THE PUBLISHING HOUSE
OF THE ROMANIAN ACADEMY

PROCEEDINGS OF THE ROMANIAN ACADEMY, Series A,
Volume 18, Number 3/2017, pp. 273–280

NUMERICAL STUDY OF A HYBRID DAMPING SYSTEM COMPOSED OF A BUCKLING RESTRAINED BRACE WITH A MAGNETO RHEOLOGICAL DAMPER

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Abstract. This paper discusses the concept of a hybrid damping system made from a combination of two dissipative devices. A steel Buckling Restrained Brace (BRB) was combined in series with a magneto-rheological (MR) Fluid Damper in order to obtain a hybrid dissipative system. This system can work either as a semi-active system, if the control unit is available, or as a passive system, tuned for working according to performance based seismic engineering scale of reference parameters (i.e. interstory drift). The two dissipative devices can work together to answer in an optimal way the demands of both low level and moderate to high level intensity of seismic actions.

Key words: hybrid damper, seismic performance, numerical model.

1. INTRODUCTION

The devastating consequences of important earthquakes in history determined the development and rapid growth of the seismic design of structures field in civil engineering. In an attempt to improve the behaviour of structures to earthquake and to limit losses, studies from around the world guided the implementation of innovative technologies in common practice. Damping devices that function on various principles, have been studied and implemented in different structural configurations. These devices can be used for both new structures and for seismic retrofit of existing structures and they reduce the seismic response and limit damage. Although damping devices such as buckling restrained braces (BRB), tuned mass dampers, magneto-rheological (MR) and viscous (FV) dampers, or friction dampers (FD) are being used in numerous buildings and are implemented in design codes, as technology advances there is a continuous need for improvement. In the last years research has opened a new and exciting path that looks into the possibility to combine already established damping devices to create Hybrid Damping Systems (HDS). These hybrid systems are conceived to provide additional damping capacity in the structure and/or provide special advantages in the structural system such as recentering capabilities or even the replaceability of damaged components [1]. One way in which these hybrid damping systems can be made is through the interaction between damping devices disposed in varied structural configurations. In parallel to the need of increased capacity and improved behaviour of structures for major seismic events there is an increased interest in recent years to protect structures from dangerous vibrations that occur on a frequent basis, including here wind action and minor seismic events which are not covered by the action of high capacity dampers. For these, the hybrid devices show great promise as they seem fit to answer both the demands of low and high level vibration in buildings and they can be used in the framework of performance based design of structures. Another concept of hybrid systems revolves around the combination between the passive damping devices installed together with the structural systems they are installed on. For example, a strain hardening friction damper can act together with the braces they are fixed on and have a combined hysteretic behaviour that is governed in turn by the behaviour of each element for different levels of seismic action, and in this way they can benefit from both the increased damping due to the device and the dissipation capacity of the dissipative steel brace [2]. The purpose of this paper is to show the potential of a hybrid damper system (HDS) made of BRB coupled with a magneto-rheological damper that can reduce the response of the structure to low and high levels of seismic action.

2. NUMERICAL MODELLING OF ELEMENTS

2.1. Numerical model for damper

Because of the limitations of passive and active damping devices, semi-active type dampers like Magneto-Rheological Fluid Dampers (MRD) appeared as an alternative. These devices have properties that can be adjusted in real-time but cannot introduce energy in the structural system, acting more like adjustable passive systems, and they have a much lower demand for power than active dampers. From constructive point of view semi-active dampers can be either mechanical or hydraulic dampers. The latter type allows the use of special fluids such as magnetic fluids to obtain certain damping characteristics. Magneto-rheological (MR) liquids change their apparent viscosity when acted upon by a magnetic field, a transformation that can occur in just milliseconds, making MR liquids a perfect candidate for semi-active devices. For the MR dampers, electromagnets act like control valves that regulate the flow of liquid. They can work either as passive devices or as semi-active ones, having a variable hysteretic behaviour that can be controlled by the variation of the magnetic field in the device with the change of current intensity. In addition to reduced power demands these MR dampers have the advantage of being capable of energy dissipation at small values of displacement and are able to produce control forces at low velocities, having a high dynamic range. Their behaviour is characterised by large rectangular type hysteretic loops (Fig .1).

Although MR dampers have become increasingly popular and are being used for both new buildings and for seismic retrofitting of existing ones in a variety of engineering projects from structures to bridges, historical buildings and industrial applications, they can still be considered limited in terms of capacity from technical point of view and can prove insufficient for high intensity seismic events. To tackle this issue the current research proposes the use of these dampers in a hybrid system with another secondary passive damping device more suitable for moderate to high levels of seismic action. The numerical modeling for the MR damper was made using Seismosoft SeismoStruct v7.0.2 [4] with the use of link element model. The model was calibrated on existing experimental results found in literature, more specifically results obtained by Sireteanu *et al*. [3] on a Lord RD1005-3 damper. The numerical model calibration was based on experimental data under a constant intensity of the electric current of 1.1A and considering a frequency of excitation of 1Hz under a constant sinusoidal loading history (Fig .1).

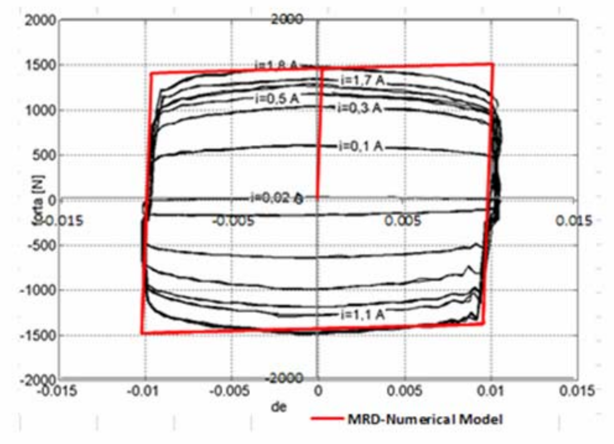

Fig. 1 – Experimental behaviour [0] *vs*. numerical model of MRD.

The dampers were initially modelled using a Ramberg-Osgood hysteresis behaviour but for the present study a symmetric simplified bilinear behaviour is used. This model has large rectangular hysteretic loops that are very close to the shape obtained for the MR dampers (Fig. 1) and is considered to be sufficiently accurate for the present study. After initial calibration the models were scaled to a higher capacity of 300 kN to be used together with the BRB for the hybrid damping system. The purpose of the MR dampers considered in the hybrid damping system proposed by this research is as an active component in reducing low level seismic excitation together with wind or vibration control.

2.2. Numerical model for BRB brace

Buckling restrained braces (BRB's) are an energy dissipation system based on the limitation of local buckling with extensive use for seismic protection of new buildings and retrofit of existing reinforced concrete, steel or even masonry structures. The main concept of this system is to prevent the buckling of a ductile steel core that is introduced in a steel casing filled with concrete. Between the steel core and the concrete a slip surface is provided to ensure that axial loads are taken entirely by the steel core. Their behaviour is characterized by symmetric behaviour in tension and compression with large stable hysteretic loops. The BRB's are meant to play their role in the hybrid system for medium to high levels of seismic action contributing with stiffness for reduction of story drift and high energy dissipation capacity due to their large symmetric hysteretic behaviour. The numerical model for the BRB was also made using a link type element in SeismoStruct, and calibrated on experimental research data from a research program in the CEMSIG centre of Politehnica University, Timisoara. In this large research program a BRB prototype was conceived, manufactured and tested. The test specimens were manufactured with different interface materials between the steel core and the concrete fill but for the numerical model used here only experimental data corresponding to the use of PVC transparent film interface material ($t = 1$mm) under ECCS type load protocol [10] was used. Several hysteretic behaviours were tested in an attempt reach a sufficiently accurate model. These behaviours were defined for the degree of freedom corresponding to axial deformation. For the sake of simplicity a bilinear symmetric behaviour (Fig. 2) with yield force $F_y = 140$ kN, stiffness of $K_0 = 67\ 000$ N/mm (Fig. 3) was selected.

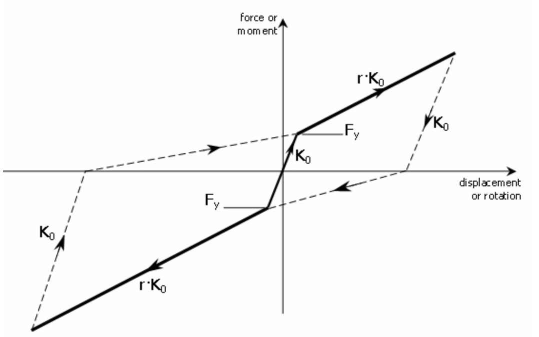

Fig. 2 – Bilinear symmetric model [4].

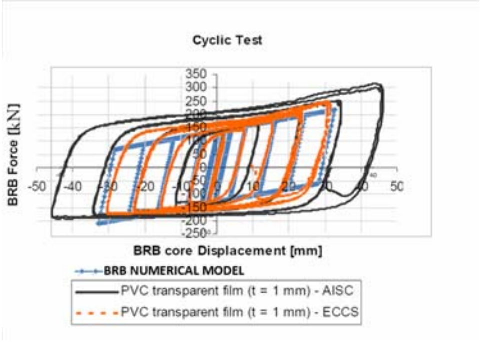

Fig. 3 – Experimental hysteretic behaviour *vs.* numerical hysteretic behaviour [6].

2.3. Numerical model for hybrid damper system

The concept of the hybrid damping system is the combination of two different dissipative devices that can work together to answer in an optimal way the demands of both low level and moderate to high level intensity of seismic motions. The model proposed here is a combination of 2 passive devices connected in series: a magneto-rheological fluid damper (MRD) working as a passive device and a buckling restrained brace, which is already a classical passive damping system. The MRD has good damping characteristics at all levels of excitation and high adaptability of the behaviour making it adequate for use both as an adaptable passive device and as a semi-active one. The BRB, a well-known passive system used in many applications, has very high energy dissipation capacity and symmetric behaviour in tension and compression. The analytical models are simple numerical models used to study the multi-phase behaviour of the hybrid system. The aim of this numerical study is to prove that the hybrid system concept has the desired behaviour and that it is a viable solution to fulfilling the demands of the structure at different performance levels. From numerical model point of view the two elements will be connected in series and modelled as 2 link elements. The multi-phase behaviour of the hybrid damper is dependant also on another critical component which is the interlock-out mechanism that enables the system to pass from one stage to another. In this case the interlock-out mechanism should transfer enough force from the damper, after it has attained its ultimate damping capacity, to the BRB, which starts developing its own hysteretic behaviour. This mechanism that can lock out the damper should provide a smooth transition during phases and must be carefully designed and calibrated. For the purpose of the current study the lock-out mechanism was introduced in the numerical model as a gap-hook element connected in parallel with the MRD damper that engages at 10 mm allowing for the transition between phases. The obtained behaviour is shown in Fig. 4.

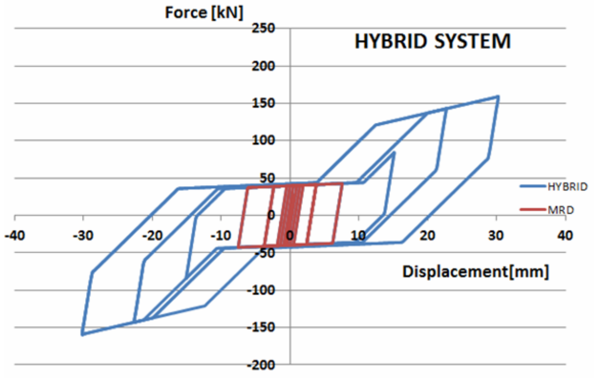

Fig. 4 – Hysteretic behaviour of hybrid MRD- BRB system.

The results obtained for the hybrid system show that the combined behaviour of the two passive devices follows the desired design concept. In the first stage the MRD is the active component providing energy dissipation at low levels of displacement, after which the lockout mechanism enables the transition to the second stage where the BRB is the active element, providing additional stiffness and energy dissipation. In a performance based design approach this hybrid damper can be thought to provide energy dissipation through the MRD for levels of seismic action corresponding to immediate occupancy (IO) performance level. For higher level seismic actions corresponding to life safety (LS) and collapse prevention (CP) performance levels the hybrid system engages the BRB passive damper that will provide adequate level of energy dissipation. This type of hybrid damper could be particularly useful in improving the behaviour of rigid structures that are sensitive to formation of plastic hinges at low levels of seismic action. A more complex system might be obtained by the connection of a control mechanism to the MRD enabling it as a semi-active device together with the BRB. The use of the MR damper as a semi-active device can ensure optimal response for low level excitation and could possibly provide also the interlock-out mechanism by itself, with the increase in stiffness in the damper that can cause the activation of the brace.

3. EXAMPLE OF APPLICATION
OF NUMERICAL MODEL FOR CBF FRAMES

The numerical model calibrated as detailed in the previous chapter is used to determine the performance of this system coupled with concentrically braced frames. The structure analysed is a 4 storey plane frame from a 3 × 3 layout with chevron bracing in the mid-span and a storey height of 3.5 m (Fig. 5). The frame was design according to EC3 and EC8 with some special considerations from the Romanian seismic design code P100/2013 [7] considering the design spectra for Bucharest with a corner period of $T_C = 1.6$ s and peak ground acceleration $a_g = 0.3g$ (Fig. 6).

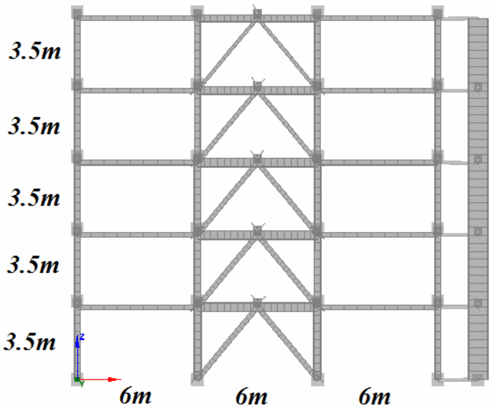

Fig. 5 – Designed frame configuration.

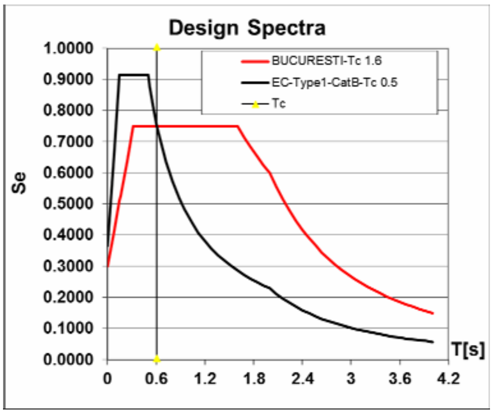

Fig. 6 – Elastic spectra for soft soil type $T_C = 1.6$s & stiff soil $T_C = 0.5$s.

Time-history analyses were conducted using two sets of seismic motions recordings scaled to the design spectra as follows: 7 semi-artificial seismic motion characteristic for soft soil type (Bucharest) and 7 artificially generated seismic motions characteristic for stiff soil (Class B soil according to SREN1998-1[8]) both with and without dampers. The two target spectra were scaled to the fundamental period of vibration of the analysed structure, so as to yield roughly the same design seismic forces (Fig. 6).

A performance based evaluation was performed using acceptance criteria for plastic axial deformation in the braces and plastic rotation for beams and columns according to FEMA356 [9]. Three performance levels were considered for each seismic motion having an acceleration multiplier of 0.5 (40 years return period), 1.0 (225 years return period), 1.5 (975 years return period) corresponding to serviceability limit state (SLS), ultimate limit state (ULS) and collapse prevention (CP).

In the case of earthquakes characterised by long corner period T_C=1.6 s (soft soil) this type of damper in the braces proved to have an unfavourable effect on the behaviour of the structures at all levels of seismic action. The structure with dampers has larger values of drift and plastic hinges form in elements considered non-dissipative such as central beams and columns. The results obtained for seismic motions characteristic for stiff soil will be presented in the following.

Maximum drift levels (Fig. 7), maximum drift at each storey (Fig. 8, Fig. 9 and Fig. 10) and top displacement for the structure (Fig. 11, Fig. 12 and Fig. 13) without dampers are presented as mean values of recorded values for all 7 seismic motions at levels corresponding to SLS, ULS and CP in comparison with the same values recorded for the structure with dampers in the braces.

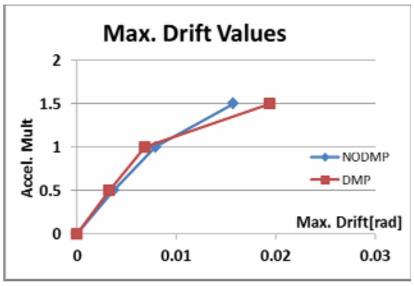

Fig. 7 – Maximum drift values for the structure with and without dampers (stiff soil).

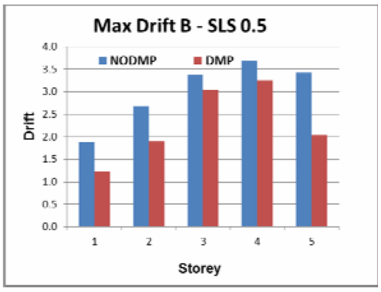

Fig. 8 – Maximum drift at each storey at SLS for the structure with and without dampers.

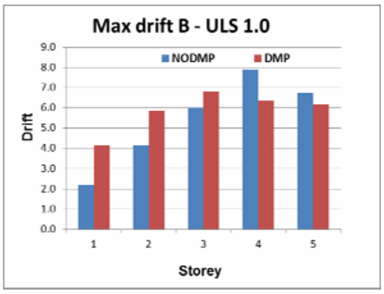

Fig. 9 – Maximum drift at each storey at ULS for the structure with and without dampers.

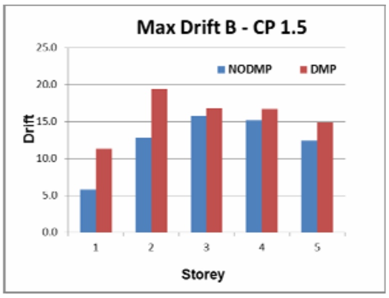

Fig. 10 – Maximum drift at each storey at CP for the structure with and without dampers.

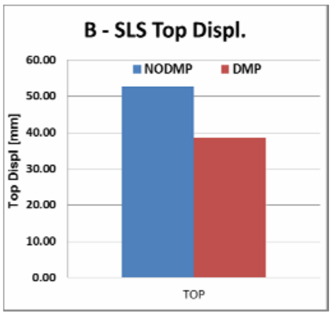

Fig. 11 – Top displacement at SLS for the structure with and without dampers.

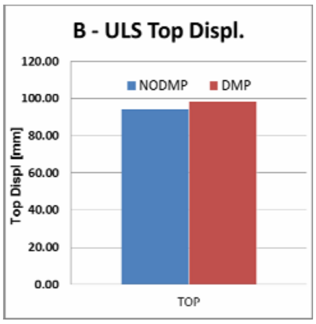

Fig. 12 – Top displacement at ULS for the structure with and without dampers.

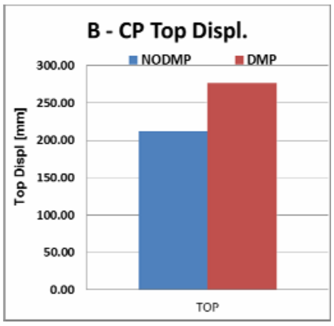

Fig. 13 – Top displacement at CP for the structure with and without dampers.

At the end of each seismic recording used the structure was left to vibrate freely for 10 s. Recorded values of permanent displacement at top of the structure are presented as mean values for all 7 recordings in Fig.14, Fig.15 and Fig.16.

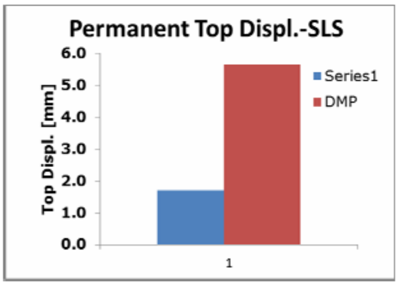

Fig.14 – Permanent top displacement at SLS for the structure with and without dampers.

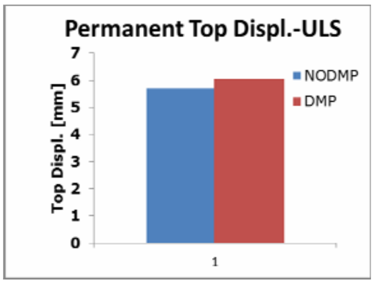

Fig.15 – Permanent top displacement at ULS for the structure with and without dampers.

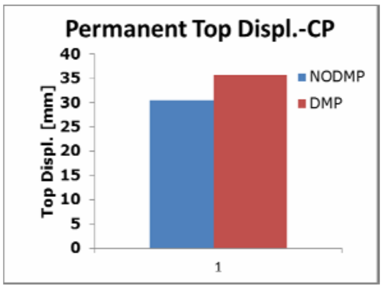

Fig.16 – Permanent top displacement at CP for the structure with and without dampers.

For seismic motions characteristic for stiff soil type the results showed that for SLS and ULS performance levels the building with hybrid dampers exhibited lower values of maximum drift. The structure with HDS has lower values of permanent displacement at the top of the structure at SLS and higher at ULS and CP. All plastic deformations/rotations satisfy the acceptance criteria at all levels.

At ULS the frames without dampers form plastic hinges in all braces and several central beams. All plastic deformations satisfy the acceptance criteria corresponding to life safety (LS) from FEMA 356 [9]. The ones with the hybrid systems do not form any plastic hinges in any elements (Fig.17 and Fig. 18). No plastic rotations of the central columns are recorded for either structures and both recorded similar values of permanent top displacement.

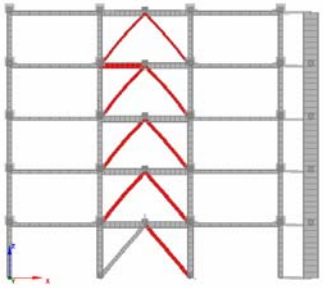

Fig.17 – Plastic hinge formation for frame without dampers-ULS.

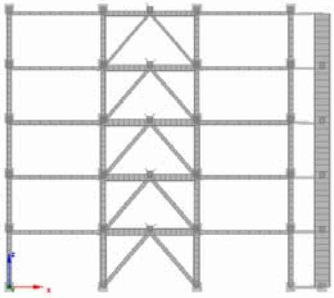

Fig. 18 – Plastic hinge formation for frame with dampers-ULS.

At CP both frames with and without dampers form plastic hinges in braces and central beams. Structure with HDS has plastic hinges in columns and central beams with higher values of drift and slightly higher values of permanent top displacement (Figs. 19 and 20). All plastic deformations satisfy the acceptance criteria corresponding to collapse prevention (CP) from FEMA 356 [9].

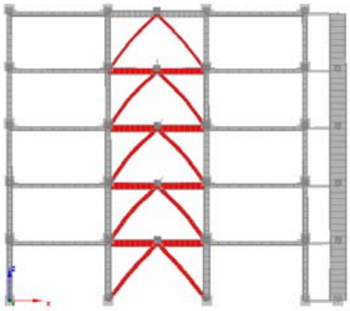

Fig. 19 – Plastic hinge formation for CBF without dampers at CP.

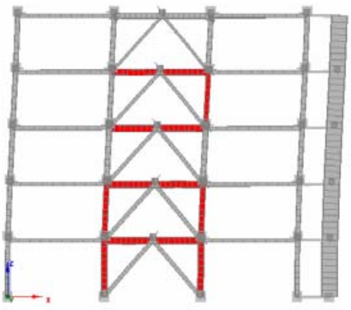

Fig. 20 – Plastic hinge formation for CBF with dampers at CP.

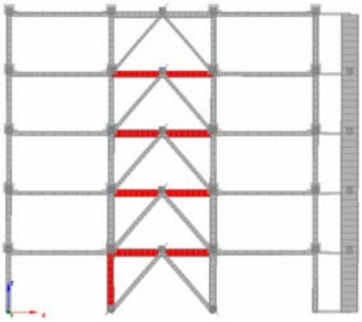

Fig. 21 – Plastic hinge formation for CBF with dampers at CP – S460.

For stiff soil the HDS reduced the values of maximum drift for SLS and ULS and improved the general behavior of the frames. The system avoided completely the formation of plastic hinges at ULS, but showed unfavorable behavior for CP where plastic hinges form in central columns due to an increase in beam and column forces. These systems should be designed to take into account this increase in forces to avoid the possibility of soft storey mechanism formation. An increase in steel grade for example, in the central columns to S460 will result in the reduction of number of plastic hinges in columns, appearing only for the base columns at the last stage of the ULS-CPS branch of the Load-Displacement curve, and can be accepted by standard (Fig. 21).

4. CONCLUDING REMARKS

A hybrid dissipative system developed from two damping devices is proposed and studied analytically. This hybrid system uses a MR fluid damper to provide damping and energy dissipation at low levels of seismic action and engages a BRB to provide energy dissipation at higher levels of seismic action. In a performance based design approach this hybrid damper can be thought to provide energy dissipation through the MRD for levels of seismic action corresponding to immediate occupancy (IO) performance level and through the BRB for higher level seismic actions corresponding to life safety (LS) and collapse prevention (CP) performance levels (Fig. 22). In the current study the MR damper was considered to work as a passive device. A simple numerical model was developed to demonstrate the concept of multi-stage behaviour of the hybrid damper concept by connecting in series two numerical models calibrated on experimental data for the MR damper and for the BRB. In parallel with the MRD damper a lock-out mechanism was modelled by means of a gap-hook type element. This element engages the buckling of the BRB for set values of displacement making the phase transition between the two elements.

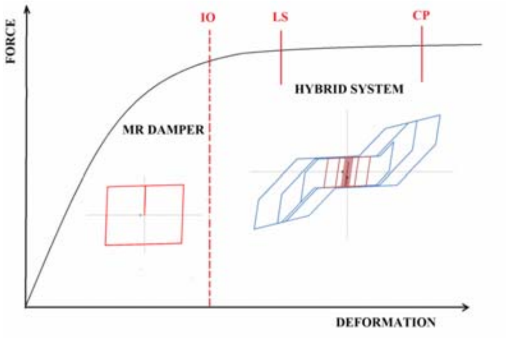

Fig. 22 – Conceptual use of hybrid MRD-BRB system.

The results of the TH analyses showed that this damping system introduce large forces in the columns of the bracing system for accelerations characteristic to soft soils and structures need to be carefully designed in order to avoid damage in these elements and in order to fully take advantage of the hybrid damping system for ULS and CP. For stiff soil the damping system improved the general behavior of the frames and avoided completely the formation of plastic hinges at ULS, reducing also the values of maximum drift. However the behavior at CP again confirmed that these systems should be designed to take into account an increase in beam and column forces as several central columns exhibited plastic hinges.

The paper summarise the first numerical trials of a hybrid system in order to design an experimental testing program as part of on-going research program and to establish a multi-phase concept for the use of such elements with chevron braced frames. As the research is ongoing, further numerical trials will be made to lead to a design philosophy that can take full advantage of such a system.

ACKNOWLEDGEMENTS

This work was supported by the strategic grant POSDRU/159/1.5/S/137070 (2014) of the Ministry of Labor, Family and Social Protection, Romania, co-financed by the European Social Fund – Investing in People, within the Sectorial Operational Program Human Resources Development 2007–2013.

The research is also part of a large cooperative project , PN-II-PT-PCCA-2013-4-1656-“ Seismic protection of engineering structures through dissipative braces of nano-micro magnetorheological fluid dampers (Semnal-MRD)”. The project is coordinated by UP Timisoara, and the partners of consortium are : Romanian Academy – CCTFA Timisoara, Institute of Solid Mechanics Romanian Academy, ROSEAL Ltd and TITAN-TEN S.A.

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Received December 4, 2015