Seismic Protection of Civil Buildings by Visco-Elastic Magneto-Rheological Fluids

Ottavia Corbi, Rui Carneiro de Barros

Abstract— The objective of mitigating the dynamic vibrations in civil buildings induced by seismic events may be considered of primary interest for safety and safeguard purposes. Mostly the need of realizing dissipative devices able to couple economy in the energetic supply of the control system and effectiveness in the mitigation of the dynamic effects pushes towards the adoption and the set up of new strategies, alternative to more classical control devices. In the paper one focuses on the possibility of mitigating the effects induced in civil structures by earthquakes by means of Magneto-Rheological (MR) dampers. Modeling as well as design issues are discussed, together with some numerical and experimental investigation demonstrating the potentials of such devices.

Keywords— Smart Fluids, Magneto-rheological devices, Structural Control, Dynamics, Modeling and Design, Experimental Investigation.

I. Introduction

In the last two decades R&D of structural vibration control devices for buildings and bridges has been intensified in order to answer the construction market needs that demand more effective systems to reduce the damage caused on structures by seismic and wind loadings.

Although the main purpose of a seismic design is to protect the population from the consequences of a severe earthquake, the protection of the building stock may also be regarded as an important option during the conception and design process, often pushing towards the adoption of dynamic control techniques for mitigating the structural response under dynamic loading [1]-[14], which are particularly useful especially in the absence of reliable forecasts of the seismic characteristics [15],[16].

For existing structures and, in particular, for historical or monumental buildings, where even analyses are difficult to be performed [17]-[34], due to the need of low invasiveness and impact on the structures of the provision, often reinforcement techniques are preferred, also adopting composites materials [35]-[37].

The interest in adopting semi-active control procedures for civil engineering structures has been growing in the past years, mainly related to their flexibility and energy economy, and also because of the possibility of adopting smart materials and decreasing the invasiveness of the intervention.

In recent years Magneto-rheological (MR) fluids are considered as possible candidates for the realization of structural applications [38]-[41], essentially aimed at mitigating the effects of structural vibrations, by realizing counter-forces contrasting the incoming excitation.

In this paper some on-going research relevant to the modelling and design of MR dampers for the vibration control of structures developed at the Universities of Naples and of Porto is addressed.

II. Applications for civil structures

Magneto-rheological Fluids (MRFs) are controllable fluids, typically non-colloidal suspensions of micronized, magnetically polarizable particles dispersed in a carrier medium such as mineral oil.

When a magnetic field is applied to the fluids, particle chains form, and the fluid becomes a semi-solid, exhibiting plastic behavior similar to that of ElectroRheological Fluids (ERFs).

Transition to rheological equilibrium can be achieved in a few milliseconds, providing devices with high bandwidth.

Therefore Magneto-rheological liquids under the action of a magnetic field can reversibly pass from the linear viscous liquid state with free-flow to the semi-solid one with a controlled stress-state.

They possess a load carrying capacity higher than other, more controllable, fluids, such as electro-rheological liquids; moreover they are less sensitive to impurities and contaminations that may possibly occur in manufacturing.

The achievable yield stress of modern MR fluids is in excess of 80 kPa, allowing for devices capable of generating large forces such as are required for full-scale installations in civil structures.

Moreover, MR fluids can operate at temperatures from –40° to 150° C with only slight variations in the yield stress. Consequently, devices based on MRFs are viable candidates for installation in both exterior civil infrastructure applications (*e.g.*, bridges, towers, *etc*.) as well as enclosed applications (*e.g.*, buildings, secondary systems, *etc*.).

Ottavia Corbi is with the Department of Structural Engineering and Architecture, University of Naples Federico II, Napoli, ITALY (corresponding author - phone: 0039 081 7683719; fax: 00390817683739; e-mail: ottavia.corbi@unina.it).

Rui Carneiro de Barros is with the Faculty of Engineering at the University of Porto, PORTUGAL (e-mail: rcb@fe.up.pt).

In the paper, the most suitable models for simulation of such devices are investigated by referring to studies developed at the University of Naples, with emphasis on the evaluation of their efficiency as structural control systems.

Experimental features are investigated as well, reporting some results developed at the University of Porto, basically focusing on the application of a semi-active structural control technique in a civil engineering experimental model frame equipped with a MR damper.

III. MR MODELING

The modelling stage represent an important feature when dealing with MR Fluids, since having at one's disposal a reliable model able to capture the essential features of the behaviour of the associated devices is necessary for the subsequent analysis refereed to the structure equipped with that dissipative device.

Moreover such model should be complete in order to reproduce results in good agreement with the real data, and, in the meanwhile, sufficiently simplified in such a way to reduce as much as possible the computational effort in numerical analyses and to be handle in a rather manageable way for the numerical investigations.

In the following some studies developed on the subject at the University of Naples are reported.

For modelling purposes one may refer to some models available in literature for MR devices.

The Bouc-Wen model [42] has been extensively used shown in Figure 1 for modelling hysteretic systems, since it is numerically tractable and versatile allowing a broad variety of hysteretic behaviours. For constant voltage levels the expression of the produced force s(t) is

$$s(t) = c_o \dot{x}(t) + k_o [x(t) - x_o] + \alpha z(t) \qquad (1)$$

where c_o is the damping coefficient, k_o the linear spring stiffness, x(t) the displacement variable, $\dot{x}$(t) its rate and z(t) the evolutionary variable governed by the rule

$$\dot{z}(t) = -\gamma\, |\dot{x}(t)|\, z(t)\, |z(t)|^{n-1} - \beta \dot{x}(t)\, |z(t)|^{n} + A\dot{x}(t) \qquad (2)$$

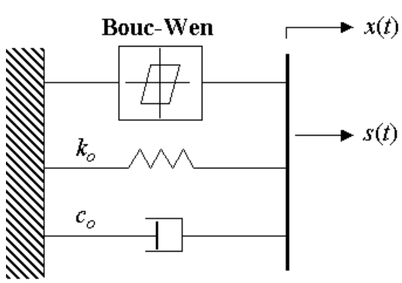

Figure 1: Bouc-Wen model.

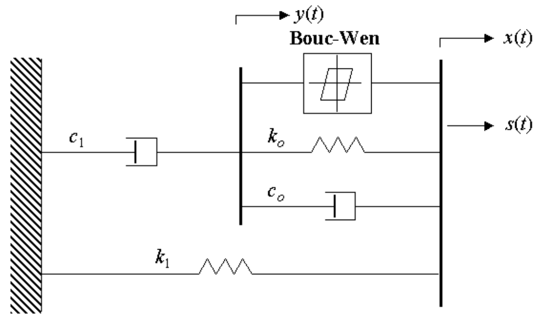

Figure 2: Spencer model.

Many models usually refer to an offset s_o included in the force to account for the asymmetry observed in the measured force s(t).

This offset, due to the presence of the accumulator, is here introduced as initial deflection x_o of the linear spring.

By the parameters γ, β and A, one can control the linearity in the unloading and the smoothness of the pre-yield to the post-yield region.

The Bouc-Wen model is usually preferred because of its reliability in predicting the mechanical behaviour of the magneto-rheological damper in terms of force-displacement relations, even if the prediction of the force-rate relation can be very far from the experimental one in cases small velocities with opposite signs with respect to the acceleration occur.

To better predict the damper response in this circumstance, a modified model, shown in Figure 2, has been proposed by Spencer [43] in order to improve the model reliability also in the range of small velocities. In this case, the accumulator stiffness is represented by k_1 and the viscous damping observed at large amplitude velocities is marked by c_o. The correction of the error observed in the range of small velocities is achieved by inserting a friction element c_1. Finally k_o controls the stiffness at large velocities and x_o is the initial displacement of spring k_1 associated with the nominal damper force due to the accumulator.

Let consider the upper part of the system. For constant voltage levels, since the forces on either side of the rigid bar are equivalent, one can write

$$c_1 \dot{y}(t) = \alpha z(t) + k_o x(t) - y(t) + c_o [\dot{x}(t) - \dot{y}(t)] \qquad (3)$$

where y(t) is the internal variable and z(t) the evolutionary variable ruled by

$$\dot{z}(t) = -\gamma\, |\dot{x}(t) - \dot{y}(t)|\, z(t)\, |z(t)|^{n-1} + \\ - \beta [\dot{x}(t) - \dot{y}(t)]\, |z(t)|^{n} + A[\dot{x}(t) - \dot{y}(t)] \qquad (4)$$

One gets

$$\dot{y}(t) = \frac{1}{(c_o - c_1)} \{\alpha z(t) + c_o \dot{x}(t) + k_o [x(t) - y(t)]\} \tag{5}$$

The total force generated by the system can be obtained by summing the upper and lower sections contributions, that is,

$$\begin{aligned} s(t) = \alpha z(t) + c_o [\dot{x}(t) - \dot{y}(t)] + \\ + k_o [x(t) - y(t)] + k_1 [x(t) - x_o(t)] \end{aligned} . \tag{6}$$

In order to extend the model to fluctuating magnetic fields, the functional dependence of the model parameters on the applied voltage is needed.

From the experimental tests, the fluid steady-state yield level (and, therefore α) and the viscous damping appear to be linearly dependent on the applied voltage u.

Therefore the generalization can be performed by introducing the following relations

$$\begin{aligned} \alpha &= \alpha(u) = \alpha_a + \alpha_b u, \\ c_1 &= c_1(u) = c_{1a} + c_{1b}, \\ c_o &= c_o(u) = c_{oa} + c_{ob} u \end{aligned} \tag{7}$$

Generally, the MR dynamics in the phase of transition to the rheological equilibrium can be accounted for by means of the first order filter

$$\dot{u} = -\eta(u - \nu) \tag{8}$$

where ν is the voltage commanded to the current driver.

In order to obtain a generalized Bouc-Wen model for fluctuating magnetic fields, the parameters α and c_o are made dependent on the variable u by means of the relations Eq. (7).

The response of the generalized Bouc-Wen model is then fitted to the one relevant to the Spencer's model (which is reliable if compared with the experimental results) for varying magnetic fields. The optimisation process is performed by minimizing the quadratic error given by the difference between the forces for the two models, with varying voltages, and the parameters characterizing the Bouc-Wen model.

One can realize that the two models are pretty coherent with regard to either the dependence of the device reactive force on the displacement of the piston, or the time rule of variation of the force.

The main difference lies in the force-rate relation: actually the generalized Bouc-Wen model exhibits a hysteresis capacity much higher than the real case (represented by Spencer's model). This could lead to prediction of a substantially different behaviour of the damper depending on the model adopted.

IV. Control Algorithm Commanding the MR Device

In order to perform the numerical analysis a single bay three-storey frame (three degree of freedom in shear frame configuration) was designed at FEUP, shown in Figure 3.

The columns at the corners, having the same stiffness, are made of aluminum with an average cross section of 1.5mm by 50mm and the diaphragm floors are made of polycarbonate plates monolithically attached to the columns.

The frame mass is around 19 kg and each floor has an average mass of 3.65 kg. The stiffness of the experimental frame was designed to keep the fundamental frequency near to 2 Hz.

The frame mass (*M*) and the stiffness matrix (*K*) are the following

$$M = \begin{bmatrix} 3.65 & 0 & 0 \\ 0 & 3.65 & 0 \\ 0 & 0 & 3.65 \end{bmatrix} (kg) \tag{9}$$

$$K = \begin{bmatrix} 5820 & -2910 & 0 \\ -2910 & 5820 & -2910 \\ 0 & -2910 & 2910 \end{bmatrix} (N/m) \tag{10}$$

The three natural frequencies obtained with the above mass and stiffness matrices are: 2.00Hz, 5.60Hz and 8.09Hz.

A damping of 0.5% along with the above mass and stiffness matrices formed the initial parameters for the modal analysis.

Figure 3: Metallic scaled frame at the shaking table.

After calibrating the MR damper numerical model it is necessary to select a proper control algorithm to efficiently use this device in reducing the dynamic response of structural systems.

The fundamental condition to operate the MR damper is based on a generated damping force that is related with the input voltage; the control strategy is selected so that the damping force can track a desired command damping force.

In the last few years several approaches have been proposed for better selection of the input voltage that must be applied to the MR damper to achieve the maximum performance [44]-[48]. In the present numerical study a Clipped Optimal control has been used as shown in Figure 4.

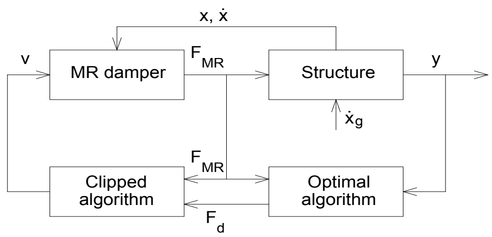

Figure 4: Clipped Optimal controller.

This strategy consists of a Bang-Bang (on-off) controller that causes the damper to generate a desirable control force that is determined by an "ideal" active controller (in state feedback form). A force feedback is used to produce the desired control force $\mathbf{f}_d(t)$, which is determined by a linear optimal controller $K_k(s)$, based on the measured structural responses y and the measured damper force $\mathbf{f}_c(t)$.

Only applied voltage v_a can be commanded (and not the damper force) that is selected by $v_a = v_{max}\, H[\mathbf{f}_d(t) - \mathbf{f}_c(t)]\, \mathbf{f}_c(t)$ in which v_{max} is the voltage level associated with the saturation of the magnetic field in the MR damper and H[·] is the Heaviside step operator.

The selected optimal controller is based on a Linear Quadratic Optimal Control, relying upon the weighting of the matrices **Q** and **R** associated with the state variables and with the input variables respectively, where **R** is made dependent on a multiplier r.

The main objective to design the optimal controller is then o obtain an optimal control vector $\mathbf{f}_c(t)$ that minimizes a quadratic performance index $J[\mathbf{z}(t), \mathbf{f}_c(t)]$, depending on the state response $\mathbf{z}(t)$ and on the damper force $\mathbf{f}_c(t)$

$$J[\mathbf{z}(t), \mathbf{f}_c(t)] = \int_0^t \left[\mathbf{z}^T(t)\mathbf{Q}\,\mathbf{z}(t) + \mathbf{f}_c^T(t)\mathbf{R}\,\mathbf{f}_c(t)\right]dt \qquad (11)$$

The magnitudes of matrices **R** and **Q** are defined according to the importance that is given to the state variables and the control forces on the minimization process.

Increasing the values of **Q** matrix elements implies the prioritization of the response reduction over the control forces.

On other hand, increasing the values of the elements of **R** implies the prioritization of the control forces over the response reduction.

As well known, the solution of the LQR problem is based on the analysis of the algebraic Riccati equation

A parametric study has shown that decreasing the r value implies a more marked reduction of the response.

A significant reduction (up to 90% of the floor displacements and accelerations) was obtained with r = 10-9.

IV. Experimental investigation

The experimental dynamic behavior of a 3DOF scaled metallic load frame equipped with a semi-active device was investigated placed on a Quanser shaking table II for producing the dynamic loading consisting of the El Centro earthquake record selected as input.

A small MR damper shown in Figure 5 was placed at the first floor level attached to the frame and rigidly attached to the shaking table.

To measure the damping force values generated during the experimental tests a load cell was placed in the MR damper support system.

Figure 5: RD-1097-01 MR Damper.

The parameters of the MR damper are: minimum force in passive-off mode < 9 N (for current 0.0A at piston velocity 200 mm/s), maximum force 100 N (for current 1.0A and piston velocity 51 mm/s), stroke ±25 and response time < 25 ms (time required to reach 90% of the steady-state value of force under a step change of the current from 0.0 to 1.0A, for 51 mm/s).

An impulse hammer test was carried out in order to obtain the modal parameters of the structure.

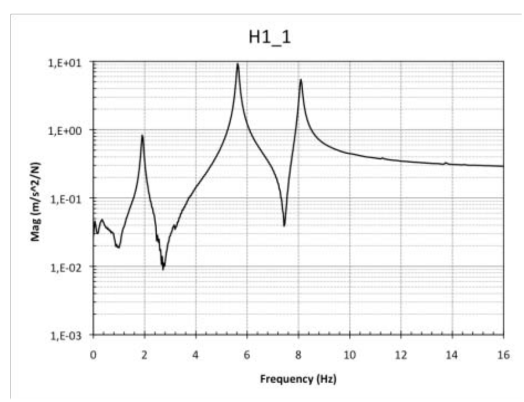

Figure 6: Frequency Response Function of H1_1.

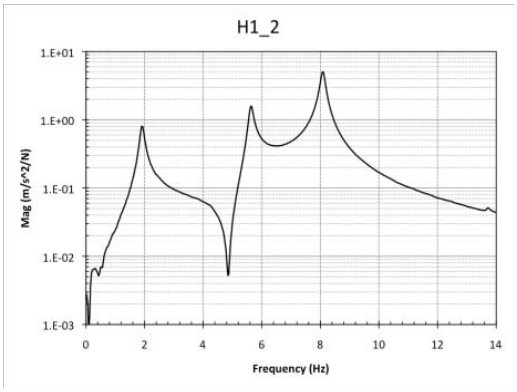

Figure 7: Frequency Response Function of H1_2.

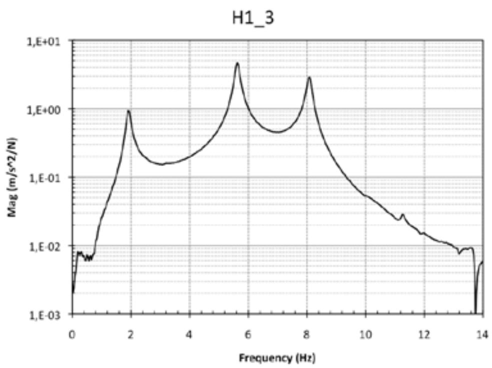

Figure 8: Frequency Response Function of H1_3.

The structural response was measured with a piezoelectric accelerometer (Bruel & Kjaer type 4393 with measuring amplifier type 2525) placed at the first floor and a portable real-time analyzer (OROS 35 real-time multi-analyzer) that was used to perform the necessary mathematical rationing on input and response signals to produce the desired transfer function.

The desired frequency response functions (magnitude) for each input/output measurements were obtained, shown in Figures 6-8.

The parameters of the scaled frame were then obtained based on the data provided by these functions and are tabulated in Table 1.

Table 1: Parameters of the scaled frame.

Mode	Frequency	Damping	Modal Participation
1^{st}	1,913986	0.03157	34.43248
2^{nd}	5,627778	0.01198	35.25975
3^{rd}	8,086245	0.00899	30.30777

The three horizontal floor displacements were selected as the parameters (output) to verify the efficiency of the control law.

Some results of the analysis are plotted in Figures 9and 10 for the uncontrolled and the semi-active controlled scenarios.

The structure response plot shown in Figure 9 was obtained without any device connected to the scaled frame (non-controlled response).

Then, the MR damper was attached to the 1^{st} floor in a passive configuration (without current applied) with a constant current of 0.25 A; the relevant displacement response plot is shown in Figure 10, exhibiting a significant displacement reduction even with the MR damper in passive mode.

The three floor displacements were considerably reduced (from 0.008 to 0.006 m) due to the increase of damping and stiffness at this level. This means that the MR damper introduces a partial constraint and as consequence the frame behaves like a 2 DOF system above the first floor level.

Finally, the semi-active controller was activated and the horizontal floor displacements were again plotted as shown in Figure 11.

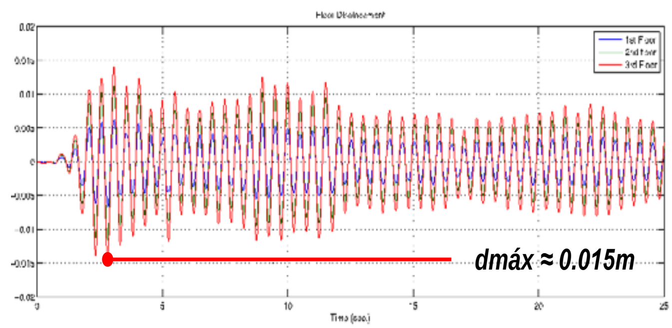

Figure 9: Uncontrolled response.

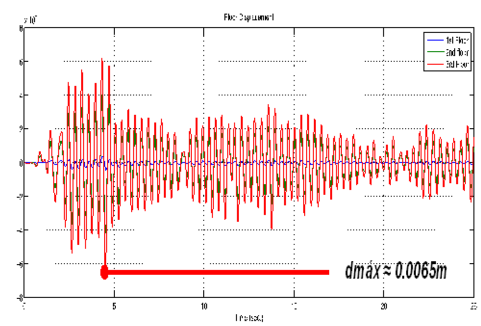

Figure 10: Uncontrolled response with MR damper @ 0.25A.

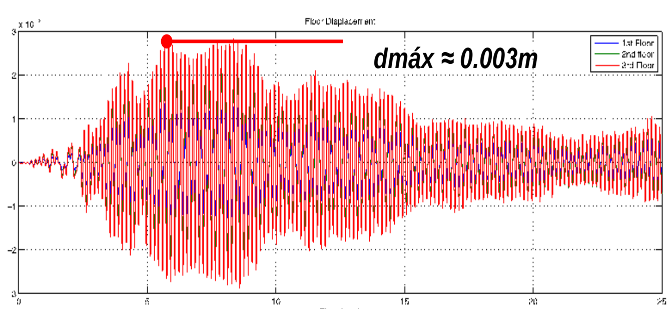

Figure 11: Semi-active control response.

As expected, the semi-active control based on the Clipped Optimal algorithm was successfully applied.

The lateral displacements of the building floors were reduced significantly during the earthquake duration, as visible by the maximum displacement of the top floor reaching a value of about 0.003 m. This value corresponds to 20% of what was reached initially without control.

V. CONCLUSION

The paper addresses the vibration control of civil structures by the design of MR dampers.

Modeling and design issues are introduced and experimental results obtained with reference to a 3-DOF metallic frame equipped with a MR damper are discussed.

The improvement in the dynamic response of the structural model subject to an earthquake simulated ground motion is shown over the uncontrolled response of the system.

ACKNOWLEDGMENT

The authors acknowledge the financial contribution of European Science Foundation (ESF) through the international collaborative research project COVICOCEPAD within the Smart Structural Systems Technologies (S3T) Program.

References:

[1] Pujol, G., Acho, L., Pozo, F., Rodrguez, A., Vidal, Y.: Active vibration control of hysteretic systems , Mechanical Systems and Signal Processing, vol.25 (1) , pp. 465-474 (2011).

[2] Roy, B.K., Chakraborty, S.: Optimal design of base isolation system considering uncertain bounded system parameters , Structural Engineering and Mechanics, vol. 46 (1) , pp. 19-37 (2013).

[3] Chen, X., Li, A.-Q., Zuo, X.-B., Ding, Y.-L.: Design and study on novel shape memory alloy isotator , Zhendong yu Chongji/Journal of Vibration and Shock. vol. 30 (6) , pp. 256-260 (2011),

[4] Jalali, A., Cardone, D., Narjabadifam, P.: Smart restorable sliding base isolation system , Bulletin of Earthquake Engineering , vol. 9 (2) , pp. 657-673 (2011).

[5] Mazza, F., Vulcano. A.: Nonlinear Seismic Analysis To Evaluate The Effectiveness Of Damped Braces Designed For Retrofitting R.C. Framed Structures. Int.Journal Mathematical Models And Methods In Applied Sciences (2013).

[6] Mazza, F., Vulcano, A.: Control of the Earthquake and Wind Dynamic Response of Steel-Framed Buildings by Using Additional Braces and/or Viscoelastic Dampers. Earthquake Engineering & Structural Dynamics, vol. 40, pp. 155-174, ISSN: 0098-8847 (2011).

[7] Baratta, A., Corbi, I., Corbi, O., Barros, R.C., Bairrão, R.: Shaking Table Experimental Researches Aimed at the Protection of Structures Subject to Dynamic Loading, Open Construction and Building Technology Journal, vol.6, pp.355-360, ISSN: 1874-8368, DOI:10.2174/1874836801206010355 (2012).

[8] Baratta, A., Corbi, O., Corbi, I.: Rocking Motion of Rigid Blocks and their Coupling with Tuned Sloshing Dampers, in B.H.V. Topping, L.F. Costa Neves, R.C. Barros, (Editors). In Proc. Twelfth Int. Conference on Civil, Structural and Environmental Engineering Computing, Civil-Comp Press, Stirlingshire, UK, Paper 175, ISBN 978-1-9050-88-32-4, DOI:10.4203/ccp.91.175 (2009).

[9] Baratta, A., Corbi, I.: Optimal design of base-isolators in multi-storey buildings, Journal Computers and Structures, vol. 82(23-26) , pp. 2199-2209, ISSN: 0045-7949, DOI: 10.1016/j.compstruc.2004.03.061 (2004).

[10] Baratta, A., Corbi, O.: Dynamic Response and Control of Hysteretic Structures, Intern. Journal of Simulation Modeling Practice and Theory, Elsevier Science,vol.11, pp.371-385, ISSN: 1569-190X, DOI: 10.1016/S1569-190X(03)00058-3 (2003).

[11] Foti, D., Catalan Goni, A., Vacca, S.: On the dynamic response of rolling base isolation systems, Structural Control and Health Monitoring, ISSN: 1545-2263. DOI: 10.1002/stc.1538 (2012).

[12] Foti D., Bozzo L., Lopez-Almansa F.: Numerical efficiency assessment of energy dissipators for seismic protection of buildings, Earthquake Engineering and Structural Dynamics, vol.27 (6) , pp. 543-556. ISSN: 0098-8847, DOI: 10.1002/(SICI)1096-9845 (1998).

[13] Baratta, A., Corbi, O.: On the dynamic behaviour of elastic-plastic structures equipped with pseudoelastic SMA reinforcements, Journal of Computational Materials Science, vol. 25(1-2), pp.1-13, ISSN: 09270256, DOI: 10.1016/S0927-0256(02)00245-8 (2002).

[14] Corbi, O.: Shape Memory Alloys and Their Application in Structural Oscillations Attenuation, Intern. Journal of Simulation Modeling Practice and Theory (SIMPAT), Elsevier Science, vol.11, pp. 387-402, ISSN: 1569-190X, Doi:10.1016/S1569-190X(03)00057-1 (2003).

[15] Baratta, A., Corbi, I.: Epicentral Distribution of seismic sources over the territory. International Journal of Advances in Engineering Software, vol.35(10-11), pp. 663-667, Elsevier. ISSN 0965-9978, DOI: 10.1016/j.advengsoft.2004.03.015 (2004).

[16] Baratta, A., Corbi, I.: Evaluation of the Hazard Density Function at the Site. International Journal of Computers & Structures, vol. 83(28-30), pp. 2503-2512, Elsevier. ISSN 0045-7949, DOI:10.1016/j.compstruc.2005.03.038 (2005).

[17] Baratta, A., Corbi, I., Coppari, S.: A method for the evaluation of the seismic vulnerability of fortified structures, Final Conference on COST Action C26: Urban Habitat Constructions under Catastrophic Events;Naples;16-18 September 2010; pp.547-552, ISBN: 978-041560685-1 (2010).

[18] Baratta, A., Corbi, I., Corbi, O., Rinaldis, D.: Experimental survey on seismic response of masonry

models, Proceedings of the 6th International Conference on Structural Analysis of Historic Constructions: Preserving Safety and Significance, SAHC08, Bath; Code83644, 2-4 July 2008, vol. 2, pp. 799-807. ISBN 0415468728;978-041546872-5 (2008).

[19] Baratta, A., Corbi, I.: Statics and Equilibrium Paths of Masonry Stairs, Open Construction and Building Technology Journal, vol.6, pp.368-372, ISSN: 1874-8368, DOI: 10.2174/1874836801206010368 (2012).

[20] Baratta, A., Corbi, O.: On Variational Approaches in NRT Continua. Intern. Journal of Solids and Structures, vol. 42, pp. 5307-5321. ISSN: 0020-7683. DOI:10.1016/j.ijsolstr.2005.03.075 (2005).

[21] Baratta, A., Corbi, I.: Iterative procedure in no-tension 2D problems: theoretical solution and experimental applications, In: G.C. Sih and L. Nobile Eds., In: Proceedings of the International Conference on Restoration, Recycling and Rejuvenation Technology for Engineering and Architecture Application; Cesena, Code64053, 7-11 June 2004, pp. 67-75. ISBN: 8879997653 (2004).

[22] Baratta, A., Corbi, I.: Equilibrium models for helicoidal laterally supported staircases, Journal of Computers and Structures, ISSN: 00457949, DOI: 10.1016/j.compstruc.2012.11.007 (2013).

[23] Baratta, A., Corbi, O.: Relationships of L.A. theorems for NRT structures by means of duality. International Journal of Theoretical and Applied Fracture Mechanics, Elsevier Science, vol. 44, pp. 261-274. ISSN: 0167-8442. DOI:10.1016/j.tafmec.2005.09.008 (2005).

[24] Baratta, A., Corbi, O.: Duality in non-linear programming for limit analysis of NRT bodies, Structural Engineering and Mechanics, An International Journal, Technopress. vol. 26(1), pp.15-30, 2007. ISSN: 1225-4568 (2007).

[25] Baratta, A., Corbi, O.: On the equilibrium and admissibility coupling in NT vaults of general shape, Int J Solids and Structures, vol. 47(17), 2276-2284. ISSN: 0020-7683. DOI: 10.1016/j.ijsolstr.2010.02.024 (2010).

[26] Baratta, A., Corbi, O.: An approach to masonry structural analysis by the no- tension assumption—Part I: material modeling, theoretical setup, and closed form solutions, Applied Mechanics Reviews, vol. 63(4), pp. 040802-1/17, ISSN: 0003-6900, DOI:10.1115/1.4002790 (2010).

[27] Baratta, A., Corbi, O.: An Approach to Masonry Structural Analysis by the No-Tension Assumption—Part II: Load Singularities, Numerical Implementation and Applications, Journal Applied Mechanics Reviews , American Society of Mechanical Engineers, ASME International, Appl. Mech. Rev., July 2010, vol.63 (4), pp. 040803-1/21, ISSN 0003-6900 (print) 0003-6900 (online), DOI:10.1115/1.4002791 (2010).

[28] Baratta, A., Corbi, O., On the statics of No-Tension masonry-like vaults and shells: solution domains, operative treatment and numerical validation, Annals of Solid and Structural Mechanics, vol.2(2-4), pp.107-122, DOI: 10.1007/s12356-011-0022-8, ISSN 1867-6936 (Print) 1867-6944 (Online), (2011).

[29] Baratta, A., Corbi, I., Corbi, O.: Stress analysis of masonry structures: Arches, walls and vaults, Proceedings of the 6th International Conference on Structural Analysis of Historic Construction: Preserving Safety and Significance, SAHC08;Bath;2 July -2008; vol.1, pp. 321-329, ISBN: 0415468728;978-041546872-5 (2008).

[30] Baratta, A., Corbi, I.: On the Statics of Masonry Helical Staircases, in B.H.V.Topping, Y. Tsompanakis, (Editors), Proceedings of the Thirteenth International Conference on Civil, Structural and Environmental Engineering Computing, Civil-Comp Press, Stirlingshire, UK, Crete;6 -9 September 2011, Paper 59, 16p, ISBN: 978-190508845-4, DOI:10.4203/ccp.96.59 (2011).

[31] Baratta, A., Corbi, I.: Plane of Elastic Non-Resisting Tension Material under Foundation Structures. International Journal for Numerical and Analytical Methods in Geomechanics, vol. 28, pp. 531-542, J. Wiley & Sons Ltd. ISSN 0363-9061, DOI: 10.1002/nag.349 (2004).

[32] Baratta, A., Corbi, I.: Spatial foundation structures over no-tension soil. International Journal for Numerical and Analytical Methods in Geomechanics, vol. 29, pp. 1363-1386, Wiley Ed. ISSN: 03639061, DOI: 10.1002/nag.464 (2005).

[33] Baratta , A., Corbi, O.: Analysis of the dynamics of rigid blocks using the theory of distributions, Journal of Advances in engineering Software, vol. 44(1), pp.15-25, ISSN: 09659978, DOI: 10.1016/j.advengsoft.2011.07.008 (2012).

[34] Baratta, A., Corbi, I., Corbi O.: Towards a Seismic Worst Scenario Approach for Rocking Systems. Analytical and Experimental Set Up for Dynamic Response, Journal Acta Mechanica, vol. 224 (4) , pp. 691-705, ISSN: 0001-5970, DOI:10.1007/s00707-012-0787-9 (2013).

[35] Corbi, I.: FRP reinforcement of masonry panels by means of c-fiber strips, Journal Composites Part B, vol.47, pp. 348-356, ISSN: 1359-8368, DOI:10.1016/j.compositesb.2012.11.005 (2013).

[36] Corbi, I.: FRP Composites Retrofitting for Protection of Monumental and Ancient Constructions, Open Construction and Building Technology Journal, vol.6, pp.361-367, ISSN: 1874-8368, DOI: 10.2174/1874836801206010361 (2012).

[37] Baratta, A., Corbi, O.: An approach to the positioning of FRP provisions in vaulted masonry structures, Composites Part B: Engineering, doi.org/10.1016/j.compositesb.2013.04.043, (2013).

[38] Carlson, J.D. and Weiss, K.D.:. A Growing Attraction to Magnetic Fluid. J. Machine Design, vol. 1(8), pp. 61-64 (1994).

[39] Pabat, A.I.: Controlled Magnetorheological Shock absorbers. J. Magnetohydrodynamics, vol.26(2), pp.222-240 (1990).

[40] Constantinou, M.C., Symans, M.D.: Experimental study of seismic response of buildings with supplemental fluid dampers, The Structural Design of Tall Buildings, vol.2, pp. 93-132 (1993).
[41] Cesar, M., Barros, R.: Semi-Active Control of a Metallic Scaled Frame with a MR Damper: Numerical and Experimental Research. in School and Symposium on Smart Structural System Technologies (S3T-2010), Eds: R. Barros and A. Preumont, pp. 419-440. Faculty of Engineering of the University of Porto (FEUP), Porto, Portugal (2010).
[42] Wen, Y.K.: Method for Random Vibration of Hysteretic Systems. J. Engineering Mechanics Division, ASCE, vol. 102(2), pp. 249-263 (1976).
[43] Spencer Jr., B.F., Dyke, S.J., Sain, M.K. and Carlson, J.D.: Phenomenological Model for Magnetorheological Dampers. J. Engineering Mechanics, ASCE. vol. 123(3), pp. 230-238 (1997).
[44] Dyke, S., Spencer B. Jr.: A Comparison of Semi-Active Control Strategies for the MR Damper, in Proc. IASTED International Conference, Intelligent Information Systems, The Bahamas (1997).
[45] Jansen, L., Dyke, S.: Semi-active control strategies for MR dampers: a comparative study. ASCE Journal of Engineering Mechanics, vol. 126(8), pp. 795-803 (1999).
[46] Dyke, S., Spencer, B., Sain, M., Carlson, J.: Modeling and Control of Magneto-Rheological Dampers for Seismic Response Reduction, Smart Materials and Structures, vol. 5, pp. 565-575 (1996).
[47] Barros, R.: Project COVICOCEPAD under Smart Structural Systems Technologies of Program Eurocores, in Smart Materials and Smart Structures Technology, Eds: B.F. Spencer, M. Tomizuka, C.B. Yun, W.M. Chen, R.W. Chen, London: Taylor & Francis Group (2008).
[48] Shen, G., Golnaraghi, M., Heppler, G.: Load-Leving suspension system with a magnetorheological damper, Vehicle System Dynamics, vol.45(4), 297-312 .(2007).