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Numerical investigation on the seismic performance of a RC framed building equipped with a novel Prestressed LEad Damper with Straight Shaft

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Abstract

This study aims at assessing the use of a novel damper, which is called the Prestressed LEad Damper with Straight Shaft (or PS-LED), for the seismic rehabilitation of RC framed buildings. This device provides high energy dissipation by the friction activated between a lead core and a shaft and achieves a high specific output force by preloading the lead during the assembly. In order to show the effectiveness of the PS-LED device for the retrofit of existing buildings, a RC structure designed according to past codes that ignored seismic actions is retrofitted with the PS-LED system considering two different damage targets: (i) in the first case, the structure is retrofitted in order to behave elastically under the design earthquake; (ii) in the second case, a partially dissipative behavior of the structure is conceived, with activation of plastic hinges, and limited and reparable damage. In order to assess the suitability of the design procedure, non-linear static analyses are performed on the upgraded building, showing a satisfactory agreement between the seismic performance and the design target. Non-linear dynamic analyses are further carried out considering a suite of bidirectional artificial ground motions with response spectra matching on average the target spectrum according to the Italian Building Code for the life-safety limit state. Finally, a comparison is performed between the performances of the building retrofitted with the PS-LED device and the building retrofitted with a conventional steel hysteretic damper (SHD), demonstrating that the PS-LED, thanks to its superior damping capacity, limits the increase in internal forces that usually affects frames equipped with SHDs, reducing the need of local strengthening of the columns and foundations and consequently the total cost of the seismic rehabilitation.

Keywords: Seismic retrofit; frame structures; Lead Damper; hysteretic damper; non-linear analyses

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1. Introduction

The retrofit of existing reinforced concrete (RC) structures is an important issue for the Italian territory, where a large part of the building heritage is noted to be vulnerable to ground motions, Bruschi (2021). In fact, the majority of the Italian stock, still fully in use today, dates back to the sixties up to the eighties of the last century, when it was designed without addressing the effects of seismic actions (as a matter of fact, only gravity loads were assumed for design from the codes in force at that time), CRESME (2021). Supplementary energy dissipation has indeed proved to be a viable solution for the rehabilitation of reinforced concrete structures, in order to prevent structural damage, increase life-safety and achieve a desired level of performance, Quaglini and Bruschi (2022). Current supplementary energy dissipation devices are bulky and architecturally invasive, get damaged from the dissipation of seismic energy, and need to be restated or even disposed after a seismic event; this poses safety issues, since after a major earthquake the structure is unprotected from future aftershocks until the dissipation devices are repaired or replaced, and increases life-cycle costs, Quaglini et al. (2021a, 2022).

In the present work, the use of a novel damper, named the Prestressed LEad Damper with Straight Shaft (or PS-LED), for the seismic rehabilitation of RC framed buildings is assessed. An existing RC building, designed according to old codes that ignored seismic actions is retrofitted with the PS-LED system considering two different damage targets: (i) in the first case, the structure is retrofitted in order to behave elastically under the design earthquake; (ii) in the second case, a partially dissipative behavior of the structure is conceived, with activation of plastic hinges, and limited and reparable damage. Non-linear dynamic analyses are carried out, considering a suite of artificial ground motions with response spectra matching on average the target spectrum provided from the Italian Building Code (NTC18) for the life-safety limit state. Eventually, a comparison between the retrofit configuration with PS-LED dampers and conventional steel hysteretic dampers (SHD) is presented.

2. Description of the PS-LED device and constitutive model in OpenSees

A novel damper, named PS-LED, has been recently presented in literature (Bruschi, 2021; Quaglini et al., 2021a; Quaglini et al., 2022). This device incorporates valuable characteristics, such as the ability to accommodate multiple design strong motions without being damaged, high stiffness and damping capability in a compact geometry and with low manufacturing cost. The energy dissipation is provided through the friction force activated between a lead core and a shaft (as shown in Figure 1) and the damper achieves a high specific output force by preloading the working material during the assembly.

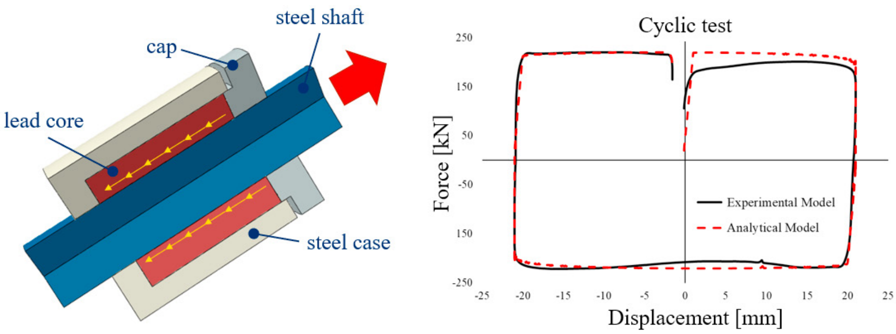


Figure 1: The PS-LED: a) longitudinal section and b) fit of analytical model to experimental curve (Bruschi, 2021)

A prototype of this device has been tested at the Materials Testing Laboratory of Politecnico di Milano (Bruschi, 2021; Quaglini et al., 2021a; Quaglini et al., 2022) following the provisions of the European standard EN 15129 on anti-seismic devices. The damper exhibits a consistent rigid-plastic behavior (Figure 1), with a ductility μ_{DB} equal to 20 and an equivalent damping ratio of 0.55, close to the maximum theoretical value of 0.63. A constitutive model of the PS-LED has been formulated in the OpenSees framework (McKenna et al., 2000) to perform non-linear dynamic analyses, and it consists in a parallel set of two systems (called EPPV, Bruschi 2021): an elastic-perfectly plastic material (*uniaxialMaterial ElasticPP* object material, OpenSeesWiki) and a Maxwell model (*uniaxialMaterial*

Viscous Damper object material, OpenSeesWiki and Akcelyan et al., 2016). This formulation is able to reproduce the essential behavior of the damper, including the shallow dependency of the axial force on the velocity that is apparent at motion reversals (Figure 1), providing accurate estimates of maximum force, effective stiffness and dissipated energy, Bruschi (2021). A simple procedure has been applied by Bruschi (2021) for tuning the EPPV system based on an experimental force – displacement; the fit of the EPPV analytical model to the experimental curve is shown in Figure 1.

3. Retrofit of a RC frame structure with the PS-LED device

In order to prove the effectiveness of the PS-LED damper for the seismic rehabilitation of existing structures, a 4-story building from literature (Di Cesare and Ponzo, 2017) is taken as case-study. It is a residential building located in Potenza, which is a medium/high seismic area in Italy. The main dimensions of the building are sketched in Figure 2; information on materials, reinforcement, masses and loads are reported in Bruschi (2021) and Di Cesare and Ponzo (2017).

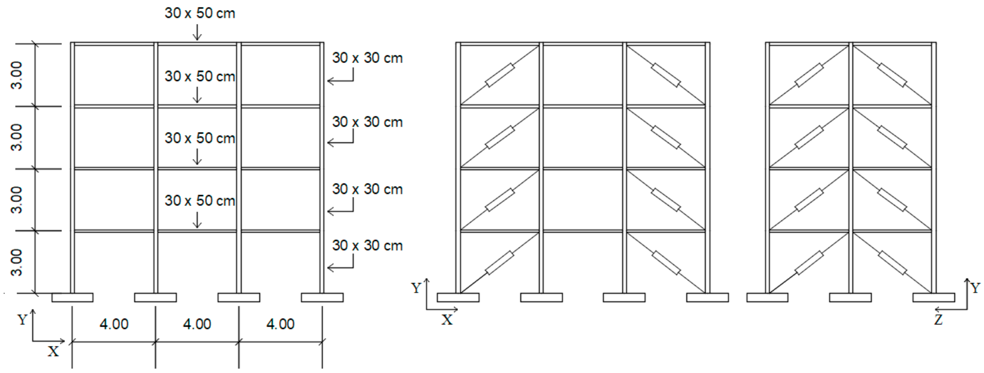


Figure 2: Elevation view and layout of steel hysteretic braces (installed in the perimetral frames) of the case-study structure (Bruschi et al., 2021)

The seismic rehabilitation is carried out by applying a design procedure recently proposed in Bruschi (2021), Bruschi et al. (2021a, 2022) and Quaglini et al. (2021b) and considering the seismic loads provided by NTC18 for life-safety limit state (SLV), site of Potenza (Long 15° 48' 20.1744'', Lat 40° 38' 25.4688''), functional class cu = II, PGA = 2.45 m/s^2, soil type B and topographic factor T_1. Four diagonal steel braces equipped with the PS-LED dampers are inserted at each story in the perimetral frames in either horizontal direction, according to the layout shown in Figure 2.

According to the retrofit procedure of Bruschi et al. (2021a), the target displacement d_p of the structure is selected depending on the required level of performance and applying the expression (1):

$$d_p = min \frac{\Delta_d \cdot h_i}{\delta_i} \tag{1}$$

where Δ_d is the target inter-story drift ratio, h_i is the height of the i^{th} story, and δ_i is the difference between the first mode eigenvector components of the adjacent stories $(\phi_i - \phi_{i-1})$. In case of elastic frame behavior, the retrofit is designed assuming a target inter-story drift ratio Δ_d equal to $0.005\ m/m$, in order to fulfill the limits recommended in Table 7.3.III of NTC18 for the protection of both structural and non-structural elements. This choice corresponds to a target displacement $d_p = 0.045\ m$ for the Multi-Degree Of Freedom (MDOF) system, and $d_p^* = 0.036\ m$ for the equivalent Single Degree Of Freedom (SDOF) system. Whereas, in case of dissipative frame retrofit, the target inter-story drift ratio Δ_d is assigned by multiplying the elastic limit $0.005\ m/m$ by a conventional factor 1.25 (Bruschi, 2021), yielding $\Delta_d = 0.00625\ m/m$, which corresponds to target displacements $d_p = 0.057\ m$ and $d_p^* = 0.045\ m$.

Note: Γ modal participation factor, d_y^* yield displacement of the SDOF main structure, V_y^{*F} yield strength of the equivalent SDOF main structure, d_p^* target displacement of the equivalent

SDOF structure, V_p^{*F} ultimate strength of the equivalent SDOF damped brace system, ξ_F equivalent viscous damping ratio of the main structure (unbraced), K_y^{DB} elastic stiffness of the equivalent SDOF damped brace, V_p^{*DB} ultimate strength of the equivalent SDOF damped brace

summarizes the parameters of the SDOF equivalent capacity curves and the properties in terms of strength and stiffness of the SDOF equivalent PS-LED damped brace system (LED-DBS) for either design target.

Table 1: Properties of the equivalent bilinear capacity curves and equivalent damped brace system in X- and Z- directions for elastic and dissipative frame retrofit

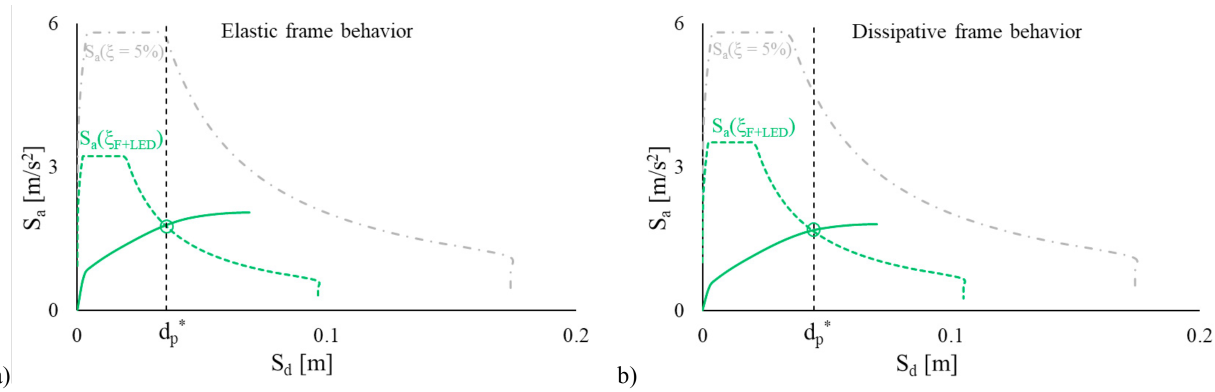
design target	*Direction*	Γ [-]	d_y^* $[m]$	V_y^{*F} $[kN]$	d_p^* $[m]$	V_p^{*F} $[kN]$	ξ_F [%]	K_y^{DB} $[kN/mm]$	V_p^{*DB} $[kN]$
Elastic frame retrofit	**X**	1.27	0.012	182	0.036	388	5.7	117.4	210.0
	Z	1.27	0.012	186	0.036	385	6.4	117.6	209.8
Dissipative frame retrofit	**X**	1.27	0.013	200.2	0.045	438.0	6.8	56.2	125.6
	Z	1.27	0.014	209.2	0.045	419.3	7.9	55.2	123.1

Note: Γ modal participation factor, d_y^* yield displacement of the SDOF main structure, V_y^{*F} yield strength of the equivalent SDOF main structure, d_p^* target displacement of the equivalent SDOF structure, V_p^{*F} ultimate strength of the equivalent SDOF damped brace system, ξ_F equivalent viscous damping ratio of the main structure (unbraced), K_y^{DB} elastic stiffness of the equivalent SDOF damped brace, V_p^{*DB} ultimate strength of the equivalent SDOF damped brace

4. Numerical investigation

The effectiveness of the design is validated by performing both non-linear static (NLSAs) and non-linear dynamic (NLDAs) analyses in the OpenSees framework (McKenna et al., 2000). A full 3D numerical model is formulated by using the *forceBeamColumn* element object of Scott and Fenves (2006), in the form of the *beamWithHinges* for beams and columns, as reported in Bruschi et al. (2021b, 2021c) and applied in Bruschi et al. (2021a, 2022) and Quaglini et al. (2021b), and choosing a modelling approach consistent with the European design code (EC8). NLDAs were performed by implementing the EPPV material model described in Section 2 and assuming that the elastic-perfectly plastic material model provides 80% of the total output force of the parallel EPPV system. Whereas in NLSAs the mechanical response of the PS-LED was modeled through the elastic-perfectly plastic material object only, since in quasi-static conditions the velocity is null, which prevents the activation of the Maxwell model. For simplicity, the stiffness of the damped brace has been assumed to coincide with the stiffness of the damper, i.e., the steel brace rods used to link the damper to the structural frame are very stiff and, under the actions induced by the design earthquake, undergo negligible deflection in comparison to the damper's one, Bruschi (2021).

Figure 3 shows the capacity curves along X-direction of the upgraded structure plotted in the acceleration-displacement response spectrum (ADRS) plane and compared with the response demand curve for the relevant damping. The design requirement is met by the upgraded frames since the displacement at the performance point, where capacity and demand curves cross each other, meets the target displacement selected at the beginning of the design process, proving that the design requirement is achieved by the upgraded frames for either elastic and dissipative retrofit; indeed, similar results are obtained also along Z-direction.



a) b)

Figure 3: Capacity curves in X- direction of the case-study structure retrofitted with the LED-DBS for (a) elastic frame behavior and (b) dissipative frame behavior.

In order to evaluate the performance of the upgraded structure in terms of engineering response parameters, such as maximum inter-story drift ratio Δ and maximum shear force V at each floor, bidirectional NLDAs are performed in compliance with the NTC18 and EC8 considering two sets of seven artificial ground motions generated using the software code SIMQKE, which are characterized by a pseudo-stationary part of 10 sec and a total duration of 25 seconds as prescribed in NTC18, and are compatible on average with the elastic spectrum defined by the code in the range of periods between 0.15 and 2 sec.

Figure 4 shows the numerical results in terms of inter-story drift ratio Δ and shear force V at each floor, comparing the as-built configuration to the retrofitted configuration with the LED-DBS for either elastic and dissipative frame behavior.

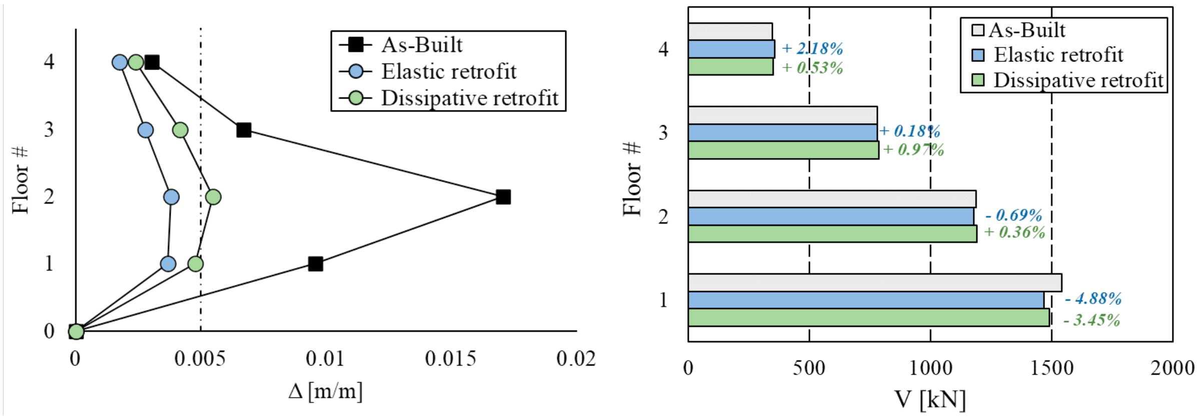


Figure 4: Maximum inter-story drift ratio Δ (left) and maximum shear force V (right) at each floor of case-study structure with and w/o LED-DBS for either elastic and dissipative frame behavior

For both retrofit designs, the inter-story drift ratio Δ drastically decreases in amplitude and shows a regular shape (Figure 4 – left). When the structure is upgraded to guarantee an elastic frame behavior, the inter-story drift ratio Δ of the upgraded configuration respects at each floor the elastic limit $\Delta_d = 0.005\, m/m$. When the rehabilitation is designed conceiving a controlled dissipation mechanism, a significant reduction of Δ with respect to the bare frame's one is again experienced, with a peak value of $0.0055\, m/m$ at the second floor, which respects also in this case the target selected at the beginning of the design $\Delta_d = 0.00625\, m/m$.

Usually, buildings retrofitted with hysteretic devices exhibit smaller lateral deformation, but increased shear forces V at the floors with respect to the bare structure. However, in the present case, shear forces remain substantially unaffected from the upgrade, thanks to the high damping introduced in the structure by the LED-DBS which limits increase in floor accelerations (Figure 4 – right). In particular, at the first floor, the shear force of the retrofitted structure is even smaller (about 5% with elastic retrofit and 3.5% with dissipative retrofit) than that of the as-built one.

5. Comparison between the PS-LED device and a conventional Steel Hysteretic Damper

In this paragraph, the case-study structure is retrofitted by using a steel hysteretic damped brace system (SHD-DBS) for both elastic and partially dissipative frame behavior. According to Gandelli et al. (2019), the SHD-DBS selected for this investigation is characterized by $\kappa_{DB} = 0.425$ and $\mu_{DB} = 10$, yielding an equivalent viscous damping ratio $\xi_{DB} = 24.4\%$, which is less than half of the equivalent viscous damping ratio of the LED-DBS, assumed based on experimental data. The retrofit design procedure is therefore applied to the SHD-DBS by selecting the same target displacements as assumed in Section 3, namely $d_p^* = 0.036\, m$ for elastic frame behavior and $d_p^* = 0.045\, m$ for dissipative frame behavior. The diagonal brace layout shown in Figure 2 is assumed for both LED-DBS and SHD-DBS retrofits. **Errore. L'origine riferimento non è stata trovata.** performs a direct comparison, in terms of strength N_{yi}^{DB} and stiffness K_{yi}^{DB} of the damped brace units at each story, between the SHD- and the LED-DBS, distributed along the height of the frame. At each floor the ratio between the initial stiffnesses K_{yi}^{DB} of the LED-DBS and the

SHD-DBS counts 1.066, i.e., the stiffness of the LED-DBS unit is only 6.6% higher than that of the SHD-DBS unit. Noteworthy, the ratio between the axial forces N_{yi}^{DB}, of the LED-DBS and the SHD-DBS is 0.533: owing to its superior energy dissipation capability, about 55% higher than that of the SHD-DBS, the LED-DBS halves the strength demand. It is worth mentioning that these considerations are valid for both elastic and partially dissipative frame behavior of the upgraded structure. Moreover, it is apparent that the properties of the SHD-DBS and LED-DBS units at each floor obtained for the retrofit with dissipative frame behavior are drastically reduced (almost halved) in comparison the ones for elastic frame behavior (**Errore. L'origine riferimento non è stata trovata.**), thanks to the contribution of energy dissipation introduced by plastic deformation of the frame.

Table 2: Comparison between design properties of the SHD-DBS and the LED-DBS at each story

		Elastic frame behavior				***Dissipative frame behavior***			
		SHD - DBS		LED - DBS		SHD - DBS		LED - DBS	
Directions	$story$	K_{yi}^{DB} $[\frac{kN}{mm}]$	N_{yi}^{DB} $[kN]$	K_{yi}^{DB} $[\frac{kN}{mm}]$	N_{yi}^{DB} $[kN]$	K_{yi}^{DB} $[\frac{kN}{mm}]$	N_{yi}^{DB} $[kN]$	K_{yi}^{DB} $[\frac{kN}{mm}]$	N_{yi}^{DB} $[kN]$
X	1^{st}	137.5	156.2	146.6	83.2	66	93.6	70.1	49.8
	2^{nd}	114.4	137.3	122	73.2	54.9	82.3	58.3	43.8
	3^{rd}	113.1	98.4	120.5	52.5	54.2	59	57.7	31.4
	4^{th}	106.7	45.1	113.7	24	51.2	27	54.4	14.4
Z	1^{st}	139.2	156.4	148.3	83.3	65.5	92	69.6	48.8
	2^{nd}	114.7	137.6	122.1	73.3	54	81	57.3	42.9
	3^{rd}	113.1	98.8	120.5	52.6	53.3	58.1	56.5	30.8
	4^{th}	105.8	45.3	112.7	24.1	49.8	26.7	52.9	14.2

Figure 5 and Figure 6 compare the capacity curves of the upgraded structure with either DBS solution. In both directions, the design requirement is met by the upgraded frames, which attain the target displacement d_p at their performance point. However, as an effect of the different dissipation capacity, dissimilar values of base shear force are achieved. In particular, considering the retrofit for elastic frame behavior, the increase in shear force in case of SHD-DBS with respect to the LED-DBS is on the order of 34% in X-direction, and of 35% in Z-direction. This result highlights a valuable advantage of the LED-DBS over the SHD-DBS. In fact, structures strengthened with dissipative braces are usually affected from stress concentrations in the structural elements surrounding the braces, as well as at foundation level (Nuzzo et al., 2019), implying the need to combine the DBS with local strengthening to increase the capacity of the structural members. Such stress concentrations can be mitigated by using the LED-DBS, resulting in an overall reduction of the cost of the retrofit intervention.

Similar conclusions are valid also in case of retrofit for dissipative frame behavior (Figure 6); however, from Figure 6, it comes out that the capacity curves of the structure retrofitted for partially dissipative frame behavior with either SHD- and LED-DBS are closer to each other, with lower differences between the strength N_{yi}^{DB} of the damped brace. This is due to the dissipation provided from the main structure which reduces the damping demand to the energy dissipation devices: in fact, in this case, the increase in base shear force of SHD-DBS with respect to the LED-DBS is on the order of 22% in X-direction, and of 23% in Z-direction.

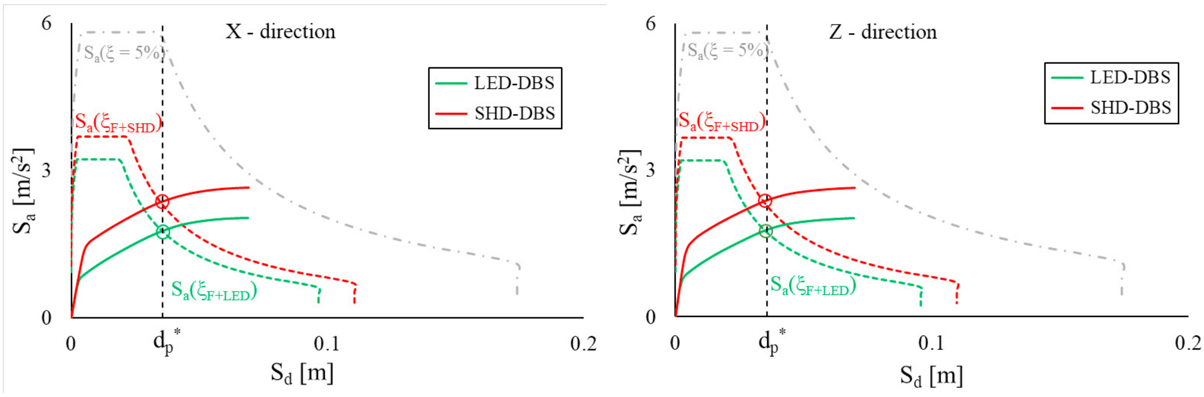


Figure 5: Comparison of the capacity curves along X- and Z- direction of the case-study structure retrofitted with the LED-DBS and the SHD-DBS for elastic frame behavior

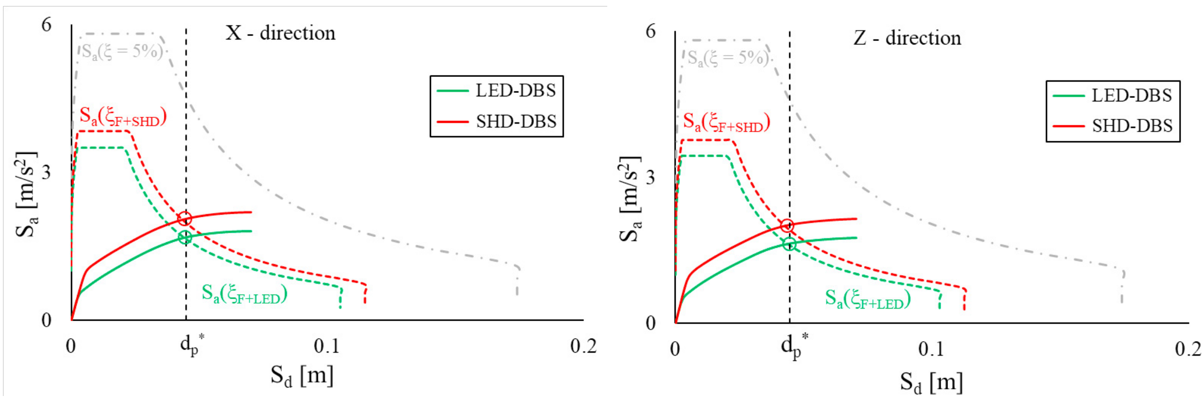


Figure 6: Comparison of the capacity curves along X- and Z- direction of the case-study structure retrofitted with the LED-DBS and the SHD-DBS for dissipative frame behavior

6. Conclusions

In this work, an emerging energy dissipation device, the PS-LED damper, has been briefly presented and the use of this system for the seismic rehabilitation of RC framed buildings has been assessed, by designing the retrofit of an existing RC structure considering two targets, namely an elastic behavior and a partially dissipative frame behavior of the building under the design earthquake.

The main outcomes of the study are recalled as follows:

(i) the design requirement is satisfied from structures upgraded with the PS-LED device for both elastic frame behavior and dissipative frame behavior, showing a consistent reduction in terms of inter-story drift ratios Δ with respect to the bare configuration, respecting the limit selected at the beginning of the design procedure;

(ii) by comparing the two DBS configurations (LED-DBS and SHD-DBS), large differences in strength between the damper units are noticed: at each floor the ratio between the axial forces N_{yi}^{DB} of the LED-DBS and the SHD-DBS counts 0.533;

(iii) the two DBS configurations are characterized by the same initial stiffness at each floor (the ratio between the initial stiffnesses K_{yi}^{DB} counts 1.066), which allows to have the same first mode period for either DBS configuration;

(iv) PS-LED outperforms SHD in significantly reducing the increasing of internal forces in structural members, thanks to its energy dissipation capability, which is substantially higher (almost 55% more) than that of the SHD-DBS;

(v) the LED-DBS is more effective than the SHD-DBS in reducing the total base shear force when the seismic rehabilitation is designed for maintaining the frame behavior in the elastic range, resulting in about 30% decrease of the damper reaction force. In contrast, the decrease is on the order of 20% when the retrofit is designed for dissipative frame behavior, because of the contribution to the total damping provided by the inelastic deformation of the main frame which adds up to the contribution of the damped brace system.

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