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A HYBRID SEISMIC ISOLATION SYSTEM MADE OF RUBBER BEARINGS AND SEMI-ACTIVE MAGNETO-RHEOLOGICAL DAMPERS

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SUMMARY

The SPACE Project [1], partially funded by the European Commission within the 5th Framework Programme and coordinated by Maurer-Söhne (Germany), was recently concluded (March 2003). The main objective of SPACE was the development of semi-active dampers based on magneto-rheological (MR) fluids for the seismic protection of critical buildings. In general, semi-active devices can strongly vary their characteristics with a little amount of external power; moreover, they must have intrinsic passive properties, in order of providing a certain level of protection even in case of failure of the control system. The MR devices developed within SPACE can change their stiffness by a factor 20 (or even higher) in few milliseconds, simply by varying the current passing trough an external circuit. Several MR dampers were developed, analysed and tested in different configurations and for many kind of structures. Among these, the Medical Centre of the Italian Navy at Ancona, Italy, was selected as critical reference building of the project, with the aim of analysing the behaviour of a hybrid system composed by Low Damping Rubber Bearings (LDRBs) acting as passive seismic isolators, and MR dampers, acting as semi-active controlling devices. The Medical Centre, built in 1991 and actually provided with a passive isolation system made of High Damping Rubber Bearings (HDRBs), was numerically modelled and subjected to natural and synthetic earthquakes. Different kinds of control algorithms have been used in order of optimising the response of the building, in terms of both displacements and accelerations. The analyses showed that significant reduction of the building accelerations (up to 50%) can be achieved with the hybrid system. This is very important for protecting not only the structure from collapse, but also the contents of the building from damaging, and to guarantee the operability of the hospital in case of earthquake.

INTRODUCTION

According to the objectives of the SPACE Project, the Medical Centre of the Italian Navy (Figure 1), a two storey concrete building whose main features are reported in [2], was analysed in the configuration with an hybrid system composed by Low Damping Rubber Bearings (LDRBs) with a damping factor (ξ)

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equal to 5% (instead of the actual High Damping Rubber Bearings - HDRBs – which has a damping factor equal to 10%), and magneto-rheological devices (MRDs) installed between the base and the ground. These devices (Figure 2) are similar to viscous dampers filled with a suitable fluid containing iron particles whose orientation can be changed by applying a magnetic field. The viscosity of the fluid, which was developed by the University of Stockholm (KTH), depends on the orientation of the particles and can be controlled by varying the magnetic field. The MRDs hysteresis loop is similar to that of an elastic-perfectly plastic device. In practice, they provide a constant force at any deformation velocity. This level of force can dramatically be changed by varying the current which generates the magnetic field [3, 4]. This property can be used for the control of the dynamic response of structures subjected to external excitations and, in particular, to earthquakes. Of course, suitable control strategies must be adopted, depending on the characteristics of the structure to be protected and the variables to be controlled (displacement, acceleration, force). The control strategy is numerically defined by a control algorithm (CA), which practically gives the correlation between the mechanical properties of the devices and the variables to be controlled. The control algorithms developed within the SPACE Project are described in detail in [5-7]. In the following, the effects different semi-active control algorithms have been analysed; in particular, a nue algorithm is proposed. Four MRDs are supposed to be installed at the corners of the building base, acting in the transversal direction only; thus, the dynamic analyses will be mono-directional. Two synthetic earthquakes, BGS and CGS (developed according to EC8 for soil B and C, respectively) and a natural record (Tolmezzo, Fiuli 1976, Italy) have been used.

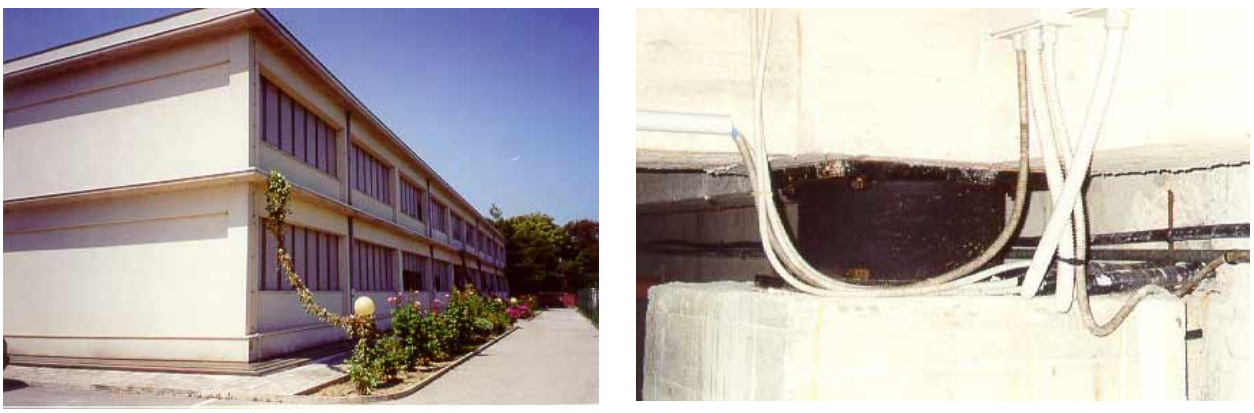

Figure 1: The Medical Centre of the Italian Navy at Ancona, Italy; view of the actual isolation system made of HDRBs.

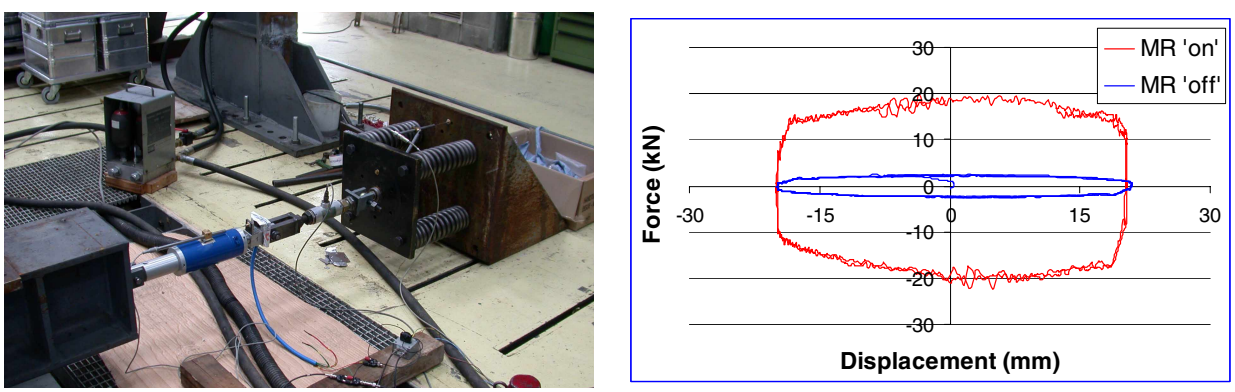

Figure 2: MRD developed by Maurer-Söhne during dynamic tests at ENEL.Hydro laboratory for the CA validation; hysteresis loop in the case of presence (MR 'on') and absence (MRD 'off') of magnetic field.

1. THE CONTROL ALGORITHM

Three different control algorithms have been initially proposed for the critical building with a hybrid isolation system (Figure 3). Based on preliminary dynamic analyses on a building mock-up model, the displacement control algorithm (DCA) seems to provide the best results in terms of deformations and accelerations reduction. In reality, the benefit seems to be not so high to justify the cost of the hybrid system (compared to the performances of the actual passive isolation system).

The DCA aims at reducing the deformation of the isolators by increasing the MRD force (and, consequently, the energy dissipation) when the relative displacement between ground and building is lower than a certain value D_0. However, it is worth noting that the rubber bearings are already quite stiff at lower deformations, due to their highly non-linear behaviour. As a matter of fact, the isolator horizontal stiffness at 20% shear strain could be even more than twice, with respect to the value at the design shear strain (100 %, usually). Thus, the use of DCA could increase too much the equivalent 'stiffness' of the hybrid isolation system at low deformations, for example, in case of moderate earthquakes. This could introduce high frequencies in the building and, consequently, high accelerations, which can be dangerous not for the structure, but for the contents. A hospital is a typical example of critical building, for which the protection of the contents must be guaranteed at any earthquake level.

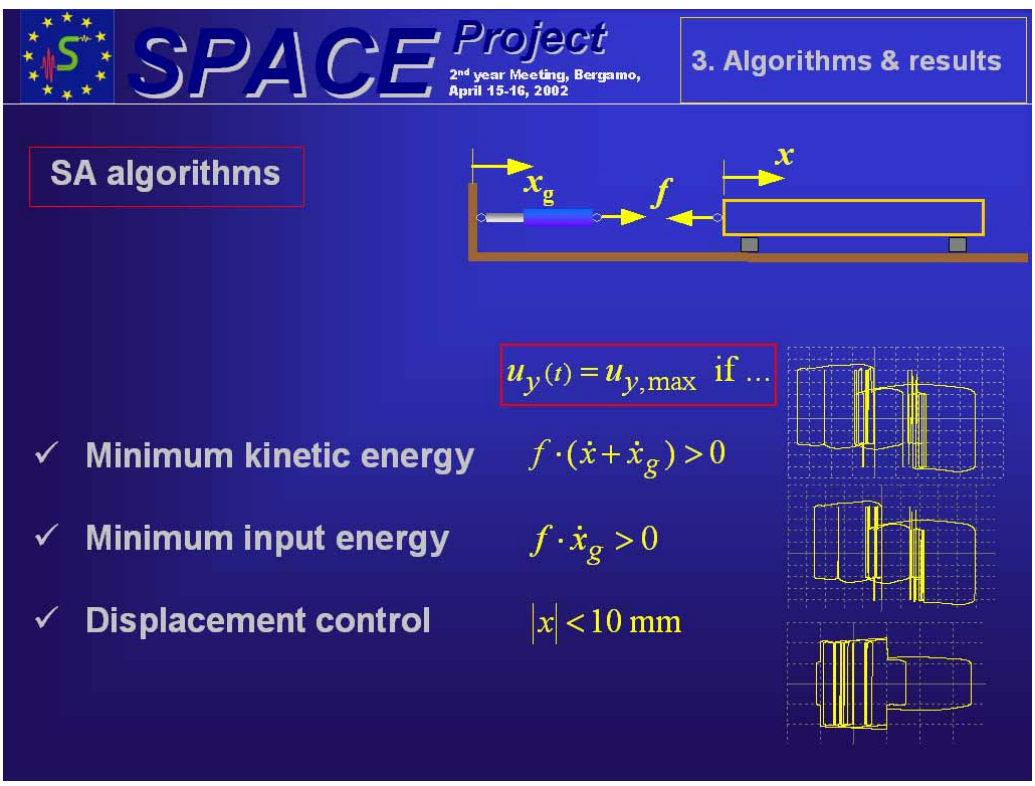

Figure 3: control algorithms initially proposed by University of Roma 3 for the critical building.

With the aim of avoiding these undesired effects, a different algorithm was proposed, based on the velocity control (VCA):

$F(t) = F_{max}$ if $|v| > V_0$

where v is the relative velocity between ground and building and V_0 a suitable threshold value.

This algorithm is quite similar to the DCA, because the range of the high velocities is that of the low deformations. However, the VCA is not activated during minor earthquakes (low velocities), where the stiffness of the passive isolation system is sufficient to limit the deformation without introducing high forces in the superstructure. Moreover, contrary to the DCA, the VCA also protect the building from the attack of unexpected violent earthquakes, which will be characterised by very high accelerations, velocities and deformations. As a matter of fact, the range of deformations in which the MRDs are activated by the VCA is not fixed 'a priori', but it is proportional to the earthquake level (velocity).

2. THE FE MODEL OF THE HYBRID ISOLATION SYSTEM

The finite element (FE) model of the rubber bearings, implemented in the ABAQUS code [8], is formed by a spring coupled in parallel with an elastoplastic truss (Figure 4). To reproduce the experimental stiffness of the actual isolators, the stiffness of the spring turns out to be 918.78 kN/m and 1323.38 kN/m for two sizes of bearings installed under the building (500 mm and 600 mm, respectively). To give a 10% damping at the design deformation (actual system), the yield point of the truss is 20,546 N/mm^2 and 29,594 N/mm^2, respectively (of course, the material is arbitrary). To reproduce the low damping rubber bearing of the hybrid system, these two values must be divided by 2.
The finite element model of the magneto-rheological devices used in the analyses is simply composed by a non linear 'dashpot' (viscous) element which provide the force F_{max} (MRD 'on') when the deformation velocity is higher than a fixed value; below this value, it provides the passive force F_{min} (MRD 'off').

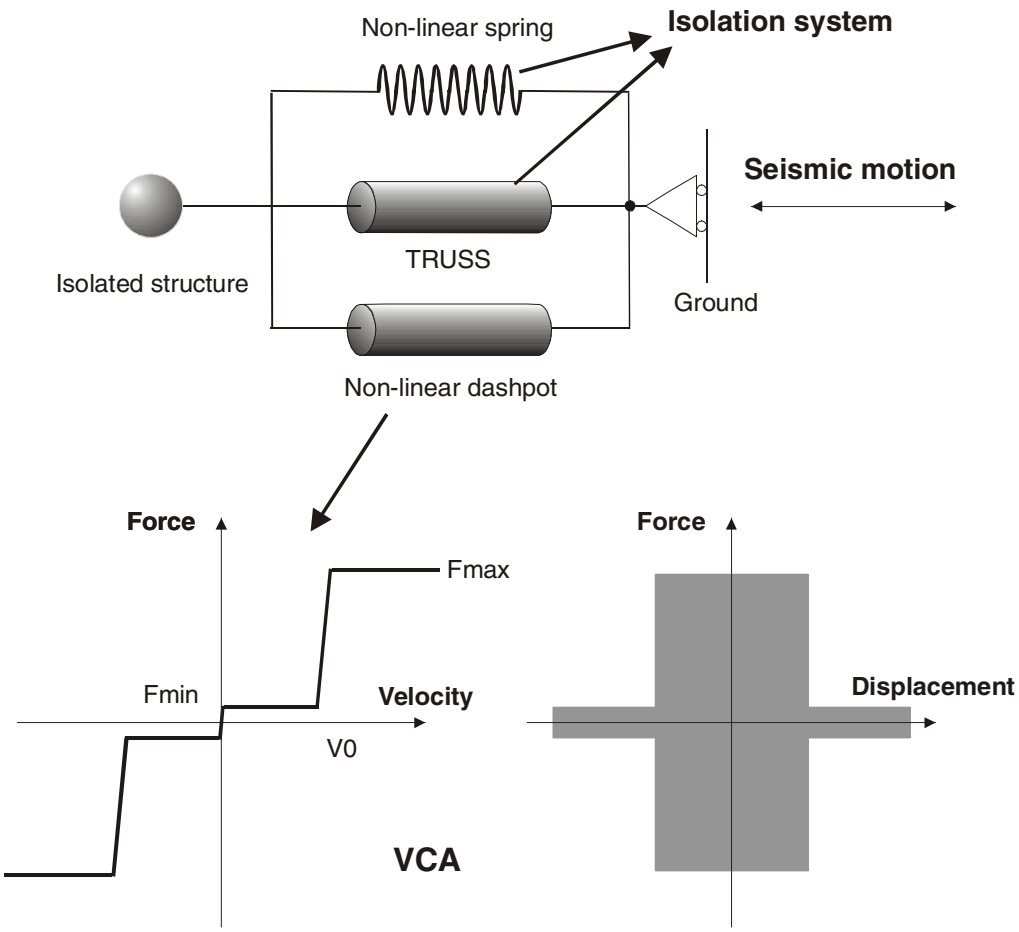

Figure 4: sketch of the simplified numerical model of the hybrid isolation system.

3. DYNAMIC ANALYSES

3.1 Actual isolation system

The reference analyses on the building in the actual passive conditions were carried out using the building FEM shown in Figure 5. The results are summarized in Table 1 and shown in Figures 6 in the case of BGS and Tolmezzo accelerograms. It's evident that the isolated building behaves like a rigid body and the maximum displacements are very close to 100% shear strain, for BGS and Tolmezzo at least (the accelerograms with the soil conditions more similar to the Ancona site). Moreover, Figure 7 shows a hysteresis loop of a HDRB and the global energy dissipation in the structure; the isolation system dissipates more than 60% of the external work made by the earthquake. Thus, the good behaviour of the building in the actual conditions is demonstrated, confirming that obtaining a significant improvement with the hybrid system will be a challenging job.

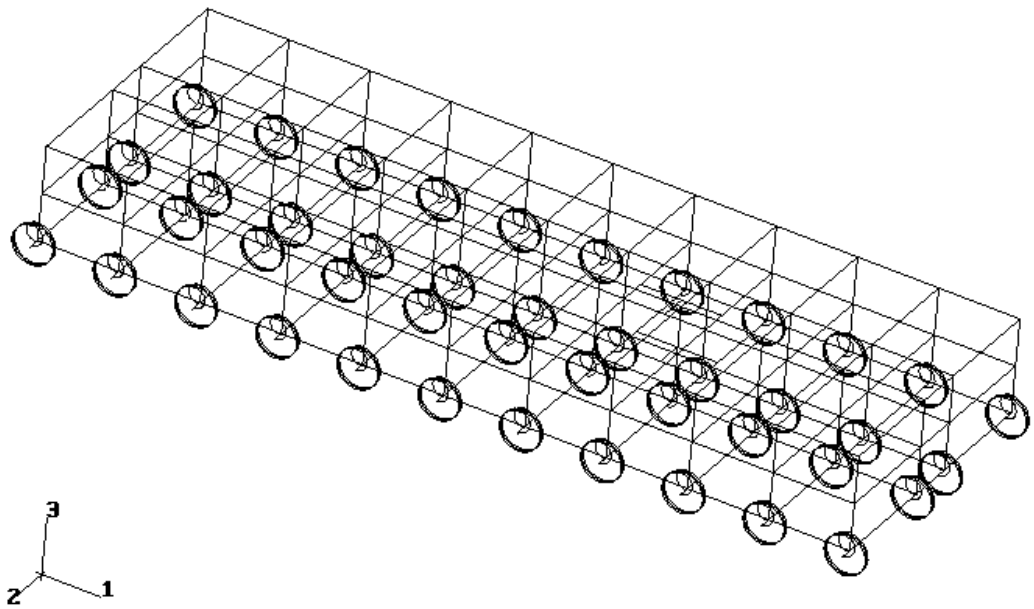

Figure 5: FEM of the Medical Centre of the Italian Navy at Ancona; the springs simulating the seismic isolators, coupled with elastoplastic truss, are evident.

Table 1: Behaviour of the Medical Centre in the actual base isolated conditions.

	BGS	CGS	Tolmezzo
Maximum ground acceleration (A1, m/s^2)	3.09	2.96	3.17
Maximum base acceleration (A2001, m/s^2)	1.85	2.33	1.10
Maximum roof acceleration (A10001, m/s^2)	1.95	2.42	1.15
Maximum deformation of devices (mm)	147	186	100
Maximum velocity deformation of devices (m/s)	0.54	0.69	0.34

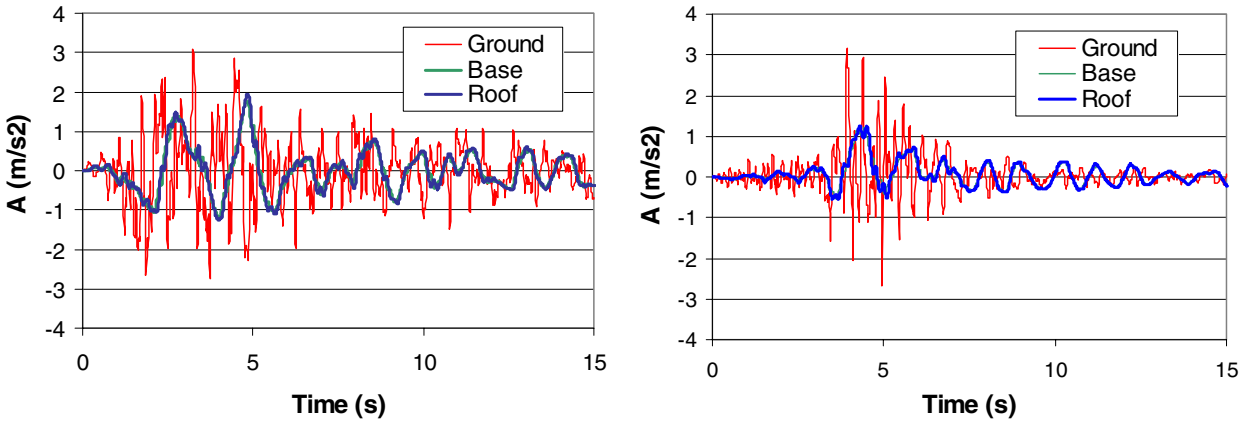

Figure 6: Acceleration of the building in the actual conditions calculated with BGS (left) and Tolmezzo (right) acceleration time histories.

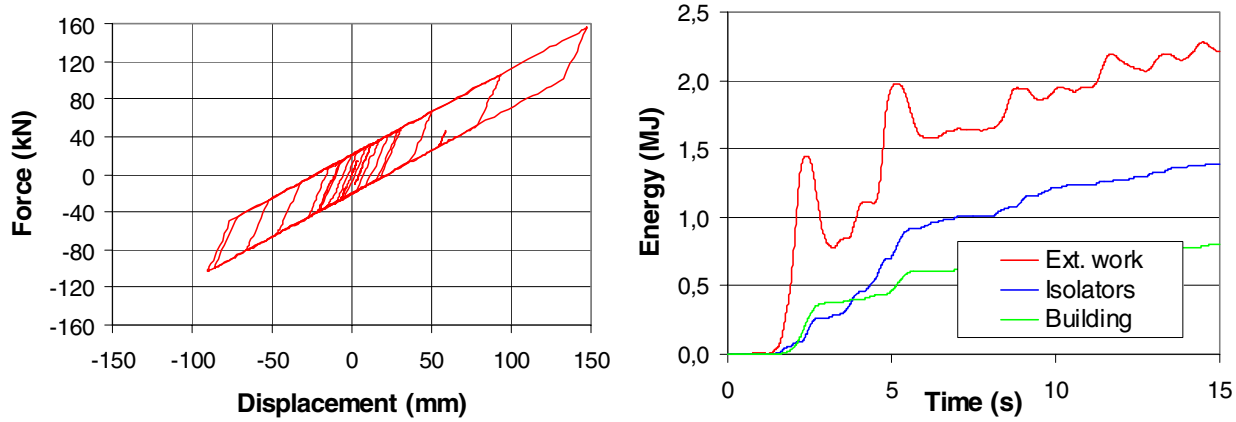

Figure 7: Hysteresis loop of the 500 mm diameter HDRB and energy dissipation in the whole structure calculated with BGS acceleration time history.

3.2 Hybrid isolation system

The numerical analyses described in § 3.1 have been repeated in the case of hybrid system, which is composed by low damping rubber bearings and 4 MR devices controlled by the VCA (§§ 1, 2). With the aim of choosing the most suitable velocity limit for the VCA and the optimal maximum force of the MRD, several parametrical analyses have been performed on a simplified FEM composed by a rigid mass and a couple spring-truss reproducing the global stiffness of the system.

The optimal maximum force turned out to be 1000 kN for each MRDs (400 t global force), while the maximum velocity was found to be 0.35 m/s for BGS and CGS, and 0.1 m/s Tolmezzo accelerograms, respectively. It was supposed that the MRDs provide gradually the maximum force (starting from V=0.3 m/s for BGS and CGS, and 0.08 m/s for Tolmezzo, respectively), to avoid acceleration peaks in the response of the building. F_{min} was chosen equal to 4% F_{max}.

It is worth noting that the Tolmezzo earthquake produces lower deformations in the isolators. Thus, to give the desired equivalent viscous damping at lower shear strains, two different yield point limits were used in the FE model (see § 2): 13,698 N/mm^2 and 19,698 N/mm^2 for the 500 mm and 600 mm diameter isolators, respectively, for the actual system (the half for the low damping isolators of the hybrid system).

The results, obtained with the complete FEM of the building (Figure 5), are summarized in Table 2 and shown in Figure 8 for BGS and Tolmezzo accelerograms. Moreover, Figure 9 shows an example of MRD hysteresis loop and the energy dissipation in the structure. It is evident that the LDRBs now dissipate the same amount of energy of the building, while the 4 MRDs dissipate 50% of the external work

Comparisons between actual and hybrid isolation systems are reported in Figure 10 for the BGS and CGS accelerograms. The hybrid system controlled by the VCA is able to significantly reduce the maximum displacement of the building with only a slight increasing of the maximum accelerations (or even a little decreasing, in case of CGS). This increasing is due to very high frequency 'spikes', probably due to numerical integration problems, related to the change of force in the MRD. In real cases, these acceleration peaks should not appear and, in any case, they should be in a frequency range far from that of interest for the structure and its contents.

It is worth noting that, for Tolmezzo and CGS earthquakes, the displacement of the building with hybrid system is 40% lower that the case of the actual isolation system. Considering that this reduction is obtained without a significant acceleration increasing (or even with a decreasing in case of CGS), we can say that the VCA works quite well. This is also showed by Figure 11, which reports a comparison of the energy dissipation of the actual and hybrid isolation systems in case of BGS and CGS accelerograms. For the latter, the hybrid system dissipates even less energy than the passive one; however, the semi-active control system, in particular the VCA, allow for a better distribution of the dissipation.

Table 2: Behaviour of the Medical Centre with the hybrid system.

	BGS	CGS	Tolmezzo
Maximum ground acceleration (A1, m/s^2)	3.09	2.96	3.17
Maximum base acceleration (AD2001, m/s^2)	2.25	2.15	2.01
Maximum roof acceleration (AD10001, m/s^2)	2.04	2.28	1.72
Maximum deformation of devices (mm)	115	109	60
Maximum velocity deformation of devices (m/s)	0.49	0.51	0.23

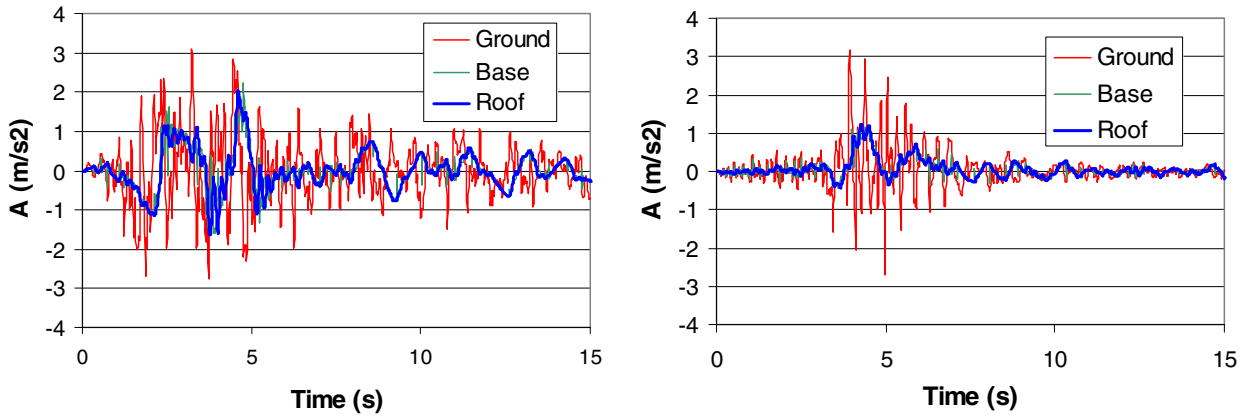

Figure 8: Accelerations of the building with the hybrid isolation system calculated with BGS (left) and Tolmezzo (right) acceleration time histories.

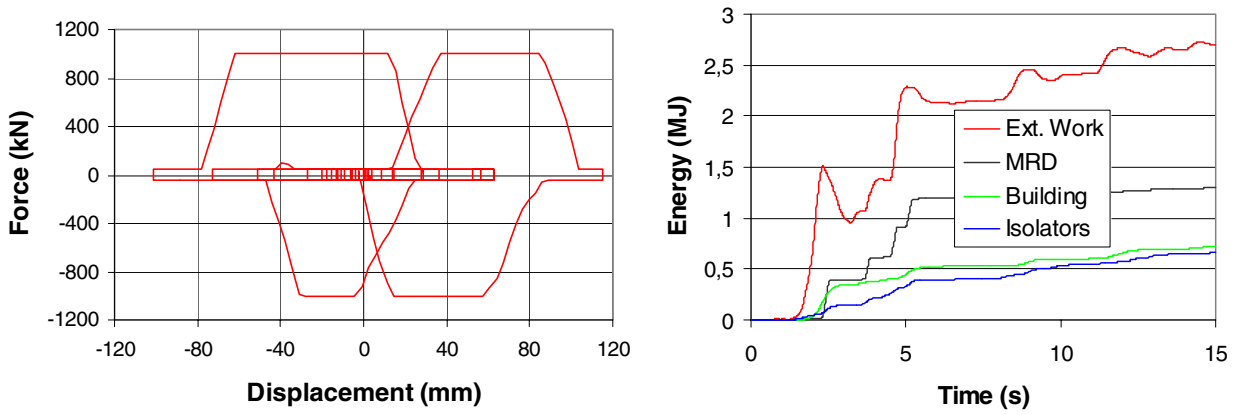

Figure 9: Hysteresis loop of a MRD with the VCA and energy dissipation in the whole structure calculated with BGS acceleration time history.

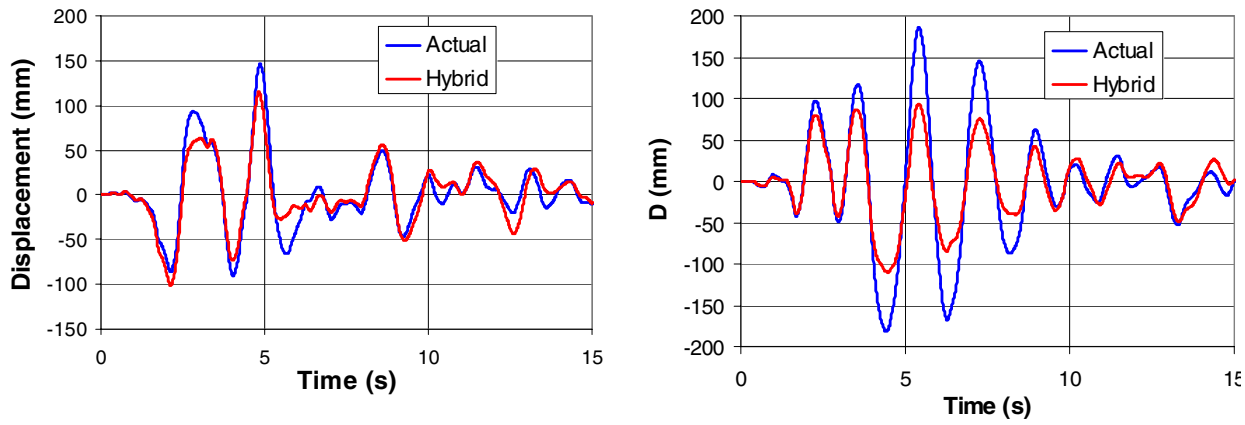

Figure 10: Comparison between devices deformation in the case of actual and hybrid isolation system calculated with BGS (left) and CGS (right) acceleration time histories.

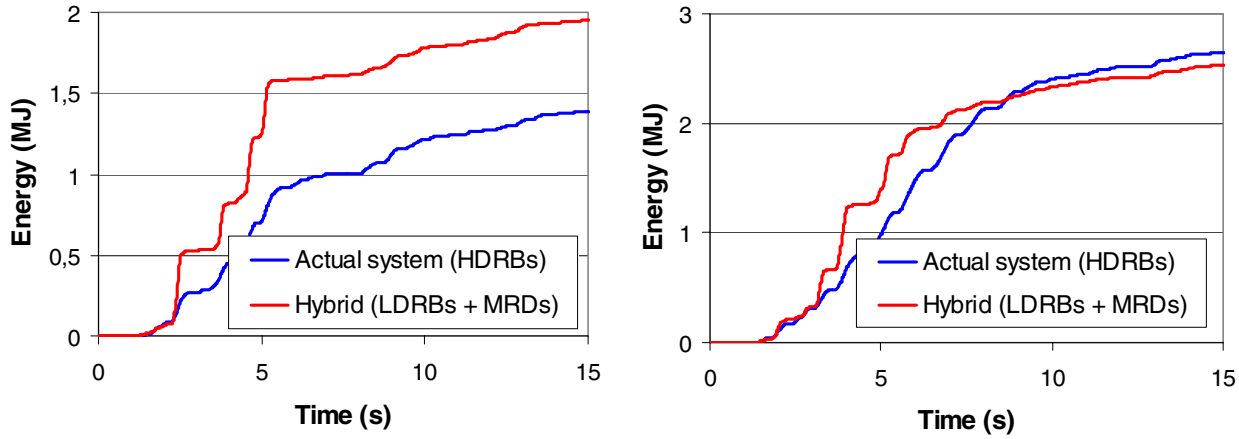

Figure 11: Comparison between the energy dissipated by the actual passive isolation system (HDRBs) and the hybrid one (LDRBs + MRDs) calculated with BGS (left) and CGS (right) acceleration time histories.

CONCLUSIONS

ENEA, in cooperation with the Universities of Ancona and Roma 3, performed a complete numerical analysis the Medical Centre of the Italian Navy, selected as critical building in the framework of the SPACE Project. The building was analysed in both the actual conditions, with the base isolation system made of 44 high damping rubber bearings, and with a hybrid isolation system made of low damping rubber bearings and 4 magneto-rheological dampers (initially considered in the two extreme passive conditions only).

Numerical analyses have been performed on an improved finite element model of the building with the hybrid system controlled by an algorithm proposed by ENEA. The Velocity Control Algorithm (VCA) activates the MR devices when the relative velocity between ground and building exceeds a chosen value. It is similar to the Displacement Control Algorithm (DCA) proposed by UR3; however, it avoids the introduction of high forces in the building in case of moderate earthquakes, giving more protection to the contents (whose cost could be higher than that of the whole structure, especially for critical buildings like hospitals, museum, etc.). Moreover, with the VCA, the working range of the MR devices is not fixed and decided 'a priori' like in the case of DCA, but is proportional to the deformation velocity, and then, to the earthquake level, giving protection to the structure also in case of unexpected higher seismic attacks.

The preliminary analyses carried out by UR3 showed that only negligible improvements can be obtained with the hybrid system, in comparison with the optimal passive isolation system. The results of the numerical analyses performed with the VCA, provided better results, notwithstanding that the building in the actual passive conditions is well designed and shows a good behaviour, which can be improved with difficulty. The maximum displacements of the building with hybrid system controlled by the VCA turned out to be 20% lower for BGS and 40% lower for CGS and Tolmezzo accelerograms, than those obtained with the actual system. It is worth noting that this was obtained with only a negligible increasing of the maximum accelerations (in the case of CGS even with a decreasing), thus, it can be considered a good result.

Moreover, the use of hybrid isolation systems allows for the use of low damping rubber bearings (less expansive and more durable) and can be also used to control undesired torsional movement of the building, which can be due to asymmetric dispositions of masses, construction tolerances and also to the seismic input.

In conclusion, hybrid isolation systems can be satisfactory used to limit the displacements of the structure without increasing the accelerations. On the other hand, they can be also adapted to limit accelerations without increasing displacements, using lower isolator stiffness.

The higher cost of the control system is partially balanced by the lower cost of the low damping rubber bearings. Anyway, this kind of application is mainly addressed to important and strategic structures.

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