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SEISMIC PROTECTION OF STRUCTURES USING A HYBRID SYSTEM: BUCKLING RESTRAINED BRACE AND MAGNETO RHEOLOGICAL DAMPER

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Keywords: Concentrically Braced Frames, Magneto-Rheological Damper, Buckling Restrained Braces, Seismic Protection;

Abstract. *The seismic protection of structures can be classified into three strategies: (i) reduction of the seismic demands, (ii) enhancement of the structural damping, and (iii) use of active or semi-active structural control. As part of an ongoing research project entitled SEMNAL-MRD (Seismic protection of engineering structures through dissipative braces of nano-micro magneto-rheological fluid dampers), the third approach is investigated. The goal of the project is to develop a seismic protection system, which uses magneto-rheological fluid dampers acting as semi-active structural control system. The current paper presents the research framework, respectively the experimental and numerical investigation program developed for the characterization of the magneto-rheological damper (10tf capacity). The ongoing experimental program includes the following investigations: (i) type tests on the MR damper, (ii) tests on a hybrid system (MR damper + buckling restraint brace; MR damper + conventional brace). The numerical investigation program is aimed to characterize and validate a model based on the tests performed on the 10tf MR damper. In addition, the numerical investigations are aimed to address the application of MR dampers in concentrically braced frames. Considering the fact that MR dampers are actually limited in terms of capacity, which could prove insufficient for high intensity seismic events, ongoing research aims at using these dampers in a hybrid system with another secondary passive damping device (i.e. buckling restraint brace) more suitable for moderate to high levels of seismic action. Consequently, the aim is to consider a performance based seismic design for which the MR dampers are active for immediate occupancy and into some extend up to life safety performance levels, while the buckling restrained braces will be activated for higher seismic intensity – corresponding to life safety up to near collapse performance levels.*

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1 INTRODUCTION

The seismic protection of structures can be classified into three strategies: (i) reduction of the seismic demands, (ii) enhancement of the structural damping, and (iii) use of active or semi-active structural control. A semi-active device has properties that can be adjusted in real time but cannot inject energy into the controlled system. The most promising devices suitable for implementation into a semi-active control appear to be magneto-rheological dampers (MRD's). One challenge in the use of semi-active technology is in developing nonlinear control algorithms that are appropriate for implementation in full-scale structures. Recent work by several researchers has indicated that semi-active control systems, when appropriately implemented, achieve significantly better results than passive control systems. The control strategy of a semi-active control system is based on the feedback of structural motions. Semi-active control systems are typically nonlinear due to the intrinsic nonlinearities of semi-active devices. The development of efficient control strategies, associated with the particular damper technology is still an open research topic.

As part of an ongoing research project entitled SEMNAL-MRD (*Seismic protection of engineering structures through dissipative braces of nano-micro magneto-rheological fluid dampers*) [1], the third approach is investigated. The goal of the project is to develop a seismic protection system, which uses magneto-rheological fluid dampers acting as semi-active structural control system. Particular objectives are:

- To develop composite nano-micro magneto-rheological fluids (MRF) compatible with application in seismic MR dampers;
- To design and built a 10tf capacity MR damper;
- To provide type tests, based on EN 15129-2009: *Anti-seismic devices* [2], with the aim to validate, calibrate and model the damper;
- To design, execute and test a brace-damper assembly in order to validate the integration of damper and brace, including connections;
- To propose structural application schemes for implementation in practice of semi-active control brace-MRD systems.

The project partnership is composed of the following institutions: UPT – Politehnica University of Timisoara (coordinator), ROSEAL S.A., TITAN-TEN S.A., IMSAR – Institute of Solid Mechanics of the Romanian Academy, and ARFT – Romanian Academy Timișoara Branch. Particular contribution of the partnership within the project can be summarized as follows:

- Nano-micro composite MR fluids for magneto-rheological devices: tuning the properties by composition to the specific requirements of semi-active MR damping devices (ROSEAL, ARFT, UPT);
- Design of the magneto-rheological damper (IMSAR, TITAN, ROSEAL, ARFT, UPT);
- Fabrication and type tests of the 10tf magneto-rheological damper (TITAN, ROSEAL);
- Experimental testing and numerical modeling of a single degree of freedom system with magneto-rheological semi-active damper (UPT, IMSAR, ARFT).

2 CASE STUDY: SEISMIC RESPONSE OF MULTISTOREY FRAMES EQUIPED WITH DAMPING SYSTEMS

As part of the ongoing research project [1], one of the tasks was related to the design of the magneto-rheological damper. Consequently, a design theme was elaborated based on the outcomes of a case study, which was aimed to assess the response of several multi-storey frames equipped with dampers. The structural configurations were designed considering two seismic locations corresponding to stiff and soft soil conditions (i.e. Timisoara and Bucharest). Further, two sets of 7 accelerograms (i.e. for stiff and soft soil) were used for the evaluation of the structural response.

Figure 1 makes an overview of the response of a three-story frame corresponding to stiff soil. It was observed that the use of dampers lead to the reduction of displacements and vibration. Furthermore, the study allowed assessing the response of the dampers, i.e the force-deformation and force-velocity curves. As a result, the study allowed the identification of the functional parameters of the dampers, i.e. maximum values of: displacement (41 mm), velocity (0.294 m/s), and force (104.9 kN). In addition, for the design of the MR damper prototype, several conditions were specified as part of the design theme: (i) overall dimensions, (ii) aspects related to the connection with the brace and structure, (iii) interlock of the damper (particularly of the piston) after reaching the working capacity of 100 kN (10 tf) – considering the use of the damper as part of a hybrid system composed of a buckling restrained brace and a damper.

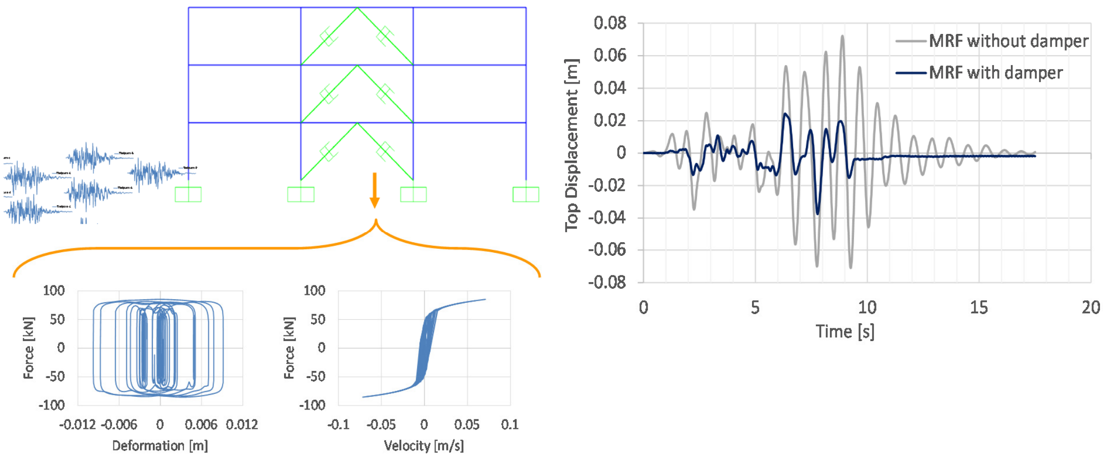

Figure 1: Response of a multi-storey frame equipped with dampers, i.e. force-deformation and force-velocity curves corresponding to a damper at the first floor, respectively the variation of the top displacement.

3 MAGNETO-RHEOLOGICAL DAMPERS

3.1 Principle and typologies of MR dampers

A magneto-rheological damper (MRD) is a special type of damper which is equipped with an electromagnet, and is filled with magneto-rheological fluid. Magneto-rheological fluids are oil based suspensions of micron sized Fe particles. When subjected to a magnetic field, the fluid increases its viscosity to the point of becoming a viscoelastic solid. Consequently, the response of the MRD can be controlled very accurately by varying the intensity of the magnetic field (through different current input). Many applications of MRD are found in the automotive industry for the alleviation of vibrations. In contrast, the application in seismic resistant structures is limited, considering the degree of novelty and the reduced amount of existing investigations.

In addition to its small power requirement, the MRDs can generate large forces at low velocities. Currently MRDs with capacities up to 200 kN exist [3] and research proved the possibility to obtain capacities up to 400-500 kN.

Typically, MR fluid can be used in three different ways [4], all of which can be applied to MR damper design depending on the damper's intended use. These modes of operation are referred to as: (i) squeeze mode (the device has a thin film of MR fluid located between two surfaces, i.e. the positive and negative pole, that are forced to draw near and squeeze the MR fluid); (ii) shear mode (the device has a thin film of MR fluid located between two surfaces that are forced to move relative to each other); and (iii) valve mode (the device operates in valve mode when the MR fluid is used to impede the flow of MR fluid from one reservoir to another).

With regard to the typology, MR dampers can be classified as [4]: (i) mono-tube MR damper, (ii) twin-tube MR damper, (iii) double-ended MR damper, (iv) other types: e.g. MR piloted hydraulic dampers (hybrid solution) in which a small MR damper controls a valve that is used to regulate the flow of hydraulic fluid.

3.2 Adopted solution for the MR damper prototype of 10tf capacity

The solution adopted within the current research for the design and fabrication of the 10tf capacity MR damper – is represented by a hybrid solution, i.e. a magneto-rheological piloted hydraulic damper. The conceptual scheme of the MR damper is illustrated in Figure 2. As can be observed, the hybrid solution implies a hydraulic damper equipped with a control cell which uses nano-micro magneto-rheological fluid developed within the current research project by the partner institutions [5][6]. It is to be highlighted that the advantage of the adopted solution resides in the reduction of the volume of MR fluid, and the corresponding costs. Considering the fact that the damper is intended to be used in series with a conventional brace, as well as with a buckling restrained brace (BRB), the control cell of MR fluid could work as an interlock (blocking) device, that is activated at the maximum capacity of the damper (in this case at 10tf / 100 kN) and which allows the activation of the buckling restrained brace in case of higher intensity earthquake. As can be observed in Figure 2, the MR damper is equipped with pinned supports. However, for the connection to a brace, the left support can be replaced with a steel plate in order to obtain a moment resisting connection.

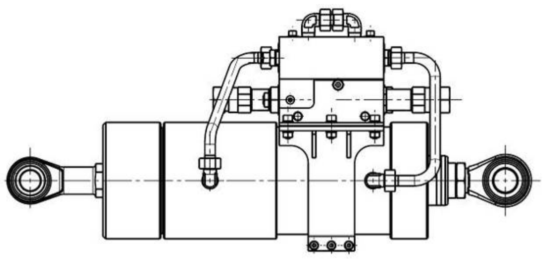

Figure 2: Conceptual scheme of the designed magneto-rheological damper.

4 EXPERIMENTAL AND NUMERICAL INVESTIGATION PROGRAM

The ongoing research project has the aim to develop a seismic protection system, which uses magneto-rheological fluid (MRF) dampers, acting as semi-active structural control system. For this purpose, an experimental and numerical investigation program was developed with the following objectives: (i) to provide type tests, based on EN 15129-2009: Anti-seismic devices [2], for the validation, calibration and modelling of the damper; (ii) to design, execute and test a brace-damper assembly for validating the integration of damper and brace, including connections. The following sections make an overview with regard to the experimental and numerical investigation program.

4.1 Parametric testing of the MR damper and development of numerical models

The MR damper of 10tf capacity will be tested in order to obtain and calibrate the hysteretic models for different loading conditions. The tests will be performed using a universal testing machine with dynamic loading capabilities. Three loading protocols, using displacement control, will be considered: triangular, sinusoidal and random. The triangular displacement excitation allows for an accurate measurement of damping forces, as the velocity is constant between peaks. Tests will be performed for different levels of: frequency (5 levels), input current (5 levels) and velocity (5 levels). Tests under sinusoidal displacement excitation will investigate parametrically the effects of different levels of: frequency (5 levels), input current (5 levels) and amplitude (5 levels). Two types of random loading protocols will be used: RDCV (random displacement and constant command voltage), and RDRV (random displacement and random command voltage). Based on the parametric testing of the MR damper, a phenomenological model will be developed for implementation into numerical tools.

Only type tests were performed on the MR damper, which evidenced the necessity to refine the solution of the damper prototype. Figure 3 illustrates the test set-up used for the testing of the MR damper.

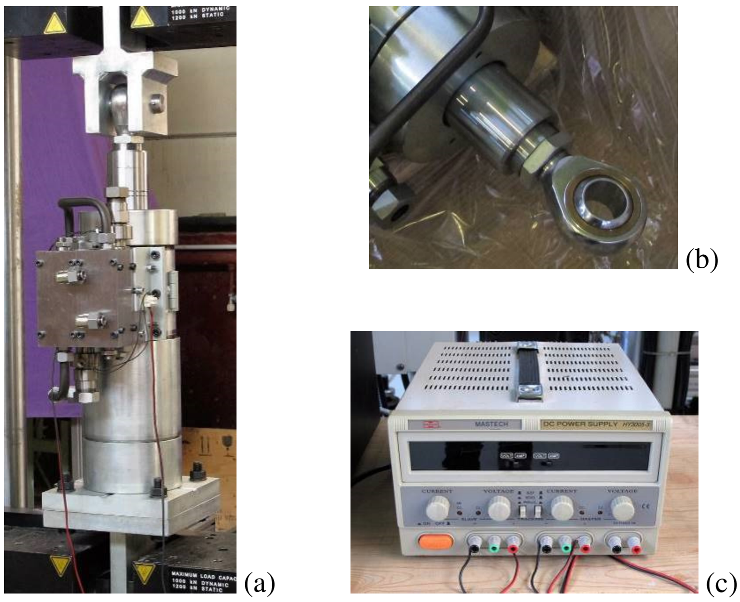

Figure 3: a) Test set-up for the investigation of the MR damper; b) rod end bearing (detail) for the pinned connection between piston and support; c) power source for the activation of the magneto-reological fluid

As can be observed, the damper is connected to a universal dynamic testing machine using two types of connections: (i) a moment resisting connection at the bottom support, (ii) a pinned connection at the top support. This was intended to reflect the actual connections within a brace-damper assembly, respectively the connections within the structural system. A detail of the pinned connection between piston and support is illustrated in Figure 3b. As can be observed, the top of the piston is equipped with a spherical rod end bearing, which allows a free rotation of the support due to the ball swivel. The power source considered for the activation of the magneto-rheological fluid is illustrated in Figure 3c. As instrumentation, the force, displacement and velocity of the actuator is measured. Furthermore, two displacement transducers are intended to measure the actual movement of the piston. Based on the parametric testing of the MRD, a phenomenological model will be developed for implementation into numerical tools.

4.2 Quasi-static testing of the brace-damper assembly

The MR damper is to be integrated within a structure as part of a bracing system. It is important that the brace-damper assembly exhibits a reliable response under seismic loading conditions. The brace is designed to resist both tensile and compression forces in elastic range, corresponding to the damper capacity. The connections between the damper and the brace on one hand, and between the assembly and the structure on the other hand should prevent development of large bending moments in the damper.

The objective of the tests on brace-damper assembly is to assess the overall cyclic performance of the system, including the connections between the damper and the brace on one hand, and between the assembly and the rest of the structure on the other hand. It is to be noted that the brace will be considered in the following cases (see Figure 4): (i) conventional brace, (ii) buckling restrained brace (BRB). The conceptual scheme (top and front view) of the buckling restrained brace is illustrated in Figure 5. The experimental test set-up, a conventional brace and a number of five buckling restrained braces were designed and fabricated. Compared to the working capacity of the MR damper (100 kN / 10 tf), the five BRB's were designed to develop an yield force of 170 kN (17 tf) and a maximum force of 310 kN (31 tf).

Figure 4: Conventional brace (yellow color) and buckling restrained braces

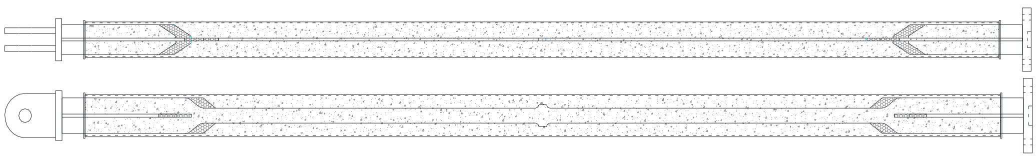

Figure 5: Conceptual scheme (top and front view) of the designed buckling restrained brace

The conceptual scheme of the testing set-up is shown in Figure 6. As can be observed, there are three test arrangements covering the investigation of: (i) buckling restrained brace - BRB (see Figure 6a); (ii) magneto-rheological damper with conventional brace (see Figure 6b); (iii) hybrid system composed of MR damper and BRB (see Figure 6c).

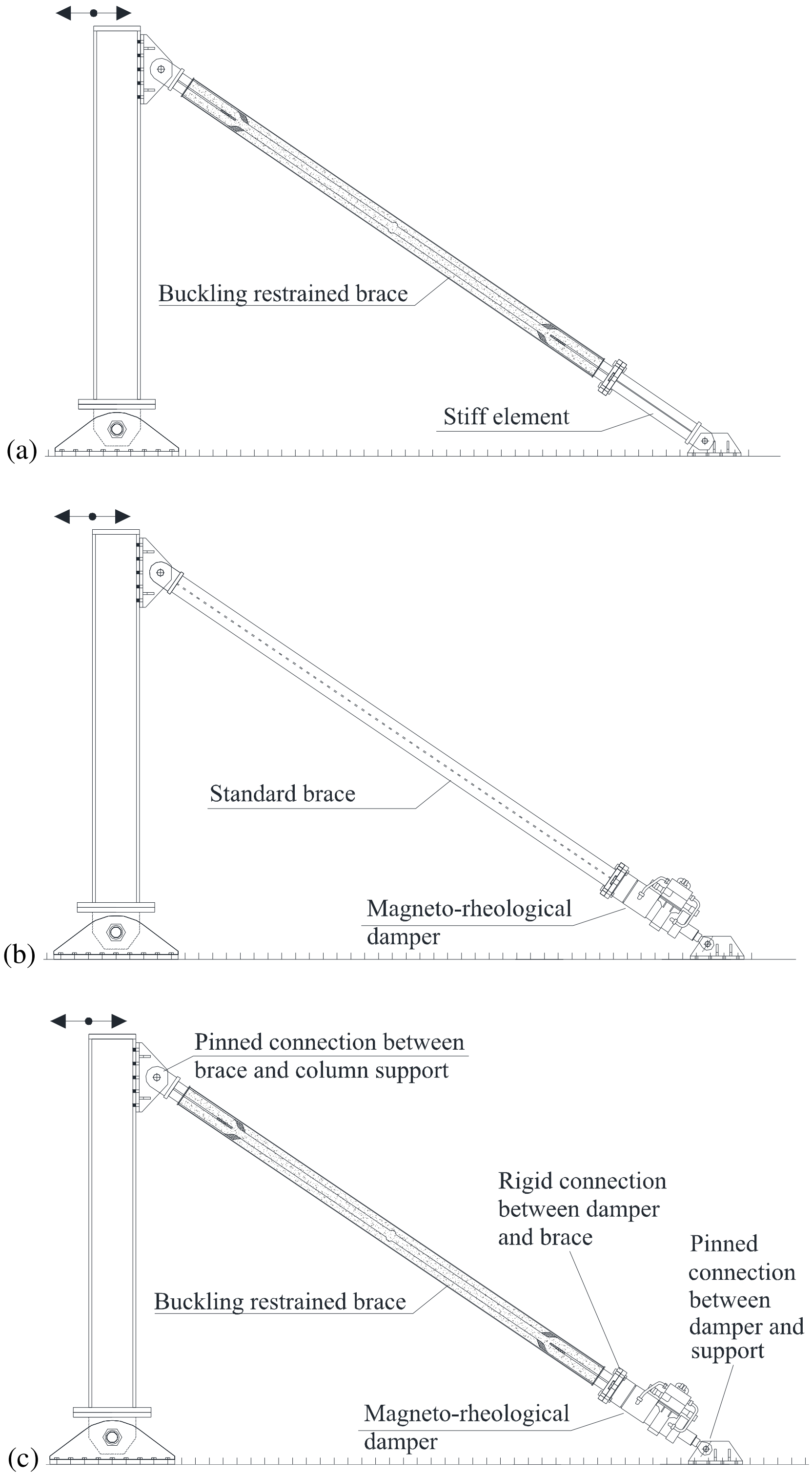

Figure 6: Conceptual scheme of testing set-up for the investigation of the brace-damper assembly based on the following testing sequence: a) buckling restrained brace (BRB), b) magneto rheological damper (MRD) with conventional brace, c) hybrid system composed of BRB and MRD.

It is to be noted that the experimental investigation program is ongoing. Tensile tests were performed on material samples corresponding to the steel core of the BRB. The outcomes (stress-strain curves), presented in Figure 7, evidenced that the yield strength was slightly higher compared to the yield strength assumed in the design of the BRB. As a result, a slightly higher capacity was expected for the BRBs.

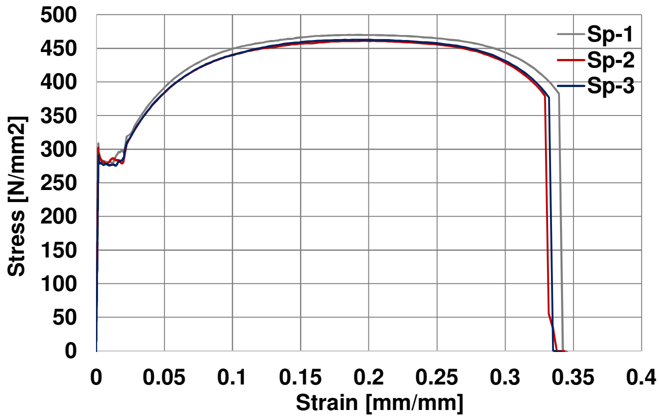

Figure 7: Stress-strain curves from the tensile tests on material samples (steel core of the BRB).

In addition, two experimental investigations were carried out on buckling restrained braces. The experimental test set-up is illustrated in Figure 8.

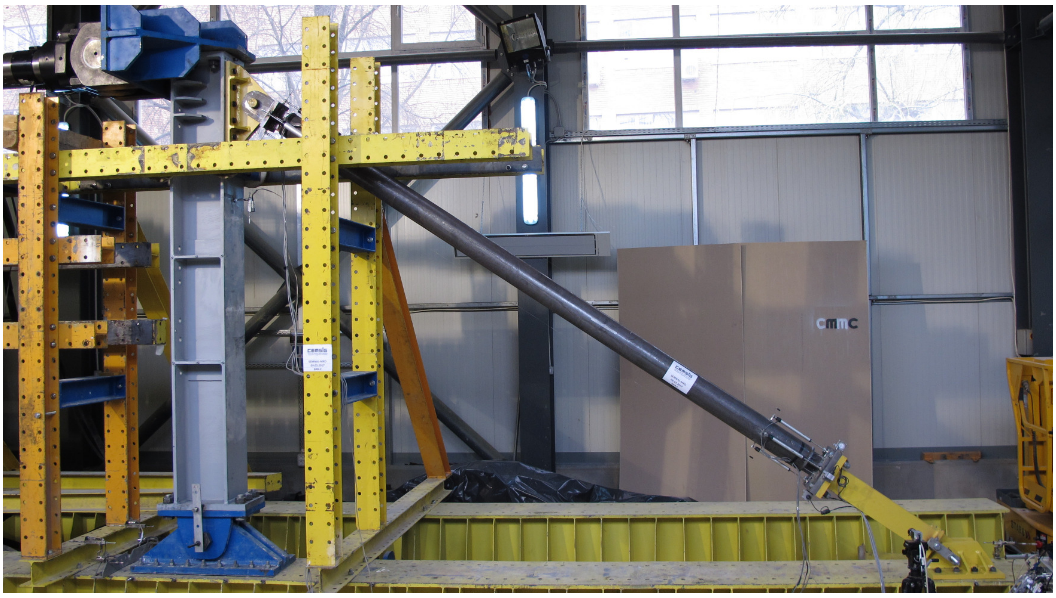

Figure 8: Experimental test set-up for the investigation of the buckling restrained brace (see Figure 6a).

As can be observed, a lateral out of plane system was used for an in plane response of the assembly. Only the column was restrained by the out of plane support system. The loading was applied using a hydraulic actuator. The BRB was connected to a column and to a stiff element (yellow color). The connection between BRB and the stiff element was considered as a continuous (moment resisting). The connection to the column and to the horizontal support considered as pinned connections. The column was connected to the horizontal support using a pinned connection. Both global and local instrumentation were considered. In particular, the global instrumentation consisted in measuring the following: force in the actuator, horizontal displacement at the tip of the column, horizontal and vertical displacement at supports. The local instrumentation consisted in measuring the actual deformation of the buckling restrained brace, i.e.: the relative displacement between outer steel tube and steel core at the two ends of the BRB, the deformation of the BRB between the two ends. With regard to the local instrumentation of the BRB, a number of four displacement transducers were used for each of the three locations (i.e. top, bottom, left and right).

The loading protocol considered for the investigation of the BRB was:

- *Monotonic loading*: the intention was to compress the BRB considering the maximum gap of 120 mm; further, with the aim to gather additional information, the BRB was subjected to the following: tension (120 mm) / compression (120 mm) / tension (120 mm).
- *Cyclic loading*: the AISC 341-10 [7] loading protocol for BRBs was considered. The control of the testing was performed by monitoring the inter-story drift. In particular, a number of two cycles were applied corresponding to the yield displacement (Δ_{by}). Further, two cycles were applied for each of the following amplitudes: $0.5 \cdot \Delta_{bm}$; $1.0 \cdot \Delta_{bm}$; $1.5 \cdot \Delta_{bm}$; $2.0 \cdot \Delta_{bm}$. Additional complete cycles of loading were considered at the deformation corresponding to $1.5 \cdot \Delta_{bm}$. It is to be noted that Δ_{bm} is the design story drift and was considered in amount of 2% of the story height according to the Romanian seismic design code P100-2013 [8].

The response of the buckling restraint braces under monotonic and cyclic loading conditions is illustrated in Figure 9. Under the AISC 341-10 [7] loading protocol, the BRB was subjected to deformations up to 4% inter-story drift, a value significantly higher compared to the 1.5% limit of from FEMA 356 [9] corresponding to braced frames. Both experimental investigations evidenced a good design and conception of the BRBs. The measurements and the observations from the tests did not reveal a global buckling of the two braces. The failure mechanism of the two BRBs consisted in development of large plastic deformations in the steel core under compression and tension. In case of BRB-M specimen, the test was stopped prior to the failure of the steel core. In case of BRB-C specimen, the test was stopped after the fracture of the steel core – which occurred under tension after several cycles (i.e. $n=11$) carried out at $1.5 \cdot \Delta_{bm}$.

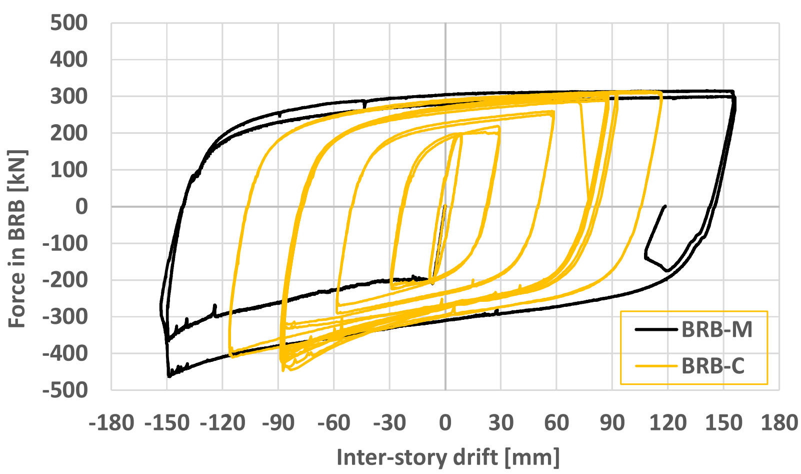

Figure 9: Response (force in BRB vs. story drift) of the buckling restrained braces under monotonic (BRB-M) and cyclic (BRB-C) loading conditions

4.3 Numerical simulations on a single degree of freedom system

As part of the numerical program, simulations will be performed on single degree of freedom systems. The numerical model will use the phenomenological model of the MR damper response (developed as part of the research activities described in Section 4.1), and the brace-damper characteristics (obtained as part of the research activities described in Section 4.2).

The concept of the hybrid damping system (see Figure 10) 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. 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.

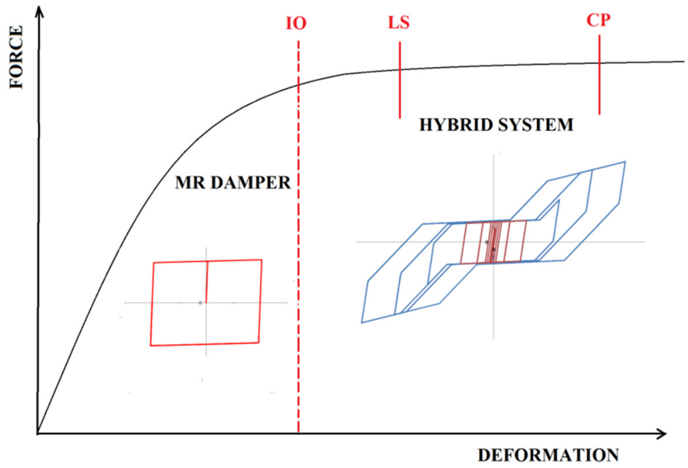

Figure 10: Conceptual use of hybrid MRD-BRB system [10]

In a performance based design approach [10], this hybrid system can be thought to provide energy dissipation through the MRD for levels of seismic action corresponding to immediate occupancy (IO) performance level. For higher seismic action, 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 behavior 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.

As part of the numerical program, simulations will be performed in order to test the efficiency of semi-active control on a simplified structural model (single degree of freedom system). Computational methods assisted by genetic algorithms will be used for finding optimum analytical models to portray dynamic behavior of the developed MR damper. Experience of one of the project partners (i.e. IMSAR) already exists [11] and offers a good starting point.

Based on the outcomes of the numerical investigation program on single degree of freedom systems, additional analyses will be performed with the aim to investigate the seismic performance of multi-story frames (i.e. multi degree of freedom systems). For this purpose, two sets of accelerograms will be considered, i.e. corresponding to stiff and soft soil.

5 CONCLUDING REMARKS

The current paper makes a brief presentation of the ongoing research project SEMNAL-MRD [1]. The aim of the project is to develop a seismic protection system employing a semi-active structural control system. Consequently, the innovative solution for a MR damper of composite nano-micro magneto-rheological fluid of passive/semi-active control – is presented in terms of technical solution.

A case study related to the seismic response of multi-storey frames equipped with dampers was presented. It was observed that the use of dampers lead to the reduction of displacements and vibration. Furthermore, the study allowed the identification of the functional parameters of the dampers, i.e. maximum values of displacement, velocity, and force.

The current paper presented the experimental and numerical investigation program. As the research is ongoing, experimental investigations were performed on two buckling restrained braces (BRBs). The response was investigated under monotonic and cyclic loading conditions. Under the AISC 341-10 [7] loading protocol, the BRB was subjected to deformations up to 4% inter-story drift, a value significantly higher compared to the 1.5% limit of from FEMA 356 [9] corresponding to braced frames. Both experimental investigations evidenced a good design and conception of the BRBs. The measurements and the observations from the tests showed that the failure mechanism of the two BRBs consisted in development of large plastic deformations in the steel core.

With regard to the numerical investigation program, the paper describes the conceptual response of the hybrid system (MRD+BRB), aimed to establish a multi-phase concept for the use of such elements with chevron braced frames. The hybrid system uses a MR fluid damper to provide damping and energy dissipation at low levels of seismic action and engages a buckling restrained brace (BRB) to provide energy dissipation at higher levels of seismic action.

The stages of the on-going experimental and numerical investigation program are represented by: (i) the parametric testing of the MR damper and development of numerical models; (ii) quasi-static testing of the brace-damper assembly; (iii) numerical simulations on a single degree of freedom system. For the latter case, the numerical model will use the phenomenological model of the damper and brace. Structural response will be investigated for two sets of accelerograms, corresponding to stiff and soft soil. As part of the numerical program, simulations will be performed in order to test the effi-ciency of semi-active control on a simplified structural model (single degree of freedom sys-tem). Computational methods assisted by genetic algorithms will be used for finding optimum analytical models to portray dynamic behavior of the developed MR damper.

6 ACKNOWLEDGEMENTS

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