Effectiveness analysis of damping control strategy to reduce structural response to near-source earthquake of L'Aquila 2009

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L. Petti, I. Marino, A. Lodato
Department of Civil Engineering, University of Salerno

SUMMARY

This paper presents an analysis of the effectiveness of hysteretic and viscous damping control strategies in improving the seismic response of built structures in the case of near-source earthquake of L'Aquila '09. With this aim in mind we have examined this seismic event in order to evaluate the expected damage incurred by existing structures which had been designed according to the Italian Seismic Code DM '96, both with and without extra-structural damping devices. In particular, a broad parametrical non-linear analysis was carried out by taking into consideration a non-linear equivalent SDOF system and varying the dynamical parameters and the damping control devices. The damage assessed, by means of the Park&Ang index have led the authors to investigate and compare the effectiveness of both damping control strategies under examination.

Keywords: Damping Control Strategies, Polar Spectrum, Damage Index, Near-Source Event

1. INTRODUCTION

Passive energy dissipation systems for seismic applications have been under development for a number of years with a rapid increase in implementation starting in the mid-1990 (17).

A large number of passive control systems with passive energy dissipation devices have been developed and installed in structures for performance enhancement under earthquake loads. In the US passive energy dissipation devices have been installed in many buildings and many bridges, either for retrofit or new construction (fig. 1).

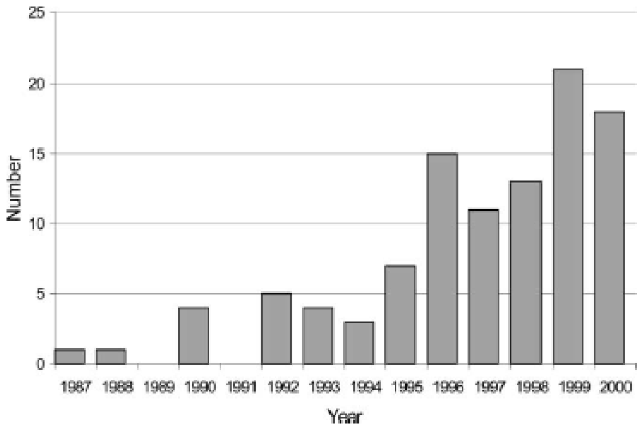


Figure 1. Passive dissipation system implementation in the US (15)

A wide-ranging discussion of the principles of energy dissipation seismic control strategy can be found in (2) and (19). As is well-known, the objective of the strategy is to improve seismic response by increasing the energy damping in ad-hoc extra-structural devices (8).

At this time, the damping devices most commonly used, are viscous fluid dampers, viscoelastic solid dampers, friction dampers and hysteretic dampers (18). In this context, the devices that could be classified as passive energy dissipation devices or, in a more general sense, passive control devices, are also tuned-mass and tuned-liquid dampers (17). Recently, numerical and experimental studies have been carried out to examine the effectiveness of TMDs in reducing the seismic response of structures (17, 10, 11). Moreover, there is a class of dampers, known as semi-active dampers, which may be regarded as controllable passive devices. Examples of such dampers are variable-orifice dampers, magneto-rheological dampers and electro-rheological dampers (4).

As previously stated, the objective of passive energy dissipation is to reduce/control damage in structural and non-structural elements by damping through the use of ad-hoc, specialized devices. The capacity of such a device to accomplish this goal depends on the inherent properties of the main structure, the properties of the device and its connecting elements, the characteristics of the ground motion as well as the target seismic performance level being investigated. Given the wide variations in each of these parameters, it is usually necessary to perform an extensive set of analyses, linear and/or non-linear, to evaluate which particular passive energy dissipation system is best suited for a given case.

This study aims to investigate the effectiveness of hysteretic and viscous devices in the case of near-source ground motion. In particular, the study investigates the seismic performance by means of the Park&Ang index estimated by analyzing the non-linear behavior of an equivalent single- degree of freedom system subjected to the L’Aquila ‘09 event. The obtained results, in terms of the Park&Ang index, are clearly shown through polar spectral representation (12).

2. L’AQUILA 2009 EARTHQUAKE CASE

On Monday April 6, 2009 at 1:32 UTC (3.32 local time), an Mw 6.3 earthquake with shallow focal depth (10 km) struck central Italy in L’Aquila, a city of about 73,000 inhabitants and the capital of the Abruzzo Region. An analysis of the recordings from the seismic stations situated within 6 kilometers (fig. 2) of the epicenter and those recording within 30 kilometers, showed that the seismic recordings from the closer stations are clearly affected by near-source phenomena.

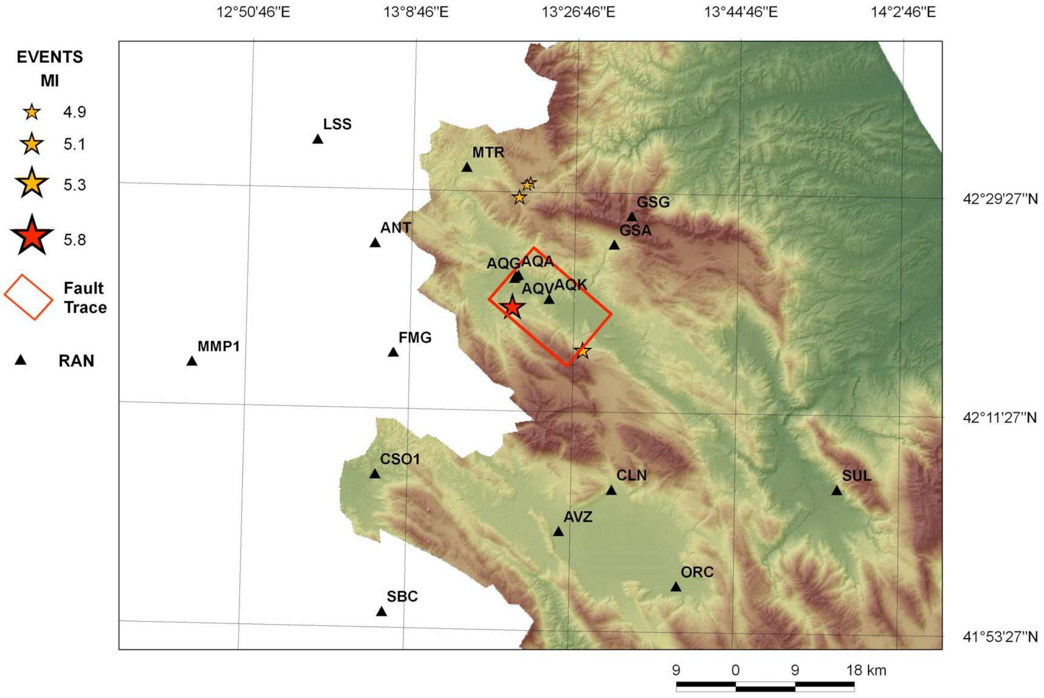


Figure 2. Fault geometry plotted against the main events.
Triangles show the RAN seismic stations installed in the area of the epicenter (13)

Table 1. PGA of the main stations

	Pga (g)		
ID station / direction analysis	**X - direction**	**Y - direction**	**Z - direction**
AQG	0.42	0.43	0.22
AQA	0.39	0.45	0.38
AQV	0.63	0.60	0.42
AQK	0.34	0.34	0.35

The L'Aquila 2009 event clearly shows directional effects due to the main propagation directions of the rupture and the displacement distribution along the fault plane near the epicenter area. These effects decrease further away from the epicenter where the impulsive phenomena led to greater seismic demand along the normal plane of direction with respect to the fault plane. The spectral demand, near the source, is characterized by a peculiar shape in the range around the period describing the impulse.

In this case, classical spectral response analysis, carried out by means of main direction records, are unsuitable for describing these directivity effects. In (12) the authors, with the aim of characterizing horizontal seismic demand in terms of pseudo-acceleration, pseudo-velocity and displacement, used a new spectral representation called "Polar Spectrum", which represents a useful tool to analyze the seismic demand in the plane.

In the following, polar spectrum in terms of pseudo-acceleration (PSA) and displacement (SD) are reported for the case of AQV recording station (12). The plots represent the seismic spectra demand in each horizontal direction by means of graduated color maps. In particular, in correspondence to each radius the in-plan projection of the spectrum response evaluated along that direction is represented. Instead, in correspondence to each circumference the spectral demand for a fixed period is plotted for each direction being considered. In the represented Polar Spectra, the periods 0.5, 1.0 and 1.5 are marked by thin black circumferences, therefore the origin corresponds to a 0 sec period.

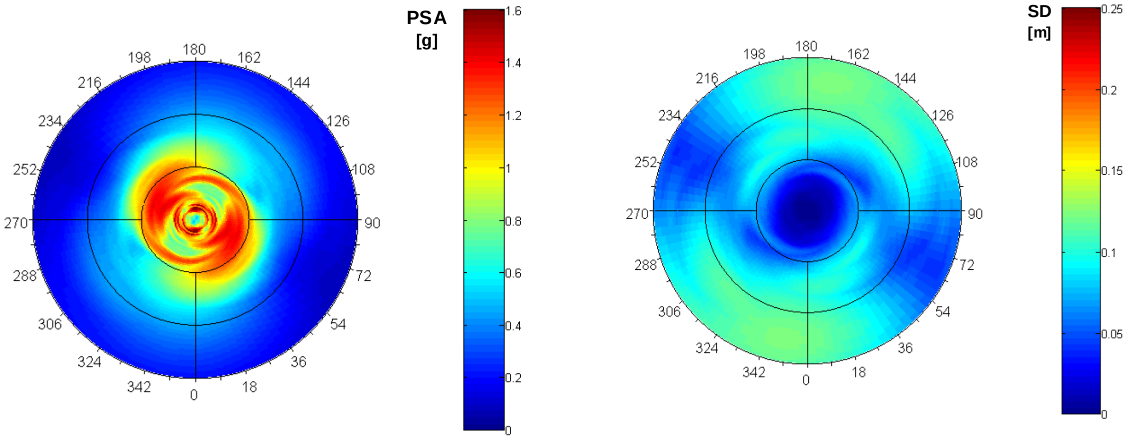


Figure 3. Polar Spectrum in terms of Pseudo-Accelerations and Displacements
(*station AQV-registration GX066*) (10)

For recording station AQV it is possible to observe larger PSA demand around 0.3-0.5 sec in the NW-SE direction. The highest demand is generally aligned along the same direction for all the periods. SD presents high values instead in the NE-SW direction for the period around 1.5 sec.

3. DAMAGE EVALUATION FOR EXISTING STRUCTURES WITHOUT DAMPING DEVICES

As is known, the seismic performance of a structure can be estimated by means of the Park and Ang (9) damage index (P&A index) which allows for a consideration of both the effect of the maximum plastic excursion and the overall hysteretic energy. This index consists of a simple linear combination of normalized deformation and energy absorption as in the following:

$$D_{P.A.} = \frac{x_{\max}}{x_{u,mon}} + \beta \frac{E_H}{F_y x_{u,mon}} \tag{3.1}$$

where $x_{\max}$ is the maximum seismic displacement; $x_{u.mon}$ is the maximum displacement for a monotonic load test, E_H is the hysteretic energy and F_y the strength of the considered structure.
The coefficient β can be seen as a decay model parameter related to the dissipated plastic energy (6).
In the analyses β is set equal to 0.15 (1).
In the following table the P&A index is reported for each level of estimated structural damage.

Tab.2. Park&Ang index values

P&A index values	**Estimated structural damage**
PA≤0.1	No damage or localized cracking
0.1≤PA≤0.25	Minor damage
0.25≤PA≤0.40	Moderate damage
0.4≤PA≤1	Severe damage
PA≥1	Collapse

Within the scope of the present study, existing structures are modeled as equivalent non-linear SDOF systems characterized by strength designed according to the Italian Seismic Code DM '96 (3):

$$S_a / g = C \cdot R \cdot \varepsilon \cdot \beta \cdot I \tag{3.2}$$

with:

$C = \frac{S-2}{100}$ where C is the seismic intensity coefficient and S is the seismicity degree of the area which, in the case of L'Aquila, assumes value 9;
R represents the response coefficient linked to the fundamental period of the structure;
ε is the foundation coefficient that takes into account the soil characteristics;
β is the structural coefficient that takes into account the structural typology;
I is the seismic protection coefficient.

In particular, the research assumes ε =1 β =1 and I=1.
Therefore, considering an implicit structural factor (q) equal to 4, representative of the ductility capacity of the existing structure designed according to DM '96, the strength of the equivalent SDOF system may be considered as follows:

$$F_y = S_a \cdot q \cdot \gamma_E \tag{3.3}$$

where γ_E=1,5 and is the partial safety coefficient.
In the following graphs (fig. 4) the polar spectrum of the P&A index for the seismic registration of

station AQV in L’Aquila are shown. The analyses are carried out in the absence of the damping devices and by varying the ductility of the system.

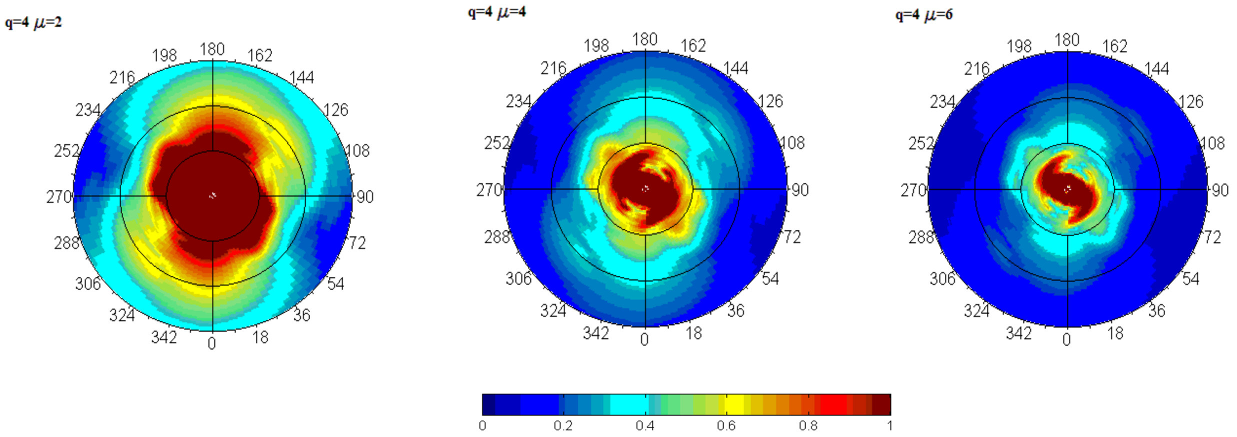


Figure 4. Polar Spectrum in terms of P&A index assuming structural factor q=4 and ductility factor μ equal to 2, 4 and 6 for the base system without damping devices (*AQV station-registration GX066*)

The results show that the damage is not uniform in each direction in the plane. In particular, it clearly demonstrates an increase in the available ductility as the damage decreases. Moreover, for low values of ductility the damage is high in the NE-SW direction where the spectral demand in terms of displacement (fig.3) is higher. Instead, for high values of ductility, the damage is high in the NW-SE direction where the seismic demand in terms of pseudo accelerations is higher.

4. DAMAGE EVALUATION OF EXISTING STRUCTURES IN THE CASE OF HYSTERETIC DEVICES

The hysteretic dampers are based on the inelastic deformation of metal elements (5,11,14) and the behavior, when applied to bare frame structures, can be summarized as in the following figure.

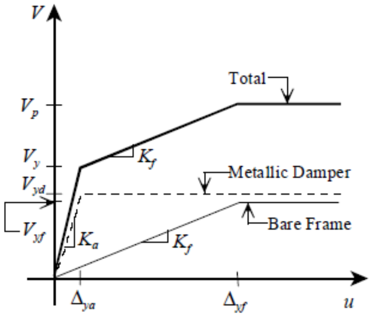


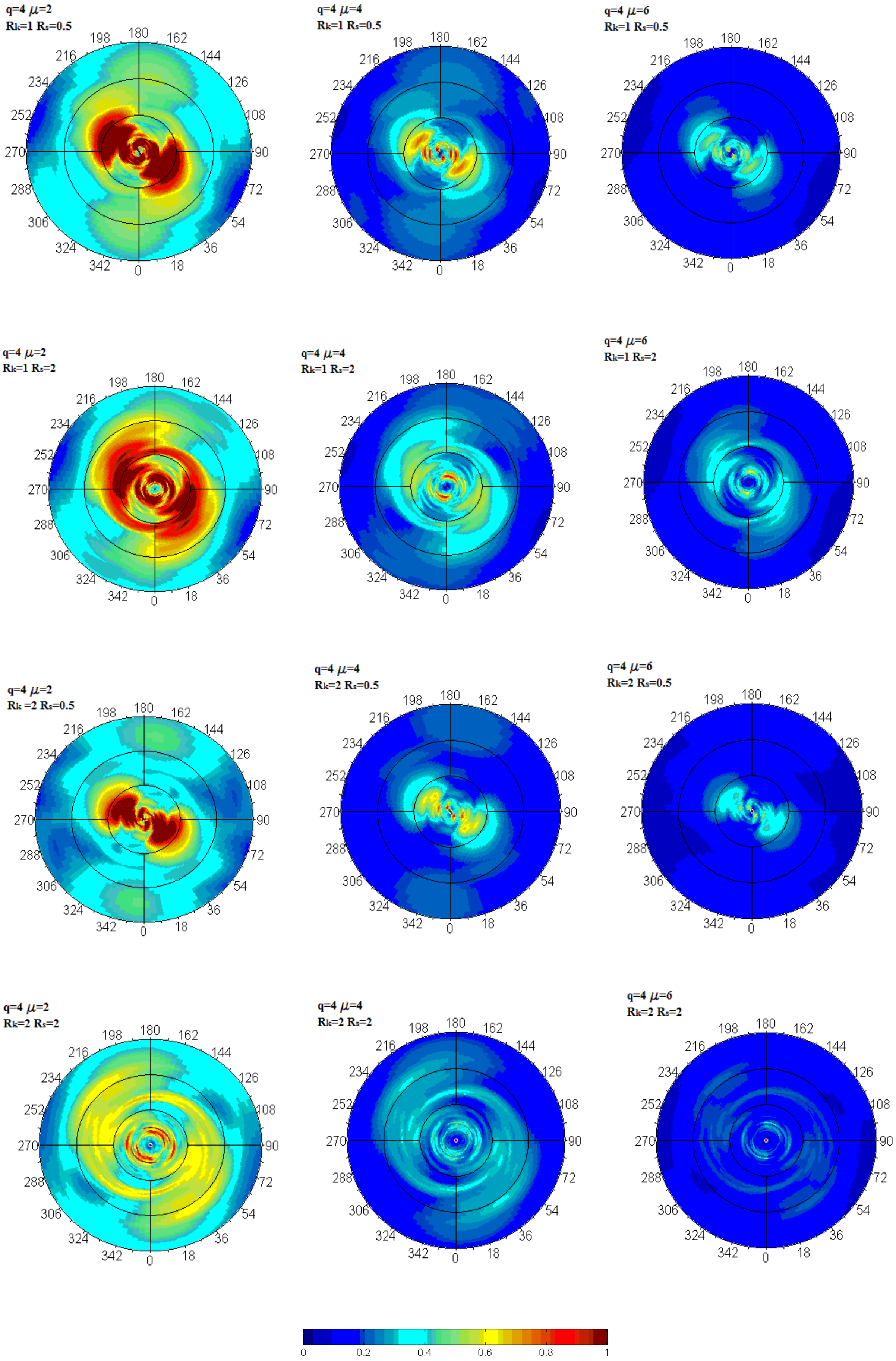
Figure 5. Bare frame and damper Force–Displacement relationship

The figure clearly shows that the introduction of hysteretic dampers in a bare frame lead to a substantial increase in the strength and stiffness capacity of the original system.

In this study, both the main structure and the damping devices are considered to have elastic perfectly plastic behavior and the viscous damping of the main structure is assumed equal to 5%.

The following pictures show the results obtained in terms of the P&A damage index having considered the following parameters:

- available ductility μ= 2, 4, 6;
- ratio between the stiffness of the damper devices and that of the bare system, R_k = 1,2, 4;
- ratio between the strength of the damper devices and that of the bare system, R_S=0.5,1, 2.


q=4 μ=2
R_k=1 R_s=0.5
q=4 μ=4
R_k=1 R_s=0.5
q=4 μ=6
R_k=1 R_s=0.5
q=4 μ=2
R_k=1 R_s=2
q=4 μ=4
R_k=1 R_s=2
q=4 μ=6
R_k=1 R_s=2
q=4 μ=2
R_k =2 R_s=0.5
q=4 μ=4
R_k=2 R_s=0.5
q=4 μ=6
R_k=2 R_s=0.5
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R_k=2 R_s=2
q=4 μ=4
R_k=2 R_s=2
q=4 μ=6
R_k=2 R_s=2
180
162
144
126
108
90
72
54
36
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0.8
1

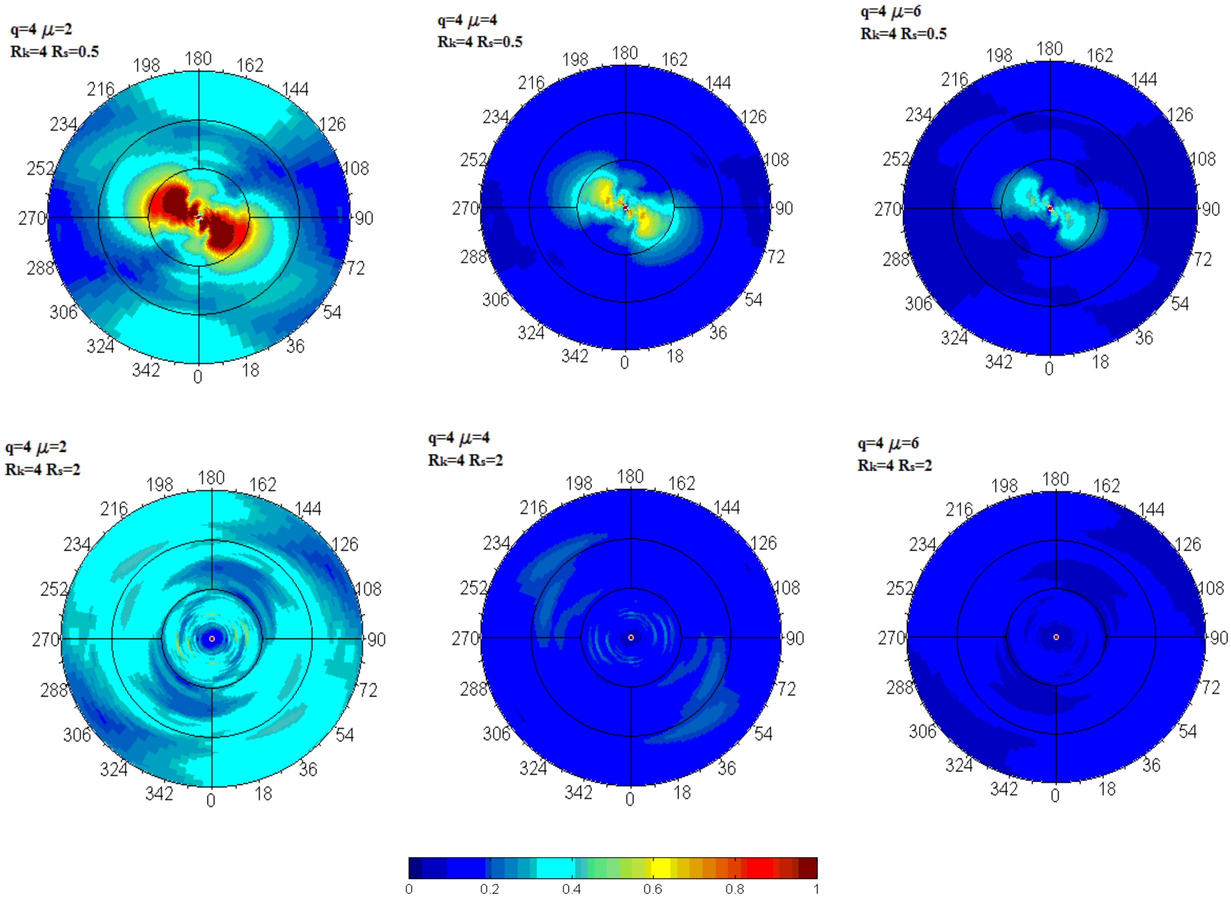


Figure 6. Polar Spectrum in terms of P&A damage index – Hysteretic devices
(AQV station-registration GX066)

An analysis of the results shows that hysteretic devices generally reduce the P&A damage index in comparison to that expected for the existing structures. Moreover, having fixed the stiffness ratio R_k and the ductility factor μ, the P&A damage index increases or decreases by varying directions and periods. Generally the available ductility plays an important role on seismic behavior and, as is well known, greater stiffness of the damping system leads to better performance.

The optimal stiffness ratio R_k and strength ratio R_s are plotted in fig. 7 for the cases under consideration. Results show that in the NW-SE direction, where the seismic demand in terms of pseudo-accelerations (fig. 3) is at its maximum, the minimum values of the P&A damage index have been obtained for the maximum ratios of both R_k and R_s in the case of lower periods and for the minimum ratios of both R_k and R_s in the case of higher periods. Instead, in the NE-SW direction, where the spectral displacement demand (fig. 3) is at its maximum, the minimum values of the P&A damage index have been generally obtained for the minimum ratios of R_s and the maximum ratios of R_k in the case of lower periods and for the maximum ratios of both R_k and R_s in the case of higher periods. Therefore, the results show that the hysteretic damping control strategy is heavily affected by in-plane seismic demand characteristics.

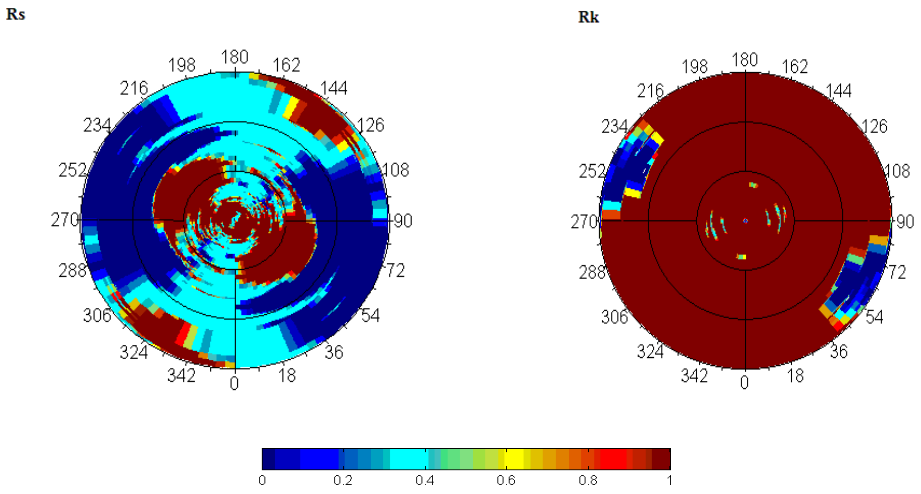


Figure 7. Rk and Rs ratios for minimum P&A damage index – Hysteretic devices (AQV station-registration GX066)

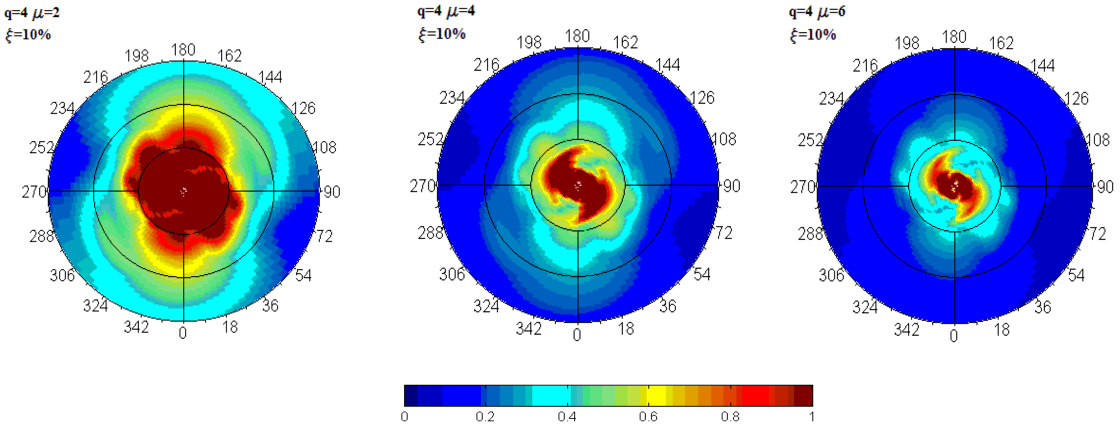
5. DAMAGE EVALUATION OF EXISTING STRUCTURES IN THE CASE OF VISCOUS DEVICES

In the case of viscous devices, the effects on overall system behavior could be taken into account by considering explicitly the extra damping devices effects ($c_d\,\dot{x}$) as shown in the following:

$$m\ddot{x} + c\dot{x} + c_d\,\dot{x} + F_S = -m\ddot{x}_g \qquad (5.1)$$

The following figures show the results obtained in terms of the P&A damage index after having considered the following parameters:

- available ductility μ= 2, 4, 6;
- viscous damping ξ=10%,20% and 30% having considered the viscous damping of the main structure equal to 5% and that added due to viscous devices (5%, 15%, 25%).



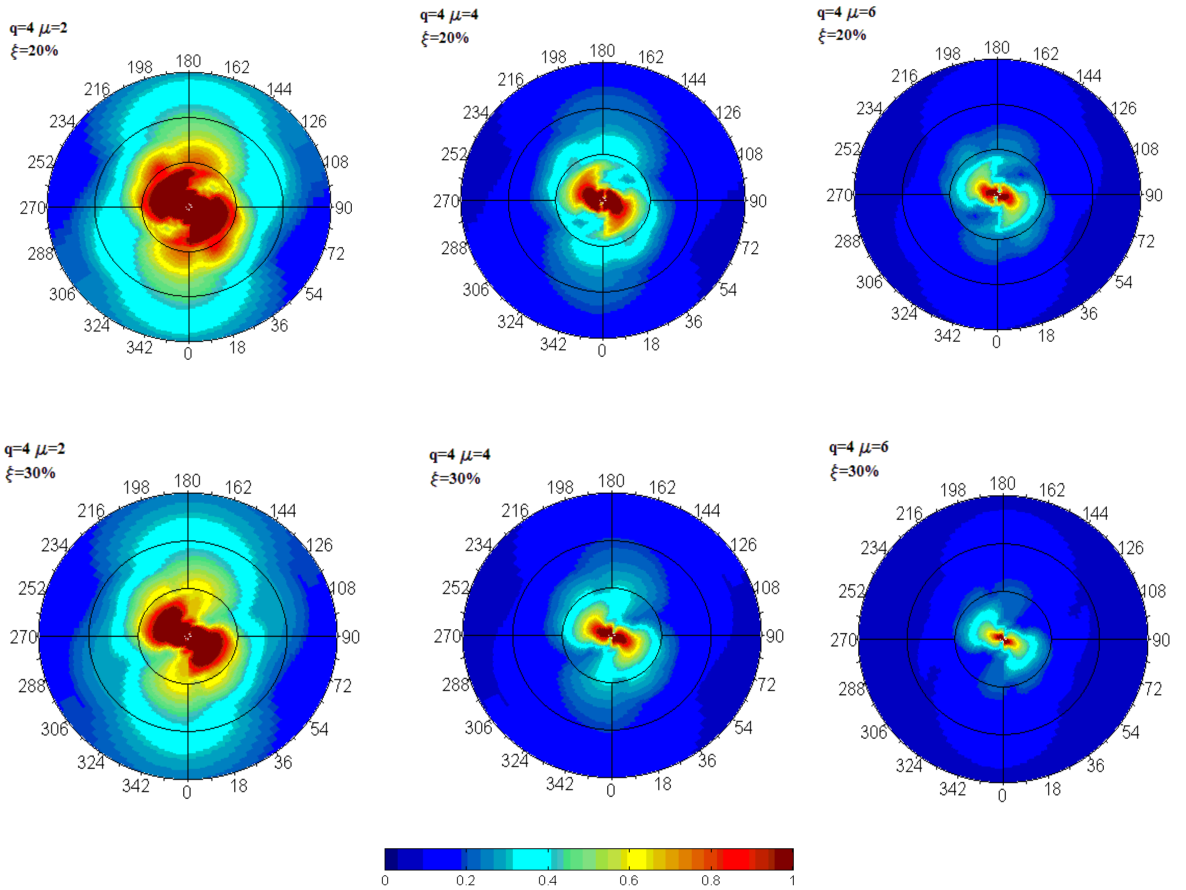


Figure 8. Polar spectrum of Park&Ang index – Viscous devices
(AQV station-registration GX066)

An analysis of the results shows clearly that the extent of the damage decreases overall with increasing extra-structural damping. Moreover, such decrease in the damage is substantially uniform for each direction and for each period. In particular, values of extra-structural damping equal to 25% lead to a reduction of estimated damage of about 30-40%. As for the case of hysteretic devices, the available ductility of the system plays an important role in the expected damage.

6. CONCLUDING REMARKS

This paper has presented an analysis of the effectiveness of hysteretic and viscous damping control strategies to improve the behavior of structures in the case of near-source earthquake L'Aquila '09. This event has been considered to evaluate the expected damage of existing structures, designed in accordance with the Italian Seismic Code DM '96, with and without extra-structural damping devices. In particular, the study has investigated seismic performance by means of the Park and Ang index plotted in the polar spectral representation.

The obtained results clearly show the effectiveness of the damping control strategy to reduce the expected damage to the existing structure in the case of a near-source event. In particular, although both the investigated control strategies, hysteretic and viscous damping, lead to a reduction of the seismic response, the viscous control strategy seems to be more efficient and robust. In particular, in this case, values of extra-structural damping equal to 25% lead to a reduction of estimated damage of about 30-40%.

The results show, instead, that the hysteretic damping control strategy is heavily affected by in-plane seismic demand characteristics.

Finally, in all the cases taken into consideration the available ductility plays an important role in the seismic behavior of the structures.

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