

XIX ANIDIS Conference, Seismic Engineering in Italy

Design and experimental assessment of a novel damper with high endurance to seismic loads

Virginio Quaglini^{a*}, Eleonora Bruschi^a, Carlo Pettorruso^a, Mauro Sartori^b

^a*Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering, Piazza Leonardo da Vinci 32, 20133 Milan, Italy*

^b*Freyssinet Products Company Italia, Via dei Missaglia, 97, 20142 Milan, Italy*

Abstract

The study presents the design and the experimental characterization of a new energy dissipation device aimed at providing improved resistance to repeated seismic loads. Differently from conventional steel hysteretic dampers, which dissipate energy by yielding of a mild steel core and are noted to suffer low-cycle fatigue, the new damper provides energy dissipation by the friction that is activated between a moving shaft and a lead core prestressed within a tube. The prestress level is controlled during the assembling process, allowing to adjust the axial strength of the damper. Thanks to the ability of lead to restore its properties by static recrystallization taking place immediately after deformation, repeated cycles of loading do not produce damages that may accrue and eventually lead to failure of the device. Moreover, prestressing of the lead core allows to achieve high specific strength (i.e., high force to volume ratio), thereby providing low dimensions which help to reduce the architectural invasiveness. Prototypes of the damper were subjected to the test procedure established in the European standard EN 15129 for Displacement Dependent Devices, fulfilling the relevant requirements. The damper provides a robust and stable response over repeated cycles, characterized by essentially rectangular hysteresis loops with an equivalent viscous damping ratio ζ_{eff} of about 55%. Moreover, it shows low sensitivity of mechanical properties on the loading rate and the ability to withstand multiple cycles of motion at the design earthquake displacement without deterioration of performance, demonstrating maintenance-free operation in presence of repeated ground shakes. Its ability to survive several strong motions without being damaged, and its high damping capability coupled to a compact design and low manufacturing cost, are the distinctive features that make it suitable for social housing.

© 2023 The Authors. Published by Elsevier B.V.

This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0>)

Peer-review under responsibility of the scientific committee of the XIX ANIDIS Conference, Seismic Engineering in Italy.

Keywords: Lead Damper, energy dissipation, experimental assessment, EN 15129

* Corresponding author. Tel.: +39 02 2399 4248

E-mail address: virginio.quaglini@polimi.it

1. Introduction

Among supplementary energy dissipation systems, the lead extrusion dampers developed by Rodgers et al. (2007a), named HF2V dampers, have been reported to provide large resistive forces while maintaining compact outer dimensions (Rodgers et al., 2019; Quaglini and Bruschi, 2022), which make these systems suitable for the retrofit of existing structures, since they do not infringe on the architectural aesthetics or function of the building, Rodgers (2009). This device consists of a central shaft with a bulge encased in lead: when the shaft moves, the bulge displaces the lead from one side of the bulge to the other; this mechanism ensures a constant force upon yielding, similar to the behavior of the mild steel energy dissipation devices (Rodgers et al., 2008), without encountering any fatigue problem experienced by the alternative solutions. Moreover, because of low-cycle fatigue and residual stresses, mild steel energy dissipation systems need replacement after an earthquake, while the lead damper does not need any maintenance and thanks to its ability of creeping out over time, ensures self-centering of any structure, Bruschi (2021). The HF2V damper has been developed starting from the earlier research of Robinson and Greenbank (1976), whose devices were volumetrically very large and consequently, relatively expensive to produce; for this reason, their use was mainly limited as part of base isolation systems, Bruschi (2021). The large dimensions of these systems were necessary to provide sufficient reaction forces. Indeed, in this damper, as the shaft moves, the material is compressed into a smaller volume leading to the formation of a trailing void; the bulge passes through this void and consequently, the damper experiences less resistance and dissipates less energy, Rodgers et al. (2007a). Rodgers et al. (2007a, 2008, 2009, 2019) increased the specific force and the dissipation capability of the damper by preloading the lead core during the assembly. Compressing the lead reduced the formation of trailing voids and boosted the force-to-volume ratio, allowing a more compact design, which was able to fit into tight volumetrically constrained applications, such as directly into beam–column joints (Rodgers et al., 2007b; Rodgers et al., 2008; Mander et al., 2009). Further research on this technology was carried out by Soydan et al. (2015, 2018), Patel (2017), Yang et al. (2015), Bruschi et al. (2020), Pettoruso et al. (2021) and Quaglini et al. (2021).

Recently, a novel lead damper, called PS-LED, has been introduced. This damper provides huge energy dissipation through the friction force activated between a lead core and a straight shaft, and achieves a high specific output force by preloading the working material during the assembly, Quaglini et al. (2022). In this paper, the tests performed at the Materials Testing Laboratory of Politecnico di Milano on a prototype of the PS-LED in accordance with the provisions of the European standard EN 15129 on anti-seismic device are presented and discussed.

Nomenclature

| | |
|---------------|--|
| d_{bd} | design displacement of the PS-LED prototype |
| D_s | shaft diameter |
| D_{cyl} | cylinder diameter |
| EDC | energy dissipated per cycle |
| K_{eff} | effective stiffness |
| L_s | length of shaft in contact with the working material in the PS-LED prototype |
| N | maximum force in the cycle |
| γ_b | amplification factor |
| γ_x | reliability factor |
| ζ_{eff} | equivalent viscous damping ratio |

2. Description of the PS-LED device

The PS-LED device, depicted in Figure 1(a), consists of four main components, namely the shaft, the tube, the cap and the lead core, Bruschi (2021) and Quaglini et al. (2022).

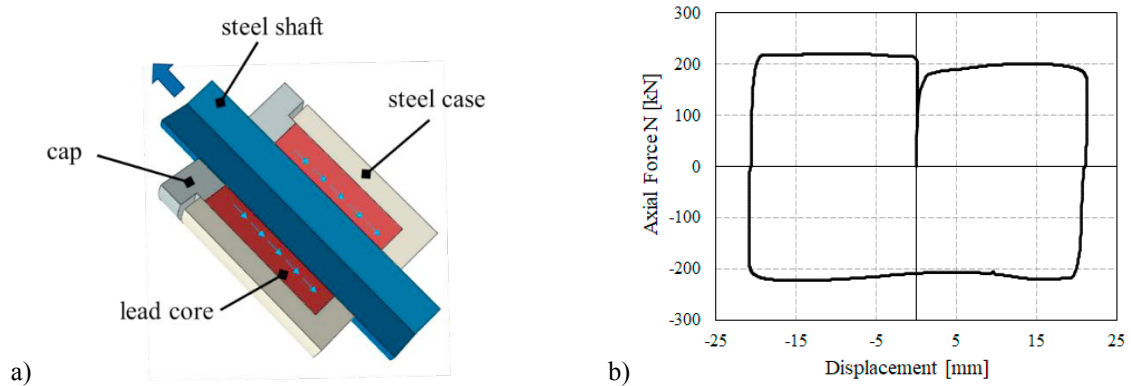


Figure 1: (a) longitudinal section of the PS-LED device; (b) hysteresis loop of the tested prototype observed in a preliminary cycle (Bruschi, 2021)

The energy dissipation is provided by the friction activated between the shaft and the lead core. Since the friction at the shaft – lead interface is substantially unaffected by the speed, the damper behaviour is characterized by a force-displacement curve with a rectangular shape, as shown in Figure 1(b), which maximizes the amount of energy dissipation. The value of the axial force is controlled by prestressing the lead core during the assembling process; in this way, voids in the working material are removed, resulting in a perfect fit to the tube and the shaft and avoiding clearances at motion reversals, Quaglini et al. (2022). Thanks to its compact geometry, the PS-LED can be installed in various configurations; in particular, Figure 2 shows the device placed either in diagonal braces or at beam-column joints.

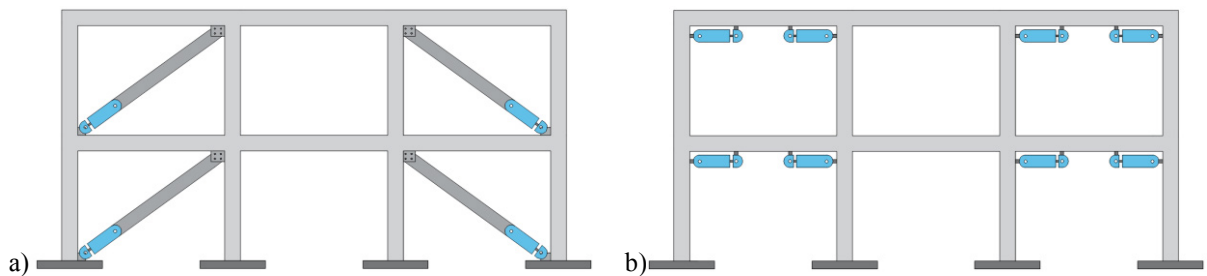


Figure 2: Installation of the PS-LED device: (a) diagonal steel braces; (b) beam-column joints

3. Experimental investigation

The PS-LED prototype, assessed in this study, is characterized by a shaft diameter $D_s = 32.5$ mm, an inner diameter of the tube $D_{cyl} = 60$ mm, and a length of shaft in contact with the working material $L_s = 80$ mm, Figure 3. The prototype was designed for a nominal force of 220 kN and a design deflection of $d_{bd} = 10$ mm in either direction (i.e., 20 mm total stroke).

The experiments were performed at the Materials Testing Laboratory of Politecnico di Milano, using a 500 kN servohydraulic testing machine (MTS Systems, Eden Prairie, MN) and following the testing protocol prescribed by the European Standard EN 15129 for assessment of Displacement Dependent Devices (DDD) and listed in **Errore. L'origine riferimento non è stata trovata.** In particular, harmonic cycles of increasing amplitude at 25%, 50% and 100% of the design deflection $d_{bd} = 10$ mm have been imposed at a loading frequency of 0.5 Hz: five cycles for each

intermediate amplitude and ten cycles for

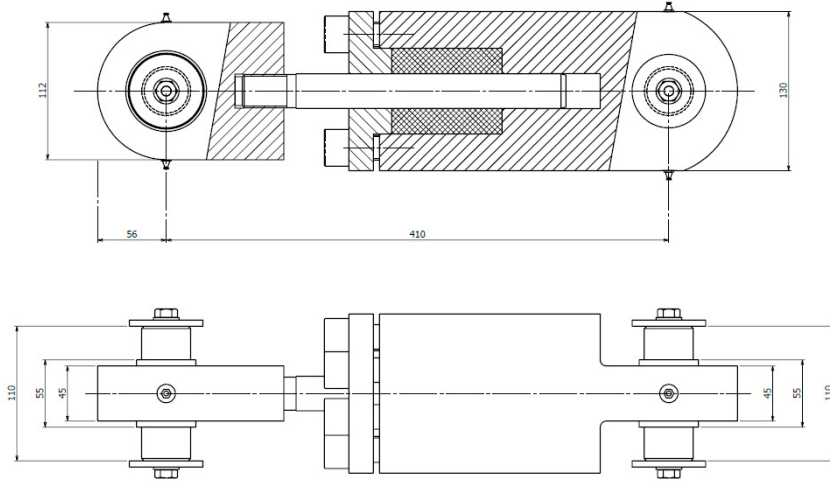


Figure 3: Cross-section and lateral view of the PS-LED prototype

the maximum amplitude were applied. Eventually, a ramp test at 0.1 mm/s rate was performed to the amplified design displacement $\gamma_x \gamma_b d_{bd} = 13.2$ mm (where $\gamma_b = 1.1$ and $\gamma_x = 1.2$ are the amplification factor and the reliability factor given in the standard EN 15129), to assess the failure condition under quasi-static condition.

Table 1: Testing protocol according to the European Standard EN 15129

| Test | Amplitude [mm] | Frequency [Hz] | n° of cycles [-] |
|--------|----------------|----------------|------------------|
| cyclic | $0.25d_{bd}$ | 0.5 | 5 |
| | $0.50d_{bd}$ | 0.5 | 5 |
| | $1.00d_{bd}$ | 0.5 | 10 |
| ramp | $1.32d_{bd}$ | 0.1 mm/s | 1 |

Figure 1(b) shows the force–displacement behaviour of the PS-LED prototype observed in a fully reversed cycle. It is apparent an elastic deflection until the breakaway friction resistance of the working material is overcome and sliding of the shaft relative to the lead core is engaged. This initial elastic part is followed by a plastic branch characterized by a constant force independent of the accommodated deflection, and the same behaviour occurs after each motion reversal. It is worth noting that owing to the high elastic stiffness of the steel members, the hysteresis loop has an essentially rectangular shape, Quaglini et al. (2022). The device shows an almost symmetric behaviour in tension and compression, Bruschi (2021), according to the theoretical Coulomb-type friction model.

The response of the PS-LED is evaluated on the basis of two quantities, namely the effective stiffness K_{eff} and the equivalent viscous damping ratio ζ_{eff} , which are determined through the equations:

$$K_{eff} = \frac{N}{d_{bd}} \quad (1)$$

$$\zeta_{eff} = \frac{2 EDC}{\pi d_{bd} N} \quad (2)$$

where N is the maximum force in the cycle, d_{bd} is the maximum deflection and EDC is the energy dissipated per cycle.

The European standard EN 15129 requires that both K_{eff} and ζ_{eff} remain almost constant during a sequence of cycles of same amplitude, and in particular the relationships of **Errore. L'origine riferimento non è stata trovata.** need to be satisfied. In **Errore. L'origine riferimento non è stata trovata.**, i is the cycle number ($i \geq 2$), and $K_{eff,3}$ and $\zeta_{eff,3}$

are the effective stiffness and the viscous equivalent damping ratio evaluated at the third cycle, respectively.

Table 2: Requirements of the European standard EN 15129

| Requirements |
|---|
| $\frac{ K_{eff,i} - K_{eff,3} }{K_{eff,3}} \leq 0.10$ |
| $\frac{ \zeta_{eff,i} - \zeta_{eff,3} }{\zeta_{eff,3}} \leq 0.10$ |

Figure 4 shows the variation of K_{eff} and ζ_{eff} of the cyclic tests of **Errore. L'origine riferimento non è stata trovata.** for different amplitudes. Disregarding the first cycle, both $K_{eff,3}$ and $\zeta_{eff,3}$ respect the stability requirements, with the maximum variations of 9.9% in K_{eff} and of 2.4% in ζ_{eff} in the most challenging test sequence at the design deflection d_{bd} , which highlight the stable and predictable behavior of this system. The average value of $\zeta_{eff,3}$ over 10 cycles performed at the design seismic displacement d_{bd} is 0.55, which is close to the maximum theoretical value of 0.63, confirming the excellent dissipation capacity of the PS-LED. Indeed, for standard buckling-restrained steel hysteretic dampers made of mild steel, the equivalent viscous damping ratio generally lies in the range of 20% to 40%, depending on the geometry and the design deflection (Sina et al., 2021; Tonon et al., 2013; Sitler et al. 2020). In the ramp test, the prototype was able to sustain the amplified design deflection $\gamma_x \gamma_b d_{bd}$ without any cracking, demonstrating the ability of the device to accommodate the prescribed displacement without any mechanical damage or deterioration of its stiffness.

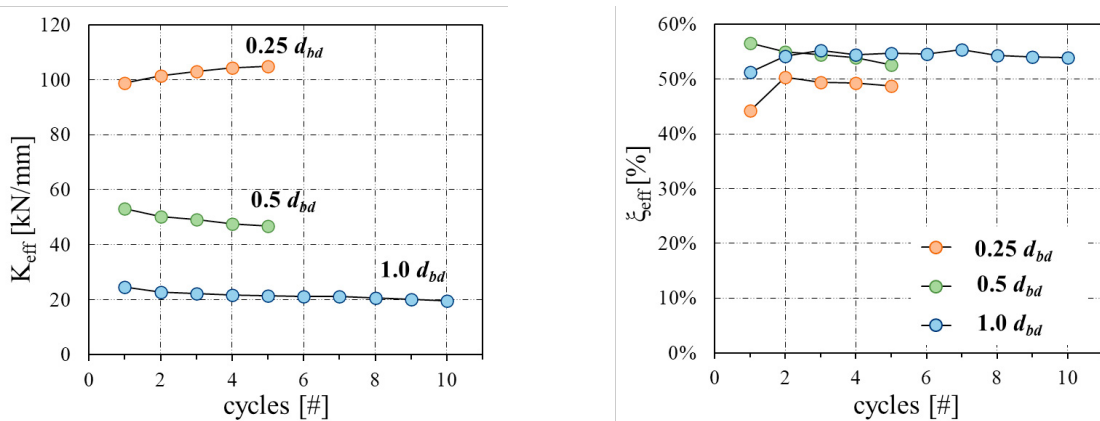


Figure 4: Plots of effective stiffness K_{eff} and equivalent viscous damping ζ_{eff} of the PS-LED vs. number of cycles at different deflection amplitudes d_{bd}

Eventually, at the end of the testing protocol according to EN 15129, the prototype was subjected to three sequences of 10 cycles each at the design displacement $d_{bd} = 10$ mm, with a 1 hour dwell between two consecutive sequences. The lead core was prestressed before the first sequence only, and the device was not re-centered after each sequence, thereby simulating the situation of a damper installed in a structure subjected to repeated ground shakes occurring in a short time. The mechanical response of the damper, shown in Figure 5, is stable and predictable, showing no substantial change in stiffness or output force throughout the sequences of loading.

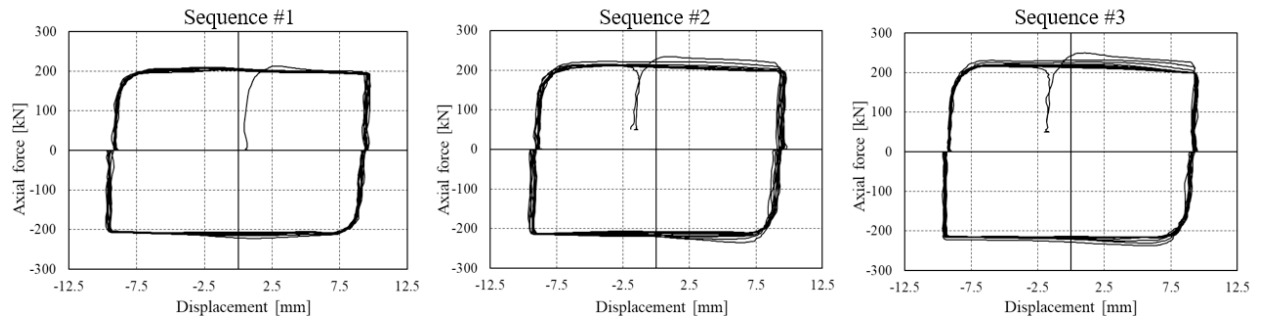


Figure 5: Sequence of tests at the design displacement d_{bd}

4. Conclusions

In this work a new energy dissipation device, the PS-LED, has been experimentally investigated according to the provisions of the European standard EN 15129 for Displacement Dependent Devices. The main outcomes are reported hereinafter:

- 1) the device is characterized by an essentially rigid–plastic behaviour, with an equivalent viscous damping ratio $\xi_{eff} = 55\%$, independent of the maximum cyclic displacement;
- 2) the prototype has shown a stable and predictable mechanical response over a series of cycles with an amplitude equal to the design seismic displacement, respecting the limits of variation prescribed in the European standard;
- 3) the tested PS-LED has been able to sustain multiple sequences of motion at the basic design earthquake displacement, demonstrating the ability to provide maintenance-free operation even in presence of repeated ground shakes.

In conclusion, the novel PS-LED represents an emerging technology which is potentially suitable to overcome the main limits that affect current supplementary energy dissipation devices. In particular, its ability to accommodate several strong motions at the design level without being damaged, and its high damping capability coupled to a compact design and low manufacturing cost, are the distinctive features that make it suitable for social housing. A prototype with 220 kN capacity has been tested so far; in the next future the experimental campaign will be extended to other prototypes with different dimensions.

A last important development concerns the design of the installation of the LED device within the building; in fact, since the PS-LED damper is characterized by a compact size, a further improvement will investigate the installation of the device in low invasiveness locations, such as at the beam-column connections, in order to adapt the retrofit system to the building layout and reduce the construction work.

Acknowledgements

The authors wish to thank Mr. Roberto Minerva and the Materials Testing Laboratory of the Politecnico di Milano for making the experimental equipment available and Mr. Giacomo Vazzana for assistance during the execution of the tests.

References

- Bruschi, E., Macobatti, F., Pettorosso, C., Quaglini, V., 2020. Characterization and numerical assessment of Lead Extrusion Damper with adaptive behavior. 17th World Conference on Earthquake Engineering, Sendai, Japan, 27 September–2 October 2020.
- Bruschi, E., 2021. Seismic Retrofit of RC Framed Buildings with Supplementary Energy Dissipation: Modelling and Application of a Novel Lead Damper. PhD Thesis, Politecnico di Milano, Milan, Italy.
- CEN (European Committee for Standardization). European Committee for Standardization (2009). EN 15129. Anti-seismic devices. Brussels.
- Mander, T.J., Rodgers, G.W., Chase, J.G., Mander, J.B., MacRae, G.A., 2009. A damage avoidance design steel beam-column moment connection using High-Force-To-Volume dissipators. *Journal of Structural Engineering* 135(11), 1390-1397.
- Patel, C.C., 2017. Seismic analysis of parallel structures coupled by lead extrusion dampers. *International Journal of Advanced Structural*

- Engineering 9, 177-190.
- Pettoroso, C., Quaglini, V., Bruschi, E., 2021. Supplemental energy dissipation with prestressed Lead Extrusion Dampers (P-LED): Experiments and modeling. COMPDYN 2021, The 8th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Athens, Greece, 28–30 June 2021.
- Quaglini, V., Pettoroso, C., Bruschi, E., 2021. Experimental and numerical assessment of prestressed lead extrusion dampers. International Journal of Earthquake Engineering 2021, Anno XXXVIII (2), 46-69.
- Quaglini, V., Bruschi, E., 2022. Controllo passivo mediante controventi dissipativi. Principi generali, requisiti normativi ed evoluzione dei principali dispositivi a comportamento dipendente dallo spostamento, Structural Magazine 240 – marzo/aprile 2022 – paper 09 – ISSN 2282-3794; DOI: 10.12917/STRU240.09.
- Quaglini, V., Pettoroso, C., Bruschi, E., 2022. Design and Experimental Assessment of a Prestressed Lead Damper with Straight Shaft for Seismic Protection of Structures. Geosciences 12(5), 182; DOI: 10.3390/geosciences12050182.
- Robinson, W.H., Greenbank, L.R., 1976. Extrusion energy absorber suitable for the protection of structures during an earthquake, Earthquake Engineering & Structural Dynamics 4(3), 251-259.
- Rodgers, G.W., Chase, J.G., Mander, J.B., Leach, N.C., Denmead, C.S., 2007a. Experimental development, tradeoff analysis and design implementation of high force-to-volume damping technology. Bulletin of the New Zealand National Society for Earthquake Engineering 40(2), 35-48.
- Rodgers, G.W., Mander, J.B., Chase, J.G., Dhakal, R.P., Solberg, K.M., 2007b. DAD post-tensioned concrete connections with lead dampers: analytical models and experimental validation. 8th Pacific Conference on Earthquake Engineering, Singapore.
- Rodgers, G.W., Solberg, K.M., Chase, J.G., Mander, J.B., Bradley, B.A., Dhakal, R.P., Li, L., 2008. Performance of a damage-protected beam-column subassembly utilizing external HF2V energy dissipation devices, Earthquake Engineering and Structural Dynamics 37(13), 1549-1564; DOI: 10.1002/eqe.830.
- Rodgers, G.W., 2009. Next generation structural technologies: implementing high force-to-volume energy absorbers Ph.D. Thesis, University of Canterbury, Christchurch, New Zealand.
- Rodgers, G.W., Chase, J.G., Mander, J.B., 2019. Repeatability and high-speed validation of supplemental lead-extrusion energy dissipation devices. Hindawi, Advances in Civil Engineering 2019(7935026).
- Sina, F., Amir, H.A., Lars, D., 2021. Equivalent viscous damping for buckling-restrained braced RC frame structures. Structures 34, 1229–1252.
- Sitler, B., Takeuchi, T., Matsui, R., Terashima, M., Terazawa, Y., 2020. Experimental investigation of a multistage buckling-restrained brace. Engineering Structures 213, 110482. DOI: 10.1016/j.engstruct.2020.110482.
- Soydan, C., Yüksel, E., İrtəm, E., 2015. The Behavior of a steel connection equipped with the Lead Extrusion Damper. Advances in Structural Engineering 17(1).
- Soydan, C., Yüksel, E., İrtəm, E., 2018. Retrofitting of pinned beam–column connections in RC precast frames using lead extrusion dampers. Bulletin of Earthquake Engineering 16 (1273).
- Tonon, E., Forte, M., Mammino, A., Moro, S., 2013. Protezione sismica degli edifici mediante dissipatori d'energia: Applicazione pratica della nuova sede della prefettura de L'Aquila. XV Conference of the Italian Association of Seismic Engineering ANIDIS, Padua, Italy, 30 June–4 July 2013.
- Yang, M.F., Xu, Z.D., Zhang, X.C., 2015. Experimental study on lead extrusion damper and its earthquake mitigation effects for large-span reticulated shell. Steel and Composite Structures 18(2), 481–496.