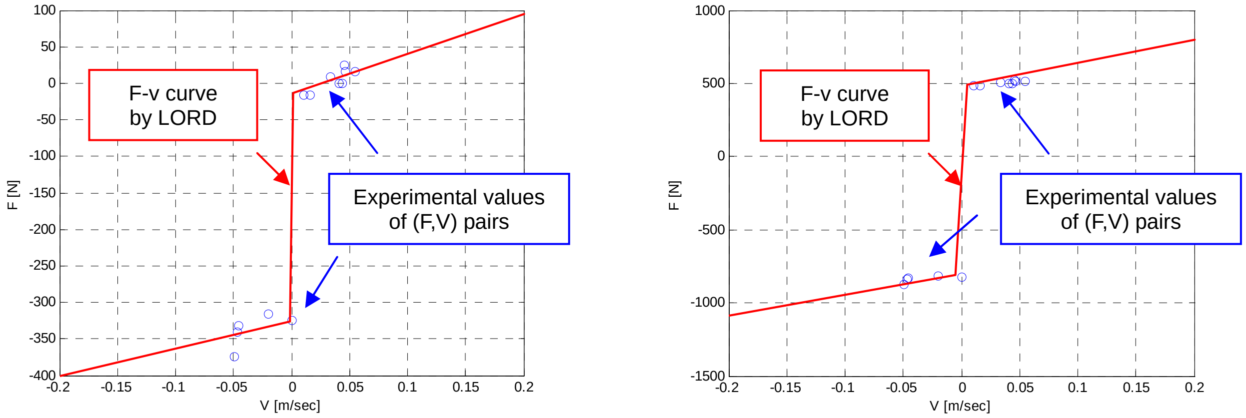

Figure 7 Device response: non activated (*left*) and activated with a current of 0.5A (*right*) devices.

The effectiveness of the MR dampers to mitigate the structural vibrations is shown in Figure 8, where the response history of roof lateral accelerations are provided. The reduction of the maximum accelerations in the structure where MR dampers activated with 0.5 Ampere is about 100% (about 0.16g versus 0.36g).

5. NUMERICAL SIMULATIONS

Refined finite element models of the sample structures were implemented to calibrate the dynamic properties and to perform non linear elastic analyses of the frames. Nominal and actual mechanical properties of the materials were employed in the performed analyses. It was found that the system response is significantly affected by the values of the properties assumed (Figure 8).

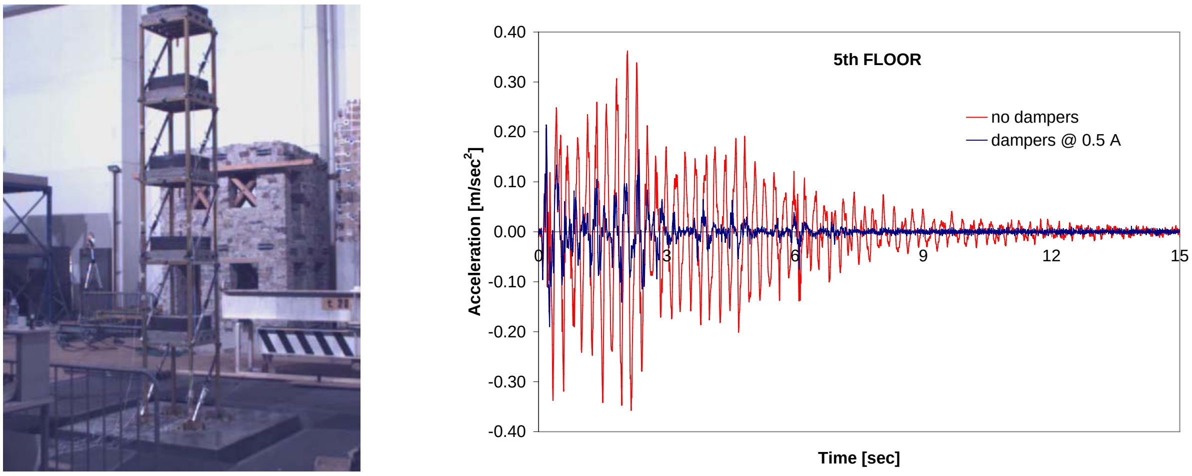

Figure 8 Earthquake response of steel 5-storey frame (*left*) and response history of roof floor (*right*)

The capacity checks may, in fact, be altered and the capacity-to-demand ratios may vary. The capacity curves plotted in Figure 9 demonstrate the effectiveness of the retrofitting strategy based on the use of BRBs to lower the demand on the existing RC frame, designed for gravity loads only. The added dampers absorb and dissipate large amount of seismic energy up to the maximum axial displacements which correspond to their collapse. At this limit state, the lateral resistance of the system is that of the existing RC frame, which act as a back-up system to withstand primarily vertical loads.

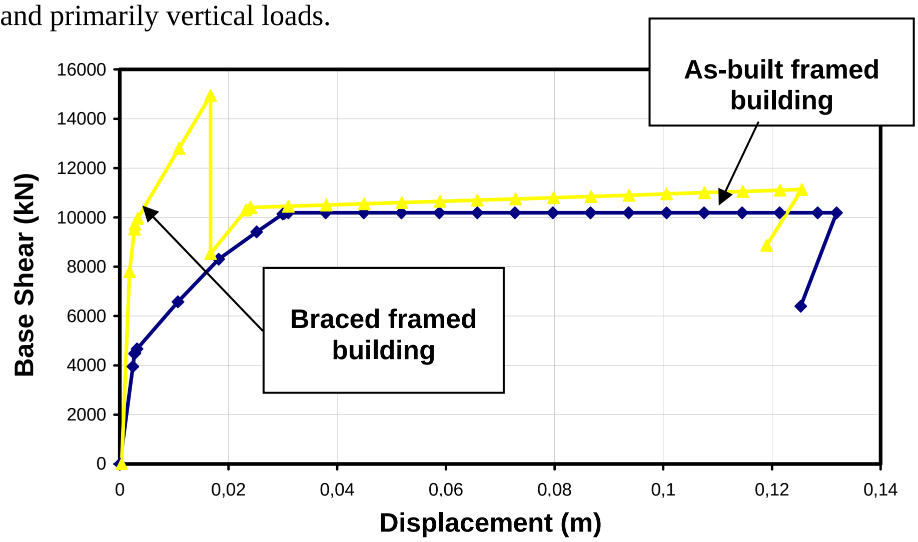

Figure 9 Capacity curves of the sample two-storey frames

6. CONCLUSIONS

This paper focused on the preliminary results of the three-year funded research project TELLUS STABILITA dealing with the vibration control of structural system subjected to environmental loading, especially wind and earthquake ground motions. Magneto-rheological, friction and buckling restrained dampers were selected to retrofit steel and RC frames which do not possess adequate stiffness, strength and ductility to withstand horizontal loads. Optimal design parameters have been selected for the dampers and extensive experimental tests were carried out on shaking tables and in site to calibrate numerical models and to investigate the efficacy of the novel devices used. It is found that the knowledge of dynamic modal properties is essential to adequately design and locate the braces along the height of the frame. Actual material properties should be employed in the numerical models to quantify reliably the capacity of the structures under horizontal loads.

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